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THE ELEMENTS, HEAT, MASS, AND WEIGHT

The Elements — Symbols, Atomic Numbers and Weights, Melting Points

Name of Element	Sym bol	Atomic		Melting Point, °C
		Num.	Weight	
Actinium	Ac	89	227.028	1050
Aluminum	Al	13	26.9815	660.37
Americium	Am	95	(243)	994 ± 4
Antimony	Sb	51	121.75	630.74
Argon	A	18	39.948	−189.2
Arsenic	As	33	74.9216	817[a]
Astatine	At	85	(210)	302
Barium	Ba	56	137.33	725
Berkelium	Bk	97	(247)	…
Beryllium	Be	4	9.01218	1278 ± 5
Bismuth	Bi	83	208.980	271.3
Boron	B	5	10.81	2079
Bromine	Br	35	79.904	−7.2
Cadmium	Cd	48	112.41	320.9
Calcium	Ca	20	40.08	839 ± 2
Californium	Cf	98	(251)	…
Carbon	C	6	12.011	3652[c]
Cerium	Ce	58	140.12	798 ± 2
Cesium	Cs	55	132.9054	28.4 ± 0.01
Chlorine	Cl	17	35.453	−100.98
Chromium	Cr	24	51.996	1857 ± 20
Cobalt	Co	27	58.9332	1495
Copper	Cu	29	63.546	1083.4 ± 0.2
Curium	Cm	96	(247)	1340 ± 40
Dysprosium	Dy	66	162.5	1409
Einsteinium	Es	99	(252)	…
Erbium	Er	68	167.26	1522
Europium	Eu	63	151.96	822 ± 5
Fermium	Fm	100	(257)	…
Fluorine	F	9	18.9984	−219.62
Francium	Fr	87	(223)	27[b]
Gadolinium	Gd	64	157.25	1311 ± 1
Gallium	Ga	31	69.72	29.78
Germanium	Ge	32	72.59	937.4
Gold	Au	79	196.967	1064.434
Hafnium	Hf	72	178.49	2227 ± 20
Helium	He	2	4.00260	−272.2[d]
Holmium	Ho	67	164.930	1470
Hydrogen	H	1	1.00794	−259.14
Indium	In	49	114.82	156.61
Iodine	I	53	126.905	113.5
Iridium	Ir	77	192.22	2410
Iron	Fe	26	55.847	1535
Krypton	Kr	36	83.80	−156.6
Lanthanum	La	57	138.906	920 ± 5
Lawrencium	Lw	103	(260)	…
Lead	Pb	82	207.2	327.502
Lithium	Li	3	6.941	180.54
Lutetium	Lu	71	174.967	1656 ± 5
Magnesium	Mg	12	24.305	648.8 ± 0.5
Manganese	Mn	25	54.9380	1244 ± 2
Mendelevium	Md	101	(258)	…
Mercury	Hg	80	200.59	−38.87
Molybdenum	Mo	42	95.94	2617
Neodymium	Nd	60	144.24	1010
Neon	Ne	10	20.1179	−248.67
Neptunium	Np	93	237.048	640 ± 1
Nickel	Ni	28	58.69	1453
Niobium	Nb	41	92.9064	2468 ± 10
Nitrogen	N	7	14.0067	−209.86
Nobelium	No	102	(259)	…
Osmium	Os	76	190.2	3045 ± 30
Oxygen	O	8	15.9994	−218.4
Palladium	Pd	46	106.42	1554
Phosphorus	P	15	30.9738	44.1
Platinum	Pt	78	195.08	1772
Plutonium	Pu	94	(244)	641
Polonium	Po	84	(209)	254
Potassium	K	19	39.0938	63.25
Praseodymium	Pr	59	140.908	931 ± 4
Promethium	Pm	61	(145)	1080[b]
Protactinium	Pa	91	231.0359	1600
Radium	Ra	88	226.025	700
Radon	Rn	86	(222)	−71
Rhenium	Re	75	186.207	3180
Rhodium	Rh	45	102.906	1965 ± 3
Rubidium	Rb	37	85.4678	38.89
Ruthenium	Ru	44	101.07	2310
Samarium	Sm	62	150.36	1072 ± 5
Scandium	Sc	21	44.9559	1539
Selenium	Se	34	78.96	217
Silicon	Si	14	28.0855	1410
Silver	Ag	47	107.868	961.93
Sodium	Na	11	22.9898	97.81 ± 0.03
Strontium	Sr	38	87.62	769
Sulfur	S	16	32.06	112.8
Tantalum	Ta	73	180.9479	2996
Technetium	Tc	43	(98)	2172
Tellurium	Te	52	127.60	449.5 ± 0.3
Terbium	Tb	65	158.925	1360 ± 4
Thallium	Tl	81	204.383	303.5
Thorium	Th	90	232.038	1750
Thulium	Tm	69	168.934	1545 ± 15
Tin	Sn	50	118.71	231.9681
Titanium	Ti	22	47.88	1660 ± 10
Tungsten	W	74	183.85	3410 ± 20
Unnilhexium	Unh	106	(266)	…
Unnilnonium	Unn	109	(266)	…
Unniloctium	Uno	108	(265)	…
Unnilpentium	Unp	105	(262)	…
Unnilquadium	Unq	104	(261)	…
Unnilseptium	Uns	107	(261)	…
Uranium	U	92	238.029	1132 ± 0.8
Vanadium	V	23	50.9415	1890 ± 10
Xenon	Xe	54	131.29	−111.9
Ytterbium	Yb	70	173.04	824 ± 5
Yttrium	Y	39	88.9059	1523 ± 8
Zinc	Zn	30	65.39	419.58
Zirconium	Zr	40	91.224	1852 ± 2

[a] At 28 atm.

[b] Approximate.

[c] Sublimates.

[d] At 26 atm.

Notes: Values in parentheses are atomic weights of the most stable known isotopes. Melting points at standard pressure except as noted.

Heat and Combustion Related Properties

Latent Heat.—When a body changes from the solid to the liquid state or from the liquid to the gaseous state, a certain amount of heat is used to accomplish this change. This heat does not raise the temperature of the body and is called latent heat. When the body changes again from the gaseous to the liquid, or from the liquid to the solid state, it gives out this quantity of heat. The *latent heat of fusion* is the heat supplied to a solid body at the melting point; this heat is absorbed by the body although its temperature remains nearly stationary during the whole operation of melting. The *latent heat of evaporation* is the heat that must be supplied to a liquid at the boiling point to transform the liquid into a vapor. The latent heat is generally given in British thermal units per pound. When it is said that the latent heat of evaporation of water is 966.6, this means that it takes 966.6 heat units to evaporate 1 pound of water after it has been raised to the boiling point, 212°F.

When a body changes from the solid to the gaseous state without passing through the liquid stage, as solid carbon dioxide does, the process is called *sublimation*.

Latent Heat of Fusion

Substance	Btu per Pound	Substance	Btu per Pound	Substance	Btu per Pound
Bismuth	22.75	Paraffine	63.27	Sulfur	16.86
Beeswax	76.14	Phosphorus	9.06	Tin	25.65
Cast iron, gray	41.40	Lead	10.00	Zinc	50.63
Cast iron, white	59.40	Silver	37.92	Ice	144.00

Latent Heat of Evaporation

Liquid	Btu per Pound	Liquid	Btu per Pound	Liquid	Btu per Pound
Alcohol, ethyl	371.0	Carbon Bisulfide	160.0	Turpentine	133.0
Alcohol, methyl	481.0	Ether	162.8	Water	966.6
Ammonia	529.0	Sulfur dioxide	164.0		

Boiling Points of Various Substances at Atmospheric Pressure

Substance	Boiling Point, °F	Substance	Boiling Point, °F	Substance	Boiling Point, °F
Aniline	363	Chloroform	140	Saturated brine	226
Alcohol	173	Ether	100	Sulfur	833
Ammonia	−28	Linseed oil	597	Sulfuric acid	590
Benzine	176	Mercury	676	Water, pure	212
Bromine	145	Napthaline	428	Water, sea	213.2
Carbon bisulfide	118	Nitric acid	248	Wood alcohol	150
		Oil of turpentine	315		

Specific Heat.—The specific heat of a substance is the ratio of the heat required to raise the temperature of a certain weight of the given substance 1°F to that required to raise the temperature of the same weight of water 1 degree. As the specific heat is not constant at all temperatures, it is generally assumed that it is determined by raising the temperature from 62 to 63°F. For most substances, however, specific heat is practically constant for temperatures up to 212°F.

Average Specific Heats (Btu/lb-°F) of Various Substance

Substance	Specific Heat	Substance	Specific Heat
Alcohol (absolute)	0.700	Kerosene	0.500
Alcohol (density 0.8)	0.622	Lead	0.031
Aluminum	0.214	Limestone	0.217
Antimony	0.051	Magnesia	0.222
Benzine	0.450	Marble	0.210
Brass	0.094	Masonry, brick	0.200
Brickwork	0.200	Mercury	0.033
Cadmium	0.057	Naphtha	0.310
Charcoal	0.200	Nickel	0.109
Chalk	0.215	Oil, machine	0.400
Coal	0.240	Oil, olive	0.350
Coke	0.203	Phosphorus	0.189
Copper, 32° to 212° F	0.094	Platinum	0.032
Copper, 32° to 572° F	0.101	Quartz	0.188
Corundum	0.198	Sand	0.195
Ether	0.503	Silica	0.191
Fusel oil	0.564	Silver	0.056
Glass	0.194	Soda	0.231
Gold	0.031	Steel, high carbon	0.117
Graphite	0.201	Steel, mild	0.116
Ice	0.504	Stone (generally)	0.200
Iron, cast	0.130	Sulfur	0.178
Iron, wrought, 32° to 212° F	0.110	Sulfuric acid	0.330
32° to 392° F	0.115	Tin	0.056
32° to 572° F	0.122	Turpentine	0.472
32° to 662° F	0.126	Water	1.000
Iron, at high temperatures:		Wood, fir	0.650
1382° to 1832° F	0.213	Wood, oak	0.570
1750° to 1840° F	0.218	Wood, pine	0.467
1920° to 2190° F	0.199	Zinc	0.095

Specific Heat of Gases (Btu/lb-°F)

Gas	Constant Pressure	Constant Volume	Gas	Constant Pressure	Constant Volume
Acetic acid	0.412	…	Chloroform	0.157	…
Air	0.238	0.168	Ethylene	0.404	0.332
Alcohol	0.453	0.399	Hydrogen	3.409	2.412
Ammonia	0.508	0.399	Nitrogen	0.244	0.173
Carbonic acid	0.217	0.171	Oxygen	0.217	0.155
Carbonic oxide	0.245	0.176	Steam	0.480	0.346
Chlorine	0.121	…			

Heat Loss from Uncovered Steam Pipes.—The loss of heat from a bare steam or hot-water pipe varies with the difference between the temperature inside the pipe and that of the surrounding air. The loss is 2.15 Btu per hour, per square foot of pipe surface, per degree F of temperature difference when the latter is 100 degrees; for a difference of 200 degrees, the loss is 2.66 Btu; for 300 degrees, 3.26 Btu; for 400 degrees, 4.03 Btu; for 500 degrees, 5.18 Btu. Thus, if the pipe area is 1.18 square feet per foot of length, and the temperature difference 300°F, the loss per hour per foot of length = 1.18 × 300 × 3.26 = 1154 Btu.

Values of Thermal Conductivity (*k*) and of Conductance (*C*) of Common Building and Insulating Materials

Type of Material	Thickness, in.	*k* or *C*[a]	Type of Material	Thick-ness, in.	*k* or *C*[a]	Max. Temp.,° F	Density, lb per cu. ft.	*k*[a]
BUILDING			BUILDING (*Continued*)					
Batt:	…	…	Siding:	…	…	…	…	…
Mineral Fiber	2–2¾	0.14	Metal[b]	Avg.	1.61	…	…	…
Mineral Fiber	3–3½	0.09	Wood, Med. Density	⁷⁄₁₆	1.49	…	…	…
Mineral Fiber	3½–6½	0.05	Stone:	…	…	…	…	…
Mineral Fiber	6–7	0.04	Lime or Sand	1	12.50	…	…	…
Mineral Fiber	8½	0.03	Wall Tile:	…	…	…	…	…
Block:	…	…	Hollow Clay, 1-Cell	4	0.9	…	…	…
Cinder	4	0.90	Hollow Clay, 2-Cell	8	0.54	…	…	…
Cinder	8	0.58	Hollow Clay, 3-Cell	12	0.40	…	…	…
Cinder	12	0.53	Hollow Gypsum	Avg.	0.7	…	…	…
Block:	…	…	INSULATING					
Concrete	4	1.40	Blanket, Mineral Fiber:	…	…	…	…	…
Concrete	8	0.90	Felt	…	…	400	3 to 8	0.26
Concrete	12	0.78	Rock or Slag	…	…	1200	6 to 12	0.26[c]
Board:	…	…	Glass	…	…	350	0.65	0.33
Asbestos Cement	¼	16.5	Textile	…	…	350	0.65	0.31
Plaster	½	2.22	Blanket, Hairfelt	…	…	180	10	0.29
Plywood	¾	1.07	Board, Block and Pipe	…	…	…	…	…
Brick:	…	…	Insulation:	…	…	…	…	…
Common	1	5.0	Amosite	…	…	1500	15 to 18	0.32[c]
Face	1	9.0	Asbestos Paper	…	…	700	30	0.40[c]
Concrete (poured)	1	12.0	Glass or Slag (for Pipe)	…	…	350	3 to 4	0.23
Floor:	…	…	Glass or Slag (for Pipe)	…	…	1000	10 to 15	0.33[c]
Wood Subfloor	¾	1.06	Glass, Cellular	…	…	800	9	0.40
Hardwood Finish	¾	1.47	Magnesia (85%)	…	…	600	11 to 12	0.35[c]
Tile	Avg.	20.0	Mineral Fiber	…	…	100	15	0.29
Glass:	…	…	Polystyrene, Beaded	…	…	170	1	0.28
Architectural	…	10.00	Polystyrene, Rigid	…	…	170	1.8	0.25
Mortar:	…	…	Rubber, Rigid Foam	…	…	150	4.5	0.22
Cement	1	5.0	Wood Felt	…	…	180	20	0.31
Plaster:	…	…	Loose Fill:	…	…	…	…	…
Sand	⅜	13.30	Cellulose	…	…	…	2.5 to 3	0.27
Sand and Gypsum	½	11.10	Mineral Fiber	…	…	…	2 to 5	0.28
Stucco	1	5.0	Perlite	…	…	…	5 to 8	0.37
Roofing:	…	…	Silica Aerogel	…	…	…	7.6	0.17
Asphalt Roll	Avg.	6.50	Vermiculite	…	…	…	7 to 8.2	0.47
Shingle, asb. cem.	Avg.	4.76	Mineral Fiber Cement:	…	…	…	…	…
Shingle, asphalt	Avg.	2.27	Clay Binder	…	…	1800	24 to 30	0.49[c]
Shingle, wood	Avg.	1.06	Hydraulic Binder	…	…	1200	30 to 40	0.75[c]

[a] Units are in Btu/hr-ft^2-°F. Where thickness is given as 1 inch, the value given is thermal conductivity (k); for other thicknesses the value given is thermal conductance (C). All values are for a test mean temperature of 75°F, except those designated with [c], which are for 100°F.

[b] Over hollowback sheathing.

[c] Test mean temperature 100°F, see footnote [a] .

Source: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.: *Handbook of Fundamentals.*

Linear Expansion of Various Substances between 32 and 212°F
Expansion of volume = 3 × linear expansion

Substance	Linear Expansion for 1°F	Substance	Linear Expansion for 1°F
Brick	0.0000030	Masonry, brick from	0.0000026
Cement, Portland	0.0000060	to	0.0000050
Concrete	0.0000080	Plaster	0.0000092
Ebonite	0.0000428	Porcelain	0.0000020
Glass, thermometer	0.0000050	Quartz, from	0.0000043
Glass, hard	0.0000040	to	0.0000079
Granite	0.0000044	Slate	0.0000058
Marble, from	0.0000031	Sandstone	0.0000065
to	0.0000079	Wood, pine	0.0000028

Coefficients of Heat Transmission

Metal	Btu per Second	Metal	Btu per Second	Metal	Btu per Second
Aluminum	0.00203	German silver	0.00050	Steel, soft	0.00062
Antimony	0.00022	Iron	0.00089	Silver	0.00610
Brass, yellow	0.00142	Lead	0.00045	Tin	0.00084
Brass, red	0.00157	Mercury	0.00011	Zinc	0.00170
Copper	0.00404	Steel, hard	0.00034	…	…

Heat transmitted, in British thermal units, per second, through metal 1 inch thick, per square inch of surface, for a temperature difference of 1°F

Coefficients of Heat Radiation

Surface	Btu per Hour	Surface	Btu per Hour
Cast-iron, new	0.6480	Sawdust	0.7215
Cast-iron, rusted	0.6868	Sand, fine	0.7400
Copper, polished	0.0327	Silver, polished	0.0266
Glass	0.5948	Tin, polished	0.0439
Iron, ordinary	0.5662	Tinned iron, polished	0.0858
Iron, sheet-, polished	0.0920	Water	1.0853
Oil	1.4800	…	…

Heat radiated, in British thermal units, per square foot of surface per hour, for a temperature difference of 1° F

Freezing Mixtures

Mixture	Temperature Change,°F	
	From	To
Common salt (NaCl), 1 part; snow, 3 parts	32	±0
Common salt (NaCl), 1 part; snow, 1 part	32	−0.4
Calcium chloride ($CaCl_2$), 3 parts; snow, 2 parts	32	−27
Calcium chloride ($CaCl_2$), 2 parts; snow, 1 part	32	−44
Sal ammoniac (NH_4Cl), 5 parts; saltpeter (KNO_3), 5 parts; water,16 parts	50	+10
Sal ammoniac (NH_4Cl), 1 part; saltpeter (KNO_3), 1 part; water,1 part	46	−11
Ammonium nitrate (NH_4NO_3), 1 part; water, 1 part	50	+3
Potassium hydrate (KOH), 4 parts; snow, 3 parts	32	−35

Ignition Temperatures.—The following temperatures are required to ignite the different substances specified: Phosphorus, transparent, 120°F; bi sulfide of carbon, 300°F; gun cotton, 430°F; nitro-glycerine, 490°F; phosphorus, amorphous, 500°F; rifle powder, 550°F; charcoal, 660°F; dry pine wood, 800°F; dry oak wood, 900°F.

Typical Thermal Properties of Various Metals

Material and Alloy Designation[a]	Density, ρ lb/in^3	Melting Point, °F		Conductivity, k, Btu/hr-ft-°F	Specific Heat, C, Btu/lb/°F	Coef. of Expansion, α µin./in.-°F
		solidus	liquidus			
Aluminum Alloys						
2011	0.102	995	1190	82.5	0.23	12.8
2017	0.101	995	1185	99.4	0.22	13.1
2024	0.100	995	1180	109.2	0.22	12.9
3003	0.099	1190	1210	111	0.22	12.9
5052	0.097	1100	1200	80	0.22	13.2
5086	0.096	1085	1185	73	0.23	13.2
6061	0.098	1080	1200	104	0.23	13.0
7075	0.101	890	1180	70	0.23	13.1
Copper-Base Alloys						
Manganese Bronze	0.302	1590	1630	61	0.09	11.8
C11000 (Electrolytic tough pitch)	0.321	1941	1981	226	0.09	9.8
C14500 (Free machining Cu)	0.323	1924	1967	205	0.09	9.9
C17200, C17300 (Beryllium Cu)	0.298	1590	1800	62	0.10	9.9
C18200 (Chromium Cu)	0.321	1958	1967	187	0.09	9.8
C18700 (Leaded Cu)	0.323	1750	1975	218	0.09	9.8
C22000 (Commercial bronze, 90%)	0.318	1870	1910	109	0.09	10.2
C23000 (Red brass, 85%)	0.316	1810	1880	92	0.09	10.4
C26000 (Cartridge brass, 70%)	0.313	1680	1750	70	0.09	11.1
C27000 (Yellow brass)	0.306	1660	1710	67	0.09	11.3
C28000 (Muntz metal, 60%)	0.303	1650	1660	71	0.09	11.6
C33000 (Low-leaded brass tube)	0.310	1660	1720	67	0.09	11.2
C35300 (High-leaded brass)	0.306	1630	1670	67	0.09	11.3
C35600 (Extra-high-leaded brass)	0.307	1630	1660	67	0.09	11.4
C36000 (Free machining brass)	0.307	1630	1650	67	0.09	11.4
C36500 (Leaded Muntz metal)	0.304	1630	1650	71	0.09	11.6
C46400 (Naval brass)	0.304	1630	1650	67	0.09	11.8
C51000 (Phosphor bronze, 5% A)	0.320	1750	1920	40	0.09	9.9
C54400 (Free cutting phos. bronze)	0.321	1700	1830	50	0.09	9.6
C62300 (Aluminum bronze, 9%)	0.276	1905	1915	31.4	0.09	9.0
C62400 (Aluminum bronze, 11%)	0.269	1880	1900	33.9	0.09	9.2
C63000 (Ni-Al bronze)	0.274	1895	1930	21.8	0.09	9.0
Nickel-Silver	0.314	1870	2030	17	0.09	9.0
Nickel-Base Alloys						
Nickel 200, 201, 205	0.321	2615	2635	43.3	0.11	8.5
Hastelloy C-22	0.314	2475	2550	7.5	0.10	6.9
Hastelloy C-276	0.321	2415	2500	7.5	0.10	6.2
Inconel 718	0.296	2300	2437	6.5	0.10	7.2
Monel	0.305	2370	2460	10	0.10	8.7
Monel 400	0.319	2370	2460	12.6	0.10	7.7
Monel K500	0.306	2400	2460	10.1	0.10	7.6
Monel R405	0.319	2370	2460	10.1	0.10	7.6

Typical Thermal Properties of Various Metals *(Continued)*

Material and Alloy Designation[a]	Density, ρ lb/in^3	Melting Point, °F		Conductivity, *k*, Btu/hr-ft-°F	Specific Heat, *C*, Btu/lb/°F	Coef. of Expansion, α µin./in.-°F
		solidus	liquidus			
Stainless Steels						
S30100	0.290	2550	2590	9.4	0.12	9.4
S30200, S30300, S30323	0.290	2550	2590	9.4	0.12	9.6
S30215	0.290	2500	2550	9.2	0.12	9.0
S30400, S30500	0.290	2550	2650	9.4	0.12	9.6
S30430	0.290	2550	2650	6.5	0.12	9.6
S30800	0.290	2550	2650	8.8	0.12	9.6
S30900, S30908	0.290	2550	2650	9.0	0.12	8.3
S31000, S31008	0.290	2550	2650	8.2	0.12	8.8
S31600, S31700	0.290	2500	2550	9.4	0.12	8.8
S31703	0.290	2500	2550	8.3	0.12	9.2
S32100	0.290	2550	2600	9.3	0.12	9.2
S34700	0.290	2550	2650	9.3	0.12	9.2
S34800	0.290	2550	2650	9.3	0.12	9.3
S38400	0.290	2550	2650	9.4	0.12	9.6
S40300, S41000, S41600, S41623	0.280	2700	2790	14.4	0.11	5.5
S40500	0.280	2700	2790	15.6	0.12	6.0
S41400	0.280	2600	2700	14.4	0.11	5.8
S42000, S42020	0.280	2650	2750	14.4	0.11	5.7
S42200	0.280	2675	2700	13.8	0.11	6.2
S42900	0.280	2650	2750	14.8	0.11	5.7
S43000, S43020, S43023	0.280	2600	2750	15.1	0.11	5.8
S43600	0.280	2600	2750	13.8	0.11	5.2
S44002, S44004	0.280	2500	2700	14.0	0.11	5.7
S44003	0.280	2500	2750	14.0	0.11	5.6
S44600	0.270	2600	2750	12.1	0.12	5.8
S50100, S50200	0.280	2700	2800	21.2	0.11	6.2
Cast Iron and Steel						
Malleable Iron, A220 (50005, 60004, 80002)	0.265	liquidus approximately, 2100 to 2200, depending on composition		29.5	0.12	7.5
Grey Cast Iron	0.25			28.0	0.25	5.8
Ductile Iron, A536 (120–90–02)	0.25				0.16	5.9–6.2
Ductile Iron, A536 (100–70–03)	0.25			20.0	0.16	5.9–6.2
Ductile Iron, A536 (80–55–06)	0.25			18.0	0.15	5.9–6.2
Ductile Iron, A536 (65–45–120)	0.25			20.8	0.15	5.9–6.2
Ductile Iron, A536 (60–40–18)	0.25				0.12	5.9–6.2
Cast Steel, 3%C	0.25	liquidus, 2640		28.0	0.12	7.0
Titanium Alloys						
Commercially Pure	0.163	3000	3040	9.0	0.12	5.1
Ti-5Al-2.5Sn	0.162	2820	3000	4.5	0.13	5.3
Ti-8Mn	0.171	2730	2970	6.3	0.19	6.0

[a] Alloy designations correspond to the AluminumAssociation numbers for aluminum alloys and to the unified numbering system (UNS) for copper and stainless steel alloys. A220 and A536 are ASTM specified irons.

Properties of Mass and Weight

Specific Gravity.—Specific gravity is a number indicating how many times a certain volume of a material is heavier than an equal volume of water. The density of water differs slightly at different temperatures, so the usual custom is to make comparisons on the basis that the water has a temperature of 62°F. The weight of 1 cubic inch of pure water at 62°F is 0.0361 pound. If the specific gravity of any material is known, the weight of a cubic inch of the material, therefore, can be found by multiplying its specific gravity by 0.0361.

Example: The specific gravity of cast iron is 7.2. Find the weight of 5 cubic inches of cast iron.

$$7.2 \times 0.0361 \times 5 = 1.2996 \text{ pounds}$$

To find the weight per cubic foot of a material, multiply the specific gravity by 62.355.

If the weight of a cubic inch of a material is known, the specific gravity is found by dividing the weight per cubic inch by 0.0361.

Example: The weight of a cubic inch of gold is 0.697 pound. Find the specific gravity.

$$0.697 \div 0.0361 = 19.31$$

If the weight per cubic foot of a material is known, the specific gravity is found by multiplying this weight by 0.01604.

Average Specific Gravity of Various Substances

Substance	Specific Gravity	Weight lb/ft^3	Substance	Specific Gravity	Weight lb/ft^3
ABS	1.05	66	Lead	11.4	711
Acrylic	1.19	74	Limestone	2.6	162
Aluminum bronze	7.8	486	Marble	2.7	168
Aluminum, cast	2.6	160	Masonry	2.4	150
Aluminum, wrought	2.7	167	Mercury	13.56	845.3
Asbestos	2.4	150	Mica	2.8	175
Asphaltum	1.4	87	Mortar	1.5	94
Borax	1.8	112	Nickel, cast	8.3	517
Brick, common	1.8	112	Nickel, rolled	8.7	542
Brick, fire	2.3	143	Nylon 6, Cast	1.16	73
Brick, hard	2.0	125	PTFE	2.19	137
Brick, pressed	2.2	137	Phosphorus	1.8	112
Brickwork, in cement	1.8	112	Plaster of Paris	1.8	112
Brickwork, in mortar	1.6	100	Platinum	21.5	1342
CPVC	1.55	97	Polycarbonate	1.19	74
Cement, Portland (set)	3.1	193	Polyethylene	0.97	60
Chalk	2.3	143	Polypropylene	0.91	57
Charcoal	0.4	25	Polyurethane	1.05	66
Coal, anthracite	1.5	94	Quartz	2.6	162
Coal, bituminous	1.3	81	Salt, common	…	48
Concrete	2.2	137	Sand, dry	…	100
Earth, loose	…	75	Sand, wet	…	125
Earth, rammed	…	100	Sandstone	2.3	143
Emery	4.0	249	Silver	10.5	656
Glass	2.6	162	Slate	2.8	175
Glass, crushed	…	74	Soapstone	2.7	168
Gold, 22 carat fine	17.5	1091	Steel	7.9	491
Gold, pure	19.3	1204	Sulfur	2.0	125
Granite	2.7	168	Tar, bituminous	1.2	75
Gravel	…	109	Tile	1.8	112
Gypsum	2.4	150	Trap rock	3.0	187
Ice	0.9	56	Water at 62°F	1.0	62.355
Iron, cast	7.2	447	White metal	7.3	457
Iron, wrought	7.7	479	Zinc, cast	6.9	429
Iron slag	2.7	168	Zinc, sheet	7.2	450

The weight per cubic foot is calculated on the basis of the specific gravity except for those substances that occur in bulk, heaped, or loose form. In these instances, only the weights per cubic foot are given because the voids present in representative samples make the values of the specific gravities inaccurate.

Specific Gravity of Gases.—The specific gravity of gases is the number that indicates their weight in comparison with that of an equal volume of air. The specific gravity of air is 1, and the comparison is made at 32°F.

Specific Gravity of Gases At 32°F

Gas	Sp. Gr.	Gas	Sp. Gr.	Gas	Sp. Gr.
Air	1.000	Ether vapor	2.586	Marsh gas	0.555
Acetylene	0.920	Ethylene	0.967	Nitrogen	0.971
Alcohol vapor	1.601	Hydrofluoric acid	2.370	Nitric oxide	1.039
Ammonia	0.592	Hydrochloric acid	1.261	Nitrous oxide	1.527
Carbon dioxide	1.520	Hydrogen	0.069	Oxygen	1.106
Carbon monoxide	0.967	Illuminating gas	0.400	Sulfur dioxide	2.250
Chlorine	2.423	Mercury vapor	6.940	Water vapor	0.623

1 cubic foot of air at 32°F and atmospheric pressure weighs 0.0807 pound.

Specific Gravity of Liquids.—The specific gravity of liquids is the number that indicates how much a certain volume of the liquid weighs compared with an equal volume of water, the same as with solid bodies. The density of liquid is often expressed in degrees on the hydrometer, an instrument for determining the density of liquids, provided with graduations made to an arbitrary scale. The hydrometer consists of a glass tube with a bulb at one end containing air, and arranged with a weight at the bottom so as to float in an upright position in the liquid, the density of which is to be measured. The depth to which the hydrometer sinks in the liquid is read off on the graduated scale. The most commonly used hydrometer is the Baumé. The value of the degrees of the Baumé scale differs according to whether the liquid is heavier or lighter than water. The specific gravity for liquids heavier than water equals 145 ÷ (145 − degrees Baumé). For liquids lighter than water, the specific gravity equals 140 ÷ (130 + degrees Baumé).

Specific Gravity of Liquids

Liquid	Sp. Gr.	Liquid	Sp. Gr.	Liquid	Sp. Gr.
Acetic acid	1.06	Fluoric acid	1.50	Petroleum oil	0.82
Alcohol, commercial	0.83	Gasoline	0.70	Phosphoric acid	1.78
Alcohol, pure	0.79	Kerosene	0.80	Rape oil	0.92
Ammonia	0.89	Linseed oil	0.94	sulfuric acid	1.84
Benzine	0.69	Mineral oil	0.92	Tar	1.00
Bromine	2.97	Muriatic acid	1.20	Turpentine oil	0.87
Carbolic acid	0.96	Naphtha	0.76	Vinegar	1.08
Carbon di sulfide	1.26	Nitric acid	1.50	Water	1.00
Cotton-seed oil	0.93	Olive oil	0.92	Water, sea	1.03
Ether, sulfuric	0.72	Palm oil	0.97	Whale oil	0.92

Degrees on Baumé's Hydrometer Converted to Specific Gravity

	Specific Gravity			Specific Gravity			Specific Gravity	
Deg. Baumé	Liquids Heavier than Water	Liquids Lighter than Water	Deg. Baumé	Liquids Heavier than Water	Liquids Lighter than Water	Deg. Baumé	Liquids Heavier than Water	Liquids Lighter than Water
0	1.000	…	27	1.229	0.892	54	1.593	0.761
1	1.007	…	28	1.239	0.886	55	1.611	0.757
2	1.014	…	29	1.250	0.881	56	1.629	0.753
3	1.021	…	30	1.261	0.875	57	1.648	0.749
4	1.028	…	31	1.272	0.870	58	1.667	0.745
5	1.036	…	32	1.283	0.864	59	1.686	0.741
6	1.043	…	33	1.295	0.859	60	1.706	0.737
7	1.051	…	34	1.306	0.854	61	1.726	0.733
8	1.058	…	35	1.318	0.849	62	1.747	0.729
9	1.066	…	36	1.330	0.843	63	1.768	0.725
10	1.074	1.000	37	1.343	0.838	64	1.790	0.721
11	1.082	0.993	38	1.355	0.833	65	1.813	0.718
12	1.090	0.986	39	1.368	0.828	66	1.836	0.714
13	1.099	0.979	40	1.381	0.824	67	1.859	0.710
14	1.107	0.972	41	1.394	0.819	68	1.883	0.707
15	1.115	0.966	42	1.408	0.814	69	1.908	0.704
16	1.124	0.959	43	1.422	0.809	70	1.933	0.700
17	1.133	0.952	44	1.436	0.805	71	1.959	0.696
18	1.142	0.946	45	1.450	0.800	72	1.986	0.693
19	1.151	0.940	46	1.465	0.796	73	2.014	0.689
20	1.160	0.933	47	1.480	0.791	74	2.042	0.686
21	1.169	0.927	48	1.495	0.787	75	2.071	0.683
22	1.179	0.921	49	1.510	0.782	76	2.101	0.679
23	1.189	0.915	50	1.526	0.778	77	2.132	0.676
24	1.198	0.909	51	1.542	0.773	78	2.164	0.673
25	1.208	0.903	52	1.559	0.769	79	2.197	0.669
26	1.219	0.897	53	1.576	0.765	80	2.230	0.666

Average Weights and Volumes of Fuels.—The average weight of a bushel of charcoal is 20 pounds; of a bushel of coke, 40 pounds; of a bushel of anthracite coal, 67 pounds; and of a bushel of bituminous coal, 60 pounds.

Anthracite coal, 1 cubic foot = 55 to 65 pounds.

Anthracite coal, 1 ton (2240 pounds) = 34 to 41 cubic feet.

Bituminous coal, 1 cubic foot = 50 to 55 pounds.

Bituminous coal, 1 ton (2240 pounds) = 41 to 45 cubic feet.

Charcoal, 1 cubic foot = 18 to 18.5 pounds.

Charcoal, 1 ton (2240 pounds) = 120 to 124 cubic feet.

Coke, 1 cubic foot = 28 pounds.

Coke, 1 ton (2240 pounds) = 80 cubic feet.

Weight of Wood.—The weight of seasoned wood per cord is approximately as follows, assuming about 70 cubic feet of *solid wood* per cord: beech, 3300 pounds; chestnut, 2600 pounds; elm, 2900 pounds; maple, 3100 pounds; poplar, 2200 pounds; white pine, 2200 pounds; red oak, 3300 pounds; white oak, 3500 pounds.

Weight per Foot of Wood, Board Measure.—The following is the weight in pounds of various kinds of woods, commercially known as dry timber, per foot board measure: white oak, 4.16; white pine, 1.98; Douglas fir, 2.65; short-leaf yellow pine, 2.65; red pine, 2.60; hemlock, 2.08; spruce, 2.08; cypress, 2.39; cedar, 1.93; chestnut, 3.43; Georgia yellow pine, 3.17; California spruce, 2.08.

How to Estimate the Weight of Natural Piles.—To calculate the upper and lower limits of the weight of a substance piled naturally on a circular plate, so as to form a cone of material, use the equation:

$$W = MD^3 \tag{1}$$

where W = weight, lb; D = diameter of plate, ft. (Fig. 1a); and, M = materials factor, whose upper and lower limits are given in Table 1.

For a rectangular plate, calculate the weight of material piled naturally by means of the following equation:

$$W = MRA^3 \tag{2}$$

where A and B = the length and width in ft., respectively, of the rectangular plate in Fig. 1b, with $B \leq A$; and, R = is a rectangular factor given in Table 2 as a function of the ratio B/A.

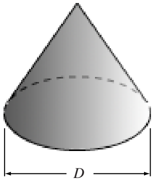


Fig. 1a. Conical Pile

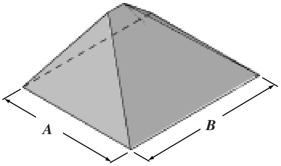


Fig. 1b. Rectangular Pile

Example 1: Find the upper and lower limits of the weight of dry ashes piled naturally on a plate 10 ft. in diameter.

Using Equation (1), $M = 4.58$ from Table 1, the lower limit $W = 4.58 \times 10^3 = 4{,}580$ lb. For $M = 5.89$, the upper limit $W = 5.89 \times 10^3 = 5{,}890$ lb.

Example 2: What weight of dry ashes rests on a rectangular plate 10 ft. by 5 ft.?

For $B/A = 5/10 = 0.5$, $R = 0.39789$ from Table 2. Using Equation (2), for $M = 4.58$, the lower limit $W = 4.58 \times 0.39789 \times 10^3 = 1{,}822$ lb. For $M = 5.89$, the upper limit $W = 5.89 \times 0.39789 \times 10^3 = 2{,}344$lb.

Table 1. Limits of Factor *M* for Various Materials

Material	Factor *M*	Material	Factor *M*	Material	Factor *M*
Aluminum chips	0.92-196	Cast-iron chips	17.02-26.18	Potassium carbonate	3.85-6.68
Aluminum silicate	3.70-6.41	Cinders, coal	3.02-5.24	Potassium sulfate	5.50-6.28
Ammonium chloride	3.93-6.81	Coal, anthracite, chestnut	2.43	Saltpeter	6.05-10.47
Asbestos, shred	2.62-3.27	Coal, ground	2.90	Salt rock, crushed	4.58
Ashes, dry	4.58-5.89	Coke, pulverized	2.21	Sand, very fine	7.36-9.00
Ashes, damp	6.24-7.80	Copper oxide, powdered	20.87	Sawdust, dry	0.95-2.85
Asphalt, crushed	3.4-5.89	Cork, granulated	1.57-1.96	Sodium nitrate	3.96-4.66
Bakelite, powdered	3.93-5.24	Dicalcium phosphate	5.63	Sodium sulfite	10.54
Baking powder	3.10-5.37	Fluorspar	10.73-14.40	Sodium sulfate	6.92
Barium carbonate	9.42	Graphite, flake	3.02-5.24	Sulfur	4.50-6.95
Boric acid	4.16-7.20	Lead silicate, granulated	25.26	Talcum powder	4.37-5.90
Bronze, chips	3.93-6.54	Lead sulfate, pulverized	24.09	Tin oxide, ground	9.17
Calcium lactate	3.40-3.80	Limestone, pulverized	8.84-10.02	Trisodium phosphate	4.53-7.85
Calcium oxide	3.30	Magnesium chloride	4.32	Wood chips, fir	2.49-2.88
Carbon, ground	2.51	Manganese sulfate	5.29-9.16	Zinc sulfate	8.85-11.12
Casein	2.72-4.71	Mica, ground	1.24-1.43		

Table 2. Factor R as a function of B/A ($B \le A$)

B/A	R	B/A	R	B/A	R	B/A	R
0.01	0.00019	0.26	0.11792	0.51	0.41231	0.76	0.82367
0.02	0.00076	0.27	0.12670	0.52	0.42691	0.77	0.84172
0.03	0.00170	0.28	0.13576	0.53	0.44170	0.78	0.85985
0.04	0.00302	0.29	0.14509	0.54	0.45667	0.79	0.87807
0.05	0.00470	0.30	0.15470	0.55	0.47182	0.80	0.89636
0.06	0.00674	0.31	0.16457	0.56	0.48713	0.81	0.91473
0.07	0.00914	0.32	0.17471	0.57	0.50262	0.82	0.93318
0.08	0.01190	0.33	0.18511	0.58	0.51826	0.83	0.95169
0.09	0.01501	0.34	0.19576	0.59	0.53407	0.84	0.97027
0.10	0.01846	0.35	0.20666	0.60	0.55004	0.85	0.98891
0.11	0.02226	0.36	0.21782	0.61	0.56616	0.86	1.00761
0.12	0.02640	0.37	0.22921	0.62	0.58243	0.87	1.02636
0.13	0.03088	0.38	0.24085	0.63	0.59884	0.88	1.04516
0.14	0.03569	0.39	0.25273	0.64	0.61539	0.89	1.06400
0.15	0.04082	0.40	0.26483	0.65	0.63208	0.90	1.08289
0.16	0.04628	0.41	0.27717	0.66	0.64891	0.91	1.10182
0.17	0.05207	0.42	0.28973	0.67	0.66586	0.92	1.12078
0.18	0.05817	0.43	0.30252	0.68	0.68295	0.93	1.13977
0.19	0.06458	0.44	0.31552	0.69	0.70015	0.94	1.15879
0.20	0.07130	0.45	0.32873	0.70	0.71747	0.95	1.17783
0.21	0.07833	0.46	0.34216	0.71	0.73491	0.96	1.19689
0.22	0.08566	0.47	0.35579	0.72	0.75245	0.97	1.21596
0.23	0.09329	0.48	0.36963	0.73	0.77011	0.98	1.23505
0.24	0.10121	0.49	0.38366	0.74	0.78787	0.99	1.25414
0.25	0.10942	0.50	0.39789	0.75	0.80572	1.00	1.27324

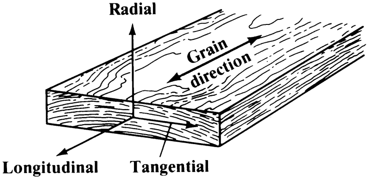
PROPERTIES OF WOOD, CERAMICS, PLASTICS, METALS, WATER, AND AIR

Properties of Wood

Mechanical Properties of Wood.—Wood is composed of cellulose, lignin, ash-forming minerals, and extractives formed into a cellular structure. (Extractives are substances that can be removed from wood by extraction with such solvents as water, alcohol, acetone, benzene, and ether.) Variations in the characteristics and volumes of the four components and differences in the cellular structure result in some woods being heavy and some light, some stiff and some flexible, and some hard and some soft. For a single species, the properties are relatively constant within limits; therefore, selection of wood by species alone may sometimes be adequate. However, to use wood most effectively in engineering applications, the effects of physical properties or specific characteristics must be considered.

The mechanical properties listed in the accompanying table were obtained from tests on small pieces of wood termed "clear" and "straight grained" because they did not contain such characteristics as knots, cross grain, checks, and splits. However, these test pieces did contain such characteristics as growth rings that occur in consistent patterns within the piece. Since wood products may contain knots, cross grain, etc., these characteristics must be taken into account when assessing actual properties or when estimating actual performance. In addition, the methods of data collection and analysis have changed over the years during which the data in the table have been collected; therefore, the appropriateness of the data should be reviewed when used for critical applications such as stress grades of lumber.

Wood is an orthotropic material; that is, its mechanical properties are unique and independent in three mutually perpendicular directions—longitudinal, radial, and tangential. These directions are illustrated in the following figure.



Modulus of Rupture: The modulus of rupture in bending reflects the maximum load-carrying capacity of a member and is proportional to the maximum moment borne by the member. The modulus is an accepted criterion of strength, although it is not a true stress because the formula used to calculate it is valid only to the proportional limit.

Work to Maximum Load in Bending: The work to maximum load in bending represents the ability to absorb shock with some permanent deformation and more or less injury to a specimen; it is a measure of the combined strength and toughness of the wood under bending stress.

Maximum Crushing Strength: The maximum crushing strength is the maximum stress sustained by a compression parallel-to-grain specimen having a ratio of length to least diameter of less than 11.

Compression Perpendicular to Grain: Strength in compression perpendicular to grain is reported as the stress at the proportional limit because there is no clearly defined ultimate stress for this property.

Shear Strength Parallel to Grain: Shear strength is a measure of the ability to resist internal slipping of one part upon another along the grain. The values listed in the table are averages of the radial and tangential shears.

Tensile Strength Perpendicular to Grain: The tensile strength perpendicular to the grain is a measure of the resistance of wood to forces acting across the grain that tend to split the material. Averages of radial and tangential measurements are listed.

Mechanical Properties of Commercially Important U.S. Grown Woods

Use the first number in each column for GREEN wood; use the second number for DRY wood.	Static Bending				Maximum Crushing Strength (10^3 psi)		Compression Strength Perpendicular to Grain (psi)		Shear Strength Parallel to Grain (psi)		Tensile Strength Perp. to Grain (psi)	
	Modulus of Rupture (10^3 psi)		Work to Max Load (in.-lb/in.^{3})									
Basswood, American	5.0	8.7	5.3	7.2	2.22	4.73	170	370	600	990	280	350
Cedar, N. white	4.2	6.5	5.7	4.8	1.90	3.96	230	310	620	850	240	240
Cedar, W. red	5.2	7.5	5.0	5.8	2.77	4.56	240	460	770	990	230	220
Douglas Fir, coast[a]	7.7	12.4	7.6	9.9	3.78	7.23	380	800	900	1,130	300	340
Douglas Fir, interior W.	7.7	12.6	7.2	10.6	3.87	7.43	420	760	940	1,290	290	350
Douglas Fir, interior N.	7.4	13.1	8.1	10.5	3.47	6.90	360	770	950	1,400	340	390
Douglas Fir, interior S.	6.8	11.9	8.0	9.0	3.11	6.23	340	740	950	1,510	250	330
Fir, balsam	5.5	9.2	4.7	5.1	2.63	5.28	190	404	662	944	180	180
Hemlock, Eastern	6.4	8.9	6.7	6.8	3.08	5.41	360	650	850	1,060	230	…
Hemlock, Mountain	6.3	11.5	11.0	10.4	2.88	6.44	370	860	930	1,540	330	…
Hemlock, Western	6.6	11.3	6.9	8.3	3.36	7.20	280	550	860	1,290	290	340
Pine, E. white	4.9	9.9	5.2	8.3	2.44	5.66	220	580	680	1,170	250	420
Pine, Virginia	7.3	13.0	10.9	13.7	3.42	6.71	390	910	890	1,350	400	380
Pine, W. white	4.7	9.7	5.0	8.8	2.43	5.04	190	470	680	1,040	260	…
Redwood, old-growth	7.5	10.0	7.4	6.9	4.20	6.15	420	700	800	940	260	240
Redwood, young-growth	5.9	7.9	5.7	5.2	3.11	5.22	270	520	890	1,110	300	250
Spruce, Engelmann	4.7	9.3	5.1	6.4	2.18	4.48	200	410	640	1,200	240	350
Spruce, red	6.0	10.8	6.9	8.4	2.72	5.54	260	550	750	1,290	220	350
Spruce, white	5.0	9.4	6.0	7.7	2.35	5.18	210	430	640	970	220	360

[a] Coast: grows west of the summit of the Cascade Mountains in OR and WA. Interior west: grows in CA and all counties in OR and WA east of but adjacent to the Cascade summit. Interior north: grows in remainder of OR and WA and ID, MT, and WY. Interior south: grows in UT, CO, AZ, and NM.

Results of tests on small, clear, straight-grained specimens. Data for dry specimens are from tests of seasoned material adjusted to a moisture content of 12%.

Source: U.S. Department of Agriculture: *Wood Handbook*.

Effect of Pressure Treatment on Mechanical Properties of Wood.—The strength of wood preserved with creosote, coal-tar, creosote-coal-tar mixtures, creosote-petroleum mixtures, or pentachlorophenol dissolved in petroleum oil is not reduced. However, waterborne salt preservatives contain chemicals such as copper, arsenic, chromium, and ammonia, which have the potential of affecting mechanical properties of treated wood and causing mechanical fasteners to corrode. Preservative salt-retention levels required for marine protection may reduce bending strength by 10 per cent or more.

Density of Wood.—The following formula can be used to find the density of wood in lb/ft^3 as a function of its moisture content.

$$\rho = 62.4\left(\frac{G}{1 + G \times 0.009 \times M}\right)\left(1 + \frac{M}{100}\right)$$

where ρ is the density, G is the specific gravity of wood, and M is the moisture content expressed in per cent.

Weights of American Woods, in Pounds per Cubic Foot (United States Department of Agriculture)

Species	Green	Airdry	Species	Green	Airdry
Alder, red	46	28	Hickory, pecan	62	45
Ash, black	52	34	Hickory, true	63	51
Ash, commercial white	48	41	Honeylocust	61	…
Ash, Oregon	46	38	Larch, western	48	36
Aspen	43	26	Locust, black	58	48
Basswood	42	26	Maple, bigleaf	47	34
Beech	54	45	Maple, black	54	40
Birch	57	44	Maple, red	50	38
Birch, paper	50	38	Maple, silver	45	33
Cedar, Alaska	36	31	Maple, sugar	56	44
Cedar, eastern red	37	33	Oak, red	64	44
Cedar, northern white	28	22	Oak, white	63	47
Cedar, southern white	26	23	Pine, lodgepole	39	29
Cedar, western red	27	23	Pine, northern white	36	25
Cherry, black	45	35	Pine, Norway	42	34
Chestnut	55	30	Pine, ponderosa	45	28
Cottonwood, eastern	49	28	Pines, southern yellow:		
Cottonwood, northern black	46	24	Pine, loblolly	53	36
Cypress, southern	51	32	Pine, longleaf	55	41
Douglas fir, coast region	38	34	Pine, shortleaf	52	36
Douglas fir, Rocky Mt. region	35	30	Pine, sugar	52	25
Elm, American	54	35	Pine, western white	35	27
Elm, rock	53	44	Poplar, yellow	38	28
Elm, slippery	56	37	Redwood	50	28
Fir, balsam	45	25	Spruce, eastern	34	28
Fir, commercial white	46	27	Spruce, Engelmann	39	23
Gum, black	45	35	Spruce, Sitka	33	28
Gum, red	50	34	Sycamore	52	34
Hemlock, eastern	50	28	Tamarack	47	37
Hemlock, western	41	29	Walnut, black	58	38

Machinability of Wood.—The ease of working wood with hand tools generally varies directly with the specific gravity of the wood; the lower the specific gravity, the easier the wood is to cut with a sharp tool. A rough idea of the specific gravity of various woods can be obtained from the preceding table by dividing the weight of wood in lb/ft^3 by 62.355.

A wood species that is easy to cut does not necessarily develop a smooth surface when it is machined. Three major factors, other than specific gravity, influence the smoothness of the surface obtained by machining: interlocked and variable grain, hard deposits in the grain, and reaction wood. Interlocked and variable grain is a characteristic of many tropical and some domestic species; this type of grain structure causes difficulty in planing quarter sawn boards unless careful attention is paid to feed rates, cutting angles, and sharpness of the knives. Hard deposits of calcium carbonate, silica, and other minerals in the grain tend to dull cutting edges quickly, especially in wood that has been dried to the usual in service moisture content. Reaction wood results from growth under some physical stress such as occurs in leaning trunks and crooked branches. Generally, reaction wood occurs as tension wood in hardwoods and as compression wood in softwoods. Tension wood is particularly troublesome, often resulting in fibrous and fuzzy surfaces, especially in woods of lower density. Reaction wood may also be responsible for pinching saw blades, resulting in burning and dulling of teeth.

The following table rates the suitability of various domestic hardwoods for machining. The data for each species represent the percentage of pieces machined that successfully met the listed quality requirement for the processes. For example, 62 per cent of the black walnut pieces planed came out perfect, but only 34 per cent of the pieces run on the shaper achieved good to excellent results.

Machinability and Related Properties of Various Domestic Hardwoods

	Planing	Shaping	Turning	Boring	Mortising	Sanding
	Quality Required					
Type of Wood	Perfect	Good to Excellent	Fair to Excellent	Good to Excellent	Fair to Excellent	Good to Excellent
Alder, red	61	20	88	64	52	…
Ash	75	55	79	94	58	75
Aspen	26	7	65	78	60	…
Basswood	64	10	68	76	51	17
Beech	83	24	90	99	92	49
Birch	63	57	80	97	97	34
Birch, paper	47	22	…	…	…	…
Cherry, black	80	80	88	100	100	…
Chestnut	74	28	87	91	70	64
Cottonwood	21	3	70	70	52	19
Elm, soft	33	13	65	94	75	66
Hackberry	74	10	77	99	72	…
Hickory	76	20	84	100	98	80
Magnolia	65	27	79	71	32	37
Maple, bigleaf	52	56	8	100	80	…
Maple, hard	54	72	82	99	95	38
Maple, soft	41	25	76	80	34	37
Oak, red	91	28	84	99	95	81
Oak, white	87	35	85	95	99	83
Pecan	88	40	89	100	98	…
Sweetgum	51	28	86	92	53	23
Sycamore	22	12	85	98	96	21
Tanoak	80	39	81	100	100	…
Tupelo, black	48	32	75	82	24	21
Tupelo, water	55	52	79	62	33	34
Walnut, black	62	34	91	100	98	…
Willow	52	5	58	71	24	24
Yellow-poplar	70	13	81	87	63	19

The data above represent the percentage of pieces attempted that meet the quality requirement listed.

Nominal and Minimum Sizes of Sawn Lumber

Type of Lumber	Thickness (inches)			Face Widths (inches)		
	Nominal, T_n	Dry	Green	Nominal, W_n	Dry	Green
Boards	1	$\frac{3}{4}$	$\frac{25}{32}$	2 to 4	$W_n - \frac{1}{2}$	$W_n - \frac{7}{16}$
	$1\frac{1}{4}$	1	$1\frac{1}{32}$	5 to 7	$W_n - \frac{1}{2}$	$W_n - \frac{3}{8}$
	$1\frac{1}{2}$	$1\frac{1}{4}$	$1\frac{9}{32}$	8 to 16	$W_n - \frac{3}{4}$	$W_n - \frac{1}{2}$
Dimension Lumber	2	$1\frac{1}{2}$	$1\frac{9}{16}$	2 to 4	$W_n - \frac{1}{2}$	$W_n - \frac{7}{16}$
	$2\frac{1}{2}$	2	$2\frac{1}{16}$	5 to 6	$W_n - \frac{1}{2}$	$W_n - \frac{3}{8}$
	3	$2\frac{1}{2}$	$2\frac{9}{16}$	8 to 16	$W_n - \frac{3}{4}$	$W_n - \frac{1}{2}$
	$3\frac{1}{2}$	3	$3\frac{1}{16}$	…	…	…
	4	$3\frac{1}{2}$	$3\frac{9}{16}$	…	…	…
	$4\frac{1}{2}$	4	$4\frac{1}{16}$	…	…	…
Timbers	5 and up	…	$T_n - \frac{1}{2}$	5 and up	…	$W_n - \frac{1}{2}$

Source: National Forest Products Association: *Design Values for Wood Construction*. Moisture content: dry lumber ≤ 19 percent; green lumber > 19 percent. Dimension lumber refers to lumber 2 to 4 inches thick (nominal) and 2 inches or greater in width. Timbers refers to lumber of approximately square cross-section, 5 × 5 inches or larger, and a width no more than 2 inches greater than the thickness.

Tabulated Properties of Ceramics, Plastics, and Metals

Material		Density[a] (lb/in.^{3})	Dielectric Strength (V/mil)	Coeff. of Expansion[b] (10^{-6} in./in.-°F)	Flexural Strength (10^3 psi)	Mohs's Hardness[c]	Operating Temperature (°F)	Tensile Strength (10^3 psi)	Compressive Strength (10^3 psi)	Thermal Conductivity[d] (Btu-ft-hr-ft^2-°F)
Machinable Glass Ceramic		0.09	1000	4.1–7.0		48 Ra	1472	…	50	0.85
		0.11	400	6	15	5.5	700	…	40	0.24
		0.10	380	5.2	14	5.0	1100	…	32	0.34
Glass-Mica	Machining-Grades{	0.09–0.10	400	10.5–11.2	12.5–13	90 Rh	750	6	40–45	0.24–0.29
		0.10	380	9.4	11	90 Rh	1100	5	32	0.34
	Molding Grades{	0.13–0.17	300–325	11–11.5	9–10	90 Rh	700–750	6–6.5	33–35	0.29–0.31
		0.14	350	10.3	9	90 Rh	1300	6	30	0.3
Aluminum Silicate		0.10	80	2.5	4.5	1–2	1000	…	12	0.92
		0.08	100	2.9	10	6.0	2100	…	25	0.75
Alumina Silicate		0.08	70	…	…	…	2370	…	…	0.38
Silica Foam		0.03	80	0.3	0.4	NA	2000	…	1.4	0.10
TiO_2 (Titania)		0.14	100	4.61	20	8	1800	7.5	100	…
Lava (Grade A)		0.08	80	1.83	9	6	2000	2.5	40	0.92
Zirconium Phosphate		0.11	NA	0.5	7.5	NA	2800	…	30	0.4 (approx.)
ZrO_2		0.21	…	6.1	102	1300 V	…	…	261	1.69
$ZrO_2 \cdot SiO_2$ (Zircon)		0.11	220	1.94	16	7.5	1825	10	90	…
$2MgO \cdot SiO_2$ (Forsterite)		0.11	240	5.56	20	7.5	1825	10	85	4.58
$MgO \cdot SiO_2$ (Steatite)		0.09–0.10	210–240	3.83–5.44	18–21	7.5	1825	8.5–10	80–90	3.17–3.42
$2MgO \cdot 2Al_2O_3 \cdot 5SiO_2$ (Cordierite)		0.06	60	0.33	3.4	6.5	2000	2.5	18.5	1.00
		0.08	100–172	1.22–1.28	8–12	7–7.5	2000	3.5–3.7	30–40	1.00
		0.09	200	1.33	15	8	2000	4	50	1.83
Al_2O_3 (Alumina)	94%	0.13	210	3.33	44	9	2700	20	315	16.00
	96%	0.13–0.14	210	3.5–3.7	48–60	9	2600–2800	25	375	20.3–20.7
	99.5%	0.14	200	3.72	70	9	2700	28	380	21.25
	99.9%	0.14	…	3.75	72	9	2900	…	400	…

[a] Obtain specific gravity by dividing density in lb/in.^{3} by 0.0361; for density in lb/ft^3, multiply lb/in.^{3} by 1728; for g/cm^3, multiply density in lb/in.^{3} by 27.68; for kg/m^3, multiply density in lb/in.^{3} by 27,679.9.

[b] To convert coefficient of expansion to 10^{-6} in./in.-°C, multiply table value by 1.8.

[c] Mohs's Hardness scale is used unless otherwise indicated as follows: Ra and Rh for Rockwell A and H scales, respectively; V for Vickers hardness.

[d] To convert conductivity from Btu-ft/hr-ft^2-°F to cal-cm/sec-cm^2-°C, divide by 241.9.

Typical Properties of Plastics Materials

Material	Density[a] (lb/in^3)	Specific Gravity	Dielectric Strength (V/mil)	Coeff. of Expansion[b] (10^{-6} in/in-°F)	Tensile Modulus (10^5 psi)	Izod Impact (ft-lb/in of notch)	Flexural Modulus (ksi at 73°F)	% Elongation	Hardness[c]	Max. Operating Temp. (°F)
ABS, Extrusion Grade	0.038	1.05	…	53.0	275	7	300	…	105 Rr	200
ABS, High Impact	0.037	1.03	…	…	200	…	330	…	105 Rr	…
Acetal, 20% Glass	0.056	1.55	…	…	1000	0.9	715	…	94 Rm	…
Acetal, Copolymer	0.051	1.41	380	47.0	437	2	400	13	94 Rm	…
Acetyl, Homopolymer	0.051	1.41	…	58.0	310	…	320	…	94 Rm	200
Acrylic	0.043	1.19	500	35.0	400	0.5	400	2.7	94 Rm	180
Azdel	0.043	1.19	500	15.0	750	14	800	2.1	94 Rm	311
CPVC	0.056	1.55	…	34.0	400	3	400	4	…	212
Fiber Glass Sheet	0.067	1.87	…	11.1	…	8	1	…	101 Rm	260
Nylon 6, 30% Glass	0.050	1.39	…	…	1350	2.8	1400	…	119 Rr	…
Nylon 6, Cast	0.042	1.16	295	45.0	380	1.4	450	20	100 Rr	210
Nylon 6⁄6, Cast	0.047	1.30	…	…	…	…	…	…	…	…
Nylon 6⁄6, Extruded	0.041	1.14	600	45.0	390	1	…	240	118 Rr	230
Nylon 60L, Cast	0.042	1.16	…	…	…	2.2	…	…	…	…
PET, unfilled	0.049	1.36	1300	39.0	500	0.5	400	70	…	230
PTFE (Teflon)	0.079	2.19	480	50.0	225	3	80	350	…	…
PVC	0.050	1.39	500	29.5	550	0.8	400	31–40	110 Rr	170
PVDF	0.064	1.77	260	60.0	320	3	200	80	100 Rr	180
Phenolics	0.050	1.38	…	11.1	…	2.4	1000	…	100 Rm	248
Polycarbonate	0.043	1.19	380	37.5	345	14	340	110	74 Rm	290
Polyetherimide	0.046	1.27	480	…	430	1.1	480	…	…	…
Polyethylene, HD	0.035	0.97	475	20.0	156	6	160	900	…	180
Polyethylene, UHMW	0.034	0.94	710	19.0	110	No Break	130	450	64 Rr	176
Polymethylpentene	0.030	0.83	…	…	220	2.5	…	…	…	…
Polymid, unfilled	0.051	1.41	560	…	300	1.5	…	…	…	…
Polyphenylene Sulfide	0.047	1.30	380	…	…	0.5	550	…	…	…
Polypropylene	0.033	0.91	600	96.0	155	0.75	200	120	92 Rr	150
Polysulfone	0.045	1.25	425	31.0	360	1.2	390	50	120 Rr	325
Polyurethane	0.038	1.05	…	…	…	…	…	465–520	…	…

[a] To obtain specific gravity, divide density in lb/in^3 by 0.0361; for density in lb/ft^3, multiply lb/in^3 by 1728; for g/cm^3, multiply density in lb/in^3 by 27.68; for kg/m^3, multiply density in lb/in^3 by 27,679.9.

[b] To convert coefficient of expansion to 10^{-6} in/in-°C, multiply table value by 1.8.

[c] Hardness value scales are as follows: Rm for Rockwell M scale; Rr for Rockwell R scale.

Mechanical Properties of Various Investment Casting Alloys

Alloy Designation	Material Condition	Tensile Strength (10^3 psi)	0.2% Yield Strength[a] (10^3 psi)	% Elonga-tion	Hardness
Aluminum					
356	As Cast	32–40	22–30	3–7	…
A356	As Cast	38–40	28–36	3–10	…
A357	As Cast	33–50	27–40	3–9	…
355, C355	As Cast	35–50	28–39	1–8	…
D712 (40E)	As Cast	34–40	25–32	4–8	…
A354	As Cast	47–55	36–45	2–5	…
RR-350	As Cast	32–45	24–38	1.5–5	…
Precedent 71	As Cast	35–55	25–45	2–5	…
KO-1	As Cast	56–60	48–55	3–5	…
Copper-Base Alloys[a]					
Al Bronze C (954)	As Cast	75–85	30–40	10–20	80–85 Rb
	Heat-Treated	90–105	45–55	6–10	91–96 Rb
Al Bronze D (955)	As Cast	90–100	40–50	6–10	91–96 Rb
	Heat-Treated	110–120	60–70	5–8	93–98 Rb
Manganese Bronze, A	…	65–75	25–40	16–24	60–65 Rb
Manganese Bronze, C	…	110–120	60–70	8–16	95–100 Rb
Silicon Bronze	…	45	18	20	…
Tin Bronze	…	40–50	18–30	20–35	40–50 Rb
Lead. Yellow Brass (854)	…	30–50	11–20	15–25	…
Red Brass	…	30–40	14–25	20–30	30–35 Rb
Silicon Brass	…	70	32	24	…
Pure Copper	…	20–30	…	4–50	35–42 Rb
Beryllium Cu 10C (820)	As Cast	45–50	40–45	15–20	50–55 Rb
	Hardened	90–100	90–130	3–8	90–95 Rb
Beryllium Cu 165C (824)	…	70–155	40–140	1–15	60 Rb–38 Rc
Beryllium Cu 20C (825)	As Cast	70–80	50–55	18–23	75–80 Rb
	Hardened	110–160	…	1–4	25–44 Rc
Beryllium Cu 275C (828)	As Cast	80–90	…	15–20	80–85 Rb
Chrome Copper	…	33–50	20–40	20–30	70–78 Rb
Carbon and Low-Alloy Steels and Iron					
IC 1010	Annealed	50–60	30–35	30–35	50–55 Rb
IC 1020	Annealed	60–70	40–45	25–40	80 Rb
IC 1030	Annealed	65–75	45–50	20–30	75 Rb
	Hardened	85–150	60–150	0–15	20–50 Rc
IC 1035	Annealed	70–80	45–55	20–30	80 Rb
	Hardened	90–150	85–150	0–15	25–52 Rc
IC 1045	Annealed	80–90	50–60	20–25	100 Rb
	Hardened	100–180	90–180	0–10	25–57 Rc
IC 1050	Annealed	90–110	50–65	20–25	100 Rb
	Hardened	125–180	100–180	0–10	30–60 Rc
IC 1060	Annealed	100–120	55–70	5–10	25 Rc
	Hardened	120–200	100–180	0–3	30–60 Rc
IC 1090	Annealed	110–150	70–80	12–20	30 Rc
IC 1090	Hardened	130–180	130–180	0–3	37–50 Rc
IC 2345	Hardened	130–200	110–180	5–10	30–58 Rc
IC 4130	Hardened	130–170	100–130	5–20	23–49 Rc
IC 4140	Hardened	130–200	100–155	5–20	29–57 Rc
IC 4150	Hardened	140–200	120–180	5–10	25–58 Rc
IC 4330	Hardened	130–190	100–175	5–20	25–48 Rc
IC 4340	Hardened	130–200	100–180	5–20	20–55 Rc
IC 4620	Hardened	110–150	90–130	10–20	20–32 Rc
IC 6150, IC 8740	Hardened	140–200	120–180	5–10	30–60 Rc
IC 8620	Hardened	100–130	80–110	10–20	20–45 Rc
IC 8630	Hardened	120–170	100–130	7–20	25–50 Rc
IC 8640	Hardened	130–200	100–180	5–20	30–60 Rc

Mechanical Properties of Various Investment Casting Alloys *(Continued)*

Alloy Designation	Material Condition	Tensile Strength (10^3 psi)	0.2% Yield Strength[a] (10^3 psi)	% Elongation	Hardness
Carbon and Low-Alloy Steels and Iron *(Continued)*					
IC 8665	Hardened	170–220	140–200	0–10	…
IC 8730	Hardened	120–170	110–150	7–20	…
IC 52100	Hardened	180–230	140–180	1–7	30–65 Rc
IC 1722AS	Hardened	130–170	100–140	6–12	25–48 Rc
1.2% Si Iron	…	50–60	37–43	30–35	55 Rb
Ductile Iron, Ferritic	Annealed	60–80	40–50	18–24	143–200 Bhn
Ductile Iron, Pearlitic	Normalized	100–120	70–80	3–10	243–303 Bhn
Hardenable Stainless Steel					
CA-15	Hardened	95–200	75–160	5–12	94 Rb–45 Rc
IC 416	Hardened	95–200	75–160	3–8	94 Rb–45 Rc
CA-40	Hardened	200–225	130–210	0–5	30–52 Rc
IC 431	Hardened	110–160	75–105	5–20	20–40 Rc
IC 17–4	Hardened	150–190	140–160	6–20	34–44 Rc
Am-355	Hardened	200–220	150–165	6–12	…
IC 15–5	Hardened	135–170	110–145	5–15	26–38 Rc
CD-4M Cu	Annealed	100–115	75–85	20–30	94–100 Rb
	Hardened	135–145	100–120	10–25	28–32 Rc
Austenitic Stainless Steels					
CF-3, CF-3M, CF-8, CF-8M, IC 316F	Annealed	70–85	40–50	35–50	90 Rb (max)
CF-8C	Annealed	70–85	32–36	30–40	90 Rb (max)
CF-16F	Annealed	65–75	30–35	35–45	90 Rb (max)
CF-20	Annealed	65–75	30–45	35–60	90 Rb (max)
CH-20	Annealed	70–80	30–40	30–45	90 Rb (max)
CN-7M	Annealed	65–75	25–35	35–45	90 Rb (max)
IC 321, CK-20	Annealed	65–75	30–40	35–45	90 Rb (max)
Nickel-Base Alloys					
Alloy B	Annealed	75–85	50–60	8–12	90–100 Rb
Alloy C	As Cast	80–95	45–55	8–12	90–100 Rb
	Annealed	75–95	45–55	8–12	90 Rb–25 Rc
Alloy X[b]	AC to 24°C	63–70	41–45	10–15	85–96 Rb
	AC to 816°C	35–45	…	12–20	…
Invar (Fe–Ni alloy)	As Cast	50–60	25–30	30–40	50–60 Rb
In 600 (Inconel)	As Cast	65–75	35–40	10–20	80–90 Rb
In 625 (Inconel)	Annealed	80–100	40–55	15–30	10–20 Rc
Monel 410	As Cast	65–75	32–38	25–35	65–75 Rb
S Monel	Annealed	100–110	55–65	5–10	20–28 Rc
	Hardened	120–140	85–100	0	32–38 Rc
RH Monel	As Cast	100–110	60–80	10–20	20–30 Rc
Monel E	As Cast	65–80	33–40	25–35	67–78 Rb
M-35 Monel	As Cast	65–80	25–35	25–40	65–85 Rb
Cobalt-Base Alloys					
Cobalt 21	As Cast	95–130	65–95	8–20	24–32 Rc
Cobalt 25	As Cast	90–120	60–75	15–25	20–25 Rc
Cobalt 31	As Cast	105–130	75–90	6–10	20–30 Rc
Cobalt 36	As Cast	90–105	60–70	15–20	30–36 Rc
F75	As Cast	95–110	70–80	8–15	25–34 Rc
N-155	Sol. Anneal	90–100	50–60	15–30	90–100 Rb

[a] For copper alloys, yield strength is determined by 0.5% extension under load or 0.2% offset method. A number in parentheses following a copper alloy indicates the UNS designation of that alloy (for example, Al Bronze C (954) identifies the alloy as UNS C95400).

[b] AC = air cooled to temperature indicated.

Source: Investment Casting Institute. Mechanical properties are average values of separately cast test bars, and are for reference only. Items marked … indicates data are not available. Alloys identified by IC followed by an SAE designation number (IC 1010 steel, for example) are generally similar to the SAE material although properties and chemical composition may be different.

Typical Properties of Compressed and Sintered Powdered Metal Alloys

Alloy Number[a] and Nominal Composition (%)		Density (g/cc)	Hardness	Strength (10^3 psi)			% Elongation
				Transverse Rupture	Ultimate Tensile	Yield	
Copper Base							
…	100Cu	7.7–7.9	81–82 Rh	54–68	24–34	…	10–26
CZP-3002	70Cu, 1.5Pb, Bal. Zn	8	75 Rh	…	33.9	…	24
CNZ-1818	63Cu, 17.5Ni, Bal. Zn	7.9	90 Rh	73	34	20	11
CTG-1004	10Sn, 4.4C, Bal. Cu	7	67 Rh	20	9.4	6.5	6
CTG-1001	10Sn, 1C, Bal. Cu	6.5	45 Rh	25.8	15.1	9.6	9.7
Iron Base (Balance of composition, Fe)							
FC-2015	23.5Cu, 1.5C	6.5	65 Rb	80	52.4	48.5	0
FC-0800	8Cu, 0.4C	6.3–6.8	39–55 Rb	75–100	38–54	32–47	1 or less
FX-2008	20Cu, 1C	7.3	93 Rb	164.2	72.3	57.7	2
FN-0408	4Ni, 1–2Cu, 0.75C	6.3–7	64–84 Rb	70–107	37–63	30–47	1–1.6
F-0000	100Fe	6.5	26 Rf	37.7	15.7	11	5.7
FN-0005	0.45C, 0.50 MnS	6.4–6.8	66–78 Rf	44–61	…	…	…
F-0000	0.02C, 0.45P	6.6–7.2	35–50 Rb	90–125	…	29–38	3.9–5.5
F-0008	0.6–0.9C	6.2–7	50–70 Rb	61–100	35–57	30–40	<0.5 to 1
FC-0508	0.6–0.9C, 4–6Cu	5.9–6.8	60–80 Rb	100–145	58–82	50–70	<0.5 to 1
FN-0405	4Ni, 0.5C	6.6–7.0	73–82 Rb	90–100	47–50	38–40	<1
FN-0208	2Ni, 0.8C	6.6–7.0	50–70 Rb	70–108	47–58	35–51	<1
FN-0205	2Ni, 0.5C	6.6–7.0	51–61 Rb	72–93	35–45	27–31	2.0–2.5
FN-0200	2Ni, 0.25C	6.6	29 Rb	57.5	25.8	19.0	1.3
FC-0208	2Cu, 0.75C	6.5–6.7	68–72 Rb	95–107	56–61	51–54	up to 1
FC-2008	20Cu, 1C	6.2	45 Rb	79.5	47.8	40.0	1.3
…	4Ni, 0.6C, 1.6Cu, 0.55Mo	7.0	92 Rb	190.0	100.0	65.0	2.5
FL-4605	1.8Ni, 0.6C, 1.6Cu, 0.55Mo	7.0	87 Rb	170.0	80.0	55.0	2.5
FL-4605	1.8Ni, 0.6C, 0.55Mo	7.0	80 Rb	150.0	…	…	…
SS-316L	17Cr, 13Ni, 2.2Mo, 0.9Si	6.5	65 Rb	94.0	45.0	30.0	6.0
…	17Cr, 13Ni, 2.2Mo, 0.9Si, 15–20Cu	7.3	66 Rb	108.6	59.2	49.7	4.3
SS-410	13Cr, 0.8Si, 0.8Mn	6.2	15 Rc	85.0	66.7	56.9	0
FL-4608	2Cu, 3.8Ni, 0.9C, 0.75Mo	6.8	24 Rc	107.3	55.8	46.5	1.5
SS-303N1	18Cr, 11Ni, 1Mn	6.4	62 Rb	86.0	39.0	32.0	0.5
SS-304N1	19Cr, 10Ni, 1Mn	6.4	61 Rb	112.0	43.0	38.0	0.5
Tungsten Base							
90W, 6Ni, 4Cu		17.0	24 Rc	…	110	80	6
90W, 7Ni, 3Cu		17.0	25 Rc	…	120	88	10
92.5W, 5.25Ni, 2.25Cu		17.5	26 Rc	…	114	84	7
92.5W, Bal. Ni, Fe, and Mo		17.6	30 Rc	…	120	90	4
93W, Bal. Ni, Fe, and Mo		17.7	32 Rc	…	125	95	4
95W, 3.5Ni, 1.5Cu		18.0	27 Rc	…	110	85	7
95W, 3.5Ni, 1.5Fe		18.0	27 Rc	…	120	90	7
97W, 2.1Ni, 0.9Fe		18.5	28 Rc	…	123	85	5

[a] Copper- and iron-base alloy designations are Metal Powder Industries Federation (MPIF) alloy numbers.

Typical Elastic Properties of Materials

Material	Modulus of Elasticity (10^6 psi)	Shear Modulus (10^6 psi)	Bulk Modulus (10^6 psi)	Poisson's Ratio
Aluminum, var. alloys	9.9–10.3	3.7–3.9	9.9–10.2	0.330–0.334
Aluminum, 6061-T6	10.2	3.8	…	0.35
Aluminum, 2024-T4	10.6	4.0	…	0.32
Beryllium copper	18	7	…	0.29
Brass, 70–30	15.9	6	15.7	0.331
Brass, cast	14.5	5.3	16.8	0.357
Bronze	14.9	6.5	…	0.14
Copper	15.6	5.8	17.9	0.355
Glass	6.7	2.7	…	0.24
Glass ceramic (machinable)	9.7	3.7	…	0.29
Inconel	31	11	…	0.27–0.38
Iron, cast	13.5–21.0	5.2–8.2	8.4–15.5	0.221–0.299
Iron, ductile	23.8–25.2	9.1–9.6	…	0.26–0.31
Iron, grey cast	14.5	6	…	0.211
Iron, malleable	23.6	9.3	17.2	0.271
Lead	5.3	1.9	…	0.43
Magnesium	6.5	2.4	…	0.35
Magnesium alloy	6.3	2.5	4.8	0.281
Molybdenum	48	17	…	0.307
Monel metal	25	9.5	22.5	0.315
Nickel silver	18.5	7	…	0.322
Nickel steel	30	11.5	…	0.291
Phosphor bronze	13.8	5.1	16.3	0.359
Stainless steel 18–8	27.6	10.6	23.6	0.305
Steel, cast	28.5	11.3	20.2	0.265
Steel, cold-rolled	29.5	11.5	23.1	0.287
Steel, all others	28.6–30.0	11.0–11.9	22.6–24.0	0.283–0.292
Titanium (99.0 Ti)	15–16	6.5	…	0.24
Titanium (Ti-8Al-1Mo-1V)	18	6.8	…	0.32
Zinc, cast alloys	10.9–12.4	…	…	0.33
Zinc, wrought alloys	6.2–14	…	…	0.33
Z-nickel	30	11	…	0.36

Data represent typical values, but material properties may vary widely, depending on exact composition, material condition, and processing. Symbol … indicates no data available.

Minimum Tensile Strength of Spring Wire by Diameter

Wire Dia. (in.)	Wire Type						
	Music Wire	Hard-Drawn MB	Oil Temp. MB	Stainless Steel 18-8	Cr–V Alloy	Phosphor Bronze	Chrome Silicon
	Minimum Tensile Strength (10^3 psi)						
0.004	439	…	…	325	…	140	…
0.008	399	…	…	325	…	140	…
0.012	377	…	…	316	…	…	…
0.020	350	283	288	300	…	…	…
0.028	333	271	281	284	…	…	…
0.032	327	265	275	278	281	…	300
0.035	322	261	268	274	276	…	298
0.041	314	255	261	270	270	135	298
0.047	307	248	254	262	263	…	292
0.054	301	243	248	258	257	…	292
0.063	293	237	242	251	251	130	290
0.072	287	232	236	245	245	…	288
0.080	282	227	230	240	240	…	285
0.092	275	220	225	233	235	…	280
0.105	269	216	220	227	229	125	275
0.120	263	210	215	221	222	…	275
0.135	258	206	210	213	219	…	270
0.148	253	203	205	207	215	…	268
0.162	249	200	200	200	212	…	162
0.177	245	195	195	195	210	…	260
0.192	241	192	190	189	206	…	260
0.207	238	190	185	185	204	…	260
0.225	225	186	183	180	200	120	255
0.250	220	182	180	174	196	…	250
0.312	…	174	178	160	189	110	245
0.375	…	167	175	…	187	…	240
0.437	…	165	170	…	186	…	235
0.500	…	156	165	…	185	100	230

For allowable working stresses and recommended design stresses in bending, related to severity of service, refer to Fig. 1 through Fig. 10 on pages 291 through 294, and for endurance limits for compression springs made from these materials refer to Fig. 11 on page 296 in the section on spring stresses.

Pressure and Flow of Water

Water Pressure.—Water is composed of two elements, hydrogen and oxygen, in the ratio of two volumes of hydrogen to one of oxygen. In the common system of measure, water boils under atmospheric pressure at 212 degrees F and freezes at 32 degrees F. Water's greatest density is 62.425 pounds per cubic foot, at 39.1 degrees F. In metric (SI) measure, water boils under atmospheric pressure at 100°C (Celsius) and freezes at 0°C. Its density is equal to 1 kilogram per liter, where 1 liter is 1 cubic decimeter. Also in metric SI, pressure is given in pascals (Pa) or the equivalent newtons per square meter. See page 2523 for additional information on the metric (SI) system of units.

For higher temperatures, the pressure slightly decreases in the proportion indicated by the table *Weight of Water per Cubic Foot at Different Temperatures*. The pressure per square inch is equal in all directions, downwards, upwards, and sideways. Water can be compressed only to a very slight degree, the compressibility being so slight that even at the depth of a mile, a cubic foot of water weighs only about one-half pound more than at the surface.

Pressure in Pounds per Square Inch for Different Heads of Water

Head, ft	0	1	2	3	4	5	6	7	8	9
0	…	0.43	0.87	1.30	1.73	2.16	2.60	3.03	3.46	3.90
10	4.33	4.76	5.20	5.63	6.06	6.49	6.93	7.36	7.79	8.23
20	8.66	9.09	9.53	9.96	10.39	10.82	11.26	11.69	12.12	12.56
30	12.99	13.42	13.86	14.29	14.72	15.15	15.59	16.02	16.45	16.89
40	17.32	17.75	18.19	18.62	19.05	19.48	19.92	20.35	20.78	21.22
50	21.65	22.08	22.52	22.95	23.38	23.81	24.25	24.68	25.11	25.55
60	25.98	26.41	26.85	27.28	27.71	28.14	28.58	29.01	29.44	29.88
70	30.31	30.74	31.18	31.61	32.04	32.47	32.91	33.34	33.77	34.21
80	34.64	35.07	35.51	35.94	36.37	36.80	37.24	37.67	38.10	38.54
90	38.97	39.40	39.84	40.27	40.70	41.13	41.57	42.00	42.43	42.87

Heads of Water in Feet Corresponding to Certain Pressures in Pounds per Square Inch

Pressure, lb/in.^{2}	0	1	2	3	4	5	6	7	8	9
0	…	2.3	4.6	6.9	9.2	11.5	13.9	16.2	18.5	20.8
10	23.1	25.4	27.7	30.0	32.3	34.6	36.9	39.3	41.6	43.9
20	46.2	48.5	50.8	53.1	55.4	57.7	60.0	62.4	64.7	67.0
30	69.3	71.6	73.9	76.2	78.5	80.8	83.1	85.4	87.8	90.1
40	92.4	94.7	97.0	99.3	101.6	103.9	106.2	108.5	110.8	113.2
50	115.5	117.8	120.1	122.4	124.7	127.0	129.3	131.6	133.9	136.3
60	138.6	140.9	143.2	145.5	147.8	150.1	152.4	154.7	157.0	159.3
70	161.7	164.0	166.3	168.6	170.9	173.2	175.5	177.8	180.1	182.4
80	184.8	187.1	189.4	191.7	194.0	196.3	198.6	200.9	203.2	205.5
90	207.9	210.2	212.5	214.8	217.1	219.4	221.7	224.0	226.3	228.6

Comparison of Different Units of Pressure

lb/in.²	oz/in.²	Water[a] Inches of	Water[a] Feet of	Mercury[b] Inches of	Mercury[b] mm of	Pascal (N/m²)
1.0	16.0	27.7066	2.3089	2.0360	51.7149	6,894.757
0.063	1.0	1.732	0.144	0.127	3.232	430.922
0.036	0.578	1.0	0.083	0.074	1.867	248.640
0.433	6.930	12.000	1.0	0.882	22.398	2,983.680
0.491	7.858	13.608	1.134	1.0	25.400	3,383.493
0.019	0.309	0.536	0.045	0.039	1.0	133.271
0.000145	0.0023	0.00402	0.00033	0.00030	0.00750	1.0
2	32	55.413	4.618	4.072	103.430	13,790
3	48	83.120	6.927	6.108	155.145	20,684
4	64	110.826	9.236	8.144	206.860	27,579
5	80	138.533	11.544	10.180	258.575	34,474
6	96	166.240	13.853	12.216	310.289	41,369
7	112	193.946	16.162	14.252	362.004	48,263
8	128	221.653	18.471	16.288	413.719	55,158
9	144	249.359	20.780	18.324	465.434	62,053
10	160	277.066	23.089	20.360	517.149	68,948
11	176	304.773	25.398	22.396	568.864	75,842
12	192	332.479	27.707	24.432	620.579	82,737
13	208	360.186	30.015	26.468	672.294	89,632
14	224	387.892	32.324	28.504	724.009	96,527
15	240	415.599	34.633	30.540	775.724	103,421
16	256	443.306	36.942	32.576	827.438	110,316
17	272	471.012	39.251	34.612	879.153	117,211
18	288	498.719	41.560	36.648	930.868	124,106
19	304	526.425	43.869	38.684	982.583	131,000
20	320	554.132	46.178	40.720	1034.298	137,895
21	336	581.839	48.487	42.756	1086.013	144,790
22	352	609.545	50.795	44.792	1137.728	151,685
23	368	637.252	53.104	46.828	1189.443	158,579
24	384	664.958	55.413	48.864	1241.158	165,474
25	400	692.665	57.722	50.901	1292.873	172,369

[a] Measured at 60°F

[b] Measured at 32°F (0°C).

To convert pascal to bars, divide by 100,000.

Volumes of Water at Different Temperatures

Degrees F	Volume	Degrees F	Volume	Degrees F	Volume	Degrees F	Volume
39.1	1.00000	86	1.00425	131	1.01423	176	1.02872
50	1.00025	95	1.00586	140	1.01678	185	1.03213
59	1.00083	104	1.00767	149	1.01951	194	1.03570
68	1.00171	113	1.00967	158	1.02241	203	1.03943
77	1.00286	122	1.01186	167	1.02548	212	1.04332

Flow of Water in Pipes.—The quantity of water that will flow through a pipe depends primarily on the head but also on the diameter of the pipe, the character of the interior surface, and the number and shape of the bends. The head may be either the distance between the levels of the surface of water in a reservoir and the point of discharge, or it may be caused by mechanically applied pressure, as by pumping, when the head is calculated as the vertical distance corresponding to the pressure.

One pound per square inch is equal to 2.309 feet head, and a 1-foot head is equal to a pressure of 0.433 pound per square inch.

Weight of Water per Cubic Foot at Different Temperatures

Temp. (°F)	Wt. per Cu Ft (lb/ft^3)	Temp. (°F)	Wt. per Cu Ft (lb/ft^3)	Temp. (°F)	Wt. per Cu Ft (lb/ft^3)	Temp. (°F)	Wt. per Cu Ft (lb/ft^3)	Temp. (°F)	Wt. per Cu Ft (lb/ft^3)	Temp. (°F)	Wt. per Cu Ft (lb/ft^3)
32	62.42	130	61.56	220	59.63	320	56.66	420	52.6	520	47.6
40	62.42	140	61.37	230	59.37	330	56.30	430	52.2	530	47.0
50	62.41	150	61.18	240	59.11	340	55.94	440	51.7	540	46.3
60	62.37	160	60.98	250	58.83	350	55.57	450	51.2	550	45.6
70	62.31	170	60.77	260	58.55	360	55.18	460	50.7	560	44.9
80	62.23	180	60.55	270	58.26	370	54.78	470	50.2	570	44.1
90	62.13	190	60.32	280	57.96	380	54.36	480	49.7	580	43.3
100	62.02	200	60.12	290	57.65	390	53.94	490	49.2	590	42.6
110	61.89	210	59.88	300	57.33	400	53.50	500	48.7	600	41.8
120	61.74	212	59.83	310	57.00	410	53.00	510	48.1	…	…

Table of Horsepower due to Certain Head of Water

Head in Feet	Horse-power	Head in Feet	Horse-power	Head in Feet	Horse-power	Head in Feet	Horse-power	Head in Feet	Horse-power
1	0.0016	170	0.274	340	0.547	520	0.837	1250	2.012
10	0.0161	180	0.290	350	0.563	540	0.869	1300	2.093
20	0.0322	190	0.306	360	0.580	560	0.901	1350	2.173
30	0.0483	200	0.322	370	0.596	580	0.934	1400	2.254
40	0.0644	210	0.338	380	0.612	600	0.966	1450	2.334
50	0.0805	220	0.354	390	0.628	650	1.046	1500	2.415
60	0.0966	230	0.370	400	0.644	700	1.127	1550	2.495
70	0.1127	240	0.386	410	0.660	750	1.207	1600	2.576
80	0.1288	250	0.402	420	0.676	800	1.288	1650	2.656
90	0.1449	260	0.418	430	0.692	850	1.368	1700	2.737
100	0.1610	270	0.435	440	0.708	900	1.449	1750	2.818
110	0.1771	280	0.451	450	0.724	950	1.529	1800	2.898
120	0.1932	290	0.467	460	0.740	1000	1.610	1850	2.978
130	0.2093	300	0.483	470	0.757	1050	1.690	1900	3.059
140	0.2254	310	0.499	480	0.773	1100	1.771	1950	3.139
150	0.2415	320	0.515	490	0.789	1150	1.851	2000	3.220
160	0.2576	330	0.531	500	0.805	1200	1.932	2100	3.381

The table gives the horsepower of 1 cubic foot of water per minute, and is based on an efficiency of 85 per cent.

All formulas for finding the amount of water that will flow through a pipe in a given time are approximate. The formula that follows will give results within 5 or 10 per cent of actual flows, if applied to pipe lines carefully laid and in fair condition.

$$V = C\sqrt{\frac{hD}{L + 54D}}$$

where V = approximate mean velocity in feet per second

C = coefficient from the accompanying table

D = diameter of pipe in feet

h = total head in feet

L = total length of pipe line in feet

Values of Coefficient *C*

Dia. of Pipe			Dia. of Pipe			Dia. of Pipe		
Feet	Inches	C	Feet	Inches	C	Feet	Inches	C
0.1	1.2	23	0.8	9.6	46	3.5	42	64
0.2	2.4	30	0.9	10.8	47	4.0	48	66
0.3	3.6	34	1.0	12.0	48	5.0	60	68
0.4	4.8	37	1.5	18.0	53	6.0	72	70
0.5	6.0	39	2.0	24.0	57	7.0	84	72
0.6	7.2	42	2.5	30.0	60	8.0	96	74
0.7	8.4	44	3.0	36.0	62	10.0	120	77

Example: A pipe line, 1 mile long, 12 inches in diameter, discharges water under a head of 100 feet. Find the velocity and quantity of discharge.

From the table, the coefficient C is found to be 48 for a pipe 1 foot in diameter, hence:

$$V = 48\sqrt{\frac{100 \times 1}{5280 + 54 \times 1}} = 6.57 \text{ feet per second}$$

To find the discharge in cubic feet per second, multiply the velocity found by the area of cross-section of the pipe in square feet:

$$6.57 \times 0.7854 = 5.16 \text{ cubic feet per second}$$

The loss of head due to a bend in the pipe is most frequently given as the equivalent length of straight pipe, which would cause the same loss in head as the bend. Experiments show that a right-angle bend should have a radius of about three times the diameter of the pipe. Assuming this curvature, then, if d is the diameter of the pipe in inches and L is the length of straight pipe in feet that causes the same loss of head as the bend in the pipe, the following formula gives the equivalent length of straight pipe that should be added to simulate a right-angle bend:

$$L = 4d \div 3$$

Thus, the loss of head due to a right-angle bend in a 6-inch pipe would be equal to that in 8 feet of straight pipe. Experiments undertaken to determine the losses due to valves in pipe lines indicate that a fully open gate valve in a pipe causes a loss of head corresponding to the loss in a length of pipe equal to six diameters.

Flow of Water Through Nozzles in Cubic Feet per Second

Head in Feet, at Nozzle	Pressure, lb/in.^{2}	Theoretical Velocity, ft/s	Diameter of Nozzle, Inches							
			1	1.5	2	2.5	3	3.5	4	4.5
5	2.17	17.93	0.10	0.22	0.39	0.61	0.88	1.20	1.56	1.98
10	4.33	25.36	0.14	0.31	0.55	0.86	1.24	1.69	2.21	2.80
20	8.66	35.87	0.20	0.44	0.78	1.22	1.76	2.40	3.13	3.96
30	12.99	43.93	0.24	0.54	0.96	1.50	2.16	2.93	3.83	4.85
40	17.32	50.72	0.28	0.62	1.11	1.73	2.49	3.39	4.43	5.60
50	21.65	56.71	0.31	0.70	1.24	1.93	2.78	3.79	4.95	6.26
60	25.99	62.12	0.34	0.76	1.36	2.12	3.05	4.15	5.42	6.86
70	30.32	67.10	0.37	0.82	1.46	2.29	3.29	4.48	5.86	7.41
80	34.65	71.73	0.39	0.88	1.56	2.45	3.52	4.79	6.26	7.92
90	38.98	76.08	0.41	0.93	1.66	2.59	3.73	5.08	6.64	8.40
100	43.31	80.20	0.44	0.98	1.75	2.73	3.94	5.36	7.00	8.86
120	51.97	87.85	0.48	1.08	1.92	2.99	4.31	5.87	7.67	9.70
140	60.63	94.89	0.52	1.16	2.07	3.23	4.66	6.34	8.28	10.48
160	69.29	101.45	0.55	1.24	2.21	3.46	4.98	6.78	8.85	11.20
180	77.96	107.60	0.59	1.32	2.35	3.67	5.28	7.19	9.39	11.88
200	86.62	113.42	0.62	1.39	2.47	3.87	5.57	7.58	9.90	12.53
250	108.27	126.81	0.69	1.56	2.77	4.32	6.22	8.47	11.07	14.01
300	129.93	138.91	0.76	1.70	3.03	4.74	6.82	9.28	12.12	15.34
350	151.58	150.04	0.82	1.84	3.27	5.11	7.37	10.02	13.09	16.57
400	173.24	160.40	0.87	1.97	3.50	5.47	7.87	10.72	14.00	17.72
450	194.89	170.13	0.93	2.09	3.71	5.80	8.35	11.37	14.85	18.79
500	216.54	179.33	0.98	2.20	3.91	6.11	8.80	11.98	15.65	19.81

Head in Feet, at Nozzle	Pressure, lb/in.^{2}	Theoretical Velocity, ft/s	Diameter of Nozzle, Inches							
			5	6	7	8	9	10	11	12
5	2.17	17.93	2.45	3.52	4.79	6.3	7.9	9.8	11.8	14.1
10	4.33	25.36	3.46	4.98	6.78	8.9	11.2	13.8	16.7	19.9
20	8.66	35.87	4.89	7.04	9.59	12.5	15.8	19.6	23.7	28.2
30	12.99	43.93	5.99	8.63	11.74	15.3	19.4	24.0	29.0	34.5
40	17.32	50.72	6.92	9.96	13.56	17.7	22.4	27.7	33.5	39.8
50	21.65	56.71	7.73	11.13	15.16	19.8	25.1	30.9	37.4	44.5
60	25.99	62.12	8.47	12.20	16.60	21.7	27.4	33.9	41.0	48.8
70	30.32	67.10	9.15	13.18	17.93	23.4	29.6	36.6	44.3	52.7
80	34.65	71.73	9.78	14.08	19.17	25.0	31.7	39.1	47.3	56.3
90	38.98	76.08	10.37	14.94	20.33	26.6	33.6	41.5	50.2	59.8
100	43.31	80.20	10.94	15.75	21.43	28.0	35.4	43.7	52.9	63.0
120	51.97	87.85	11.98	17.25	23.48	30.7	38.8	47.9	58.0	69.0
140	60.63	94.89	12.94	18.63	25.36	33.1	41.9	51.8	62.6	74.5
160	69.29	101.45	13.83	19.92	27.11	35.4	44.8	55.3	66.9	79.7
180	77.96	107.60	14.67	21.13	28.76	37.6	47.5	58.7	71.0	84.5
200	86.62	113.42	15.47	22.27	30.31	39.6	50.1	61.9	74.9	89.1
250	108.27	126.81	17.29	24.90	33.89	44.3	56.0	69.2	83.7	99.6
300	129.93	138.91	18.94	27.27	37.12	48.5	61.4	75.8	91.7	109.1
350	151.58	150.04	20.46	29.46	40.10	52.4	66.3	81.8	99.0	117.8
400	173.24	160.40	21.87	31.49	42.87	56.0	70.9	87.5	105.9	126.0
450	194.89	170.13	23.20	33.40	45.47	59.4	75.2	92.8	112.3	133.6
500	216.54	179.33	24.45	35.21	47.93	62.6	79.2	97.8	118.4	140.8

Theoretical Velocity of Water Due to Head in Feet

Head in Feet	Theoretical Velocity		Head in Feet	Theoretical Velocity		Head in Feet	Theoretical Velocity	
	ft/s	ft/min		ft/s	ft/min		ft/s	ft/min
1	8.01	481	48	55.56	3334	95	78.16	4690
2	11.34	681	49	56.13	3368	96	78.57	4715
3	13.89	833	50	56.70	3403	97	78.98	4739
4	16.04	962	51	57.27	3436	98	79.39	4764
5	17.93	1076	52	57.83	3470	99	79.79	4788
6	19.64	1179	53	58.38	3503	100	80.19	4812
7	21.21	1273	54	58.93	3536	105	82.18	4931
8	22.68	1361	55	59.47	3569	110	84.11	5047
9	24.05	1444	56	60.01	3601	115	86.00	5160
10	25.36	1522	57	60.54	3633	120	87.85	5271
11	26.59	1596	58	61.07	3665	125	89.66	5380
12	27.78	1667	59	61.60	3696	130	91.44	5487
13	28.91	1735	60	62.12	3727	135	93.18	5591
14	30.00	1800	61	62.63	3758	140	94.89	5694
15	31.06	1864	62	63.14	3789	145	96.57	5794
16	32.07	1925	63	63.65	3819	150	98.22	5893
17	33.06	1984	64	64.15	3850	155	99.84	5991
18	34.02	2042	65	64.65	3880	160	101.44	6087
19	34.95	2097	66	65.15	3909	165	103.01	6181
20	35.86	2152	67	65.64	3939	170	104.56	6274
21	36.75	2205	68	66.13	3968	175	106.09	6366
22	37.61	2257	69	66.61	3997	180	107.59	6456
23	38.46	2308	70	67.09	4026	185	109.08	6545
24	39.28	2357	71	67.57	4055	190	110.54	6633
25	40.09	2406	72	68.05	4083	195	111.99	6720
26	40.89	2454	73	68.52	4111	200	113.42	6805
27	41.67	2500	74	68.99	4139	205	114.82	6890
28	42.43	2546	75	69.45	4167	210	116.22	6973
29	43.18	2591	76	69.91	4195	215	117.59	7056
30	43.92	2636	77	70.37	4222	220	118.95	7137
31	44.65	2679	78	70.83	4250	225	120.30	7218
32	45.36	2722	79	71.28	4277	230	121.62	7298
33	46.07	2764	80	71.73	4304	235	122.94	7377
34	46.76	2806	81	72.17	4331	240	124.24	7455
35	47.44	2847	82	72.62	4357	245	125.53	7532
36	48.11	2887	83	73.06	4384	250	126.80	7608
37	48.78	2927	84	73.50	4410	255	128.06	7684
38	49.43	2966	85	73.94	4436	260	129.31	7759
39	50.08	3005	86	74.37	4462	270	131.78	7907
40	50.72	3043	87	74.80	4488	280	134.20	8052
41	51.35	3081	88	75.23	4514	290	136.57	8195
42	51.97	3119	89	75.66	4540	300	138.91	8335
43	52.59	3155	90	76.08	4565	310	141.20	8472
44	53.19	3192	91	76.50	4590	320	143.46	8608
45	53.79	3228	92	76.92	4615	330	145.69	8741
46	54.39	3264	93	77.34	4641	340	147.88	8873
47	54.98	3299	94	77.75	4665	350	150.04	9002

Gallons of Water per Foot of Pipe

Nominal Pipe Size (in.)	Iron or Steel		Copper		
	Sched. 40	Sched. 80	Type K	Type L	Type M
1⁄8	0.0030	0.0019	0.0014	0.0016	0.0016
1⁄4	0.0054	0.0037	0.0039	0.0040	0.0043
3⁄8	0.0099	0.0073	0.0066	0.0075	0.0083
1⁄2	0.0158	0.0122	0.0113	0.0121	0.0132
5⁄8	…	…	0.0173	0.0181	0.0194
3⁄4	0.0277	0.0225	0.0226	0.0251	0.0268
1	0.0449	0.0374	0.0404	0.0429	0.0454

Multiply the length of pipe in feet by the factor from the table to find the volume contained in gallons.

Friction Loss in Fittings—Equivalent Length of Pipe in Feet

Nominal Pipe Size (in.)	Elbows						Standard Tee	
	90° Std.	45° Std.	90° Long Radius	90° Street	45° Street	Square Corner	Flow thru Run	Flow thru Branch
1⁄4	0.9	0.5	0.6	1.5	0.8	1.7	0.6	1.8
1⁄2	1.6	0.8	1.0	2.6	1.3	3.0	1.0	4.0
3⁄4	2.1	1.1	1.4	3.4	1.8	3.9	1.4	5.1
1	2.6	1.4	1.7	4.4	2.3	5.0	1.7	6.0
1 1⁄4	3.5	1.8	2.3	5.8	3.0	6.5	2.3	6.9
1 1⁄2	4.0	2.1	2.7	6.7	3.5	7.6	2.7	8.1
2	5.5	2.8	4.3	8.6	4.5	9.8	4.3	12.0
2 1⁄2	6.2	3.3	5.1	10.3	5.4	11.7	5.1	14.3
3	7.7	4.1	6.3	12.8	6.6	14.6	6.3	16.3
4	10.1	5.4	8.3	16.8	8.7	19.1	8.3	22.1
6	15.2	8.1	12.5	25.3	13.1	28.8	12.5	32.2
8	20.0	10.6	16.5	33.3	17.3	37.9	16.5	39.9
10	25.1	13.4	20.7	41.8	21.7	47.6	20.7	50.1
12	29.8	15.9	24.7	49.7	25.9	56.7	24.7	59.7

Pipe Expansion Due to Temperature Changes.—The expansion for any length of pipe caused by a given temperature change can be determined from the following table. Find the expansion factor corresponding to the expected difference in the minimum and maximum pipe temperatures and divide by 100 to obtain the increase in length per foot of pipe. Multiply the increase per foot result by the length of the pipe run to get the total change in pipe length.

Linear Expansion and Contraction Factors per 100 Feet of Pipe

Temperature Change, °F	Pipe Material				
	Steel	Copper	PVC	FRP	PP & PVDF
0	0	0	0	0	0
20	0.15	0.25	0.62	0.26	2.00
40	0.30	0.45	1.30	0.52	4.00
60	0.46	0.65	2.20	0.78	6.00
80	0.61	0.87	2.80	1.05	8.00
100	0.77	1.10	3.50	1.31	10.00
120	0.92	1.35	4.25	1.57	12.00
140	1.08	1.57	4.80	1.83	14.00
160	1.24	1.77	5.50	2.09	16.00
180	1.40	2.00	6.30	2.35	18.00
200	1.57	2.25	7.12	2.62	20.00

Multiply the length of pipe by the table factor and divide by 100 for the increase or decrease in length.

Properties, Compression, and Flow of Air

Properties of Air.—Air is a mechanical mixture composed of 78 per cent of nitrogen, 21 per cent of oxygen, and 1 per cent of argon, by volume. The density of dry air at 32 degrees F and atmospheric pressure (29.92 inches of mercury or 14.70 pounds per square inch) is 0.08073 pound per cubic foot. The density of air at any other temperature or pressure is

$$\rho = \frac{1.325 \times B}{T}$$

in which ρ = density in pounds per cubic foot; B = height of barometric pressure in inches of mercury; T = absolute temperature in degrees Rankine. (When using pounds as a unit, here and elsewhere, care must be exercised to differentiate between pounds mass and pounds force. See *Acceleration of Gravity g Used in Mechanics Formulas* on page 114 and *The Use of the Metric SI System in Mechanics Calculations* on page 116.)

Volumes and Weights of Air at Different Temperatures, at Atmospheric Pressure

Temperature, °F	Volume of 1 lb of Air in Cubic Feet	Density, Pounds per Cubic Foot	Temperature, °F	Volume of 1 lb of Air in Cubic Feet	Density, Pounds per Cubic Foot	Temperature, °F	Volume of 1 lb of Air in Cubic Feet	Density, Pounds per Cubic Foot
0	11.57	0.0864	172	15.92	0.0628	800	31.75	0.0315
12	11.88	0.0842	182	16.18	0.0618	900	34.25	0.0292
22	12.14	0.0824	192	16.42	0.0609	1000	37.31	0.0268
32	12.39	0.0807	202	16.67	0.0600	1100	39.37	0.0254
42	12.64	0.0791	212	16.92	0.0591	1200	41.84	0.0239
52	12.89	0.0776	230	17.39	0.0575	1300	44.44	0.0225
62	13.14	0.0761	250	17.89	0.0559	1400	46.95	0.0213
72	13.39	0.0747	275	18.52	0.0540	1500	49.51	0.0202
82	13.64	0.0733	300	19.16	0.0522	1600	52.08	0.0192
92	13.89	0.0720	325	19.76	0.0506	1700	54.64	0.0183
102	14.14	0.0707	350	20.41	0.0490	1800	57.14	0.0175
112	14.41	0.0694	375	20.96	0.0477	2000	62.11	0.0161
122	14.66	0.0682	400	21.69	0.0461	2200	67.11	0.0149
132	14.90	0.0671	450	22.94	0.0436	2400	72.46	0.0138
142	15.17	0.0659	500	24.21	0.0413	2600	76.92	0.0130
152	15.41	0.0649	600	26.60	0.0376	2800	82.64	0.0121
162	15.67	0.0638	700	29.59	0.0338	3000	87.72	0.0114

The absolute zero from which all temperatures must be counted when dealing with the weight and volume of gases is assumed to be −459.7 degrees F. Hence, to obtain the absolute temperature T used in preceding formula, add the value 459.7 to the temperature observed on a regular Fahrenheit thermometer.

In obtaining the value of B, 1 inch of mercury at 32 degrees F may be taken as equal to a pressure of 0.491 pound per square inch.

Example: What would be the weight of a cubic foot of air at atmospheric pressure (29.92 inches of mercury) at 100 degrees F? The weight, W, is given by $W = \rho V$.

$$W = \rho V = \frac{1.325 \times 29.92}{100 + 459.7} \times 1 = 0.0708 \text{ pound}$$

Density of Air at Different Pressures and Temperatures

Temp. of Air, °F	Gage Pressure, Pounds														
	0	5	10	20	30	40	50	60	80	100	120	150	200	250	300
	Density in Pounds per Cubic Foot														
-20	0.0900	0.1205	0.1515	0.2125	0.274	0.336	0.397	0.458	0.580	0.702	0.825	1.010	1.318	1.625	1.930
-10	0.0882	0.1184	0.1485	0.2090	0.268	0.328	0.388	0.448	0.567	0.687	0.807	0.989	1.288	1.588	1.890
0	0.0864	0.1160	0.1455	0.2040	0.263	0.321	0.380	0.438	0.555	0.672	0.790	0.968	1.260	1.553	1.850
10	0.0846	0.1136	0.1425	0.1995	0.257	0.314	0.372	0.429	0.543	0.658	0.774	0.947	1.233	1.520	1.810
20	0.0828	0.1112	0.1395	0.1955	0.252	0.307	0.364	0.420	0.533	0.645	0.757	0.927	1.208	1.489	1.770
30	0.0811	0.1088	0.1366	0.1916	0.246	0.301	0.357	0.412	0.522	0.632	0.742	0.908	1.184	1.460	1.735
40	0.0795	0.1067	0.1338	0.1876	0.241	0.295	0.350	0.404	0.511	0.619	0.727	0.890	1.161	1.431	1.701
50	0.0780	0.1045	0.1310	0.1839	0.237	0.290	0.343	0.396	0.501	0.607	0.713	0.873	1.139	1.403	1.668
60	0.0764	0.1025	0.1283	0.1803	0.232	0.284	0.336	0.388	0.493	0.596	0.700	0.856	1.116	1.376	1.636
80	0.0736	0.0988	0.1239	0.1738	0.224	0.274	0.324	0.374	0.473	0.572	0.673	0.824	1.074	1.325	1.573
100	0.0710	0.0954	0.1197	0.1676	0.215	0.264	0.312	0.360	0.455	0.551	0.648	0.794	1.035	1.276	1.517
120	0.0680	0.0921	0.1155	0.1618	0.208	0.255	0.302	0.348	0.440	0.533	0.626	0.767	1.001	1.234	1.465
140	0.0663	0.0889	0.1115	0.1565	0.201	0.246	0.291	0.336	0.426	0.516	0.606	0.742	0.968	1.194	1.416
150	0.0652	0.0874	0.1096	0.1541	0.198	0.242	0.286	0.331	0.419	0.508	0.596	0.730	0.953	1.175	1.392
175	0.0626	0.0840	0.1054	0.1482	0.191	0.233	0.275	0.318	0.403	0.488	0.573	0.701	0.914	1.128	1.337
200	0.0603	0.0809	0.1014	0.1427	0.184	0.225	0.265	0.305	0.388	0.470	0.552	0.674	0.879	1.084	1.287
225	0.0581	0.0779	0.0976	0.1373	0.177	0.216	0.255	0.295	0.374	0.452	0.531	0.649	0.846	1.043	1.240
250	0.0560	0.0751	0.0941	0.1323	0.170	0.208	0.247	0.284	0.360	0.436	0.513	0.627	0.817	1.007	1.197
275	0.0541	0.0726	0.0910	0.1278	0.164	0.201	0.238	0.274	0.348	0.421	0.494	0.605	0.789	0.972	1.155
300	0.0523	0.0707	0.0881	0.1237	0.159	0.194	0.230	0.265	0.336	0.407	0.478	0.585	0.762	0.940	1.118
350	0.0491	0.0658	0.0825	0.1160	0.149	0.183	0.216	0.249	0.316	0.382	0.449	0.549	0.715	0.883	1.048
400	0.0463	0.0621	0.0779	0.1090	0.140	0.172	0.203	0.235	0.297	0.360	0.423	0.517	0.674	0.831	0.987
450	0.0437	0.0586	0.0735	0.1033	0.133	0.163	0.192	0.222	0.281	0.340	0.399	0.488	0.637	0.786	0.934
500	0.0414	0.0555	0.0696	0.978	0.126	0.154	0.182	0.210	0.266	0.322	0.379	0.463	0.604	0.746	0.885
550	0.0394	0.0528	0.0661	0.930	0.120	0.146	0.173	0.200	0.253	0.306	0.359	0.440	0.573	0.749	0.841
600	0.0376	0.0504	0.0631	0.885	0.114	0.139	0.165	0.190	0.241	0.292	0.343	0.419	0.547	0.675	0.801

Relation Between Pressure, Temperature, and Volume of Air.—This relationship is expressed by the formula:

$$\frac{P \times V}{T} = 53.3$$

in which P = absolute pressure in pounds per square foot; V = volume in cubic feet of one pound of air at the given pressure and temperature; T = absolute temperature in degrees R.

Example: What is the volume of one pound of air at a pressure of 24.7 pounds per square inch and at a temperature of 210 degrees F?

$$\frac{24.7 \times 144 \times V}{210 + 459.7} = 53.3 \text{ or } V = \frac{53.3 \times 669.7}{24.7 \times 144} = 10.04 \text{ cubic feet}$$

Relation Between Barometric Pressure, and Pressures in Pounds per Square Inch and Square Foot

Barometer, Inches	Pressure in Pounds per Square Inch	Pressure in Pounds per Square Foot	Barometer, Inches	Pressure in Pounds per Square Inch	Pressure in Pounds per Square Foot	Barometer, Inches	Pressure in Pounds per Square Inch	Pressure in Pounds per Square Foot
28.00	13.75	1980	29.25	14.36	2068	30.50	14.98	2156
28.25	13.87	1997	29.50	14.48	2086	30.75	15.10	2174
28.50	13.99	2015	29.75	14.61	2103	31.00	15.22	2192
28.75	14.12	2033	30.00	14.73	2121	31.25	15.34	2210
29.00	14.24	2050	30.25	14.85	2139	…	…	…

Expansion and Compression of Air.—The formula for the relationship between pressure, temperature, and volume of air just given indicates that when the pressure remains constant the volume is directly proportional to the absolute temperature. If the temperature remains constant, the volume is inversely proportional to the absolute pressure. Theoretically, air (as well as other gases) can be expanded or compressed according to different laws. *Adiabatic* expansion or compression takes place when the air is expanded or compressed without transmission of heat to or from it, as, for example, if the air could be expanded or compressed in a cylinder of an absolutely nonconducting material.

Let: P_1 = initial absolute pressure in pounds per square foot
V_1 = initial volume in cubic feet
T_1 = initial absolute temperature in degrees R
P_2 = absolute pressure in pounds per square foot, after compression
V_2 = volume in cubic feet, after compression
T_2 = absolute temperature in degrees R, after compression

Then:

$$\frac{V_2}{V_1} = \left(\frac{P_1}{P_2}\right)^{0.71} \qquad \frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{1.41} \qquad \frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{0.41}$$

$$\frac{V_2}{V_1} = \left(\frac{T_1}{T_2}\right)^{2.46} \qquad \frac{P_2}{P_1} = \left(\frac{T_2}{T_1}\right)^{3.46} \qquad \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{0.29}$$

These formulas are also applicable if all pressures are in pounds per square inch; if all volumes are in cubic inches; or if any other consistent set of units is used for pressure or volume.

Isothermal: expansion or compression takes place when a gas is expanded or compressed with an addition or transmission of sufficient heat to maintain a constant temperature.

Let: P_1 = initial absolute pressure in pounds per square foot
V_1 = initial volume in cubic feet
P_2 = absolute pressure in pounds per square foot, after compression
V_2 = volume in cubic feet, after compression
R = 53.3
T = temperature in degrees Rankine maintained during isothermal expansion or contraction

Then:

$$P_1 \times V_1 = P_2 \times V_2 = RT$$

Example: A volume of 165 cubic feet of air, at a pressure of 15 pounds per square inch, is compressed adiabatically to a pressure of 80 pounds per square inch. What will be the volume at this pressure?

$$V_2 = V_1\left(\frac{P_1}{P_2}\right)^{0.71} = 165\left(\frac{15}{80}\right)^{0.71} = 50 \text{ cubic feet, approx.}$$

Example: The same volume of air is compressed isothermally from 15 to 80 pounds per square inch. What will be the volume after compression?

$$V_2 = \frac{P_1 \times V_1}{P_2} = \frac{15 \times 165}{80} = 31 \text{ cubic feet}$$

Foot-pounds of Work Required in Compression of Air
Initial Pressure = 1 atmosphere = 14.7 pounds per square inch

Gage Pressure in Pounds per Square Inch	Isothermal Compression	Adiabatic Compression	Actual Compression	Gage Pressure in Pounds per Square Inch	Isothermal Compression	Adiabatic Compression	Actual Compression
	Foot-pounds Required per Cubic Foot of Air at Initial Pressure				Foot-pounds Required per Cubic Foot of Air at Initial Pressure		
5	619.6	649.5	637.5	55	3393.7	4188.9	3870.8
10	1098.2	1192.0	1154.6	60	3440.4	4422.8	4029.8
15	1488.3	1661.2	1592.0	65	3577.6	4645.4	4218.2
20	1817.7	2074.0	1971.4	70	3706.3	4859.6	4398.1
25	2102.6	2451.6	2312.0	75	3828.0	5063.9	4569.5
30	2353.6	2794.0	2617.8	80	3942.9	5259.7	4732.9
35	2578.0	3111.0	2897.8	85	4051.5	5450.0	4890.1
40	2780.8	3405.5	3155.6	90	4155.7	5633.1	5042.1
45	2966.0	3681.7	3395.4	95	4254.3	5819.3	5187.3
50	3136.2	3942.3	3619.8	100	4348.1	5981.2	5327.9

Work Required in Compression of Air.—The total work required for compression and expulsion of air, adiabatically compressed, is:

$$\text{Total work in foot-pounds} = 3.46 P_1 V_1\left[\left(\frac{P_2}{P_1}\right)^{0.29} - 1\right]$$

where P_1 = initial absolute pressure in pounds per square foot
P_2 = absolute pressure in pounds per square foot, after compression
V_1 = initial volume in cubic feet

The total work required for isothermal compression is:

$$\text{Total work in foot-pounds} = P_1 V_1 \log_e \frac{V_1}{V_2}$$

in which P_1, P_2, and V_1 denote the same quantities as in the previous equation, and V_2 = volume of air in cubic feet, after compression.

The work required to compress air isothermally, that is, when the heat of compression is removed as rapidly as produced, is considerably less than the work required for compressing air adiabatically, or when all the heat is retained. In practice, neither of these two theoretical extremes is obtainable, but the power required for air compression is about the median between the powers that would be required for each. The accompanying table gives the average number of foot-pounds of work required to compress air.

Horsepower Required to Compress Air.—In the accompanying tables is given the horsepower required to compress one cubic foot of free air per minute (isothermally and adiabatically) from atmospheric pressure (14.7 pounds per square inch) to various gage pressures, for one-, two-, and three-stage compression. The formula for calculating the horsepower required to compress, adiabatically, a given volume of free air to a given pressure is:

$$\text{HP} = \frac{144NPVn}{33{,}000(n-1)}\left[\left(\frac{P_2}{P}\right)^{\frac{n-1}{Nn}} - 1\right]$$

where N = number of stages in which compression is accomplished

P = atmospheric pressure in pounds per square inch

P_2 = absolute terminal pressure in pounds per square inch

V = volume of air, in cubic feet, compressed per minute, at atmospheric pressure

n = exponent of the compression curve = 1.41 for adiabatic compression

For different methods of compression and for one cubic foot of air per minute, this formula may be simplified as follows:

For one-stage compression: $\text{HP} = 0.015P(R^{0.29} - 1)$

For two-stage compression: $\text{HP} = 0.030\,P(R^{0.145} - 1)$

For three-stage compression: $\text{HP} = 0.045\,P(R^{0.0975} - 1)$

For four-stage compression: $\text{HP} = 0.060\,P(R^{0.0725} - 1)$

In these latter formulas $R = \dfrac{P^2}{P}$ = number of atmospheres to be compressed

The formula for calculating the horsepower required to compress isothermally a given volume of free air to a given pressure is:

$$\text{HP} = \frac{144PV}{33000}\left(\log_e \frac{P_2}{P}\right)$$

Natural logarithms are obtained by multiplying common logarithms by 2.30259 or by using a handheld calculator.

Horsepower Required to Compress Air

Horsepower Required To Compress One Cubic Foot of Free Air per Minute (Isothermally and Adiabatically) from Atmospheric Pressure (14.7 pounds per square inch) to Various Gage Pressures. — Single-Stage Compression
(Initial Temperature of Air, 60°F — Jacket cooling not considered)

Gage Pressure, Pounds	Absolute Pressure, Pounds	Number of Atmospheres	Isothermal Compression		Adiabatic Compression			
			Mean Effective Pressure[a]	Horsepower	Mean Effective Pressure,[a] Theoretical	Mean Eff. Pressure plus 15 per cent Friction	Horsepower, Theoretical	Horsepower plus 15 per cent Friction
5	19.7	1.34	4.13	0.018	4.46	5.12	0.019	0.022
10	24.7	1.68	7.57	0.033	8.21	9.44	0.036	0.041
15	29.7	2.02	11.02	0.048	11.46	13.17	0.050	0.057
20	34.7	2.36	12.62	0.055	14.30	16.44	0.062	0.071
25	39.7	2.70	14.68	0.064	16.94	19.47	0.074	0.085
30	44.7	3.04	16.30	0.071	19.32	22.21	0.084	0.096
35	49.7	3.38	17.90	0.078	21.50	24.72	0.094	0.108
40	54.7	3.72	19.28	0.084	25.53	27.05	0.103	0.118
45	59.7	4.06	20.65	0.090	25.40	29.21	0.111	0.127
50	64.7	4.40	21.80	0.095	27.23	31.31	0.119	0.136
55	69.7	4.74	22.95	0.100	28.90	33.23	0.126	0.145
60	74.7	5.08	23.90	0.104	30.53	35.10	0.133	0.153
65	79.7	5.42	24.80	0.108	32.10	36.91	0.140	0.161
70	84.7	5.76	25.70	0.112	33.57	38.59	0.146	0.168
75	89.7	6.10	26.62	0.116	35.00	40.25	0.153	0.175
80	94.7	6.44	27.52	0.120	36.36	41.80	0.159	0.182
85	99.7	6.78	28.21	0.123	37.63	43.27	0.164	0.189
90	104.7	7.12	28.93	0.126	38.89	44.71	0.169	0.195
95	109.7	7.46	29.60	0.129	40.11	46.12	0.175	0.201
100	114.7	7.80	30.30	0.132	41.28	47.46	0.180	0.207
110	124.7	8.48	31.42	0.137	43.56	50.09	0.190	0.218
120	134.7	9.16	32.60	0.142	45.69	52.53	0.199	0.229
130	144.7	9.84	33.75	0.147	47.72	54.87	0.208	0.239
140	154.7	10.52	34.67	0.151	49.64	57.08	0.216	0.249
150	164.7	11.20	35.59	0.155	51.47	59.18	0.224	0.258
160	174.7	11.88	36.30	0.158	53.70	61.80	0.234	0.269
170	184.7	12.56	37.20	0.162	55.60	64.00	0.242	0.278
180	194.7	13.24	38.10	0.166	57.20	65.80	0.249	0.286
190	204.7	13.92	38.80	0.169	58.80	67.70	0.256	0.294
200	214.7	14.60	39.50	0.172	60.40	69.50	0.263	0.303

[a] Mean Effective Pressure (MEP) is defined as that single pressure rise, above atmospheric, which would require the same horsepower as the actual varying pressures during compression.

Horsepower Required to Compress Air

Horsepower Required to Compress One Cubic Foot of Free Air per Minute (Isothermally and Adiabatically) from Atmospheric Pressure (14.7 pounds per square inch) to Various Gage Pressures.—Two-Stage Compression

(Initial Temperature of Air, 60°F —Jacket cooling not considered)

Gage Pressure, Pounds	Absolute Pressure, Pounds	Number of Atmospheres	Correct Ratio of Cylinder Volumes	Intercooler Gage Pressure	Isothermal Compression		Adiabatic Compression				Percentage of Saving over One-stage Compression
					Mean Effective Pressure[a]	Horsepower	Mean Eff. Pressure,[a] Theoretical	Mean Eff. Pressure plus 15 per cent Friction	Horsepower, Theoretical	HP plus 15 per cent Friction	
50	64.7	4.40	2.10	16.2	21.80	0.095	24.30	27.90	0.106	0.123	10.9
60	74.7	5.08	2.25	18.4	23.90	0.104	27.20	31.30	0.118	0.136	11.3
70	84.7	5.76	2.40	20.6	25.70	0.112	29.31	33.71	0.128	0.147	12.3
80	94.7	6.44	2.54	22.7	27.52	0.120	31.44	36.15	0.137	0.158	13.8
90	104.7	7.12	2.67	24.5	28.93	0.126	33.37	38.36	0.145	0.167	14.2
100	114.7	7.80	2.79	26.3	30.30	0.132	35.20	40.48	0.153	0.176	15.0
110	124.7	8.48	2.91	28.1	31.42	0.137	36.82	42.34	0.161	0.185	15.2
120	134.7	9.16	3.03	29.8	32.60	0.142	38.44	44.20	0.168	0.193	15.6
130	144.7	9.84	3.14	31.5	33.75	0.147	39.86	45.83	0.174	0.200	16.3
140	154.7	10.52	3.24	32.9	34.67	0.151	41.28	47.47	0.180	0.207	16.7
150	164.7	11.20	3.35	34.5	35.59	0.155	42.60	48.99	0.186	0.214	16.9
160	174.7	11.88	3.45	36.1	36.30	0.158	43.82	50.39	0.191	0.219	18.4
170	184.7	12.56	3.54	37.3	37.20	0.162	44.93	51.66	0.196	0.225	19.0
180	194.7	13.24	3.64	38.8	38.10	0.166	46.05	52.95	0.201	0.231	19.3
190	204.7	13.92	3.73	40.1	38.80	0.169	47.16	54.22	0.206	0.236	19.5
200	214.7	14.60	3.82	41.4	39.50	0.172	48.18	55.39	0.210	0.241	20.1
210	224.7	15.28	3.91	42.8	40.10	0.174	49.35	56.70	0.216	0.247	…
220	234.7	15.96	3.99	44.0	40.70	0.177	50.30	57.70	0.220	0.252	…
230	244.7	16.64	4.08	45.3	41.30	0.180	51.30	59.10	0.224	0.257	…
240	254.7	17.32	4.17	46.6	41.90	0.183	52.25	60.10	0.228	0.262	…
250	264.7	18.00	4.24	47.6	42.70	0.186	52.84	60.76	0.230	0.264	…
260	274.7	18.68	4.32	48.8	43.00	0.188	53.85	62.05	0.235	0.270	…
270	284.7	19.36	4.40	50.0	43.50	0.190	54.60	62.90	0.238	0.274	…
280	294.7	20.04	4.48	51.1	44.00	0.192	55.50	63.85	0.242	0.278	…
290	304.7	20.72	4.55	52.2	44.50	0.194	56.20	64.75	0.246	0.282	…
300	314.7	21.40	4.63	53.4	45.80	0.197	56.70	65.20	0.247	0.283	…
350	364.7	24.80	4.98	58.5	47.30	0.206	60.15	69.16	0.262	0.301	…
400	414.7	28.20	5.31	63.3	49.20	0.214	63.19	72.65	0.276	0.317	…
450	464.7	31.60	5.61	67.8	51.20	0.223	65.93	75.81	0.287	0.329	…
500	514.7	35.01	5.91	72.1	52.70	0.229	68.46	78.72	0.298	0.342	…

[a] Mean Effective Pressure (MEP) is defined as that single pressure rise, above atmospheric, which would require the same horsepower as the actual varying pressures during compression.

Horsepower Required to Compress Air

Horsepower Required for Compressing One Cubic Foot of Free Air per Minute (Isothermally and Adiabatically) from Atmospheric Pressure (14.7 pounds per square inch) to Various Gage Pressures.—Three-stage Compression (Initial Temperature of Air, 60°F.—Jacket-cooling not considered)

Gage Pressure, Pounds	Absolute Pressure, Pounds	Number of Atmospheres	Correct Ratio of Cylinder Volumes	Intercooler Gage Pressure, First and Second Stages	Isothermal Compression		Adiabatic Compression				Percentage of Saving over Two-stage Compression
					Mean Effective Pressure[a]	Horsepower	Mean Eff. Pressure,[a] Theoretical	Mean Eff. Pressure plus 15 per cent Friction	Horsepower Theoretical	HP plus 15 per cent Friction	
100	114.7	7.8	1.98	14.4– 42.9	30.30	0.132	33.30	38.30	0.145	0.167	5.23
150	164.7	11.2	2.24	18.2– 59.0	35.59	0.155	40.30	46.50	0.175	0.202	5.92
200	214.7	14.6	2.44	21.2– 73.0	39.50	0.172	45.20	52.00	0.196	0.226	6.67
250	264.7	18.0	2.62	23.8– 86.1	42.70	0.186	49.20	56.60	0.214	0.246	6.96
300	314.7	21.4	2.78	26.1– 98.7	45.30	0.197	52.70	60.70	0.229	0.264	7.28
350	364.7	24.8	2.92	28.2–110.5	47.30	0.206	55.45	63.80	0.242	0.277	7.64
400	414.7	28.2	3.04	30.0–121.0	49.20	0.214	58.25	66.90	0.253	0.292	8.33
450	464.7	31.6	3.16	31.8–132.3	51.20	0.223	60.40	69.40	0.263	0.302	8.36
500	514.7	35.0	3.27	33.4–142.4	52.70	0.229	62.30	71.70	0.273	0.314	8.38
550	564.7	38.4	3.38	35.0–153.1	53.75	0.234	65.00	74.75	0.283	0.326	8.80
600	614.7	41.8	3.47	36.3–162.3	54.85	0.239	66.85	76.90	0.291	0.334	8.86
650	664.7	45.2	3.56	37.6–171.5	56.00	0.244	67.90	78.15	0.296	0.340	9.02
700	714.7	48.6	3.65	38.9–180.8	57.15	0.249	69.40	79.85	0.303	0.348	9.18
750	764.7	52.0	3.73	40.1–189.8	58.10	0.253	70.75	81.40	0.309	0.355	…
800	814.7	55.4	3.82	41.4–199.5	59.00	0.257	72.45	83.25	0.315	0.362	…
850	864.7	58.8	3.89	42.5–207.8	60.20	0.262	73.75	84.90	0.321	0.369	…
900	914.7	62.2	3.95	43.4–214.6	60.80	0.265	74.80	86.00	0.326	0.375	…
950	964.7	65.6	4.03	44.6–224.5	61.72	0.269	76.10	87.50	0.331	0.381	…
1000	1014.7	69.0	4.11	45.7–233.3	62.40	0.272	77.20	88.80	0.336	0.383	…
1050	1064.7	72.4	4.15	46.3–238.3	63.10	0.275	78.10	90.10	0.340	0.391	…
1100	1114.7	75.8	4.23	47.5–248.3	63.80	0.278	79.10	91.10	0.344	0.396	…
1150	1164.7	79.2	4.30	48.5–256.8	64.40	0.281	80.15	92.20	0.349	0.401	…
1200	1214.7	82.6	4.33	49.0–261.3	65.00	0.283	81.00	93.15	0.353	0.405	…
1250	1264.7	86.0	4.42	50.3–272.3	65.60	0.286	82.00	94.30	0.357	0.411	…
1300	1314.7	89.4	4.48	51.3–280.8	66.30	0.289	82.90	95.30	0.362	0.416	…
1350	1364.7	92.8	4.53	52.0–287.3	66.70	0.291	84.00	96.60	0.366	0.421	…
1400	1414.7	96.2	4.58	52.6–293.5	67.00	0.292	84.60	97.30	0.368	0.423	…
1450	1464.7	99.6	4.64	53.5–301.5	67.70	0.295	85.30	98.20	0.371	0.426	…
1500	1514.7	103.0	4.69	54.3–309.3	68.30	0.298	85.80	98.80	0.374	0.430	…
1550	1564.7	106.4	4.74	55.0–317.3	68.80	0.300	86.80	99.85	0.378	0.434	…
1600	1614.7	109.8	4.79	55.8–323.3	69.10	0.302	87.60	100.80	0.382	0.438	…

[a] Mean Effective Pressure (MEP) is defined as that single pressure rise, above atmospheric, which would require the same horsepower as the actual varying pressures during compression.

Flow of Air in Pipes.—The following formulas are used:

$$v = \sqrt{\frac{25,000\ dp}{L}} \qquad p = \frac{Lv^2}{25,000\ d}$$

where v = velocity of air in feet per second
p = loss of pressure due to flow through the pipes in ounces per square inch
d = inside diameter of pipe in inches
L = length of pipe in feet

The quantity of air discharged in cubic feet per second is the product of the velocity as obtained from the preceding formula and the area of the pipe in square feet. The horsepower required to drive air through a pipe equals the volume of air in cubic feet per second multiplied by the pressure in pounds per square foot, and this product divided by 550.

Volume of Air Transmitted Through Pipes, in Cubic Feet per Minute

Velocity of Air in Feet per Second	Actual Inside Diameter of Pipe, Inches									
	1	2	3	4	6	8	10	12	16	24
1	0.33	1.31	2.95	5.2	11.8	20.9	32.7	47.1	83.8	188
2	0.65	2.62	5.89	10.5	23.6	41.9	65.4	94.2	167.5	377
3	0.98	3.93	8.84	15.7	35.3	62.8	98.2	141.4	251.3	565
4	1.31	5.24	11.78	20.9	47.1	83.8	131.0	188.0	335.0	754
5	1.64	6.55	14.7	26.2	59.0	104.0	163.0	235.0	419.0	942
6	1.96	7.85	17.7	31.4	70.7	125.0	196.0	283.0	502.0	1131
7	2.29	9.16	20.6	36.6	82.4	146.0	229.0	330.0	586.0	1319
8	2.62	10.50	23.5	41.9	94.0	167.0	262.0	377.0	670.0	1508
9	2.95	11.78	26.5	47.0	106.0	188.0	294.0	424.0	754.0	1696
10	3.27	13.1	29.4	52.0	118.0	209.0	327.0	471.0	838.0	1885
12	3.93	15.7	35.3	63.0	141.0	251.0	393.0	565.0	1005.0	2262
15	4.91	19.6	44.2	78.0	177.0	314.0	491.0	707.0	1256.0	2827
18	5.89	23.5	53.0	94.0	212.0	377.0	589.0	848.0	1508.0	3393
20	6.55	26.2	59.0	105.0	235.0	419.0	654.0	942.0	1675.0	3770
24	7.86	31.4	71.0	125.0	283.0	502.0	785.0	1131.0	2010.0	4524
25	8.18	32.7	73.0	131.0	294.0	523.0	818.0	1178.0	2094.0	4712
28	9.16	36.6	82.0	146.0	330.0	586.0	916.0	1319.0	2346.0	5278
30	9.80	39.3	88.0	157.0	353.0	628.0	982.0	1414.0	2513.0	5655

Flow of Compressed Air in Pipes.—When there is a comparatively small difference of pressure at the two ends of the pipe, the volume of flow in cubic feet per minute is found by the formula:

$$V = 58\sqrt{\frac{pd^5}{WL}}$$

where V = volume of air in cubic feet per minute
p = difference in pressure at the two ends of the pipe in pounds per square inch
d = inside diameter of pipe in inches
W = weight in pounds of one cubic foot of entering air
L = length of pipe in feet

Velocity of Escaping Compressed Air.—If air, or gas, flows from one chamber to another, as from a chamber or tank through an orifice or nozzle into the open air, large changes in velocity may take place owing to the difference in pressures. Since the change takes place almost instantly, little heat can escape from the fluid and the flow may be assumed to be adiabatic.

For a large container with a small orifice or hole from which the air escapes, the velocity of escape (theoretical) may be calculated from the formula:

$$v_2 = \sqrt{2g \cdot \frac{k}{k-1} \cdot 53.3(459.7+F)\left[1-\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}\right]}$$

In this formula, v_2 = velocity of escaping air in feet per second; g = acceleration due to gravity, 32.16 feet per second squared; $k = 1.41$ for adiabatic expansion or compression of air; F = temperature, degrees F; p_2 = atmospheric pressure = 14.7 pounds per square inch; and p_1 = pressure of air in container, pounds per square inch. In applying the preceding formula, when the ratio p_2/p_1 approximately equals 0.53, under normal temperature conditions at sea level, the escape velocity v_2 will be equal to the velocity of sound. Increasing the pressure p_1 will not increase the velocity of escaping air beyond this limiting velocity unless a special converging diverging nozzle design is used rather than an orifice.

The accompanying table provides velocity of escaping air for various values of p_1. These values were calculated from the preceding formula simplified by substituting the appropriate constants:

$$v_2 = 108.58\sqrt{(459.7+F)\left[1-\left(\frac{14.7}{p_1}\right)^{0.29}\right]}$$

Velocity of Escaping Air at 70-Degrees F

Pressure Above Atmospheric Pressure			Theoretical Velocity, Feet per Second	Pressure Above Atmospheric Pressure			Theoretical Velocity, Feet per Second
In Atmospheres	In Inches Mercury	In lbs per sq. in.		In Atmospheres	In Inches Mercury	In lbs per sq. in.	
0.010	0.30	0.147	134	0.408	12.24	6.00	769
0.068	2.04	1.00	344	0.500	15.00	7.35	833
0.100	3.00	1.47	413	0.544	16.33	8.00	861
0.136	4.08	2.00	477	0.612	18.37	9.00	900
0.204	6.12	3.00	573	0.680	20.41	10.0	935
0.272	8.16	4.00	650	0.816	24.49	12.0	997
0.340	10.20	5.00	714	0.884	26.53	13.0	1025

The theoretical velocities in the preceding table must be reduced by multiplying by a "coefficient of discharge," which varies with the orifice and the pressure. The following coefficients are used for orifices in thin plates and short tubes.

	Pressures in Atmospheres Above Atmospheric Pressure			
Type of Orifice	0.01	0.1	0.5	1
Orifice in thin plate	0.65	0.64	0.57	0.54
Orifice in short tube	0.83	0.82	0.71	0.67

STANDARD STEELS

Standard Steels—Compositions, Applications, and Heat Treatments

Steel is the generic term for a large family of iron–carbon alloys, which are malleable, within some temperature range, immediately after solidification from the molten state. The principal raw materials used in steelmaking are iron ore, coal, and limestone. These materials are converted in a blast furnace into a product known as "pig iron," which contains considerable amounts of carbon, manganese, sulfur, phosphorus, and silicon. Pig iron is hard, brittle, and unsuitable for direct processing into wrought forms. Steelmaking is the process of refining pig iron as well as iron and steel scrap by removing undesirable elements from the melt and then adding desirable elements in predetermined amounts. A primary reaction in most steelmaking is the combination of carbon with oxygen to form a gas. If dissolved oxygen is not removed from the melt prior to or during pouring, the gaseous products continue to evolve during solidification. If the steel is strongly deoxidized by the addition of deoxidizing elements, no gas is evolved, and the steel is called "killed" because it lies quietly in the molds. Increasing degrees of gas evolution (decreased deoxidation) characterize steels called "semikilled", "capped," or "rimmed." The degree of deoxidation affects some of the properties of the steel. In addition to oxygen, liquid steel contains measurable amounts of dissolved hydrogen and nitrogen. For some critical steel applications, special deoxidation practices as well as vacuum treatments may be used to reduce and control dissolved gases.

The carbon content of common steel grades ranges from a few hundredths of a per cent to about 1 per cent. All steels also contain varying amounts of other elements, principally manganese, which acts as a deoxidizer and facilitates hot working. Silicon, phosphorus, and sulfur are also always present, if only in trace amounts. Other elements may be present, either as residuals that are not intentionally added, but result from the raw materials or steelmaking practice, or as alloying elements added to effect changes in the properties of the steel.

Steels can be cast to shape, or the cast ingot or strand can be reheated and hot worked by rolling, forging, extrusion, or other processes into a wrought mill shape. Wrought steels are the most widely used of engineering materials, offering a multitude of forms, finishes, strengths, and usable temperature ranges. No other material offers comparable versatility for product design.

Numbering Systems for Metals and Alloys.—Several different numbering systems have been developed for metals and alloys by various trade associations, professional engineering societies, standards organizations, and by private industries for their own use. The numerical code used to identify the metal or alloy may or may not be related to a specification, which is a statement of the technical and commercial requirements that the product must meet. Numbering systems in use include those developed by the American Iron and Steel Institute (AISI), Society of Automotive Engineers (SAE), American Society for Testing and Materials (ASTM), American National Standards Institute (ANSI), Steel Founders Society of America, American Society of Mechanical Engineers (ASME), American Welding Society (AWS), Aluminum Association, Copper Development Association, U.S. Department of Defense (Military Specifications), and the General Accounting Office (Federal Specifications).

The Unified Numbering System (UNS) was developed through a joint effort of the ASTM and the SAE to provide a means of correlating the different numbering systems for metals and alloys that have a commercial standing. This system avoids the confusion caused when more than one identification number is used to specify the same material, or when the same number is assigned to two entirely different materials. It is important to understand that a UNS number is not a specification; it is an identification number for metals and alloys for which detailed specifications are provided elsewhere. UNS numbers are shown in Table 1; each number consists of a letter prefix followed by five digits. In some, the letter is suggestive of the family of metals identified by the series, such as A for aluminum and C for copper. Whenever possible, the numbers in the UNS groups contain numbering sequences taken directly from other systems to facilitate identification of the material; e.g., the corresponding UNS number for AISI 1020 steel is G10200. The UNS numbers corresponding to the commonly used AISI-SAE numbers that are used to identify plain carbon alloy and tool steels are given in Table 1.

Table 1. Unified Numbering System (UNS) for Metals and Alloys

UNS Series	Metal
A00001 to A99999	Aluminum and aluminum alloys
C00001 to C99999	Copper and copper alloys
D00001 to D99999	Specified mechanical property steels
E00001 to E99999	Rare earth and rare earthlike metals and alloys
F00001 to F99999	Cast irons
G00001 to G99999	AISI and SAE carbon and alloy steels (except tool steels)
H00001 to H99999	AISI and SAE H-steels
J00001 to J99999	Cast steels (except tool steels)
K00001 to K99999	Miscellaneous steels and ferrous alloys
L00001 to L99999	Low-melting metals and alloys
M00001 to M99999	Miscellaneous nonferrous metals and alloys
N00001 to N99999	Nickel and nickel alloys
P00001 to P99999	Precious metals and alloys
R00001 to R99999	Reactive and refractory metals and alloys
S00001 to S99999	Heat and corrosion resistant (stainless) steels
T00001 to T99999	Tool steels, wrought and cast
W00001 to W99999	Welding filler metals
Z00001 to Z99999	Zinc and zinc alloys

Table 1. AISI and SAE Numbers and Their Corresponding UNS Numbers for Plain Carbon, Alloy, and Tool Steels

AISI-SAE Numbers	UNS Numbers	AISI-SAE Numbers	UNS Numbers	AISI-SAE Numbers	UNS Numbers	AISI-SAE Numbers	UNS Numbers
Plain Carbon Steels							
1005	G10050	1030	G10300	1070	G10700	1566	G15660
1006	G10060	1035	G10350	1078	G10780	1110	G11100
1008	G10080	1037	G10370	1080	G10800	1117	G11170
1010	G10100	1038	G10380	1084	G10840	1118	G11180
1012	G10120	1039	G10390	1086	G10860	1137	G11370
1015	G10150	1040	G10400	1090	G10900	1139	G11390
1016	G10160	1042	G10420	1095	G10950	1140	G11400
1017	G10170	1043	G10430	1513	G15130	1141	G11410
1018	G10180	1044	G10440	1522	G15220	1144	G11440
1019	G10190	1045	G10450	1524	G15240	1146	G11460
1020	G10200	1046	G10460	1526	G15260	1151	G11510
1021	G10210	1049	G10490	1527	G15270	1211	G12110
1022	G10220	1050	G10500	1541	G15410	1212	G12120
1023	G10230	1053	G10530	1548	G15480	1213	G12130
1025	G10250	1055	G10550	1551	G15510	1215	G12150
1026	G10260	1059	G10590	1552	G15520	12L14	G12144
1029	G10290	1060	G10600	1561	G15610	…	…
Alloy Steels							
1330	G13300	4150	G41500	5140	G51400	8642	G86420
1335	G13350	4161	G41610	5150	G51500	8645	G86450
1340	G13400	4320	G43200	5155	G51550	8655	G86550
1345	G13450	4340	G43400	5160	G51600	8720	G87200
4023	G40230	E4340	G43406	E51100	G51986	8740	G87400
4024	G40240	4615	G46150	E52100	G52986	8822	G88220
4027	G40270	4620	G46200	6118	G61180	9260	G92600
4028	G40280	4626	G46260	6150	G61500	50B44	G50441
4037	G40370	4720	G47200	8615	G86150	50B46	G50461
4047	G40470	4815	G48150	8617	G86170	50B50	G50501
4118	G41180	4817	G48170	8620	G86200	50B60	G50601
4130	G41300	4820	G48200	8622	G86220	51B60	G51601
4137	G41370	5117	G51170	8625	G86250	81B45	G81451
4140	G41400	5120	G51200	8627	G86270	94B17	G94171
4142	G41420	5130	G51300	8630	G86300	94B30	G94301
4145	G41450	5132	G51320	8637	G86370	…	…
4147	G41470	5135	G51350	8640	G86400	…	…
Tool Steels (AISI and UNS Only)							
M1	T11301	T6	T12006	A6	T30106	P4	T51604
M2	T11302	T8	T12008	A7	T30107	P5	T51605
M4	T11304	T15	T12015	A8	T30108	P6	T51606
M6	T11306	H10	T20810	A9	T30109	P20	T51620
M7	T11307	H11	T20811	A10	T30110	P21	T51621
M10	T11310	H12	T20812	D2	T30402	F1	T60601
M3-1	T11313	H13	T20813	D3	T30403	F2	T60602
M3-2	T11323	H14	T20814	D4	T30404	L2	T61202
M30	T11330	H19	T20819	D5	T30405	L3	T61203
M33	T11333	H21	T20821	D7	T30407	L6	T61206
M34	T11334	H22	T20822	O1	T31501	W1	T72301
M36	T11336	H23	T20823	O2	T31502	W2	T72302
M41	T11341	H24	T20824	O6	T31506	W5	T72305
M42	T11342	H25	T20825	O7	T31507	CA2	T90102
M43	T11343	H26	T20826	S1	T41901	CD2	T90402
M44	T11344	H41	T20841	S2	T41902	CD5	T90405
M46	T11346	H42	T20842	S4	T41904	CH12	T90812
M47	T11347	H43	T20843	S5	T41905	CH13	T90813
T1	T12001	A2	T30102	S6	T41906	CO1	T91501
T2	T12002	A3	T30103	S7	T41907	CS5	T91905
T4	T12004	A4	T30104	P2	T51602	…	…
T5	T12005	A5	T30105	P3	T51603	…	…

Standard Steel Classification.—Wrought steels may be classified systematically into groups based on some common characteristic, such as chemical composition, deoxidation practice, finishing method, or product form. Chemical composition is the most often used basis for identifying and assigning standard designations to wrought steels. Although carbon is the principal hardening and strengthening element in steel, no single element controls the steel's characteristics. The combined effect of several elements influences response to heat treatment, hardness, strength, microstructure, corrosion resistance, and formability. The standard steels can be divided broadly into three main groups: carbon steels, alloy steels, and stainless steels.

Carbon Steels: A steel qualifies as a carbon steel when its manganese content is limited to 1.65 per cent (max), silicon to 0.60 per cent (max), and copper to 0.60 per cent (max). With the exception of deoxidizers and boron when specified, no other alloying elements are added intentionally, but they may be present as residuals. If any of these incidental elements are considered detrimental for special applications, maximum acceptable limits may be specified. In contrast to most alloy steels, carbon steels are most often used without a final heat treatment; however, they may be annealed, normalized, case hardened, or quenched and tempered to enhance fabrication or mechanical properties. Carbon steels may be killed, semikilled, capped, or rimmed, and, when necessary, the method of deoxidation may be specified.

Alloy Steels: Alloy steels comprise not only those grades that exceed the element content limits for carbon steel, but also any grade to which different elements than used for carbon steel are added, within specific ranges or specific minimums, to enhance mechanical properties, fabricating characteristics, or any other attribute of the steel. By this definition, alloy steels encompass all steels other than carbon steels; however, by convention, steels containing over 3.99 per cent chromium are considered "special types" of alloy steel, which include the stainless steels and many of the tool steels.

In a technical sense, the term alloy steel is reserved for those steels that contain a modest amount of alloying elements (about 1–4 per cent) and generally depend on thermal treatments to develop specific mechanical properties. Alloy steels are always killed, but special deoxidation or melting practices, including vacuum, may be specified for special critical applications. Alloy steels generally require additional care throughout their manufacture, because they are more sensitive to thermal and mechanical operations.

Stainless Steels: Stainless steels are high-alloy steels and have superior corrosion resistance to the carbon and conventional low-alloy steels because they contain relatively large amounts of chromium. Although other elements may also increase corrosion resistance, their usefulness in this respect is limited.

Stainless steels generally contain at least 10 per cent chromium, with or without other elements. It has been customary in the United States, however, to include in the stainless steel classification those steels that contain as little as 4 per cent chromium. Together, these steels form a family known as the stainless and heat-resisting steels, some of which possess very high strength and oxidation resistance. Few, however, contain more than 30 per cent chromium or less than 50 per cent iron.

In the broadest sense, the standard stainless steels can be divided into three groups based on their structures: austenitic, ferritic, and martensitic. In each of the three groups, there is one composition that represents the basic, general-purpose alloy. All other compositions are derived from the basic alloy, with specific variations in composition being made to obtain very specific properties.

The *austenitic grades* are nonmagnetic in the annealed condition, although some may become slightly magnetic after cold working. They can be hardened only by cold working, and not by heat treatment, and combine outstanding corrosion and heat resistance with good mechanical properties over a wide temperature range. The austenitic grades are further classified into two subgroups: the chromium–nickel types and the less frequently used

Table 2. Composition of AISI-SAE Standard Carbon Steels

AISI-SAE No.	UNS No.	Composition(%)[a]			
		C	Mn	P(max)[b]	S(max)[b]
Nonresulfurized Grades — 1 per cent Mn (max)					
1005[c]	G10050	0.06 max	0.35 max	0.040	0.050
1006[c]	G10060	0.08 max	0.25–0.40	0.040	0.050
1008	G10080	0.10 max	0.30–0.50	0.040	0.050
1010	G10100	0.08–0.13	0.30–0.60	0.040	0.050
1012	G10120	0.10–0.15	0.30–0.60	0.040	0.050
1015	G10150	0.13–0.18	0.30–0.60	0.040	0.050
1016	G10160	0.13–0.18	0.60–0.90	0.040	0.050
1017	G10170	0.15–0.20	0.30–0.60	0.040	0.050
1018	G10180	0.15–0.20	0.60–0.90	0.040	0.050
1019	G10190	0.15–0.20	0.70–1.00	0.040	0.050
1020	G10200	0.18–0.23	0.30–0.60	0.040	0.050
1021	G10210	0.18–0.23	0.60–0.90	0.040	0.050
1022	G10220	0.18–0.23	0.70–1.00	0.040	0.050
1023	G10230	0.20–0.25	0.30–0.60	0.040	0.050
1025	G10250	0.22–0.28	0.30–0.60	0.040	0.050
1026	G10260	0.22–0.28	0.60–0.90	0.040	0.050
1029	G10290	0.25–0.31	0.60–0.90	0.040	0.050
1030	G10300	0.28–0.34	0.60–0.90	0.040	0.050
1035	G10350	0.32–0.38	0.60–0.90	0.040	0.050
1037	G10370	0.32–0.38	0.70–1.00	0.040	0.050
1038	G10380	0.35–0.42	0.60–0.90	0.040	0.050
1039	G10390	0.37–0.44	0.70–1.00	0.040	0.050
1040	G10400	0.37–0.44	0.60–0.90	0.040	0.050
1042	G10420	0.40–0.47	0.60–0.90	0.040	0.050
1043	G10430	0.40–0.47	0.70–1.00	0.040	0.050
1044	G10440	0.43–0.50	0.30–0.60	0.040	0.050
1045	G10450	0.43–0.50	0.60–0.90	0.040	0.050
1046	G10460	0.43–0.50	0.70–1.00	0.040	0.050
1049	G10490	0.46–0.53	0.60–0.90	0.040	0.050
1050	G10500	0.48–0.55	0.60–0.90	0.040	0.050
1053	G10530	0.48–0.55	0.70–1.00	0.040	0.050
1055	G10550	0.50–0.60	0.60–0.90	0.040	0.050
1059[c]	G10590	0.55–0.65	0.50–0.80	0.040	0.050
1060	G10600	0.55–0.65	0.60–0.90	0.040	0.050
1064[c]	G10640	0.60–0.70	0.50–0.80	0.040	0.050
1065[c]	G10650	0.60–0.70	0.60–0.90	0.040	0.050
1069[c]	G10690	0.65–0.75	0.40–0.70	0.040	0.050
1070	G10700	0.65–0.75	0.60–0.90	0.040	0.050
1078	G10780	0.72–0.85	0.30–0.60	0.040	0.050
1080	G10800	0.75–0.88	0.60–0.90	0.040	0.050
1084	G10840	0.80–0.93	0.60–0.90	0.040	0.050
1086[c]	G10860	0.80–0.93	0.30–0.50	0.040	0.050
1090	G10900	0.85–0.98	0.60–0.90	0.040	0.050
1095	G10950	0.90–1.03	0.30–0.50	0.040	0.050

Table 2. *(Continued)* **Composition of AISI-SAE Standard Carbon Steels**

AISI-SAE No.	UNS No.	Composition(%)[a]			
		C	Mn	P(max)[b]	S(max)[b]
Nonresulfurized Grades — Over 1 per cent Mn					
1513	G15130	0.10–0.16	1.10–1.40	0.040	0.050
1522	G15220	0.18–0.24	1.10–1.40	0.040	0.050
1524	G15240	0.19–0.25	1.35–1.65	0.040	0.050
1526	G15260	0.22–0.29	1.10–1.40	0.040	0.050
1527	G15270	0.22–0.29	1.20–1.50	0.040	0.050
1541	G15410	0.36–0.44	1.35–1.65	0.040	0.050
1548	G15480	0.44–0.52	1.10–1.40	0.040	0.050
1551	G15510	0.45–0.56	0.85–1.15	0.040	0.050
1552	G15520	0.47–0.55	1.20–1.50	0.040	0.050
1561	G15610	0.55–0.65	0.75–1.05	0.040	0.050
1566	G15660	0.60–0.71	0.85–1.15	0.040	0.050
Free-Machining Grades — Resulfurized					
1110	G11100	0.08–0.13	0.30–0.60	0.040	0.08–0.13
1117	G11170	0.14–0.20	1.00–1.30	0.040	0.08–0.13
1118	G11180	0.14–0.20	1.30–1.60	0.040	0.08–0.13
1137	G11370	0.32–0.39	1.35–1.65	0.040	0.08–0.13
1139	G11390	0.35–0.43	1.35–1.65	0.040	0.13–0.20
1140	G11400	0.37–0.44	0.70–1.00	0.040	0.08–0.13
1141	G11410	0.37–0.45	1.35–1.65	0.040	0.08–0.13
1144	G11440	0.40–0.48	1.35–1.65	0.040	0.24–0.33
1146	G11460	0.42–0.49	0.70–1.00	0.040	0.08–0.13
1151	G11510	0.48–0.55	0.70–1.00	0.040	0.08–0.13
Free-Machining Grades — Resulfurized and Rephosphorized					
1211	G12110	0.13 max	0.60–0.90	0.07–0.12	0.10–0.15
1212	G12120	0.13 max	0.70–1.00	0.07–0.12	0.16–0.23
1213	G12130	0.13 max	0.70–1.00	0.07–0.12	0.24–0.33
1215	G12150	0.09 max	0.75–1.05	0.04–0.09	0.26–0.35
12L14[d]	G12144	0.15 max	0.85–1.15	0.04–0.09	0.26–0.35

[a] The following notes refer to boron, copper, lead, and silicon additions: Boron: Standard killed carbon steels, which are generally fine grain, may be produced with a boron treatment addition to improve hardenability. Such steels are produced to a range of 0.0005–0.003 per cent B. These steels are identified by inserting the letter "B" between the second and third numerals of the AISI or SAE number, e.g., 10B46. Copper: When copper is required, 0.20 per cent (min) is generally specified. Lead: Standard carbon steels can be produced with a lead range of 0.15–0.35 per cent to improve machinability. Such steels are identified by inserting the letter "L" between the second and third numerals of the AISI or SAE number, e.g., 12L15 and 10L45. Silicon: It is not common practice to produce the 12XX series of resulfurized and rephosphorized steels to specified limits for silicon because of its adverse effect on machinability. When silicon ranges or limits are required for resulfurized or nonresulfurized steels, however, these values apply: a range of 0.08 per cent Si for Si max up to 0.15 per cent inclusive, a range of 0.10 per cent Si for Si max over 0.15 to 0.20 per cent inclusive, a range of 0.15 per cent Si for Si max over 0.20 to 0.30 per cent inclusive, and a range of 0.20 per cent Si for Si max over 0.30 to 0.60 per cent inclusive. Example: Si max is 0.25 per cent, range is 0.10–0.25 per cent.

[b] Values given are maximum percentages, except where a range of values is given.

[c] Standard grades for wire rods and wire only.

[d] 0.15–0.35 per cent Pb.

chromium–manganese–low–nickel types. The basic composition in the chromium–nickel group is widely known as 18–8 (Cr–Ni) and is the general-purpose austenitic grade. This grade is the basis for over 20 modifications that can be characterized as follows: the chromium–nickel ratio has been modified to change the forming characteristics; the carbon content has been decreased to prevent intergranular corrosion; the elements niobium or titanium have been added to stabilize the structure; or molybdenum has been added or the chromium and nickel contents have been increased to improve corrosion or oxidation resistance.

The standard *ferritic grades* are always magnetic and contain chromium but no nickel. They can be hardened to some extent by cold working, but not by heat treatment, and they combine corrosion and heat resistance with moderate mechanical properties and decorative appeal. The ferritic grades generally are restricted to a narrower range of corrosive conditions than the austenitic grades. The basic ferritic grade contains 17 per cent chromium. In this series, there are free-machining modifications and grades with increased chromium content to improve scaling resistance. Also in this ferritic group is a 12 per cent chromium steel (the basic composition of the martensitic group) with other elements, such as aluminum or titanium, added to prevent hardening.

The standard *martensitic grades* are magnetic and can be hardened by quenching and tempering. They contain chromium and, with two exceptions, no nickel. The basic martensitic grade normally contains 12 per cent chromium. There are more than 10 standard compositions in the martensitic series; some are modified to improve machinability and others have small additions of nickel or other elements to improve the mechanical properties or their response to heat treatment. Still others have greatly increased carbon content, in the tool steel range, and are hardenable to the highest levels of all the stainless steels. The martensitic grades are excellent for service in mild environments such as the atmosphere, freshwater, steam, and weak acids, but are not resistant to severely corrosive solutions.

Standard Steel Numbering System.—The most widely used systems for identifying wrought carbon, low–alloy, and stainless steels are based on chemical composition, and are those of the American Iron and Steel Institute (AISI) and the Society of Automotive Engineers (SAE). These systems are almost identical, but they are carefully coordinated. The standard steels so designated have been developed cooperatively by producers and users and have been found through long experience to cover most of the wrought ferrous metals used in automotive vehicles and related equipment. These designations, however, are not specifications, and should not be used for purchasing unless accompanied by supplementary information necessary to describe commercially the product desired. Engineering societies, associations, and institutes whose members make, specify, or purchase steel products publish standard specifications, many of which have become well known and respected. The most comprehensive and widely used specifications are those published by the American Society for Testing and Materials (ASTM). The U.S. government and various companies also publish their own specification for steel products to serve their own special procurement needs. The Unified Numbering System (UNS) for metals and alloys is also used to designate steels (see pages 403 and 405).

The numerical designation system used by both AISI and SAE for wrought carbon, alloy, and stainless steels is summarized in Table 3 . Table 2 lists the compositions of the standard carbon steels; Table 4 lists the standard low–alloy steel compositions; and Table 5 includes the typical compositions of the standard stainless steels.

Table 3. AISI-SAE System of Designating Carbon and Alloy Steels

AISI-SAE Designation[a]	Type of Steel and Nominal Alloy Content (%)
	Carbon Steels
10xx	Plain Carbon (Mn 1.00% max.)
11xx	Resulfurized
12xx	Resulfurized and Rephosphorized
15xx	Plain Carbon (Max. Mn range 1.00 to 1.65%)
	Manganese Steels
13xx	Mn 1.75
	Nickel Steels
23xx	Ni 3.50
25xx	Ni 5.00
	Nickel–Chromium Steels
31xx	Ni 1.25; Cr 0.65 and 0.80
32xx	Ni 1.75; Cr 1.07
33xx	Ni 3.50; Cr 1.50 and 1.57
34xx	Ni 3.00; Cr 0.77
	Molybdenum Steels
40xx	Mo 0.20 and 0.25
44xx	Mo 0.40 and 0.52
	Chromium–Molybdenum Steels
41xx	Cr 0.50, 0.80, and 0.95; Mo 0.12, 0.20, 0.25, and 0.30
	Nickel–Chromium–Molybdenum Steels
43xx	Ni 1.82; Cr 0.50 and 0.80; Mo 0.25
43BVxx	Ni 1.82; Cr 0.50; Mo 0.12 and 0.35; V 0.03 min.
47xx	Ni 1.05; Cr 0.45; Mo 0.20 and 0.35
81xx	Ni 0.30; Cr 0.40; Mo 0.12
86xx	Ni 0.55; Cr 0.50; Mo 0.20
87xx	Ni 0.55; Cr 0.50; Mo 0.25
88xx	Ni 0.55; Cr 0.50; Mo 0.35
93xx	Ni 3.25; Cr 1.20; Mo 0.12
94xx	Ni 0.45; Cr 0.40; Mo 0.12
97xx	Ni 0.55; Cr 0.20; Mo 0.20
98xx	Ni 1.00; Cr 0.80; Mo 0.25
	Nickel–Molybdenum Steels
46xx	Ni 0.85 and 1.82; Mo 0.20 and 0.25
48xx	Ni 3.50; Mo 0.25
	Chromium Steels
50xx	Cr 0.27, 0.40, 0.50, and 0.65
51xx	Cr 0.80, 0.87, 0.92, 0.95, 1.00, and 1.05
50xxx	Cr 0.50; C 1.00 min.
51xxx	Cr 1.02; C 1.00 min.
52xxx	Cr 1.45; C 1.00 min.
	Chromium–Vanadium Steels
61xx	Cr 0.60, 0.80, and 0.95; V 0.10 and 0.15 min
	Tungsten–Chromium Steels
72xx	W 1.75; Cr 0.75
	Silicon–Manganese Steels
92xx	Si 1.40 and 2.00; Mn 0.65, 0.82, and 0.85; Cr 0.00 and 0.65
	High–Strength Low–Alloy Steels
9xx	Various SAE grades
xxBxx	B denotes boron steels
xxLxx	L denotes leaded steels

AISI	SAE	Stainless Steels
2xx	302xx	Chromium–Manganese–Nickel Steels
3xx	303xx	Chromium–Nickel Steels
4xx	514xx	Chromium Steels
5xx	515xx	Chromium Steels

[a] xx in the last two digits of the carbon and low–alloy designations (but not the stainless steels) indicates that the carbon content (in hundredths of a per cent) is to be inserted.

Table 4. Compositions of AISI-SAE Standard Alloy Steels

AISI-SAE No.	UNS No.	Composition (%)[a,b]							
		C	Mn	P (max)	S (max)	Si	Ni	Cr	Mo
1330	G13300	0.28–0.33	1.60–1.90	0.035	0.040	0.15–0.35	…	…	…
1335	G13350	0.33–0.38	1.60–1.90	0.035	0.040	0.15–0.35	…	…	…
1340	G13400	0.38–0.43	1.60–1.90	0.035	0.040	0.15–0.35	…	…	…
1345	G13450	0.43–0.48	1.60–1.90	0.035	0.040	0.15–0.35	…	…	…
4023	G40230	0.20–0.25	0.70–0.90	0.035	0.040	0.15–0.35	…	…	0.20–0.30
4024	G40240	0.20–0.25	0.70–0.90	0.035	0.035–0.050	0.15–0.35	…	…	0.20–0.30
4027	G40270	0.25–0.30	0.70–0.90	0.035	0.040	0.15–0.35	…	…	0.20–0.30
4028	G40280	0.25–0.30	0.70–0.90	0.035	0.035–0.050	0.15–0.35	…	…	0.20–0.30
4037	G40370	0.35–0.40	0.70–0.90	0.035	0.040	0.15–0.35	…	…	0.20–0.30
4047	G40470	0.45–0.50	0.70–0.90	0.035	0.040	0.15–0.35	…	…	0.20–0.30
4118	G41180	0.18–0.23	0.70–0.90	0.035	0.040	0.15–0.35	…	0.40–0.60	0.08–0.15
4130	G41300	0.28–0.33	0.40–0.60	0.035	0.040	0.15–0.35	…	0.80–1.10	0.15–0.25
4137	G41370	0.35–0.40	0.70–0.90	0.035	0.040	0.15–0.35	…	0.80–1.10	0.15–0.25
4140	G41400	0.38–0.43	0.75–1.00	0.035	0.040	0.15–0.35	…	0.80–1.10	0.15–0.25
4142	G41420	0.40–0.45	0.75–1.00	0.035	0.040	0.15–0.35	…	0.80–1.10	0.15–0.25
4145	G41450	0.43–0.48	0.75–1.00	0.035	0.040	0.15–0.35	…	0.80–1.10	0.15–0.25
4147	G41470	0.45–0.50	0.75–1.00	0.035	0.040	0.15–0.35	…	0.80–1.10	0.15–0.25
4150	G41500	0.48–0.53	0.75–1.00	0.035	0.040	0.15–0.35	…	0.80–1.10	0.15–0.25
4161	G41610	0.56–0.64	0.75–1.00	0.035	0.040	0.15–0.35	…	0.70–0.90	0.25–0.35
4320	G43200	0.17–0.22	0.45–0.65	0.035	0.040	0.15–0.35	1.65–2.00	0.40–0.60	0.20–0.30
4340	G43400	0.38–0.43	0.60–0.80	0.035	0.040	0.15–0.35	1.65–2.00	0.70–0.90	0.20–0.30
E4340[c]	G43406	0.38–0.43	0.65–0.85	0.025	0.025	0.15–0.35	1.65–2.00	0.70–0.90	0.20–0.30
4615	G46150	0.13–0.18	0.45–0.65	0.035	0.040	0.15–0.35	1.65–2.00	…	0.20–0.30
4620	G46200	0.17–0.22	0.45–0.65	0.035	0.040	0.15–0.35	1.65–2.00	…	0.20–0.30
4626	G46260	0.24–0.29	0.45–0.65	0.035	0.040	0.15–0.35	0.70–1.00	…	0.15–0.25
4720	G47200	0.17–0.22	0.50–0.70	0.035	0.040	0.15–0.35	0.90–1.20	0.35–0.55	0.15–0.25
4815	G48150	0.13–0.18	0.40–0.60	0.035	0.040	0.15–0.35	3.25–3.75	…	0.20–0.30
4817	G48170	0.15–0.20	0.40–0.60	0.035	0.040	0.15–0.35	3.25–3.75	…	0.20–0.30
4820	G48200	0.18–0.23	0.50–0.70	0.035	0.040	0.15–0.35	3.25–3.75	…	0.20–0.30
5117	G51170	0.15–0.20	0.70–0.90	0.035	0.040	0.15–0.35	…	070–0.90	…
5120	G51200	0.17–0.22	0.70–0.90	0.035	0.040	0.15–0.35	…	0.70–0.90	…
5130	G51300	0.28–0.33	0.70–0.90	0.035	0.040	0.15–0.35	…	0.80–1.10	…
5132	G51320	0.30–0.35	0.60–0.80	0.035	0.040	0.15–0.35	…	0.75–1.00	…
5135	G51350	0.33–0.38	0.60–0.80	0.035	0.040	0.15–0.35	…	0.80–1.05	…
5140	G51400	0.38–0.43	0.70–0.90	0.035	0.040	0.15–0.35	…	0.70–0.90	…
5150	G51500	0.48–0.53	0.70–0.90	0.035	0.040	0.15–0.35	…	0.70–0.90	…
5155	G51550	0.51–0.59	0.70–0.90	0.035	0.040	0.15–0.35	…	0.70–0.90	…
5160	G51600	0.56–0.64	0.75–1.00	0.035	0.040	0.15–0.35	…	0.70–0.90	…

Table 4. *(Continued)* **Compositions of AISI-SAE Standard Alloy Steels**

AISI-SAE No.	UNS No.	Composition (%)[a,b]							
		C	Mn	P (max)	S (max)	Si	Ni	Cr	Mo
E51100[c]	G51986	0.98–1.10	0.25–0.45	0.025	0.025	0.15–0.35	…	0.90–1.15	…
E52100[c]	G52986	0.98–1.10	0.25–0.45	0.025	0.025	0.15–0.35	…	1.30–1.60	…
6118	G61180	0.16–0.21	0.50–0.70	0.035	0.040	0.15–0.35	…	0.50–0.70	0.10–0.15 V
6150	G61500	0.48–0.53	0.70–0.90	0.035	0.040	0.15–0.35	…	0.80–1.10	0.15 V min
8615	G86150	0.13–0.18	0.70–0.90	0.035	0.040	0.15–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8617	G86170	0.15–0.20	0.70–0.90	0.035	0.040	0.15–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8620	G86200	0.18–0.23	0.70–0.90	0.035	0.040	0.15–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8622	G86220	0.20–0.25	0.70–0.90	0.035	0.040	0.15–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8625	G86250	0.23–0.28	0.70–0.90	0.035	0.040	0.15–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8627	G86270	0.25–0.30	0.70–0.90	0.035	0.040	0.15–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8630	G86300	0.28–0.33	0.70–0.90	0.035	0.040	0.15–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8637	G86370	0.35–0.40	0.75–1.00	0.035	0.040	0.15–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8640	G86400	0.38–0.43	0.75–1.00	0.035	0.040	0.15–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8642	G86420	0.40–0.45	0.75–1.00	0.035	0.040	0.15–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8645	G86450	0.43–0.48	0.75–1.00	0.035	0.040	0.15–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8655	G86550	0.51–0.59	0.75–1.00	0.035	0.040	0.15–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8720	G87200	0.18–0.23	0.70–0.90	0.035	0.040	0.15–0.35	0.40–0.70	0.40–0.60	0.20–0.30
8740	G87400	0.38–0.43	0.75–1.00	0.035	0.040	0.15–0.35	0.40–0.70	0.40–0.60	0.20–0.30
8822	G88220	0.20–0.25	0.75–1.00	0.035	0.040	0.15–0.35	0.40–0.70	0.40–0.60	0.30–0.40
9260	G92600	0.56–0.64	0.75–1.00	0.035	0.040	1.80–2.20	…	…	…
Standard Boron Grades[d]									
50B44	G50441	0.43–0.48	0.75–1.00	0.035	0.040	0.15–0.35	…	0.40–0.60	…
50B46	G50461	0.44–0.49	0.75–1.00	0.035	0.040	0.15–0.35	…	0.20–0.35	…
50B50	G50501	0.48–0.53	0.75–1.00	0.035	0.040	0.15–0.35	…	0.40–0.60	…
50B60	G50601	0.56–0.64	0.75–1.00	0.035	0.040	0.15–0.35	…	0.40–0.60	…
51B60	G51601	0.56–0.64	0.75–1.00	0.035	0.040	0.15–0.35	…	0.70–0.90	…
81B45	G81451	0.43–0.48	0.75–1.00	0.035	0.040	0.15–0.35	0.20–0.40	0.35–0.55	0.08–0.15
94B17	G94171	0.15–0.20	0.75–1.00	0.035	0.040	0.15–0.35	0.30–0.60	0.30–0.50	0.08–0.15
94B30	G94301	0.28–0.33	0.75–1.00	0.035	0.040	0.15–0.35	0.30–0.60	0.30–0.50	0.08–0.15

[a] Small quantities of certain elements are present that are not specified or required. These incidental elements may be present to the following maximum amounts: Cu, 0.35 per cent; Ni, 0.25 per cent; Cr, 0.20 per cent; and Mo, 0.06 per cent.

[b] Standard alloy steels can also be produced with a lead range of 0.15–0.35 per cent. Such steels are identified by inserting the letter “L” between the second and third numerals of the AISI or SAE number, e.g., 41L40.

[c] Electric furnace steel.

[d] 0.0005–0.003 per cent B.

Source: American Iron and Steel Institute: *Steel Products Manual.*

Table 5. Standard Stainless Steels — Typical Compositions

AISI Type (UNS)	Typical Composition (%)	AISI Type (UNS)	Typical Composition (%)
Austenitic			
201 (S20100)	16–18 Cr, 3.5–5.5 Ni, 0.15 C, 5.5–7.5 Mn, 0.75 Si, 0.060 P, 0.030 S, 0.25 N	310 (S31000)	24–26 Cr, 19–22 Ni, 0.25 C, 2.0 Mn, 1.5 Si, 0.045 P, 0.030 S
202 (S20200)	17–19 Cr, 4–6 Ni, 0.15 C, 7.5–10.0 Mn, 0.75 Si, 0.060 P, 0.030 S, 0.25 N	310S (S31008)	24–26 Cr, 19–22 Ni, 0.08 C, 2.0 Mn, 1.5 Si, 0.045 P, 0.30 S
205 (S20500)	16.5–18 Cr, 1–1.75 Ni, 0.12–0.25 C, 14–15.5 Mn, 0.75 Si, 0.060 P, 0.030 S, 0.32–0.40 N	314 (S31400)	23–26 Cr, 19–22 Ni, 0.25 C, 2.0 Mn, 1.5–3.0 Si, 0.045 P, 0.030 S
301 (S30100)	16–18 Cr, 6–8 Ni, 0.15 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S	316 (S31600)	16–18 Cr, 10–14 Ni, 0.08 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S, 2.0–3.0 Mo, 0.10 N
302 (S30200)	17–19 Cr, 8–10 Ni, 0.15 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S, 0.10 N	316L (S31603)	16–18 Cr, 10–14 Ni, 0.03 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S, 2.0–3.0 Mo, 0.10 N
302B (S30215)	17–19 Cr, 8–10 Ni, 0.15 C, 2.0 Mn, 2.0–3.0 Si, 0.045 P, 0.030 S	316F (S31620)	16–18 Cr, 10–14 Ni, 0.08 C, 2.0 Mn, 1.0 Si, 0.20 P, 0.10 S min, 1.75–2.50 Mo
303 (S30300)	17–19 Cr, 8–10 Ni, 0.15 C, 2.0 Mn, 1.0 Si, 0.20 P, 0.015 S min, 0.60 Mo (optional)	316N (S31651)	16–18 Cr, 10–14 Ni, 0.08 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S, 2–3 Mo, 0.10–0.16 N
303Se (S30323)	17–19 Cr, 8–10 Ni, 0.15 C, 2.0 Mn, 1.0 Si, 0.20 P, 0.060 S, 0.15 Se min	317 (S31700)	18–20 Cr, 11–15 Ni, 0.08 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S, 3.0–4.0 Mo, 0.10 N max
304 (S30400)	18–20 Cr, 8–10.50 Ni, 0.08 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S, 0.10 N	317L (S31703)	18–20 Cr, 11–15 Ni, 0.03 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S, 3–4 Mo, 0.10 N max
304L (S30403)	18–20 Cr, 8–12 Ni, 0.03 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S, 0.10 N	321 (S32100)	17–19 Cr, 9–12 Ni, 0.08 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S [Ti, 5(C + N) min, 0.70 max], 0.10 max
304 Cu (S30430)	17–19 Cr, 8–10 Ni, 0.08 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S, 3–4 Cu	329 (S32900)	23–28 Cr, 2.5–5 Ni, 0.08 C, 2.0 Mn, 0.75 Si, 0.040 P, 0.030 S, 1–2 Mo
304N (S30451)	18–20 Cr, 8–10.5 Ni, 0.08 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S, 0.10–0.16 N	330 (N08330)	17–20 Cr, 34–37 Ni, 0.08 C, 2.0 Mn, 0.75–1.50 Si, 0.040 P, 0.030 S
305 (S30500)	17–19 Cr, 10.50–13 Ni, 0.12 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S	347 (S34700)	17–19 Cr, 9–13 Ni, 0.08 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S (Nb + Ta, 10 × C min, 1 max)
308 (S30800)	19–21 Cr, 10–12 Ni, 0.08 C, 2.0 Mn, 1.0 Si, 0.045 P, 0.030 S	348 (S34800)	17–19 Cr, 9–13 Ni, 0.08 C, 2.0 Mn, 0.75 Si, 0.045 P, 0.030 S (Nb + Ta, 10 × C min, 1 max, but 0.10 Ta max), 0.20 Ca
309 (S30900)	22–24 Cr, 12–15 Ni, 0.20 C, 2.0 Mn, 1.0 Si, 0.045 P, 0.030 S	384 (S38400)	15–17 Cr, 17–19 Ni, 0.08 C, 2.0 Mn, 1.0 Si, 0.045 P, 0.030 S
309S (S30908)	22–24 Cr, 12–15 Ni, 0.08 C, 2.0 Mn, 1.0 Si, 0.045 P, 0.030 S	…	…
Ferritic			
405 (S40500)	11.5–14.5 Cr, 0.08 C, 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S, 0.1–0.3 Al, 0.60 max	430FSe (S43023)	16–18 Cr, 0.12 C, 1.25 Mn, 1.0 Si, 0.060 P, 0.060 S, 0.15 Se min
409 (S40900)	10.5–11.75 Cr, 0.08 C, 1.0 Mn, 1.0 Si, 0.045 P, 0.030 S, 0.05 Ni (Ti 6 × C, but with 0.75 max)	434 (S43400)	16–18 Cr, 0.12 C, 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S, 0.75–1.25 Mo
429 (S42900)	14–16 Cr, 0.12 C, 1.0 Mn, 1.0 Si, 0.040 P, 030 S, 0.75 Ni	436 (S43600)	16–18 Cr, 0.12 C, 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S, 0.75–1.25 Mo (Nb + Ta 5 × C min, 0.70 max)
430 (S43000)	16–18 Cr, 0.12 C, 1.0 Mn, 1.0 Si, 0.040 P, 030 S, 0.75 Ni	442 (S44200)	18–23 Cr, 0.20 C, 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S
430F (S43020)	16–18 Cr, 0.12 C, 1.25 Mn, 1.0 Si, 0.060 P, 0.15 S min, 0.60 Mo (optional)	446 (S44600)	23–27 Cr, 0.20 C, 1.5 Mn, 1.0 Si, 0.040 P, 0.030 S, 0.025 N

Table 5. *(Continued)* **Standard Stainless Steels — Typical Compositions**

AISI Type (UNS)	Typical Composition (%)	AISI Type (UNS)	Typical Composition (%)
Martensitic			
403 (S40300)	11.5–13.0 Cr, 1.15 C, 1.0 Mn, 0.5 Si, 0.040 P, 0.030 S, 0.60 Ni	420F (S42020)	12–14 Cr, over 0.15 C, 1.25 Mn, 1.0 Si, 0.060 P, 0.15 S min, 0.60 Mo max (optional)
410 (S41000)	11.5–13.5 Cr, 0.15 C, 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S, 0.75 Ni	422 (S42200)	11–12.50 Cr, 0.50–1.0 Ni, 0.20– 0.25 C, 0.50–1.0 Mn, 0.50 Si, 0.025 P, 0.025 S, 0.90–1.25 Mo, 0.20–0.30 V, 0.90–1.25 W
414 (S41400)	11.5–13.5 Cr, 1.25–2.50 Ni, 0.15 C, 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S, 1.25–2.50 Ni	431 (S41623)	15–17 Cr, 1.25–2.50 Ni, 0.20 C, 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S
416 (S41600)	12–14 Cr, 0.15 C, 1.25 Mn, 1.0 Si, 0.060 P, 0.15 S min, 0.060 Mo (optional)	440A (S44002)	16–18 Cr, 0.60–0.75 C, 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S, 0.75 Mo
416Se (S41623)	12–14 Cr, 0.15 C, 1.25 Mn, 1.0 Si, 0.060 P, 0.060 S, 0.15 Se min	440B (S44003)	16–18 Cr, 0.75–0.95 C, 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S, 0.75 Mo
420 (S42000)	12–14 Cr, 0.15 C min, 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S	440C (S44004)	16–18 Cr, 0.95–1.20 C, 1.0 Mn, 1.0 Si, 0040 P, 0.030 S, 0.75 Mo
Heat-Resisting			
501 (S50100)	4–6 Cr, 0.10 C min, 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S, 0.40–0.65 Mo	502 (S50200)	4–6 Cr, 0.10 C. 1.0 Mn, 1.0 Si, 0.040 P, 0.030 S, 0.40–0.65 Mo

Thermal Treatment of Steel.—Steel's versatility is due to its response to thermal treatment. Although most steel products are used in the as-rolled or un-heat-treated condition, thermal treatment greatly increases the number of properties that can be obtained, because at certain "critical temperatures" iron changes from one type of crystal structure to another. This structural change, known as an allotropic transformation, is spontaneous and reversible and can be made to occur by simply changing the temperature of the metal.

In steel, the transformation in crystal structure occurs over a range of temperatures, bounded by lower and upper critical points. When heated, most carbon and low–alloy steels have a critical temperature range between 1300 and 1600 degrees F. Steel above this temperature, but below the melting range, has a crystalline structure known as austenite, in which the carbon and alloying elements are dissolved in a solid solution. Below this critical range, the crystal structure changes to a phase known as ferrite, which is capable of maintaining only a very small percentage of carbon in solid solution. The remaining carbon exists in the form of carbides, which are compounds of carbon and iron and certain of the other alloying elements. Depending primarily on cooling rate, the carbides may be present as thin plates alternating with the ferrite (pearlite); as spheroidal globular particles at ferrite grain boundaries or dispersed throughout the ferrite; or as a uniform distribution of extremely fine particles throughout a "ferritelike" phase, which has an acicular (needle-like) appearance, named martensite. In some of the highly alloyed stainless steels the addtion of certain elements stabilizes the austenite structure so that it persists even at very low temperatures (austenitic grades). Other alloying elements can prevent the formation of austenite entirely up to the melting point (ferritic grades).

Fundamentally, all steel heat treatments are intended to either harden or soften the metal. They involve one or a series of operations in which the solid metal is heated and cooled under specified conditions to develop a required structure and properties. In general, there are five major forms of heat treatment for the standard steels that modify properties to suit either fabrication or end use.

Quenching and Tempering: The primary hardening treatment for steel, quenching and tempering, usually consists of three successive operations: heating the steel above the critical range and holding it at these temperatures for a sufficient time to approach a uniform solid solution (austenitizing); cooling the steel rapidly by quenching in oil, water, brine, salt or air to form a hard, usually brittle, metastable structure known as untempered or white martensite; tempering the steel by reheating it to a temperature below the critical range in order to obtain the required combination of hardness, strength, ductility, toughness, and structural stability (tempered martensite).

Two well-known modifications of conventional quenching and tempering are "austempering" and "martempering." They involve interrupted quenching techniques (two or more quenching media) that can be utilized for some steels to obtain desired structures and properties while minimizing distortion and cracking problems that may occur in conventional hardening.

Normalizing: The steel is heated to a temperature above the critical range, after which it is cooled in still air to produce a generally fine pearlite structure. The purpose is to promote uniformity of structure and properties after a hot-working operation such as forging or extrusion. Steels may be placed in service in the normalized condition, or they may be subjected to additional thermal treatment after subsequent machining or other operations.

Annealing: The steel is heated to a temperature above or within the critical range, then cooled at a predetermined slow rate (usually in a furnace) to produce a coarse pearlite structure. This treatment is used to soften the steel for improved machinability; to improve or restore ductility for subsequent forming operations; or to eliminate the residual stresses and microstructural effects of cold working.

Spheroidize Annealing: This is a special form of annealing that requires prolonged heating at an appropriate temperature followed by slow cooling in order to produce globular carbides, a structure desirable for machining, cold forming, or cold drawing, or for the effect it will have on subsequent heat treatment.

Stress Relieving: This process reduces internal stresses, caused by machining, cold working, or welding, by heating the steel to a temperature below the critical range and holding it there long enough to equalize the temperature throughout the piece.

See the sections *HARDENING, TEMPERING, AND ANNEALING* on page 479 and *HEAT-TREATING HIGH-SPEED STEELS* on page 508 for more information about the heat treatment of steels.

Hardness and Hardenability.—Hardenability is the property of steel that determines the *depth and distribution of hardness* induced by quenching from the austenitizing temperature. Hardenability should not be confused with hardness as such or with maximum hardness. Hardness is a measure of the ability of a metal to resist penetration as determined by any one of a number of standard tests (Brinell, Rockwell, Vickers, etc). The maximum attainable hardness of any steel depends solely on carbon content and is not significantly affected by alloy content. Maximum hardness is realized only when the cooling rate in quenching is rapid enough to ensure full transformation to martensite.

The as-quenched surface hardness of a steel part is dependent on carbon content and cooling rate, but the *depth* to which a certain hardness level is maintained with given quenching conditions is a function of its hardenability. Hardenability is largely determined by the percentage of alloying elements in the steel; however, austenite grain size, time and temperature during austenitizing, and prior microstructure also significantly affect the hardness depth. The hardenability required for a particular part depends on size, design, and service stresses. For highly stressed parts, the best combination of strength and toughness is obtained by through hardening to a martensitic structure followed by adequate tempering. There are applications, however, where through hardening is not necessary or even desirable. For parts that are stressed principally at or near the surface, or in which wear resistance or resistance to shock loading is anticipated, a shallow hardening steel with a moderately soft core may be appropriate.

For through hardening of thin sections, carbon steels may be adequate; but as section size increases, alloy steels of increasing hardenability are required. The usual practice is to select the most economical grade that can meet the desired properties consistently. It is not good practice to utilize a higher alloy grade than necessary, because excessive use of alloying elements adds little to the properties and can sometimes induce susceptibility to quenching cracks.

Quenching Media: The choice of quenching media is often a critical factor in the selection of steel of the proper hardenability for a particular application. Quenching severity can be varied by selection of quenching medium, agitation control, and additives that improve the cooling capability of the quenchant. Increasing the quenching severity permits the use of less expensive steels of lower hardenability; however, consideration must also be given to the amount of distortion that can be tolerated and the susceptibility to quench cracking. In general, the more severe the quenchant and the less symmetrical the part being quenched, the greater are the size and shape changes that result from quenching and the greater is the risk of quench cracking. Consequently, although water quenching is less costly than oil quenching, and water quenching steels are less expensive than those requiring oil quenching, it is important to know that the parts being hardened can withstand the resulting distortion and the possibility of cracking.

Oil, salt, and synthetic water-polymer quenchants are also used, but they often require steels of higher alloy content and hardenability. A general rule for the selection of steel and quenchant for a particular part is that the steel should have a hardenability not exceeding that required by the severity of the quenchant selected. The carbon content of the steel should also not exceed that required to meet specified hardness and strength, because quench cracking susceptibility increases with carbon content.

The choice of quenching media is important in hardening, but another factor is agitation of the quenching bath. The more rapidly the bath is agitated, the more rapidly heat is removed from the steel and the more effective is the quench.

Hardenability Test Methods: The most commonly used method for determining hardenability is the end-quench test developed by Jominy and Boegehold, and described in detail in both SAE J06 and ASTM A255. In this test a normalized 1-inch-round, approximately 4-inch-long specimen of the steel to be evaluated is heated uniformly to its austenitizing temperature. The specimen is then removed from the furnace, placed in a jig, and immediately end quenched by a jet of room-temperature water. The water is played on the end face of the specimen, without touching the sides, until the entire specimen has cooled. Longitudinal flat surfaces are ground on opposite sides of the piece and Rockwell C scale hardness readings are taken at $\frac{1}{16}$-inch intervals from the quenched end. The resulting data are plotted on graph paper with the hardness values as ordinates (y-axis) and distances from the quenched end as abscissas (x-axis). Representative data have been accumulated for a variety of standard steel grades and are published by SAE and AISI as "H-bands." These data show graphically and in tabular form the high and low limits applicable to each grade. The suffix H following the standard AISI/SAE numerical designation indicates that the steel has been produced to specific hardenability limits.

Experiments have confirmed that the cooling rate at a given point along the Jominy bar corresponds closely to the cooling rate at various locations in round bars of various sizes. In general, when end-quench curves for different steels coincide approximately, similar treatments will produce similar properties in sections of the same size. On occasion it is necessary to predict the end-quench hardenability of a steel not available for testing, and reasonably accurate means of calculating hardness for any Jominy location on a section of steel of known analysis and grain size have been developed.

Tempering: As-quenched steels are in a highly stressed condition and are seldom used without tempering. Tempering imparts plasticity or toughness to the steel, and is inevitably accompanied by a loss in hardness and strength. The loss in strength, however, is only incidental to the very important increase in toughness, which is due to the relief of residual stresses induced during quenching and to precipitation, coalescence, and spheroidization of iron and alloy carbides resulting in a microstructure of greater plasticity.

Alloying slows the tempering rate, so that alloy steel requires a higher tempering temperature to obtain a given hardness than carbon steel of the same carbon content. The higher tempering temperature for a given hardness permits a greater relaxation of residual stress and thereby improves the steel's mechanical properties. Tempering is done in furnaces or in oil or salt baths at temperatures varying from 300 to 1200 degrees F. With most grades of alloy steel, the range between 500 and 700 degrees F is avoided because of a phenomenon known as "blue brittleness," which reduces impact properties. Tempering the martensitic stainless steels in the range of 800-1100 degrees F is not recommended because of the low and erratic impact properties and reduced corrosion resistance that result. Maximum toughness is achieved at higher temperatures. It is important to temper parts as soon as possible after quenching, because any delay greatly increases the risk of cracking resulting from the high-stress condition in the as-quenched part.

Surface Hardening Treatment (Case Hardening).—Many applications require high hardness or strength primarily at the surface, and complex service stresses frequently require not only a hard, wear–resistant surface, but also core strength and toughness to withstand impact stress.

To achieve these different properties, two general processes are used: 1) The chemical composition of the surface is altered, prior to or after quenching and tempering; the processes used include carburizing, nitriding, cyaniding, and carbonitriding; and 2) Only the surface layer is hardened by the heating and quenching process; the most common processes used for surface hardening are flame hardening and induction hardening.

Carburizing: Carbon is diffused into the part's surface to a controlled depth by heating the part in a carbonaceous medium. The resulting depth of carburization, commonly referred to as case depth, depends on the carbon potential of the medium used and the time and temperature of the carburizing treatment. The steels most suitable for carburizing to enhance toughness are those with sufficiently low carbon contents, usually below 0.03 per cent. Carburizing temperatures range from 1550 to 1750 degrees F, with the temperature and time at temperature adjusted to obtain various case depths. Steel selection, hardenability, and type of quench are determined by section size, desired core hardness, and service requirements.

Three types of carburizing are most often used: 1) *Liquid carburizing* involves heating the steel in molten barium cyanide or sodium cyanide. The case absorbs some nitrogen in addition to carbon, thus enhancing surface hardness; 2) *Gas carburizing* involves heating the steel in a gas of controlled carbon content. When used, the carbon level in the case can be closely controlled; and 3) *Pack carburizing*, which involves sealing both the steel and solid carbonaceous material in a gas-tight container, then heating this combination.

With any of these methods, the part may be either quenched after the carburizing cycle without reheating or air cooled followed by reheating to the austenitizing temperature prior to quenching. The case depth may be varied to suit the conditions of loading in service. However, service characteristics frequently require that only selective areas of a part have to be case hardened. Covering the areas not to be cased, with copper plating or a layer of commercial paste, allows the carbon to penetrate only the exposed areas. Another method involves carburizing the entire part, then removing the case in selected areas by machining, prior to quench hardening.

Nitriding: The steel part is heated to a temperature of 900–1150 degrees F in an atmosphere of ammonia gas and dissociated ammonia for an extended period of time that depends on the case depth desired. A thin, very hard case results from the formation of nitrides. Strong nitride-forming elements (chromium and molybdenum) are required to be present in the steel, and often special nonstandard grades containing aluminum (a strong nitride former) are used. The major advantage of this process is that parts can be quenched and tempered, then machined, prior to nitriding, because only a little distortion occurs during nitriding.

Cyaniding: This process involves heating the part in a bath of sodium cyanide to a temperature slightly above the transformation range, followed by quenching, to obtain a thin case of high hardness.

Carbonitriding: This process is similar to cyaniding except that the absorption of carbon and nitrogen is accomplished by heating the part in a gaseous atmosphere containing hydrocarbons and ammonia. Temperatures of 1425–1625 degrees F are used for parts to be quenched, and lower temperatures, 1200–1450 degrees F, may be used where a liquid quench is not required.

Flame Hardening: This process involves rapid heating with a direct high-temperature gas flame, such that the surface layer of the part is heated above the transformation range, followed by cooling at a rate that causes the desired hardening. Steels for flame hardening are usually in the range of 0.30–0.60 per cent carbon, with hardenability appropriate for the case depth desired and the quenchant used. The quenchant is usually sprayed on the surface a short distance behind the heating flame. Immediate tempering is required and may be done in a conventional furnace or by a flame-tempering process, depending on part size and costs.

Induction Hardening: This process is similar in many respects to flame hardening except that the heating is caused by a high-frequency electric current sent through a coil or inductor surrounding the part. The depth of heating depends on the frequency, the rate of heat conduction from the surface, and the length of the heating cycle. Quenching is usually accomplished with a water spray introduced at the proper time through jets in or near the inductor block or coil. In some instances, however, parts are oil-quenched by immersing them in a bath of oil after they reach the hardening temperature.

Applications.—Many factors enter into the selection of a steel for a particular application. These factors include the mechanical and physical properties needed to satisfy the design requirements and service environment; the cost and availability of the material; the cost of processing (machining, heat treatment, welding, etc.); and the suitability of available processing equipment or the cost of any new equipment required.

These steel selection considerations require input from designers, metallurgists, manufacturing engineers, service engineers, and procurement specialists, and can be considered proper or optimum when the part is made from the lowest cost material consistent with satisfying engineering and service requirements. The factors in selection can vary widely among different organizations, so that several different steels may be used successfully for similar applications. The best choice of a steel for any application most often results from a balance or trade-offs among the various selection considerations.

The AISI/SAE designated “standard steels” provide a convenient way for engineers and metallurgists to state briefly but clearly the chemical composition and, in some instances, some of the properties desired, and they are widely recognized and used in the United States and in many other countries. There are, however, numerous nonstandard carbon, alloy, and stainless steel grades that are widely used for special applications.

The following sections and tables illustrate the general characteristics and typical applications of most of the standard carbon, alloy, and stainless steel grades.

General Application of SAE Steels: These applications are intended as a general guide only since the selection may depend on the exact character of the service, cost of material, machinability when machining is required, or other factors. When more than one steel is recommended for a given application, information on the characteristics of each steel listed will be found in the section beginning on page 420.

Adapters, 1145

Agricultural steel, 1070, 1080

Aircraft forgings, 4140

Axles front or rear, 1040, 4140

Axle shafts, 1045, 2340, 2345, 3135, 3140, 3141, 4063, 4340

Ball-bearing races, 52100

Balls for ball bearings, 52100

Body stock for cars, rimmed[*]

- Bolts and screws, 1035
- Bolts
  - anchor, 1040
  - cold-headed, 4042
  - connecting-rod, 3130
  - heat-treated, 2330
  - heavy-duty, 4815, 4820
  - steering-arm, 3130
- Brake levers, 1030, 1040
- Bumper bars, 1085
- Cams free-wheeling, 4615, 4620
- Camshafts, 1020, 1040
- Carburized parts, 1020, 1022, 1024, 1117, 1118, 1320, 2317, 2515, 3310, 3115, 3120, 4023, 4032
- Chain pins transmission, 4320, 4815, 4820
- Chains transmission, 3135, 3140
- Clutch disks, 1060, 1070, 1085
- Clutch springs, 1060
- Coil springs, 4063
- Cold-headed bolts, 4042
- Cold-heading
  - steel, 30905, 1070
  - wire or rod, rimmed*, 1035
- Cold-rolled steel, 1070
- Connecting-rods, 1040, 3141
- Connecting-rod bolts, 3130
- Corrosion resisting, 51710, 30805
- Covers transmission, rimmed*
- Crankshafts, 1045, 1145, 3135, 3140, 3141
- Crankshafts Diesel engine, 4340
- Cushion springs, 1060
- Cutlery stainless, 51335
- Cylinder studs, 3130
- Deep-drawing steel, rimmed*, 30905
- Differential gears, 4023
- Disks clutch, 1070, 1060
- Ductile steel, 30905
- Fan blades, 1020
- Fatigue resisting 4340, 4640
- Fender stock for cars, rimmed*
- Forgings
  - aircraft, 4140
  - carbon steel, 1040, 1045
  - heat-treated, 3240, 5140, 6150
  - high-duty, 6150
  - small or medium, 1035
  - large, 1036
- Free-cutting steel
  - carbon, 1111, 1113
  - chromium-nickel steel, 30615
  - manganese steel, 1132, 1137
- Gears
  - carburized, 1320, 2317, 3115, 3120, 3310, 4119, 4125, 4320, 4615, 4620, 4815, 4820
  - heat-treated, 2345
  - car and truck, 4027, 4032
  - cyanide-hardening, 5140
  - differential, 4023
  - high duty, 4640, 6150
  - oil-hardening, 3145, 3150, 4340, 5150
  - ring, 1045, 3115, 3120, 4119
  - transmission, 3115, 3120, 4119
  - truck and bus, 3310, 4320
- Gear shift levers, 1030
- Harrow disks, 1080
- Hay-rake teeth, 1095
- Key stock, 1030, 2330, 3130
- Leaf springs, 1085, 9260
- Levers
  - brake, 1030, 1040
  - gear shift, 1030
  - heat-treated, 2330
- Lock washers, 1060
- Mower knives, 1085
- Mower sections, 1070
- Music wire, 1085
- Nuts, 3130
  - heat-treated, 2330
- Oil pans automobile, rimmed*
- Pinions carburized, 3115, 3120, 4320
- Piston pins, 3115, 3120
- Plow
  - beams, 1070
  - disks, 1080
  - shares, 1080
- Propeller shafts, 2340, 2345, 4140
- Races ball-bearing, 52100
- Ring gears, 3115, 3120, 4119
- Rings snap, 1060, 1070, 1090
- Rivets, rimmed*
- Rod and wire, killed*
- Rod cold-heading, 1035
- Roller bearings, 4815
- Rollers for bearings, 52100
- Screws and bolts, 1035
- Screw stock
  - Bessemer, 1111, 1112, 1113
  - open-hearth, 1115

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* The "rimmed" and "killed" steels listed are in the SAE 1008, 1010, and 1015 group. See general description of these steels.

- Screws heat-treated, 2330
- Seat springs, 10956
- Shafts
  - axle, 1045
  - cyanide-hardening, 5140
  - heavy-duty, 4340, 6150, 4615, 4620
  - oil-hardening, 5150
  - propeller, 2340, 2345, 4140
  - transmission, 4140
- Sheets and strips, rimmed*
- Snap rings, 1060, 1070, 1090
- Spline shafts, 1045, 1320, 2340, 2345, 3115, 3120, 3135, 3140, 4023
- Spring clips, 1060
- Springs
  - coil, 1095, 4063, 6150
  - clutch, 1060
  - cushion, 1060
  - hard-drawn coiled, 1066
  - leaf, 1085, 1095, 4063, 4068, 9260, 6150
  - oil-hardening, 5150
  - oil-tempered wire, 1066
  - seat, 1095
  - valve, 1060
- Spring wire, 1045
  - hard-drawn, 1055
  - oil-tempered, 1055
- Stainless irons, 51210, 51710
- Steel
  - cold-rolled, 1070
  - cold-heading, 30905
  - free-cutting carbon, 11111, 1113
  - free-cutting chrome-nickel, 30615
  - free-cutting manganese, 1132
  - minimum distortion, 4615, 4620, 4640
  - soft ductile, 30905
- Steering arms, 4042
- Steering-arm bolts, 3130
- Steering knuckles, 3141
- Steering-knuckle pins, 4815, 4820
- Tacks, rimmed*
- Thrust washers, 1060
  - oil-hardened, 5150
- Transmission shafts, 4140
- Tubing, 1040
  - front axle, 4140
  - seamless, 1030
  - welded, 1020
- Universal joints, 1145
- Valve springs, 1060
- Washers lock, 1060
- Welded structures, 30705
- Wire and rod, killed*
- Wire
  - cold-heading, rimmed*
  - hard-drawn spring, 1045, 1055
  - music, 1085
  - oil-tempered spring, 1055
- Wrist-pins automobile, 1020
- Yokes, 1145

Carbon Steels.—*SAE Steels 1006, 1008, 1010, 1015:* These steels are the lowest carbon steels of the plain carbon type, and are selected where cold formability is the primary requisite of the user. They are produced both as rimmed and killed steels. Rimmed steel is used for sheet, strip, rod, and wire where excellent surface finish or good drawing qualities are required, such as body and fender stock, hoods, lamps, oil pans, and other deep-drawn and -formed products. This steel is also used for cold-heading wire for tacks, and rivets and low carbon wire products. Killed steel (usually aluminum killed or special killed) is used for difficult stampings, or where nonaging properties are needed. Killed steels (usually silicon killed) should be used in preference to rimmed steel for forging or heat-treating applications.

These steels have relatively low tensile values and should not be selected where much strength is desired. Within the carbon range of the group, strength and hardness will rise with increases in carbon and/or with cold work, but such increases in strength are at the sacrifice of ductility or the ability to withstand cold deformation. Where cold rolled strip is used, the proper temper designation should be specified to obtain the desired properties.

With less than 0.15 carbon, the steels are susceptible to serious grain growth, causing brittleness, which may occur as the result of a combination of critical strain (from cold work) followed by heating to certain elevated temperatures. If cold-worked parts formed from these steels are to be later heated to temperatures in excess of 1100 degrees F, the user should exercise care to avoid or reduce cold working. When this condition develops, it can be overcome by heating the parts to a temperature well in excess of the upper critical point, or at least 1750 degrees F.

Steels in this group, being nearly pure iron or ferritic in structure, do not machine freely and should be avoided for cut screws and operations requiring broaching or smooth finish on turning. The machinability of bar, rod, and wire products is improved by cold drawing. Steels in this group are readily welded.

SAE 1016, 1017, 1018, 1019, 1020, 1021, 1022, 1023, 1024, 1025, 1026, 1027, 1030:

Steels in this group, due to the carbon range covered, have increased strength and hardness, and reduced cold formability compared to the lowest carbon group. For heat-treating purposes, they are known as carburizing or case hardening grades. When uniform response to heat treatment is required, or for forgings, killed steel is preferred; for other uses, semikilled or rimmed steel may be indicated, depending on the combination of properties desired. Rimmed steels can ordinarily be supplied up to 0.25 carbon.

Selection of one of these steels for carburizing applications depends on the nature of the part, the properties desired, and the processing practice preferred. Increases in carbon give greater core hardness with a given quench, or permit the use of thicker sections. Increases in manganese improve the hardenability of both the core and case; in carbon steels this is the only change in composition that will increase case hardenability. The higher manganese variants also machine much better. For carburizing applications, SAE 1016, 1018, and 1019 are widely used for thin sections or water-quenched parts. SAE 1022 and 1024 are used for heavier sections or where oil quenching is desired, and SAE 1024 is sometimes used for such parts as transmission and rear axle gears. SAE 1027 is used for parts given a light case to obtain satisfactory core properties without drastic quenching. SAE 1025 and 1030, although not usually regarded as carburizing types, are sometimes used in this manner for larger sections or where greater core hardness is needed.

For cold-formed or -headed parts, the lowest manganese grades (SAE 1017, 1020, and 1025) offer the best formability at their carbon level. SAE 1020 is used for fan blades and some frame members, and SAE 1020 and 1025 are widely used for low-strength bolts. The next higher manganese types (SAE 1018, 1021, and 1026) provide increased strength.

All steels listed may be readily welded or brazed by the common commercial methods. SAE 1020 is frequently used for welded tubing. These steels are used for numerous forged parts, the lower-carbon grades where high strength is not essential. Forgings from the lower-carbon steels usually machine better in the as-forged condition without annealing, or after normalizing.

SAE 1030, 1033, 1034, 1035, 1036, 1038, 1039, 1040, 1041, 1042, 1043, 1045, 1046, 1049, 1050, 1052: These steels, of the medium-carbon type, are selected for uses where higher mechanical properties are needed and are frequently further hardened and strengthened by heat treatment or by cold work. These grades are ordinarily produced as killed steels.

Steels in this group are suitable for a wide variety of automotive-type applications. The particular carbon and manganese level selected is affected by a number of factors. Increases in the mechanical properties required in section thickness, or in depth of hardening, ordinarily indicate either higher carbon or manganese or both. The heat-treating practice preferred, particularly the quenching medium, has a great effect on the steel selected. In general, any of the grades over 0.30 carbon may be selectively hardened by induction or flame methods.

The lower-carbon and manganese steels in this group find usage for certain types of cold-formed parts. SAE 1030 is used for shift and brake levers. SAE 1034 and 1035 are used in the form of wire and rod for cold upsetting such as bolts, and SAE 1038 for bolts and studs. The parts cold-formed from these steels are usually heat-treated prior to use. Stampings are generally limited to flat parts or simple bends. The higher-carbon SAE 1038, 1040, and 1042 are frequently cold drawn to specified physical properties for use without heat treatment for some applications such as cylinder head studs.

Any of this group of steels may be used for forgings, the selection being governed by the section size and the physical properties desired after heat treatment. Thus, SAE 1030 and 1035 are used for shifter forks and many small forgings where moderate properties are desired, but the deeper-hardening SAE 1036 is used for more critical parts where a higher strength level and more uniformity are essential, such as some front suspension parts. Forgings such as connecting rods, steering arms, truck front axles, axle shafts, and tractor wheels are commonly made from the SAE 1038 to 1045 group. Larger forgings at similar strength levels need more carbon and perhaps more manganese. Examples are crankshafts made from SAE 1046 and 1052. These steels are also used for small forgings where high hardness after oil quenching is desired. Suitable heat treatment is necessary on forgings from this group to provide machinability. These steels are also widely used for parts machined from bar stock, the selection following an identical pattern to that described for forgings. They are used both with and without heat treatment, depending on the application and the level of properties needed. As a class, they are considered good for normal machining operations. It is also possible to weld these steels by most commercial methods, but precautions should be taken to avoid cracking from too rapid cooling.

SAE 1055, 1060, 1062, 1064, 1065, 1066, 1070, 1074, 1078, 1080, 1085, 1086, 1090, 1095: Steels in this group are of the high-carbon type, having more carbon than is required to achieve maximum as quenched hardness. They are used for applications where the higher carbon is needed to improve wear characteristics for cutting edges, to make springs, and for special purposes. Selection of a particular grade is affected by the nature of the part, its end use, and the manufacturing methods available.

In general, cold-forming methods are not practical on this group of steels, being limited to flat stampings and springs coiled from small-diameter wire. Practically all parts from these steels are heat treated before use, with some variations in heat-treating methods to obtain optimum properties for the particular use to which the steel is to be put.

Uses in the spring industry include SAE 1065 for pretempered wire and SAE 1066 for cushion springs of hard-drawn wire, SAE 1064 may be used for small washers and thin stamped parts, SAE 1074 for light flat springs formed from annealed stock, and SAE 1080 and 1085 for thicker flat springs. SAE 1085 is also used for heavier coil springs. Valve spring wire and music wire are special products.

Due to good wear properties when properly heat-treated, the high-carbon steels find wide usage in the farm implement industry. SAE 1070 has been used for plow beams, SAE 1074 for plow shares, and SAE 1078 for such parts as rake teeth, scrapers, cultivator shovels, and plow shares. SAE 1085 has been used for scraper blades, disks, and for spring tooth harrows. SAE 1086 and 1090 find use as mower and binder sections, twine holders, and knotter disks.

Free Cutting Steels.—*SAE 1111, 1112, 1113:* This class of steels is intended for those uses where easy machining is the primary requirement. They are characterized by a higher sulfur content than comparable carbon steels. This composition results in some sacrifice of cold-forming properties, weldability, and forging characteristics. In general, the uses are similar to those for carbon steels of similar carbon and manganese content.

These steels are commonly known as Bessemer screw stock, and are considered the best machining steels available, machinability improving within the group as sulfur increases. They are used for a wide variety of machined parts. Although of excellent strength in the cold-drawn condition, they have an unfavorable property of cold shortness and are not commonly used for vital parts. These steels may be cyanided or carburized, but when uniform response to heat-treating is necessary, open-hearth steels are recommended.

SAE 1109, 1114, 1115, 1116, 1117, 1118, 1119, 1120, 1126: Steels in this group are used where a combination of good machinability and more uniform response to heat treatment is needed. The lower-carbon varieties are used for small parts that are to be cyanided or carbonitrided. SAE 1116, 1117, 1118, and 1119 carry more manganese for better hardenability, permitting oil quenching after case-hardening heat treatments in many instances. The higher-carbon SAE 1120 and 1126 provide more core hardness when this is needed.

SAE 1132, 1137, 1138, 1140, 1141, 1144, 1145, 1146, 1151: This group of steels has characteristics comparable to carbon steels of the same carbon level, except for changes due to higher sulfur as noted previously. They are widely used for parts where large amounts of machining are necessary, or where threads, splines, or other contours present special problems with tooling. SAE 1137, for example, is widely used for nuts and bolts and studs with machined threads. The higher-manganese SAE 1132, 1137, 1141, and 1144 offer greater hardenability, the higher-carbon types being suitable for oil quenching for many parts. All these steels may be selectively hardened by induction or flame heating if desired.

Carburizing Grades of Alloy Steels.—*Properties of the Case:* The properties of carburized and hardened cases (surface layers) depend on the carbon and alloy content, the structure of the case, and the degree and distribution of residual stresses. The carbon content of the case depends on the details of the carburizing process, and the response of iron and the alloying elements present, to carburization. The original carbon content of the steel has little or no effect on the carbon content produced in the case. The hardenability of the case, therefore, depends on the alloy content of the steel and the final carbon content produced by carburizing, but not on the initial carbon content of the steel.

With complete carbide solution, the effect of alloying elements on the hardenability of the case is about the same as the effect of these elements on the hardenability of the core. As an exception to this statement, any element that inhibits carburizing may reduce the hardenability of the case. Some elements that raise the hardenability of the core may tend to produce more retained austenite and consequently somewhat lower hardness in the case.

Alloy steels are frequently used for case hardening because the required surface hardness can be obtained by moderate speeds of quenching. Slower quenching may mean less distortion than would be encountered with water quenching. It is usually desirable to select a steel that will attain a minimum surface hardness of 58 or 60 Rockwell C after carburizing and oil quenching. Where section sizes are large, a high-hardenability alloy steel may be necessary, whereas for medium and light sections, low-hardenability steels will suffice.

In general, the case-hardening alloy steels may be divided into two classes as far as the hardenability of the case is concerned. Only the general type of steel (SAE 3300–4100, etc.) is discussed. The original carbon content of the steel has no effect on the carbon content of the case, so the last two digits in the specification numbers are not meaningful as far as the case is concerned.

A) High-Hardenability Case: SAE 2500, 3300, 4300, 4800, 9300

As these are high-alloy steels, both the case and the core have high hardenability. They are used particularly for carburized parts having thick sections, such as bevel drive pinions and heavy gears. Good case properties can be obtained by oil quenching. These steels are likely to have retained austenite in the case after carburizing and quenching; consequently, special precautions or treatments, such as refrigeration, may be required.

B) Medium-Hardenability Case: SAE 1300, 2300, 4000, 4100, 4600, 5100, 8600, 8700

Carburized cases of these steels have medium hardenability, which means that their hardenability is intermediate between that of plain carbon steel and the higher-alloy carburizing steels discussed earlier. In general, these steels can be used for average-size case-hardened automotive parts such as gears, pinions, piston pins, ball studs, universal joint crosses, crankshafts, etc. Satisfactory case hardness is usually produced by oil quenching.

Core Properties: The core properties of case-hardened steels depend on both carbon and alloy content of the steel. Each of the general types of alloy case-hardening steel is usually made with two or more carbon contents to permit different hardenability in the core.

The most desirable hardness for the core depends on the design and functioning of the individual part. In general, where high compressive loads are encountered, relatively high core hardness is beneficial in supporting the case. Low core hardnesses may be desirable where great toughness is essential.

The case-hardening steels may be divided into three general classes, depending on hardenability of the core.

A) Low-Hardenability Core: SAE 4017, 4023, 4024, 4027,* 4028,* 4608, 4615, 4617,* 8615,* 8617*

B) Medium-Hardenability Core: SAE 1320, 2317, 2512, 2515,* 3115, 3120, 4032, 4119, 4317, 4620, 4621, 4812, 4815,* 5115, 5120, 8620, 8622, 8720, 9420

C) High-Hardenability Core: SAE 2517, 3310, 3316, 4320, 4817, 4820, 9310, 9315, 9317

Heat Treatments: In general, all the alloy carburizing steels are made with fine grain and most are suitable for direct quenching from the carburizing temperature. Several other types of heat treatment involving single and double quenching are also used for most of these steels. (See on page 504 and on page 505)

Directly Hardenable Grades of Alloy Steels.—These steels may be considered in five groups on the basis of approximate mean carbon content of the SAE specification. In general, the last two figures of the specification agree with the mean carbon content. Consequently the heading “0.30–0.37 Mean Carbon Content of SAE Specification” includes steels such as SAE 1330, 3135, and 4137.

It is necessary to deviate from the above plan in the classification of the carbon molybdenum steels. When carbon molybdenum steels are used, it is customary to specify higher carbon content for any given application than would be specified for other alloy steels, due to the low alloy content of these steels. For example, SAE 4063 is used for the same applications as SAE 4140, 4145, and 5150. Consequently, in the following discussion, the carbon molybdenum steels have been shown in the groups where they belong on the basis of applications rather than carbon content.

Mean Carbon Content of SAE Specification	Common Applications
(a) 0.30–0.37 per cent	Heat-treated parts requiring moderate strength and great toughness.
(b) 0.40–0.42 per cent	Heat-treated parts requiring higher strength and good toughness.
(c) 0.45–0.50 per cent	Heat-treated parts requiring fairly high hardness and strength with moderate toughness.
(d) 0.50–0.62 per cent	Springs and hand tools.
(e) 1.02 per cent	Ball and roller bearings.

For the present discussion, steels of each carbon content are divided into two or three groups on the basis of hardenability. Transformation ranges and consequently heat-treating practices vary somewhat with different alloying elements even though the hardenability is not changed.

0.30–0.37 Mean Carbon Content of SAE Specification: These steels are frequently used for water-quenched parts of moderate section size and for oil-quenched parts of small section size. Typical applications of these steels are connecting rods, steering arms and steering knuckles, axle shafts, bolts, studs, screws, and other parts requiring strength and toughness where section size is small enough to permit the desired physical properties to be obtained with the customary heat treatment.

Steels falling in this classification may be subdivided into two groups on the basis of hardenability:

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* Borderline classifications might be considered in the next higher hardenability group.

A) Low Hardenability: SAE 1330, 1335, 4037, 4042, 4130, 5130, 5132, 8630

B) Medium Hardenability: SAE 2330, 3130, 3135, 4137, 5135, 8632, 8635, 8637, 8735, 9437

0.40–0.42 Mean Carbon Content of SAE Specification: In general, these steels are used for medium and large size parts requiring high degree of strength and toughness. The choice of the proper steel depends on the section size and the mechanical properties that must be produced. The low and medium hardenabilty steels are used for average size automotive parts such as steering knuckles, axle shafts, propeller shafts, etc. The high hardenability steels are used particularly for large axles and shafts for large aircraft parts.

These steels are usually considered as oil quenching steels, although some large parts made of the low and medium hardenability classifications may be quenched in water under properly controlled conditions.

These steels may be divided into three groups on the basis of hardenability:

A) Low Hardenability: SAE 1340, 4047, 5140, 9440

B) Medium Hardenability: SAE 2340, 3140, 3141, 4053, 4063, 4140, 4640, 8640, 8641, 8642, 8740, 8742, 9442

C) High Hardenability: SAE 4340, 9840

0.45–0.50 Mean Carbon Content of SAE Specification: These steels are used primarily for gears and other parts requiring fairly high hardness as well as strength and toughness. Such parts are usually oil-quenched and a minimum of 90 per cent martensite in the as-quenched condition is desirable.

A) Low Hardenability: SAE 5045, 5046, 5145, 9747, 9763

B) Medium Hardenability: SAE 2345, 3145, 3150, 4145, 5147, 5150, 8645, 8647, 8650, 8745, 8747, 8750, 9445, 9845

C) High Hardenability: SAE 4150, 9850

0.50–0.63 Mean Carbon Content of SAE Specification: These steels are used primarily for springs and hand tools. The hardenability necessary depends on the thickness of the material and the quenching practice.

A) Medium hardenability: SAE 4068, 5150, 5152, 6150, 8650, 9254, 9255, 9260, 9261

B) High Hardenability: SAE 8653, 8655, 8660, 9262

1.02 Mean Carbon Content of SAE Specification—SAE 50100, 51100, 52100: These straight chromium electric furnace steels are used primarily for the races and balls or rollers of antifriction bearings. They are also used for other parts requiring high hardness and wear resistance. The compositions of the three steels are identical, except for a variation in chromium, with a corresponding variation in hardenability.

A) Low Hardenability: SAE 50100

B) Medium Hardenability: SAE 51100, 52100

Resulfurized Steel: Some of the alloy steels, SAE 4024, 4028, and 8641, are made resulfurized so as to give better machinability at a relatively high hardness. In general, increased sulfur results in decreased transverse ductility, notched impact toughness, and weldability.

Characteristics and Typical Applications of Standard Stainless Steels.—Typical applications of various stainless steel alloys are given in the following. The first number given is the AISI designation followed by the UNS number in parenthesis. (See also *Numbering Systems for Metals and Alloys* on page 403)

201 (S20100): High work-hardening rate; low-nickel equivalent of type 301. Flatware; automobile wheel covers, trim.

202 (S20200): General-purpose low-nickel equivalent of type 302. Kitchen equipment; hub caps; milk handling.

205 (S20500): Lower work-hardening rate than type 202; used for spinning and special drawing operations. Nonmagnetic and cryogenic parts.

301 (S30100): High work-hardening rate; used for structural applications where high strength plus high ductility are required. Railroad cars; trailer bodies; aircraft structurals; fasteners; automobile wheel covers, trim; pole line hardware.

302 (S30200): General-purpose austenitic stainless steel. Trim; food-handling equipment; aircraft cowlings; antennas; springs; cookware; building exteriors; tanks; hospital, household appliances; jewelry; oil refining equipment; signs.

302B (S30215): More resistant to scale than type 302. Furnace parts; still liners; heating elements; annealing covers; burner sections.

303 (S30300): Free-machining modification of type 302, for heavier cuts. Screw machine products; shafts; valves; bolts; bushings; nuts.

303Se (S30323): Free-machining modification of type 302, for lighter cuts; used where hot working or cold heading may be involved. Aircraft fittings; bolts; nuts; rivets; screws; studs.

304 (S30400): Low-carbon modification of type 302 for restriction of carbide precipitation during welding. Chemical and food processing equipment; brewing equipment; cryogenic vessels; gutters; downspouts; flashings.

304L (S30403): Extra-low-carbon modification of type 304 for further restriction of carbide precipitation during welding. Coal hopper linings; tanks for liquid fertilizer and tomato paste.

304Cu (S30430): Lower work-hardening rate than type 304. Severe cold-heading applications.

304N (S30451): Higher nitrogen than type 304 to increase strength with minimum effect on ductility and corrosion resistance, more resistant to increased magnetic permeability. Type 304 applications requiring higher strength.

305 (S30500): Low work-hardening rate; used for spin forming, severe drawing, cold heading, and forming. Coffee urn tops; mixing bowls; reflectors.

308 (S30800): Higher-alloy steel having high corrosion and heat resistance. Welding filler metals to compensate for alloy loss in welding; industrial furnaces.

309 (S30900): High-temperature strength and scale resistance. Aircraft heaters; heat-treating equipment; annealing covers; furnace parts; heat exchangers; heat-treating trays; oven linings; pump parts.

309S (S30908): Low-carbon modification of type 309. Welded constructions; assemblies subject to moist corrosion conditions.

310 (S31000): Higher elevated temperature strength and scale resistance than type 309. Heat exchangers; furnace parts; combustion chambers; welding filler metals; gas-turbine parts; incinerators; recuperators; rolls for roller hearth furnaces.

310S (S31008): Low-carbon modification of type 310. Welded constructions; jet engine rings.

314 (S31400): More resistant to scale than type 310. Severe cold-heading or -forming applications. Annealing and carburizing boxes; heat-treating fixtures; radiant tubes.

316 (S31600): Higher corrosion resistance than types 302 and 304; high creep strength. Chemical and pulp handling equipment; photographic equipment; brandy vats; fertilizer parts; ketchup cooking kettles; yeast tubs.

316L (S31603): Extra-low-carbon modification of type 316. Welded construction where intergranular carbide precipitation must be avoided. Type 316 applications requiring extensive welding.

316F (S31620): Higher phosphorus and sulfur than type 316 to improve machining and nonseizing characteristics. Automatic screw machine parts.

316N (S31651): Higher nitrogen than type 316 to increase strength with minimum effect on ductility and corrosion resistance. Type 316 applications requiring extra strength.

317 (S31700): Higher corrosion and creep resistance than type 316. Dyeing and ink manufacturing equipment.

317L (S31703): Extra-low-carbon modification of type 317 for restriction of carbide precipitation during welding. Welded assemblies.

321 (S32100): Stabilized for weldments subject to severe corrosive conditions, and for service from 800 to 1650°F Aircraft exhaust manifolds; boiler shells; process equipment; expansion joints; cabin heaters; fire walls; flexible couplings; pressure vessels.

329 (S32900): Austenitic-ferritic type with general corrosion resistance similar to type 316 but with better resistance to stress-corrosion cracking; capable of age hardening. Valves; valve fittings; piping; pump parts.

330 (N08330): Good resistance to carburization and oxidation and to thermal shock. Heat-treating fixtures.

347 (S34700): Similar to type 321 with higher creep strength. Airplane exhaust stacks; welded tank cars for chemicals; jet engine parts.

348 (S34800): Similar to type 321; low retentivity. Tubes and pipes for radioactive systems; nuclear energy uses.

384 (S38400): Suitable for severe cold heading or cold forming; lower cold-work-hardening rate than type 305. Bolts; rivets; screws; instrument parts.

403 (S40300): “Turbine quality” grade. Steam turbine blading and other highly stressed parts including jet engine rings.

405 (S40500): Nonhardenable grade for assemblies where air-hardening types such as 410 or 403 are objectionable. Annealing boxes; quenching racks; oxidation-resistant partitions.

409 (S40900): General-purpose construction stainless. Automotive exhaust systems; transformer and capacitor cases; dry fertilizer spreaders; tanks for agricultural sprays.

410 (S41000): General-purpose heat-treatable type. Machine parts; pump shafts; bolts; bushings; coal chutes; cutlery; hardware; jet engine parts; mining machinery; rifle barrels; screws; valves.

414 (41400): High hardenability steel. Springs; tempered rules; machine parts, bolts; mining machinery; scissors; ships’ bells; spindles; valve seats.

416 (S41600): Free-machining modification of type 410, for heavier cuts. Aircraft fittings; bolts; nuts; fire extinguisher inserts; rivets; screws.

416Se (S41623): Free-machining modification of type 410, for lighter cuts. Machined parts requiring hot working or cold heading.

420 (S42000): Highercarbon modification of type 410. Cutlery; surgical instruments; valves; wear-resisting parts; glass molds; hand tools; vegetable choppers.

420F (S42020): Free-machining modification of type 420. Applications similar to those for type 420 requiring better machinability.

422 (S42200): High strength and toughness at service temperatures up to 1200 degrees F. Steam turbine blades; fasteners.

429 (S42900): Improved weldability as compared to type 430. Nitric acid and nitrogen-fixation equipment.

430 (S43000): General-purpose nonhardenable chromium type. Decorative trim; nitric acid tanks; annealing baskets; combustion chambers; dishwashers; heaters; mufflers; range hoods; recuperators; restaurant equipment.

430F (S43020): Free-machining modification of type 430, for heavier cuts. Screw machine parts.

430FSe (S43023): Free-machining modification of type 430, for lighter cuts. Machined parts requiring light cold heading or forming.

431 (S43100): Special-purpose hardenable steel used where particularly high mechanical properties are required. Aircraft fittings; beater bars; paper machinery; bolts.

434 (S43400): Modification of type 430 designed to resist atmospheric corrosion in the presence of winter road conditioning and dust-laying compounds. Automotive trim and fasteners.

436 (S43600): Similar to types 430 and 434. Used where low “roping” or “ridging” required. General corrosion and heat-resistant applications such as automobile trim.

440A (S44002): Hardenable to higher hardness than type 420 with good corrosion resistance. Cutlery; bearings; surgical tools.

440B (S44003): Cutlery grade. Cutlery, valve parts; instrument bearings.

440C (S44004): Yields highest hardnesses of hardenable stainless steels. Balls; bearings; races; nozzles; balls and seats for oil well pumps; valve parts.

442 (S44200): High-chromium steel, principally for parts that must resist high service temperatures without scaling. Furnace parts; nozzles; combustion chambers.

446 (S44600): High-resistance to corrosion and scaling at high temperatures, especially for intermittent service; often used in sulfur-bearing atmosphere. Annealing boxes; combustion chambers; glass molds; heaters; pyrometer tubes; recuperators; stirring rods; valves.

501 (S50100): Heat resistance; good mechanical properties at moderately elevated temperatures. Heat exchangers; petroleum refining equipment.

502 (S50200): More ductility and less strength than type 501. Heat exchangers; petroleum refining equipment; gaskets.

Chromium Nickel Austenitic Steels (Not capable of heat treatment).—*SAE 30201:*

This steel is an austenitic chromium–nickel–manganese stainless steel usually required in flat products. In the annealed condition, it exhibits higher strength values than the corresponding chromium–nickel stainless steel (SAE 30301). It is nonmagnetic in the annealed condition, but may be magnetic when cold-worked. SAE 30201 is used to obtain high strength by work-hardening and is well suited for corrosion-resistant structural members requiring high strength with low weight. It has excellent resistance to a wide variety of corrosive media, showing behavior comparable to stainless grade SAE 30301. It has high ductility and excellent forming properties. Owing to this steel's work-hardening rate and yield strength, tools for forming must be designed to allow for a higher springback or recovery rate. It is used for automotive trim, automotive wheel covers, railroad passenger car bodies and structural members, and truck trailer bodies.

SAE 30202: Like its corresponding chromium–nickel stainless steel SAE 30302, this is a general-purpose stainless steel. It has excellent corrosion resistance and deep drawing qualities. It is nonhardenable by thermal treatments, but may be cold worked to high tensile strengths. In the annealed condition, it is nonmagnetic but slightly magnetic when cold-worked. Applications for this stainless steel are hub cap, railcar and truck trailer bodies, and spring wire.

SAE 30301: Capable of attaining high tensile strength and ductility by moderate or severe cold working. It is used largely in the cold-rolled or cold-drawn condition in the form of sheet, strip, and wire. Its corrosion resistance is good but not equal to SAE 30302.

SAE 30302: The most widely used of the general-purpose austenitic chromium–nickel stainless steels. It is used for deep drawing largely in the annealed condition. It can be worked to high tensile strengths but with slightly lower ductility than SAE 30301.

SAE 30303F: A free-machining steel recommended for the manufacture of parts produced on automatic screw machines. Caution must be used in forging this steel.

SAE 30304: Similar to SAE 30302 but somewhat superior in corrosion resistance and having superior welding properties for certain types of equipment.

SAE 30305: Similar to SAE 30304 but capable of lower hardness. Has greater ductility with slower work-hardening tendency.

SAE 30309: A steel with high heat-resisting qualities which is resistant to oxidation at temperatures up to about 1800 degrees F.

SAE 30310: This teel has the highest heat-resisting properties of any of the chromium nickel steels listed here and will resist oxidation at temperatures up to about 1900 degrees F.

SAE 30316: Recommended for use in parts where unusual resistance to chemical or salt water corrosion is necessary. It has superior creep strength at elevated temperatures.

SAE 30317: Similar to SAE 30316 but has the highest corrosion resistance of all these alloys in many environments.

SAE 30321: Recommended for use in the manufacture of welded structures where heat treatment after welding is not feasible. It is also recommended for use where temperatures up to 1600 degrees F are encountered in service.

SAE 30325: Used for such parts as heat control shafts.

SAE 30347: This steel is similar to SAE 30321. This niobium alloy is sometimes preferred to titanium because niobium is less likely to be lost in welding operations.

Stainless Chromium Irons and Steels.—*SAE 51409:* An 11 per cent chromium alloy developed, especially for automotive mufflers and tailpipes. Resistance to corrosion and oxidation is very similar to SAE 51410. It is nonhardenable and has good forming and welding characteristics. This alloy is recommended for mildly corrosive applications where surface appearance is not critical.

SAE 51410: A general-purpose stainless steel capable of heat treatment to show good physical properties. It is used for general stainless applications, both in the heat-treated and annealed condition but is not as resistant to corrosion as SAE 51430 in either the annealed or heat-treated condition.

SAE 51414: A corrosion and heat-resisting nickel-bearing chromium steel with somewhat better corrosion resistance than SAE 51410. It will attain slightly higher mechanical properties when heat-treated than SAE 51410. It is used in the form of tempered strip or wire, and in bars and forgings for heat-treated parts.

SAE 51416F: A free-machining grade for the manufacture of parts produced in automatic screw machines.

SAE 51420: This steel is capable of being heat-treated to a relatively high hardness. It will harden to a maximum of approximately 500 Brinell. Maximum corrosion resisting qualities exist only in the fully hardened condition. It is used for cutlery, hardened pump shafts, etc.

SAE 51420F: This is similar to SAE 51420 except for its free-machining properties.

SAE 51430: This high-chromium steel is not capable of heat treatment and is recommended for use in shallow parts requiring moderate draw. Corrosion and heat resistance are superior to SAE 51410.

SAE 51430F: This steel is similar to SAE 51430 except for its free-machining properties.

SAE 51431: This nickel-bearing chromium steel is designed for heat treatment to high mechanical properties. Its corrosion resistance is superior to other hardenable steels.

SAE 51440A: A hardenable chromium steel with greater quenched hardness than SAE 51420 and greater toughness than SAE 51440B and 51440C. Maximum corrosion resistance is obtained in the fully hardened and polished condition.

SAE 51440B: A hardenable chromium steel with greater quenched hardness than SAE 51440A. Maximum corrosion resistance is obtained in the fully hardened and polished condition. Capable of hardening to 50–60 Rockwell C depending on carbon content.

SAE 51440C: This steel has the greatest quenched hardness and wear resistance on heat treatment of any corrosion- or heat-resistant steel.

SAE 51440F: The same as SAE 51440C, except for its free-machining characteristics.

SAE 51442: A corrosion- and heat-resisting chromium steel with corrosion-resisting properties slightly better than SAE 51430 and with good scale resistance up to 1600 degrees F.

SAE 51446: A corrosion- and heat-resisting steel with maximum amount of chromium consistent with commercial malleability. Used principally for parts that must resist high temperatures in service without scaling. Resists oxidation up to 2000 degrees F.

SAE 51501: Used for its heat and corrosion resistance and good mechanical properties at temperatures up to approximately 1000 degrees F.

Typical Mechanical Properties of Steel.—Tables 6 through 8 provide expected minimum and/or typical mechanical properties of selected standard carbon and alloy steels and stainless steels.

Table 6. Expected Minimum Mechanical Properties of Cold-Drawn Carbon-Steel Rounds, Squares, and Hexagons

Size, in.	As Cold-Drawn					Cold-Drawn Followed by Low-Temperature Stress Relief					Cold-Drawn Followed by High-Temperature Stress Relief				
	Strength		Elongation in 2 in., Per cent	Reduction in Area, Per cent	Hardness, Bhn	Strength		Elongation in 2 in., Per cent	Reduction in Area, Per cent	Hardness, Bhn	Strength		Elongation in 2 in., Per cent	Reduction in Area, Per cent	Hardness, Bhn
	Tensile	Yield				Tensile	Yield				Tensile	Yield			
	1000 lb/in.^{2}					1000 lb/in^2					1000 lb/in^2				
AISI 1018 and 1025 Steels															
5⁄8–7⁄8	70	60	18	40	143	....	....	....	....	…	65	45	20	45	131
Over 7⁄8–1¼	65	55	16	40	131	....	....	....	....	…	60	45	20	45	121
Over 1¼–2	60	50	15	35	121	....	....	....	....	…	55	45	16	40	111
Over 2–3	55	45	15	35	111	....	....	....	....	…	50	40	15	40	101
AISI 1117 and 1118 Steels															
5⁄8–7⁄8	75	65	15	40	149	80	70	15	40	163	70	50	18	45	143
Over 7⁄8–¼	70	60	15	40	143	75	65	15	40	149	65	50	16	45	131
Over 1¼–2	65	55	13	35	131	70	60	13	35	143	60	50	15	40	121
Over 2–3	60	50	12	30	121	65	55	12	35	131	55	45	15	40	111
AISI 1035 Steel															
5⁄8–7⁄8	85	75	13	35	170	90	80	13	35	179	80	60	16	45	163
Over 7⁄8–1¼	80	70	12	35	163	85	75	12	35	170	75	60	15	45	149
Over 1¼–2	75	65	12	35	149	80	70	12	35	163	70	60	15	40	143
Over 2–3	70	60	10	30	143	75	65	10	30	149	65	55	12	35	131
AISI 1040 and 1140 Steels															
5⁄8–7⁄8	90	80	12	35	179	95	85	12	35	187	85	65	15	45	170
Over 7⁄8–1¼	85	75	12	35	170	90	80	12	35	179	80	65	15	45	163
Over 1¼–2	80	70	10	30	163	85	75	10	30	170	75	60	15	40	149
Over 2–3	75	65	10	30	149	80	70	10	30	163	70	55	12	35	143

Table 6. *(Continued)* **Expected Minimum Mechanical Properties of Cold-Drawn Carbon-Steel Rounds, Squares, and Hexagons**

Size, in.	As Cold-Drawn					Cold-Drawn Followed by Low-Temperature Stress Relief					Cold-Drawn Followed by High-Temperature Stress Relief				
	Strength		Elongation in 2 in., Per cent	Reduction in Area, Per cent	Hardness, Bhn	Strength		Elongation in 2 in., Per cent	Reduction in Area, Per cent	Hardness, Bhn	Strength		Elongation in 2 in., Per cent	Reduction in Area, Per cent	Hardness, Bhn
	Tensile	Yield				Tensile	Yield				Tensile	Yield			
	1000 lb/in.^{2}					1000 lb/in^2					1000 lb/in^2				
AISI 1045, 1145, and 1146 Steels															
⅝–⅞	95	85	12	35	187	100	90	12	35	197	90	70	15	45	179
Over ⅞–1¼	90	80	11	30	179	95	85	11	30	187	85	70	15	45	170
Over 1¼–2	85	75	10	30	170	90	80	10	30	179	80	65	15	40	163
Over 2–3	80	70	10	30	163	85	75	10	25	170	75	60	12	35	149
AISI 1050, 1137, and 1151 Steels															
⅝–⅞	100	90	11	35	197	105	95	11	35	212	95	75	15	45	187
Over ⅞–1¼	95	85	11	30	187	100	90	11	30	197	90	75	15	40	179
Over 1¼–2	90	80	10	30	179	95	85	10	30	187	85	70	15	40	170
Over 2–3	85	75	10	30	170	90	80	10	25	179	80	65	12	35	163
AISI 1141 Steel															
⅝–⅞	105	95	11	30	212	110	100	11	30	223	100	80	15	40	197
Over ⅞–1¼	100	90	10	30	197	105	95	10	30	212	95	80	15	40	187
Over 1¼–2	95	85	10	30	187	100	90	10	25	197	90	75	15	40	179
Over 2–3	90	80	10	20	179	95	85	10	20	187	85	70	12	30	170
AISI 1144 Steel															
⅝–⅞	110	100	10	30	223	115	105	10	30	229	105	85	15	40	212
Over ⅞–1¼	105	95	10	30	212	110	100	10	30	223	100	85	15	40	197
Over 1¼–2	100	90	10	25	197	105	95	10	25	212	95	80	15	35	187
Over 2–3	95	85	10	20	187	100	90	10	20	197	90	75	12	30	179

Source: AISI Committee of Hot-Rolled and Cold-Finished Bar Producers and published in 1974 DATABOOK issue of the American Society for Metals' *METAL PROGRESS* magazine and used with its permission.

Table 7a. Charactertics and Typical Applications of Standard Stainless Steels

AISI No.[a]	Treatment	Strength		Elongation, Per cent	Reduction in Area, Per cent	Hard-ness, Bhn	Impact Strength (Izod), ft-lb
		Tensile	Yield				
		lb/in.^{2}					
1015	As-rolled	61,000	45,500	39.0	61.0	126	81.5
	Normalized (1700 F)	61,500	47,000	37.0	69.6	121	85.2
	Annealed (1600 F)	56,000	41,250	37.0	69.7	111	84.8
1020	As-rolled	65,000	48,000	36.0	59.0	143	64.0
	Normalized (1600 F)	64,000	50,250	35.8	67.9	131	86.8
	Annealed (1600 F)	57,250	42,750	36.5	66.0	111	91.0
1022	As-rolled	73,000	52,000	35.0	67.0	149	60.0
	Normalized (1700 F)	70,000	52,000	34.0	67.5	143	86.5
	Annealed (1600 F)	65,250	46,000	35.0	63.6	137	89.0
1030	As-rolled	80,000	50,000	32.0	57.0	179	55.0
	Normalized (1700 F)	75,000	50,000	32.0	60.8	149	69.0
	Annealed (1550 F)	67,250	49,500	31.2	57.9	126	51.2
1040	As-rolled	90,000	60,000	25.0	50.0	201	36.0
	Normalized (1650 F)	85,500	54,250	28.0	54.9	170	48.0
	Annealed (1450 F)	75,250	51,250	30.2	57.2	149	32.7
1050	As-rolled	105,000	60,000	20.0	40.0	229	23.0
	Normalized (1650 F)	108,500	62,000	20.0	39.4	217	20.0
	Annealed (1450 F)	92,250	53,000	23.7	39.9	187	12.5
1060	As-rolled	118,000	70,000	17.0	34.0	241	13.0
	Normalized (1650 F)	112,500	61,000	18.0	37.2	229	9.7
	Annealed (1450 F)	90,750	54,000	22.5	38.2	179	8.3
1080	As-rolled	140,000	85,000	12.0	17.0	293	5.0
	Normalized (1650 F)	146,500	76,000	11.0	20.6	293	5.0
	Annealed (1450 F)	89,250	54,500	24.7	45.0	174	4.5
1095	As-rolled	140,000	83,000	9.0	18.0	293	3.0
	Normalized (1650 F)	147,000	72,500	9.5	13.5	293	4.0
	Annealed (1450 F)	95,250	55,000	13.0	20.6	192	2.0
1117	As-rolled	70,600	44,300	33.0	63.0	143	60.0
	Normalized (1650 F)	67,750	44,000	33.5	63.8	137	62.8
	Annealed (1575 F)	62,250	40,500	32.8	58.0	121	69.0
1118	As-rolled	75,600	45,900	32.0	70.0	149	80.0
	Normalized (1700 F)	69,250	46,250	33.5	65.9	143	76.3
	Annealed (1450 F)	65,250	41,250	34.5	66.8	131	78.5
1137	As-rolled	91,000	55,00	28.0	61.0	192	61.0
	Normalized (1650 F)	97,000	57,500	22.5	48.5	197	47.0
	Annealed (1450 F)	84,750	50,000	26.8	53.9	174	36.8
1141	As-rolled	98,000	52,000	22.0	38.0	192	8.2
	Normalized (1650 F)	102,500	58,750	22.7	55.5	201	38.8
	Annealed (1500 F)	86,800	51,200	25.5	49.3	163	25.3
1144	As-rolled	102,000	61,000	21.0	41.0	212	39.0
	Normalized (1650 F)	96,750	58,000	21.0	40.4	197	32.0
	Annealed (1450 F)	84,750	50,250	24.8	41.3	167	48.0

Table 7a. Charactertics and Typical Applications of Standard Stainless Steels

AISI No.[a]	Treatment	Strength		Elongation, Per cent	Reduction in Area, Per cent	Hardness, Bhn	Impact Strength (Izod), ft-lb
		Tensile	Yield				
		lb/in.^{2}					
1340	Normalized (1600 F)	121,250	81,000	22.0	62.9	248	68.2
	Annealed (1475 F)	102,000	63,250	25.5	57.3	207	52.0
3140	Normalized (1600 F)	129,250	87,000	19.7	57.3	262	39.5
	Annealed (1500 F)	100,000	61,250	24.5	50.8	197	34.2
4130	Normalized (1600 F)	97,000	63,250	25.5	59.5	197	63.7
	Annealed (1585 F)	81,250	52,250	28.2	55.6	156	45.5
4140	Normalized (1600 F)	148,000	95,000	17.7	46.8	302	16.7
	Annealed (1500 F)	95,000	60,500	25.7	56.9	197	40.2
4150	Normalized (1600 F)	167,500	106,500	11.7	30.8	321	8.5
	Annealed (1500 F)	105,750	55,000	20.2	40.2	197	18.2
4320	Normalized (1640 F)	115,000	67,250	20.8	50.7	235	53.8
	Annealed (1560 F)	84,000	61,625	29.0	58.4	163	81.0
4340	Normalized (1600 F)	185,500	125,000	12.2	36.3	363	11.7
	Annealed (1490 F)	108,000	68,500	22.0	49.9	217	37.7
4620	Normalized (1650 F)	83,250	53,125	29.0	66.7	174	98.0
	Annealed (1575 F)	74,250	54,000	31.3	60.3	149	69.0
4820	Normalized (1580 F)	109,500	70,250	24.0	59.2	229	81.0
	Annealed (1500 F)	98,750	67,250	22.3	58.8	197	68.5
5140	Normalized (1600 F)	115,000	68,500	22.7	59.2	229	28.0
	Annealed (1525 F)	83,000	42,500	28.6	57.3	167	30.0
5150	Normalized (1600 F)	126,250	76,750	20.7	58.7	255	23.2
	Annealed (1520 F)	98,000	51,750	22.0	43.7	197	18.5
5160	Normalized (1575 F)	138,750	77,000	17.5	44.8	269	8.0
	Annealed (1495 F)	104,750	40,000	17.2	30.6	197	7.4
6150	Normalized (1600 F)	136,250	89,250	21.8	61.0	269	26.2
	Annealed (1500 F)	96,750	59,750	23.0	48.4	197	20.2
8620	Normalized (1675 F)	91,750	51,750	26.3	59.7	183	73.5
	Annealed (1600 F)	77,750	55,875	31.3	62.1	149	82.8
8630	Normalized (1600 F)	94,250	62,250	23.5	53.5	187	69.8
	Annealed (1550 F)	81,750	54,000	29.0	58.9	156	70.2
8650	Normalized (1600 F)	148,500	99,750	14.0	40.4	302	10.0
	Annealed (1465 F)	103,750	56,000	22.5	46.4	212	21.7
8740	Normalized (1600 F)	134,750	88,000	16.0	47.9	269	13.0
	Annealed (1500 F)	100,750	60,250	22.2	46.4	201	29.5
9255	Normalized (1650 F)	135,250	84,000	19.7	43.4	269	10.0
	Annealed (1550 F)	112,250	70,500	21.7	41.1	229	6.5
9310	Normalized (1630 F)	131,500	82,750	18.8	58.1	269	88.0
	Annealed (1550 F)	119,000	63,750	17.3	42.1	241	58.0

[a] All grades are fine-grained except those in the 1100 series that are coarse-grained. Austenitizing temperatures are given in parentheses. Heat-treated specimens were oil-quenched unless otherwise indicated.

Source: Bethlehem Steel Corp. and Republic Steel Corp. as published in 1974 DATABOOK issue of the American Society for Metals' METAL PROGRESS magazine and used with its permission.

Table 7b. Typical Mechanical Properties of Selected Carbon and Alloy Steels (Quenched and Tempered)

AISI No.[a]	Tempering Temperature, °F	Strength		Elongation, Per cent	Reduction in Area, Per cent	Hardness, Bhn
		Tensile	Yield			
		1000 lb/in.^{2}				
1030[b]	400	123	94	17	47	495
	600	116	90	19	53	401
	800	106	84	23	60	302
	1000	97	75	28	65	255
	1200	85	64	32	70	207
1040[b]	400	130	96	16	45	514
	600	129	94	18	52	444
	800	122	92	21	57	352
	1000	113	86	23	61	269
	1200	97	72	28	68	201
1040	400	113	86	19	48	262
	600	113	86	20	53	255
	800	110	80	21	54	241
	1000	104	71	26	57	212
	1200	92	63	29	65	192
1050[b]	400	163	117	9	27	514
	600	158	115	13	36	444
	800	145	110	19	48	375
	1000	125	95	23	58	293
	1200	104	78	28	65	235
1050	400	…	…	…	…	…
	600	142	105	14	47	321
	800	136	95	20	50	277
	1000	127	84	23	53	262
	1200	107	68	29	60	223
1060	400	160	113	13	40	321
	600	160	113	13	40	321
	800	156	111	14	41	311
	1000	140	97	17	45	277
	1200	116	76	23	54	229
1080	400	190	142	12	35	388
	600	189	142	12	35	388
	800	187	138	13	36	375
	1000	164	117	16	40	321
	1200	129	87	21	50	255
1095[b]	400	216	152	10	31	601
	600	212	150	11	33	534
	800	199	139	13	35	388
	1000	165	110	15	40	293
	1200	122	85	20	47	235
1095	400	187	120	10	30	401
	600	183	118	10	30	375
	800	176	112	12	32	363
	1000	158	98	15	37	321
	1200	130	80	21	47	269
1137	400	157	136	5	22	352
	600	143	122	10	33	285
	800	127	106	15	48	262
	1000	110	88	24	62	229
	1200	95	70	28	69	197

Table 7b. *(Continued)* **Typical Mechanical Properties of Selected Carbon and Alloy Steels** (Quenched and Tempered)

AISI No.[a]	Tempering Temperature, °F	Strength		Elongation, Per cent	Reduction in Area, Per cent	Hardness, Bhn
		Tensile	Yield			
		1000 lb/in.^{2}				
1137[b]	400	217	169	5	17	415
	600	199	163	9	25	375
	800	160	143	14	40	311
	1000	120	105	19	60	262
	1200	94	77	25	69	187
1141	400	237	176	6	17	461
	600	212	186	9	32	415
	800	169	150	12	47	331
	1000	130	111	18	57	262
	1200	103	86	23	62	217
1144	400	127	91	17	36	277
	600	126	90	17	40	262
	800	123	88	18	42	248
	1000	117	83	20	46	235
	1200	105	73	23	55	217
1330[b]	400	232	211	9	39	459
	600	207	186	9	44	402
	800	168	150	15	53	335
	1000	127	112	18	60	263
	1200	106	83	23	63	216
1340	400	262	231	11	35	505
	600	230	206	12	43	453
	800	183	167	14	51	375
	1000	140	120	17	58	295
	1200	116	90	22	66	252
4037	400	149	110	6	38	310
	600	138	111	14	53	295
	800	127	106	20	60	270
	1000	115	95	23	63	247
	1200	101	61	29	60	220
4042	400	261	241	12	37	516
	600	234	211	13	42	455
	800	187	170	15	51	380
	1000	143	128	20	59	300
	1200	115	100	28	66	238
4130[b]	400	236	212	10	41	467
	600	217	200	11	43	435
	800	186	173	13	49	380
	1000	150	132	17	57	315
	1200	118	102	22	64	245
4140	400	257	238	8	38	510
	600	225	208	9	43	445
	800	181	165	13	49	370
	1000	138	121	18	58	285
	1200	110	95	22	63	230
4150	400	280	250	10	39	530
	600	256	231	10	40	495
	800	220	200	12	45	440
	1000	175	160	15	52	370
	1200	139	122	19	60	290
4340	400	272	243	10	38	520
	600	250	230	10	40	486
	800	213	198	10	44	430
	1000	170	156	13	51	360
	1200	140	124	19	60	280

Table 7b. *(Continued)* **Typical Mechanical Properties of Selected Carbon and Alloy Steels** (Quenched and Tempered)

AISI No.[a]	Tempering Temperature, °F	Strength		Elongation, Per cent	Reduction in Area, Per cent	Hardness, Bhn
		Tensile	Yield			
		1000 lb/in.^{2}				
5046	400	253	204	9	25	482
	600	205	168	10	37	401
	800	165	135	13	50	336
	1000	136	111	18	61	282
	1200	114	95	24	66	235
50B46	400	…	…	…	…	560
	600	258	235	10	37	505
	800	202	181	13	47	405
	1000	157	142	17	51	322
	1200	128	115	22	60	273
50B60	400	…	…	…	…	600
	600	273	257	8	32	525
	800	219	201	11	34	435
	1000	163	145	15	38	350
	1200	130	113	19	50	290
5130	400	234	220	10	40	475
	600	217	204	10	46	440
	800	185	175	12	51	379
	1000	150	136	15	56	305
	1200	115	100	20	63	245
5140	400	260	238	9	38	490
	600	229	210	10	43	450
	800	190	170	13	50	365
	1000	145	125	17	58	280
	1200	110	96	25	66	235
5150	400	282	251	5	37	525
	600	252	230	6	40	475
	800	210	190	9	47	410
	1000	163	150	15	54	340
	1200	117	118	20	60	270
5160	400	322	260	4	10	627
	600	290	257	9	30	555
	800	233	212	10	37	461
	1000	169	151	12	47	341
	1200	130	116	20	56	269
51B60	400	…	…	…	…	600
	600	…	…	…	…	540
	800	237	216	11	36	460
	1000	175	160	15	44	355
	1200	140	126	20	47	290
6150	400	280	245	8	38	538
	600	250	228	8	39	483
	800	208	193	10	43	420
	1000	168	155	13	50	345
	1200	137	122	17	58	282
81B45	400	295	250	10	33	550
	600	256	228	8	42	475
	800	204	190	11	48	405
	1000	160	149	16	53	338
	1200	130	115	20	55	280

Table 7b. *(Continued)* **Typical Mechanical Properties of Selected Carbon and Alloy Steels** (Quenched and Tempered)

AISI No.[a]	Tempering Temperature, °F	Strength		Elongation, Per cent	Reduction in Area, Per cent	Hardness, Bhn
		Tensile	Yield			
		1000 lb/in.^{2}				
8630	400	238	218	9	38	465
	600	215	202	10	42	430
	800	185	170	13	47	375
	1000	150	130	17	54	310
	1200	112	100	23	63	240
8640	400	270	242	10	40	505
	600	240	220	10	41	460
	800	200	188	12	45	400
	1000	160	150	16	54	340
	1200	130	116	20	62	280
86B45	400	287	238	9	31	525
	600	246	225	9	40	475
	800	200	191	11	41	395
	1000	160	150	15	49	335
	1200	131	127	19	58	280
8650	400	281	243	10	38	525
	600	250	225	10	40	490
	800	210	192	12	45	420
	1000	170	153	15	51	340
	1200	140	120	20	58	280
8660	400	…	…	…	…	580
	600	…	…	…	…	535
	800	237	225	13	37	460
	1000	190	176	17	46	370
	1200	155	138	20	53	315
8740	400	290	240	10	41	578
	600	249	225	11	46	495
	800	208	197	13	50	415
	1000	175	165	15	55	363
	1200	143	131	20	60	302
9255	400	305	297	1	3	601
	600	281	260	4	10	578
	800	233	216	8	22	477
	1000	182	160	15	32	352
	1200	144	118	20	42	285
9260	400	…	…	…	…	600
	600	…	…	…	…	540
	800	255	218	8	24	470
	1000	192	164	12	30	390
	1200	142	118	20	43	295
94B30	400	250	225	12	46	475
	600	232	206	12	49	445
	800	195	175	13	57	382
	1000	145	135	16	65	307
	1200	120	105	21	69	250

[a] All grades are fine-grained except those in the 1100 series that are coarse-grained. Austenitizing temperatures are given in parentheses. Heat-treated specimens were oil-quenched unless otherwise indicated.

[b] Water quenched.

Source: Bethlehem Steel Corp. and Republic Steel Corp. as published in 1974 DATABOOK issue of the American Society for Metals' *METAL PROGRESS* magazine and used with its permission.

Table 8. Nominal Mechanical Properties of Selected Standard Stainless Steels

Grade	Condition	Tensile Strength (psi)	0.2 Per Cent Yield Strength (psi)	Elongation in 2 in. (%)	Reduction of Area (%)	Hardness	
						Rockwell	Bhn
Austenitic Steels							
201	Annealed	115,000	55,000	55	…	B90	…
	¼-hard	125,000[a]	75,000[a]	20[a]	…	C25	…
	½-hard	150,000[a]	110,000[a]	10[a]	…	C32	…
	¾-hard	175,000[a]	135,000[a]	5[a]	…	C37	…
	Full-hard	185,000[a]	140,000[a]	4[a]	…	C41	…
202	Annealed	105,000	55,000	55	…	B90	…
	¼-hard	125,000[a]	75,000[a]	12[a]	…	C27	…
301	Annealed	110,000	40,000	60	…	B85	165
	¼-hard	125,000[a]	75,000[a]	25[a]	…	C25	…
	½-hard	150,000[a]	110,000[a]	15[a]	…	C32	…
	¾-hard	175,000[a]	135,000[a]	12[a]	…	C37	…
	Full-hard	185,000	140,000[a]	8[a]	…	C41	…
302	Annealed	90,000	37,000	55	65	B82	155
	1/4-hard (sheet, strip)	125,000[a]	75,000[a]	12[a]	…	C25	…
	Cold-drawn (bar, wire)[b]	To 350,000	…	…	…	…	…
302B	Annealed	95,000	40,000	50	65	B85	165
303, 303 (Se)	Annealed	90,000	35,000	50	55	B84	160
304	Annealed	85,000	35,000	55	65	B80	150
304L	Annealed	80,000	30,000	55	65	B76	140
305	Annealed	85,000	37,000	55	70	B82	156
308	Annealed	85,000	35,000	55	65	B80	150
309, 309S	Annealed	90,000	40,000	45	65	B85	165
310, 310S	Annealed	95,000	40,000	45	65	B87	170
314	Annealed	100,000	50,000	45	60	B87	170
316	Annealed	85,000	35,000	55	70	B80	150
	Cold-drawn (bar, wire)[b]	To 300,000	…	…	…	…	…
316L	Annealed	78,000	30,000	55	65	B76	145
317	Annealed	90,000	40,000	50	55	B85	160
321	Annealed	87,000	35,000	55	65	B80	150
347, 348	Annealed	92,000	35,000	50	65	B84	160
Martensitic Steels							
403, 410, 416, 416 (Se)	Annealed	75,000	40,000	30	65	B82	155
	Hardened[c]	…	…	…	…	C43	410
	Tempered at						
	400°F	190,000	145,000	15	55	C41	390
	600°F	180,000	140,000	15	55	C39	375
	800°F	195,000	150,000	17	55	C41	390
	1000°F	145,000	115,000	20	65	C31	300
	1200°F	110,000	85,000	23	65	B97	225
	1400°F	90,000	60,000	30	70	B89	180

Table 8. *(Continued)* **Nominal Mechanical Properties of Selected Standard Stainless**

Grade	Condition	Tensile Strength (psi)	0.2 Per Cent Yield Strength (psi)	Elongation in 2 in. (%)	Reduction of Area (%)	Hardness	
						Rockwell	Bhn
414	Annealed	120,000	95,000	17	55	C22	235
	Hardened[c]	…	…	…	…	C44	426
	Tempered at						
	400°F	200,000	150,000	15	55	C43	415
	600°F	190,000	145,000	15	55	C41	400
	800°F	200,000	150,000	16	58	C43	415
	1000°F	145,000	120,000	20	60	C34	325
	1200°F	120,000	105,000	20	65	C24	260
420, 420F	Annealed	95,000	50,000	25	55	B92	195
	Hardened[d]	…	…	…	…	C54	540
	Tempered at						
	600°F	230,000	195,000	8	25	C50	500
431	Annealed	125,000	95,000	20	60	C24	260
	Hardened[d]	…	…	…	…	C45	440
	Tempered at						
	400°F	205,000	155,000	15	55	C43	415
	600°F	195,000	150,000	15	55	C41	400
	800°F	205,000	155,000	15	60	C43	415
	1000°F	150,000	130,000	18	60	C34	325
	1200°F	125,000	95,000	20	60	C24	260
440A	Annealed	105,000	60,000	20	45	B95	215
	Hardened[d]	…	…	…	…	C56	570
	Tempered						
	600°F	260,000	240,000	5	20	C51	510
440B	Annealed	107,000	62,000	18	35	B96	220
	Hardened[d]	…	…	…	…	C58	590
	Tempered						
	600°F	280,000	270,000	3	15	C55	555
440C, 440F	Annealed	110,000	65,000	13	25	B97	230
	Hardened[d]	…	…	…	…	C60	610
	Tempered						
	600°F	285,000	275,000	2	10	C57	580
501	Annealed	70,000	30,000	28	65	…	160
502	Annealed	70,000	30,000	30	75	B80	150
Ferritic Steels							
405	Annealed	70,000	40,000	30	60	B80	150
430	Annealed	75,000	45,000	30	60	B82	155
430F, 430F (Se)	Annealed	80,000	55,000	25	60	B86	170
446	Annealed	80,000	50,000	23	50	B86	170

[a] Minimum.

[b] Depending on size and amount of cold reduction.

[c] Hardening temperature 1800 degrees F, 1-in.-diam. bars.

[d] Hardening temperature 1900 degrees F, 1-in.-diam. bars.

Source: Metals Handbook, 8th edition, Volume 1.

High-Strength, Low-Alloy Steels.—High-strength, low-alloy (HSLA) steel represents a specific group of steels in which enhanced mechanical properties and, sometimes, resistance to atmospheric corrosion are obtained by the addition of moderate amounts of one or more alloying elements other than carbon. Different types are available, some of which are carbon–manganese steels and others contain further alloy additions, governed by special requirements for weldability, formability, toughness, strength, and economics. These steels may be obtained in the form of sheet, strip, plates, structural shapes, bars, and bar size sections.

HSLA steels are especially characterized by their mechanical properties, obtained in the as-rolled condition. They are not intended for quenching and tempering. For certain applications, they are sometimes annealed, normalized, or stress relieved with some influence on mechanical properties.

Where these steels are used for fabrication by welding, care must be exercised in selection of grade and in the details of the welding process. Certain grades may be welded without preheat or postheat.

Because of their high strength-to-weight ratio, abrasion resistance, and, in certain compositions, improved atmospheric corrosion resistance, these steels are adapted particularly for use in mobile equipment and other structures where substantial weight savings are generally desirable. Typical applications are truck bodies, frames, structural members, scrapers, truck wheels, cranes, shovels, booms, chutes, and conveyors.

Grade 942X: A niobium- or vanadium-treated carbon–manganese high-strength steel similar to 945X and 945C except for somewhat improved welding and forming properties.

Grade 945A: A HSLA steel with excellent welding characteristics, both arc and resistance, and the best formability, weldability, and low-temperature notch toughness of the high-strength steels. It is generally used in sheets, strip, and light plate thicknesses.

Grade 945C: A carbon–manganese high-strength steel with satisfactory arc welding properties if adequate precautions are observed. It is similar to grade 950C, except that lower carbon and manganese improve arc welding characteristics, formability, and low-temperature notch toughness at some sacrifice in strength.

Grade 945X: A niobium- or vanadium-treated carbon–manganese high-strength steel similar to 945C, except for somewhat improved welding and forming properties.

Grade 950A: A HSLA steel with good weldability, both arc and resistance, with good low-temperature notch toughness, and good formability. It is generally used in sheet, strip, and light plate thicknesses.

Grade 950B: A HSLA steel with satisfactory arc welding properties and fairly good low-temperature notch toughness and formability.

Grade 950C: A carbon–manganese high-strength steel that can be arc welded with special precautions, but is unsuitable for resistance welding. The formability and toughness are fair.

Grade 950D: A HSLA steel with good weldability, both arc and resistance, and fairly good formability. Where low-temperature properties are important, the effect of phosphorus in conjunction with other elements present should be considered.

Grade 950X: A niobium- or vanadium-treated carbon–manganese high-strength steel similar to 950C, except for somewhat improved welding and forming properties.

Grades 955X, 960X, 965X, 970X, 980X: These are steels similar to 945X and 950X with higher strength obtained by increased amounts of strengthening elements, such as carbon or manganese, or by the addition of nitrogen up to about 0.015 per cent. This increased strength involves reduced formability and usually decreased weldability. Toughness will vary considerably with composition and mill practice.

The composition, minimum mechanical properties, and formability of the HSLA steel grades are shown in Tables 9 through 13.

Table 9. Chemical Composition Ladle Analysis (max. per cent)

Grade	C	Mn	P
942X	0.21	1.35	0.04
945A	0.15	1.00	0.04
945C	0.23	1.40	0.04
945X	0.22	1.35	0.04
950A	0.15	1.30	0.04
950B	0.22	1.30	0.04
950C	0.25	1.60	0.04
950D	0.15	1.00	0.15
950X	0.23	1.35	0.04
955X	0.25	1.35	0.04
960X	0.26	1.45	0.04
965X	0.26	1.45	0.04
970X	0.26	1.65	0.04
980X	0.26	1.65	0.04

Sulfur, 0.05 per cent max; silicon, 0.90 per cent max.

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Table 10. Minimum Mechanical Properties

Grade	Form	Yield Strength[a] (psi min)	Tensile Strength (psi min)	Elongation (% min)	
				2 in.	8 in.
942X	Plates, shapes, bars to 4 in. incl.	42,000	60,000	24	20
945A, C	Sheet and strip	45,000	60,000	22	…
	Plates, shapes, bars				
	To ½ in. incl.	45,000	65,000	22	18
	½–1½ in. incl.	42,000	62,000	24	19
	1½–3 in. incl.	40,000	62,000	24	19
945X	Sheet and strip	45,000	60,000	25	…
	Plates, shapes, bars				
	To 1½ in. incl.	45,000	60,000	22	19
950A, B, C, D	Sheet and strip	50,000	70,000	22	…
	Plates, shapes, bars				
	To ½ in. incl.	50,000	70,000	22	18
	½–1½ in. incl.	45,000	67,000	24	19
	1½–3 in. incl.	42,000	63,000	24	19
950X	Sheet and strip	50,000	65,000	22	…
	Plates, shapes, bars				
	To 1½ in. incl.	50,000	65,000	…	18
955X	Sheet and strip	55,000	70,000	20	…
	Plates, shapes, bars				
	To 1½ in. incl.	55,000	70,000	…	17
960X	Sheet and strip	60,000	75,000	18	…
	Plates, shapes, bars				
	To 1½ in. incl.	60,000	75,000	…	16
965X	Sheet and strip	65,000	80,000	16	…
	Plates, shapes, bars				
	To ¾ in. incl.	65,000	80,000	…	15
970X	Sheet and strip	70,000	85,000	14	…
	Plates, shapes, bars				
	To ¾ in. incl.	70,000	85,000	…	14
980X	Sheet and strip	80,000	95,000	12	…
	Plates to ⅜ in. incl.	80,000	95,000	…	10

[a] Yield strength to be measured at 0.2 per cent offset.

Mechanical properties to be determined in accordance with ASTM A 370.

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Table 11. Steel Grades in Approximate Order of Increasing Excellence

Weldability	Formability	Toughness
980X	980X	980X
970X	970X	970X
965X	965X	965X
960X	960X	960X
955X, 950C, 942X	955X	955X
945C	950C	945C, 950C, 942X
950B, 950X	950D	945X, 950X
945X	950B, 950X, 942X	950D
950D	945C, 945X	950B
950A	950A	950A
945A	945A	945A

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Table 12. Typical SAE heat treatments for Grades of Chromium–Nickel Austenitic Steels Not Hardenable by Thermal Treatment

SAE Steels	AISI No.	Annealing[a] Temperature (degrees F)	Annealing Temperature (deg. C)	Quenching Medium
30201	201	1850–2050	1010–1120	Air
30202	202	1850–2050	1010–1120	Air
30301	301	1850–2050	1010–1120	Air
30302	302	1850–2050	1010–1120	Air
30303	303	1850–2050	1010–1120	Air
30304	304	1850–2050	1010–1120	Air
30305	305	1850–2050	1010–1120	Air
30309	309	1900–2050	1040–1120	Air
30310	310	1900–2100	1040–1150	Air
30316	316	1850–2050	1010–1120	Air
30317	317	1850–2050	1010–1120	Air
30321	321	1750–2050	955–1120	Air
30325	325	1800–2100	980–1150	Air
30330	…	1950–2150	1065–1175	Air
30347	347	1850–2050	1010–1120	Air

[a] Quench to produce full austenitic structure in accordance with the thickness of the section. Annealing temperatures given cover process and full annealing as already established and used by industry, the lower end of the range being used for process annealing.

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Table 13. Typical SAE Heat Treatments for Stainless Chromium Steels

SAE Steels	AISI No.	Normalizing Temperature (degrees F)	Subcritical Annealing Temperature (degrees F)	Full Annealing[a] Temperature (degrees F)	Hardening Temperature (degrees F)	Quenching Medium	Temper
51409	…	…	…	1625	…	Air	…
51410	410	…	1300–1350[b]	1500–1650	…	Oil or air	To desired hardness
		…	…	…	1700–1850		
51414	414	…	1200–1250[b]	…	…	Oil or air	To desired hardness
		…	…	…	1800–1900		
51416	416	…	1300–1350[c]	1500–1650	…	Oil or air	To desired hardness
		…	…	…	1700–1850		
51420	420	…	1350–1450[b]	1550–1650	…	Oil or air	To desired hardness
		…	…	…	1800–1900		
51420F[d]	…	…	1350–1450[b]	1550–1650	…	Oil or air	To desired hardness
		…	…	…	1800–1900		
51430	430	…	1400–1500[c]	…	…	…	…
51430F[d]	…	…	1250–1400[c]	…	…	…	…
51431	431	…	1150–1225[b]	…	1800–1950	Oil or air	To desired hardness
51434	…	…	1400–1600[c]	…	…	…	…
51436	…						
51440A[d]	440A[d]	…	1350–1440[b]	1550–1650	1850–1950	Oil or air	To desired hardness
51440B[d]	440B[d]						
51440C[d]	440C[d]						
51440F[d]	…						
51442	442	…	1350–1500[c]	…	…	…	…
51446	446	…	1450–1600[b]	…	…	…	…
51501	501	…	1325–1375[c]	1525–1600	1600–1700	Oil or air	To desired hardness

[a] Cool slowly in furnace.

[b] Usually air cooled but may be furnace cooled.

[c] Cool rapidly in air.

[d] Suffixes A, B, and C denote three types of steel differing only in carbon content. Suffix F denotes a free-machining steel.

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TOOL STEELS

Tool Steels

As the designation implies, tool steels serve primarily for making tools used in manufacturing and in the trades for the working and forming of metals, wood, plastics, and other industrial materials. Tools must withstand high specific loads, often concentrated at exposed areas, may have to operate at elevated or rapidly changing temperatures and in continual contact with abrasive types of work materials, and are often subjected to shocks, or may have to perform under other varieties of adverse conditions. Nevertheless, when employed under circumstances that are regarded as normal operating conditions, the tool should not suffer major damage, untimely wear resulting in the dulling of the edges, or be susceptible to detrimental metallurgical changes.

Tools for less demanding uses, such as ordinary handtools, including hammers, chisels, files, mining bits, etc., are often made of standard AISI steels that are not considered as belonging to any of the tool steel categories.

The steel for most types of tools must be used in a heat-treated state, generally hardened and tempered, to provide the properties needed for the particular application. The adaptability to heat treatment with a minimurn of harmful effects, which dependably results in the intended beneficial changes in material properties, is still another requirement that tool steels must satisfy.

To meet such varied requirements, steel types of different chemical composition, often produced by special metallurgical processes, have been developed. Due to the large number of tool steel types produced by the steel mills, which generally are made available with proprietary designations, it is rather difficult for the user to select those types that are most suitable for any specific application, unless the recommendations of a particular steel producer or producers are obtained.

Substantial clarification has resulted from the development of a classification system that is now widely accepted throughout the industry, on the part of both the producers and the users of tool steels. That system is used in the following as a base for providing concise information on tool steel types, their properties, and methods of tool steel selection.

The tool steel classification system establishes seven basic categories of tool and die steels. These categories are associated with the predominant applicational characteristics of the tool steel types they comprise. A few of these categories are composed of several groups to distinguish between families of steel types that, while serving the same general purpose, differ with regard to one or more dominant characteristics.

To provide an easily applicable guide for the selection of tool steel types best suited for a particular application, the subsequent discussions and tables are based on the previously mentioned application-related categories. As an introduction to the detailed surveys, a concise discussion is presented of the principal tool steel characteristics that govern the suitability for varying service purposes and operational conditions. A brief review of the major steel alloying elements and of the effect of these constituents on the significant characteristics of tool steels is also given in the following sections.

The Properties of Tool Steels.—Tool steels must possess certain properties to a higher than ordinary degree to make them adaptable for uses that require the ability to sustain heavy loads and perform dependably even under adverse conditions.

The extent and the types of loads, the characteristics of the operating conditions, and the expected performance with regard to both the duration and the level of consistency are the principal considerations, in combination with the aspects of cost, that govern the selection of tool steels for specific applications.

Although it is not possible to define and apply exact parameters for measuring significant tool steel characteristics, certain properties can be determined that may greatly assist in appraising the suitability of various types of tool steels for specific uses.

Because tool steels are generally heat-treated to make them adaptable to the intended use by enhancing the desirable properties, *the behavior of the steel during heat treatment* is of prime importance. The behavior of the steel comprises, in this respect, both the resistance to harmful effects and the attainment of the desirable properties. The following are considered the major properties related to heat treatment:

Safety in Hardening: This designation expresses the ability of the steel to withstand the harmful effects of exposure to very high heat and particularly to the sudden temperature changes during quenching, without harmful effects. One way of obtaining this property is by adding alloying elements that reduce the critical speed at which the quenching must be carried out, thus permitting the use of milder quenching media such as oil, salt, or just still air.

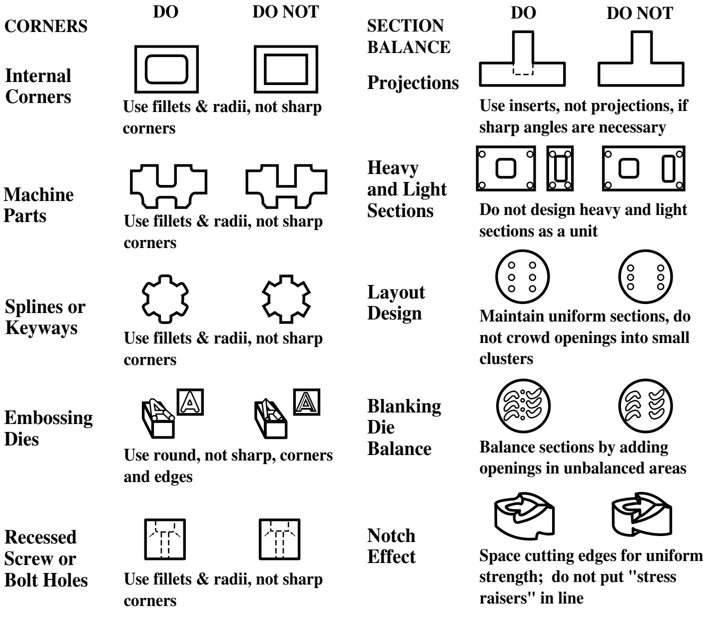


Fig. 1. Tool and die design tips to reduce breakage in heat treatment.
Courtesy of Society of Automotive Engineers, Inc.

The most common harm parts made of tool steel suffer from during heat treatment is the development of cracks. In addition to the composition of the steel and the applied heat-treating process, the configuration of the part can also affect the sensitivity to cracking. The preceding figure illustrates a few design characteristics related to cracking and warpage in heat treatment; the observation of these design tips, which call for generous filleting, avoidance of sharp angles, and major changes without transition in the cross-section, is particularly advisable when using tool steel types with a low index value for safety in hardening.

In current practice, the previously mentioned property of tool steels is rated in the order of decreasing safety (i.e., increasing sensitivity) as Highest, Very High, High, Medium, and Low safety, expressed in Tables 8 through 13 by the letters A, B, C, D, and E.

Distortions in Heat Treating: In parts made from tool steels, distortions are often a consequence of inadequate design (See Fig. 1.) or improper heat treatment (e.g., lack of stress relieving). However, certain types of tool steels display different degrees of sensitivity to distortion. Steels that are less stable require safer design of the parts for which they are used, more careful heat treatment, including the proper support for long and slender parts, or thin sections, and possibly greater grinding allowance to permit subsequent correction of the distorted shape. Some parts made of a type of steel generally sensitive to distortions can be heat-treated with very little damage when the requirements of the part call for a relatively shallow hardened layer over a soft core. However, for intricate shapes and large tools, steel types should be selected that possess superior nondeforming properties. The ratings used in Tables 8 through 13 express the nondeforming properties (stability of shape in heat treatment) of the steel types and start with the lowest distortion (the best stability) designated as A; the greatest susceptibility to distortion is designated as E.

Depth of Hardening: Hardening depth is indicated by a relative rating based on how deep the phase transformation penetrates from the surface and thus produces a hardened layer. Because of the effect of the heat-treating process, and particularly of the applied quenching medium, on the depth of hardness, reference is made in Tables 8 through 13 to the quench that results in the listed relative hardenability values. These values are designated by letters A, B, and C, expressing deep, medium, and shallow depth, respectively.

Resistance to Decarburization: Higher or lower sensitivity to losing a part of the carbon content of the surface exposed to heat depends on the chemistry of the steel. The sensitivity can be balanced partially by appropriate heat-treating equipment and processes. Also, the amount of material to be removed from the surface after heat treatment, usually by grinding, should be specified in such a manner as to avoid the retention of a decarburized layer on functional surfaces. The relative resistance of individual tool steel types to decarburization during heat treatment is rated in Tables 8 through 13 from High to Low, expressed by the letters A, B, and C.

Tool steels must be workable with generally available means, without requiring highly specialized processes. The tools made from these steels must, of course, perform adequately, often under adverse environmental and burdensome operational conditions. The ability of the individual types of tool steels to satisfy, to different degrees, such applicational requirements can also be appraised on the basis of significant properties, such as the following.

Machinability: Tools are precision products whose final shape and dimensions must be produced by machining, a process to which not all tool steel types lend themselves equally well. The difference in machinability is particularly evident in tool steels that, depending on their chemical composition, may contain substantial amounts of metallic carbides, beneficial to increased wear resistance, yet detrimental to the service life of tools with which the steel has to be worked. The microstructure of the steel type can also affect the ease of machining and, in some types, certain phase conditions, such as those due to low carbon content, may cause difficulties in achieving a fine surface finish. Certain types of tool steels have their machinability improved by the addition of small amounts of sulfur or lead. Machinability affects the cost of making the tool, particularly for intricate tool shapes, and must be considered in selection of the steel to be used. The ratings in Tables 8 through 13, starting with A for the greatest ease of machining to E for the lowest machinability, refer to working of the steel in an unhardened condition. Machinability is not necessarily identical with grindability, which expresses how well the steel is adapted to grinding after heat treating. The ease of grinding, however, may become an important consideration in tool steel selection, particularly for cutting tools and dies, which require regular sharpening involving extensive grinding. AVCO Bay State Abrasives Company compiled information on the relative grindability of frequently used types of tool steels. A simplified version of that information is presented in Table 1, which assigns the listed tool steel types to one of the following grindability grades: High (A), Medium (B), Low (C), and Very Low (D), expressing decreasing ratios of volume of metal removed to wheel wear.

Table 1. Relative Grindability of Selected Types of Frequently Used Tool Steels

AISI Tool Steel Type	H41	H42	H43	Other H	D2	D3	D5	D7	A Types	O Types	L Types	F Types
Relative Grindability Index	B	B	B	A	B	B	B	C	A	A	A	B

AISI High-Speed Tool Steel Type	M1	M2	M3 (1)	M3 (2)	M4	M7	M8	M10	M15	M36	M43	T1	T2	T3	T5	T6	T15
Relative Grindability Index	A	B	C	C	D	B	A	B	D	B	B	A	B	C	B	B	D

Hot Hardness: This property designates the steel's resistance to the softening effect of elevated temperature. This characteristic is related to the tempering temperature of the type of steel, which is controlled by various alloying elements such as tungsten, molybdenum, vanadium, cobalt, and chromium.

Hot hardness is a necessary property of tools used for hot work, like forging, casting, and hot extrusion. Hot hardness is also important in cutting tools operated at high-speed, which generate sufficient heat to raise their temperature well above the level where ordinary steels lose their hardness; hence the designation *high-speed steels*, which refers to a family of tool steels developed for use at high cutting speeds. Frequently it is the degree of the tool steel's resistance to softening at elevated temperature that governs important process data, such as the applicable cutting speed. In the ratings of Tables 8 through 13, tool steel types having the highest hot hardness are marked with A, subsequent letters expressing gradually decreasing capacity to endure elevated temperature without losing hardness.

Wear Resistance: The gradual erosion of the tool's operating surface, most conspicuously occurring at the exposed edges, is known as wear. Resistance to wear prolongs the useful life of the tool by delaying the degradation of its surface through abrasive contact with the work at regular operating temperatures; these temperatures vary according to the type of process. Wear resistance is observable experimentally and measurable by comparison. Certain types of metallic carbides embedded into the steel matrix are considered to be the prime contributing factors to wear resistance, besides the hardness of the heat-treated steel material. The ratings of Tables 8 through 13, starting with A for the best to E for poor, are based on conditions thought to be normal in operations for which various types of tool materials are primarily used.

Toughness: In tool steels, this property expresses ability to sustain shocks, suddenly applied and relieved loads, or major impacts, without breaking. Steels used for making tools must also be able to absorb such forces with only a minimum of elastic deformation and without permanent deformation to any extent that would interfere with the proper functioning of the tool. Certain types of tool steels, particularly those with high carbon content and without the presence of beneficial alloying constituents, tend to be the most sensitive to shocks, although they can also be made to act tougher when used for tools that permit a hardened case to be supported by a soft core. Tempering improves toughness, while generally reducing hardness. The rating indexes in Tables 8 through 13, A for the highest toughness through E for the types most sensitive to shocks, apply to tools heat treated to hardness values normally used for the particular type of tool steel.

Common Tool Faults and Failures.—The proper selection of the steel grade used for any particular type of tool is of great importance, but it should be recognized that many of the failures experienced in common practice originate from causes other than those related to the tool material.

To permit a better appraisal of the actual causes of failure and possible corrective action, a general, although not complete, list of common tool faults, resulting failures, and corrective actions is shown in Tables 2 through Tables 5. In this list, the potential failure causes are grouped into four categories. The possibility of more than a single cause being responsible for the experienced failure should not be excluded.

Finally, it must be remembered that the proper usage of tools is indispensable for obtaining satisfactory performance and tool life. Using the tools properly involves, for example, the avoidance of damage to the tool; overloading; excessive speeds and feeds; the application of adequate coolant when called for; a rigid setup; proper alignment; and firm tool and work holding.

Table 2. Common Tool Faults, Failures, and Cures

Improper Tool Design

Fault Description	Probable Failure	Possible Cure
Drastic section changes—widely different thicknesses of adjacent wall sections or protruding elements	In liquid quenching, the thin section will cool and then harden more rapidly than the adjacent thicker section, setting up stresses that may exceed the strength of the steel.	Make such parts of two pieces or use an air-hardening tool steel that avoids the harsh action of a liquid quench.
Sharp corners on shoulders or in square holes	Cracking can occur, particularly in liquid quenching, due to stress concentrations.	Apply fillets to the corners and/or use an air-hardening tool steel.
Sharp cornered keyways	Failure may arise during service, and is usually considered to be caused by fatigue.	The use of round keyways should be preferred when the general configuration of the part makes it prone to failure due to square keyways.
Abrupt section changes in battering tools	Due to impact in service, pneumatic tools are particularly sensitive to stress concentrations that lead to fatigue failures.	Use taper transitions, which are better than even generous fillets.
Functional inadequacy of tool design—e.g., insufficient guidance for a punch	Excessive wear or breakage in service may occur.	Assure solid support, avoid unnecessary play, adapt travel length to operational conditions (e.g., punch to penetrate to four-fifths of thickness in hard work material).
Improper tool clearance, such as in blanking and punching tools	Deformed and burred parts may be produced, excessive tool wear or breakage can result.	Adapt clearances to material conditions and dimensions to reduce tool load and to obtain clean sheared surfaces.

Table 3. Common Tool Faults, Failures, and Cures

Faulty Condition or Inadequate Grade of Tool Steel

Fault Description	Probable Failure	Possible Cure
Improper tool steel grade selection	Typical failures: Chipping—insufficient toughness. Wear—poor abrasion resistance. Softening—inadequate “red hardness.”	Choose the tool steel grade by following recommendations and improve selection when needed, guided by property ratings.
Material defects—voids, streaks, tears, flakes, surface cooling cracks, etc.	When not recognized during material inspection, tools made of defective steel often prove to be useless.	Obtain tool steels from reliable sources and inspect tool material for detectable defects.

Table 3. *(Continued)* **Common Tool Faults, Failures, and Cures**

Faulty Condition or Inadequate Grade of Tool Steel

Fault Description	Probable Failure	Possible Cure
Decarburized surface layer (“bark”) in rolled tool steel bars	Cracking may originate from the decarburized layer or it will not harden (“soft skin”).	Provide allowance for stock to be removed from all surfaces of hot-rolled tool steel. Recommended amounts are listed in tool steel catalogs and vary according to section size, generally about 10 per cent for smaller and 5 per cent for larger diameters.
Brittleness caused by poor carbide distribution in high-alloy tool steels	Excessive brittleness can cause chipping or breakage during service.	Bars with large diameter (above about 4 inches) tend to be prone to nonuniform carbide distribution. Choose upset forged discs instead of large-diameter bars.
Unfavorable grain flow	Improper grain flow of the steel used for milling cutters and similar tools can cause teeth to break out.	Upset forged discs made with an upset ratio of about 2 to 1 (starting to upset thickness) display radial grain flow. Highly stressed tools, such as gear-shaper cutters, may require the cross forging of blanks.

Table 4. Common Tool Faults, Failures, and Cures

Heat-Treatment Faults

Fault Description	Probable Failure	Possible Cure
Improper preparation for heat treatment. Certain tools may require stress relieving or annealing, and often preheating, too	Tools highly stressed during machining or forming, unless stress relieved, may aggravate the thermal stresses of heat treatment, thus causing cracks. Excessive temperature gradients developed in nonpreheated tools with different section thicknesses can cause warpage.	Stress relieve, when needed, before hardening. Anneal prior to heavy machining or cold forming (e.g., hobbing). Preheat tools (a) having substantial section thickness variations or (b) requiring high quenching temperatures, as those made of high-speed tool steels.
Overheating during hardening; quenching from too high a temperature	Causes grain coarsening and a sensitivity to cracking that is more pronounced in tools with drastic section changes.	Overheated tools have a characteristic microstructure that aids recognition of the cause of failure and indicates the need for improved temperature control.
Low hardening temperature	The tool may not harden at all, or in its outer portion only, thereby setting up stresses that can lead to cracks.	Controlling both the temperature of the furnace and the time of holding the tool at quenching temperature will prevent this not too frequent deficiency.
Inadequate composition or condition of the quenching media	Water-hardening tool steels are particularly sensitive to inadequate quenching media, which can cause soft spots or even violent cracking.	For water-hardening tool steels, use water free of dissolved air and contaminants, also assure sufficient quantity and proper agitation of the quench.
Improper handling during and after quenching	Cracking, particularly of tools with sharp corners, during the heat treatment can result from holding the part too long in the quench or incorrectly applied tempering.	Following the steel producer’s specifications is a safe way to assure proper heat-treatment handling. In general, the tool should be left in the quench until it reaches a temperature of 150 to 200°F, and should then be transferred promptly into a warm tempering furnace.
Insufficient tempering	Omission of double tempering for steel types that require it may cause early failure by heat checking in hot-work steels or make the tool abnormally sensitive to grinding checks.	Double temper highly alloyed tool steel of the high-speed, hot-work, and high-chromium categories, to remove stresses caused by martensite formed during the first tempering phase. Second temper also increases hardness of most high-speed steels.

Table 4. *(Continued)* Common Tool Faults, Failures, and Cures
Heat-Treatment Faults

Fault Description	Probable Failure	Possible Cure
Decarburization and carburization	Unless hardened in a neutral atmosphere the original carbon content of the tool surface may be changed: Reduced carbon (decarburization) causes a soft layer that wears rapidly. Increased carbon (carburization) when excessive may cause brittleness.	Heating in neutral atmosphere or well-maintained salt bath and controlling the furnace temperature and the time during which the tool is subjected to heating can usually keep the carbon imbalance within acceptable limits.

Table 5. Common Tool Faults, Failures, and Cures
Grinding Damages

Fault Description	Probable Failure	Possible Cure
Grinding Damages		
Excessive stock removal rate causing heating of the part surface beyond the applied tempering temperature	Scorched tool surface displaying temper colors varying from yellow to purple, depending on the degree of heat, causes softening of the ground surface. When coolant is used, a local rehardening can take place, often resulting in cracks.	Prevention: by reducing speed and feed, or using coarser, softer, more open-structured grinding wheel, with ample coolant. Correction: eliminate the discolored layer by subsequent light stock removal. Not always a cure, because the effects of abusive grinding may not be corrected.
Improper grinding wheel specifications; grain too fine or bond too hard	Intense localized heating during grinding may set up surface stresses causing grinding cracks. These cracks are either parallel but at right angles to the direction of grinding or, when more advanced, form a network. May need cold etch or magnetic particle testing to become recognizable.	Prevention: by correcting the grinding wheel specifications. Correction: in shallow (0.002- to 0.004-inch) cracks, by removing the damaged layer, when permitted by the design of the tool, using very light grinding passes.
Incorrectly dressed or loaded grinding wheel	Heating of the work surface can cause scorching or cracking. Incorrect dressing can also cause a poor finish of the ground work surface.	Dress wheel with sharper diamond and faster diamond advance to produce coarser wheel surface. Alternate dressing methods, like crush-dressing, can improve wheel surface conditions. Dress wheel regularly to avoid loading or glazing of the wheel surface.
Inadequate coolant, with regard to composition, amount, distribution, and cleanliness	Introducing into the tool surface heat that is not adequately dissipated or absorbed by the coolant can cause softening, or even the development of cracks.	Improve coolant supply and quality, or reduce stock removal rate to reduce generation of heat in grinding.
Damage caused by abusive abrasive cutoff	The intensive heat developed during this process can cause a hardening of the steel surface, or may even result in cracks.	Reduce rate of advance; adopt wheel specifications better suited for the job. Use ample coolant or, when harmful effect not eliminated, replace abrasive cutoff by some cooler-acting stock separation method (e.g., sawing or lathe cutoff) unless damaged surface is being removed by subsequent machining.

Note: Illustrated examples of tool failures from causes such as listed above may be found in "The Tool Steel Trouble Shooter" handbook, published by Bethlehem Steel Corporation.

The Effect of Alloying Elements on Tool Steel Properties.—*Carbon (C):* The presence of carbon, usually in excess of 0.60 per cent for nonalloyed types, is essential for raising the hardenability of steels to the levels needed for tools. Raising the carbon content by different amounts up to a maximum of about 1.3 per cent increases the hardness slightly and the wear resistance considerably. The amount of carbon in tool steels is designed to attain certain properties (such as in the water-hardening category where higher carbon content may be chosen to improve wear resistance, although to the detriment of toughness) or, in the alloyed types of tool steels, in conformance with the other constituents to produce well-balanced metallurgical and performance properties.

Manganese (Mn): In small amounts, to about 0.60 per cent, manganese is added to reduce brittleness and to improve forgeability. Larger amounts of manganese improve hardenability, permitting oil quenching for nonalloyed carbon steels, thus reducing deformation, although with regard to several other properties, manganese is not an equivalent replacement for the regular alloying elements.

Silicon (Si): In itself, silicon may not be considered an alloying element of tool steels, but it is needed as a deoxidizer and improves the hot-forming properties of the steel. In combination with certain alloying elements, the silicon content is sometimes raised to about 2 per cent to increase the strength and toughness of steels used for tools that have to sustain shock loads.

Tungsten (W): Tungsten is one of the important alloying elements of tool steels, particularly because of two valuable properties: it improves “hot hardness,” that is, the resistance of the steel to the softening effect of elevated temperature, and it forms hard, abrasion-resistant carbides, thus improving the wear properties of tool steels.

Vanadium (V): Vanadium contributes to the refinement of the carbide structure and thus improves the forgeability of alloy tool steels. Vanadium has a very strong tendency to form a hard carbide, which improves both the hardness and the wear properties of tool steels. However, a large amount of vanadium carbide makes the grinding of the tool very difficult (causing low grindability).

Molybdenum (Mo): In small amounts, molybdenum improves certain metallurgical properties of alloy steels such as deep hardening and toughness. It is used often in larger amounts in certain high-speed tool steels to replace tungsten, primarily for economic reasons, often with nearly equivalent results.

Cobalt (Co): As an alloying element of tool steels, cobalt increases hot hardness and is used in applications where that property is needed. Substantial addition of cobalt, however, raises the critical quenching temperature of the steel with a tendency to increase the decarburization of the surface, and reduces toughness.

Chromium (Cr): This element is added in amounts of several per cent to high-alloy tool steels, and up to 12 per cent to types in which chromium is the major alloying element. Chromium improves hardenability and, together with high carbon, provides both wear resistance and toughness, a combination valuable in certain tool applications. However, high chromium raises the hardening temperature of the tool steel, and thus can make it prone to hardening deformations. A high percentage of chromium also affects the grindability of the tool steel.

Nickel (Ni): Generally in combination with other alloying elements, particularly chromium, nickel is used to improve the toughness and, to some extent, the wear resistance of tool steels.

The addition of more than one element to a steel often produces what is called a synergistic effect. Thus, the combined effects of two or more alloy elements may be greater than the sum of the individual effects of each element.

Classification of Tool Steels.—Steels for tools must satisfy a number of different, often conflicting requirements. The need for specific steel properties arising from widely varying applications has led to the development of many compositions of tool steels, each intended to meet a particular combination of applicational requirements. The resultant diversity of tool steels, their number being continually expanded by the addition of new developments, makes it extremely difficult for the user to select the type best suited to his needs, or to find equivalent alternatives for specific types available from particular sources.

As a cooperative industrial effort under the sponsorship of AISI and SAE, a tool classification system has been developed in which the commonly used tool steels are grouped into seven major categories. These categories, several of which contain more than a single group, are listed in the following with the letter symbols used for their identification. The individual types of tool steels within each category are identified by suffix numbers following the letter symbols.

Category Designation	Letter Symbol	Group Designation
High-Speed Tool Steels	M	Molybdenum types
	T	Tungsten types
Hot-Work Tool Steels	H1–H19	Chromium types
	H20–H39	Tungsten types
	H40–H59	Molybdenum types
Cold-Work Tool Steels	D	High-carbon, high-chromium types
	A	Medium-alloy, air-hardening types
	O	Oil-hardening types
Shock-Resisting Tool Steels	S	…
Mold Steels	P	…
Special-Purpose Tool Steels	L	Low-alloy types
	F	Carbon–tungsten types
Water-Hardening Tool Steels	W	…

The following detailed discussion of tool steels will be in agreement with these categories, showing for each type the percentages of the major alloying elements. However, these values are for identification only; elements in tool steels of different producers in the mean analysis of the individual types may deviate from the listed percentages.

The Selection of Tool Steels for Particular Applications.—Although the advice of the specialized steel producer is often sought as a reliable source of information, the engineer is still faced with the task of selecting the tool steel. It must be realized that frequently the designation of the tool or of the process will not define the particular tool steel type best suited for the job. For that reason, tool steel selection tables naming a single type for each listed application cannot take into consideration such often conflicting work factors as ease of tool fabrication and maintenance (resharpening), productivity, product quality, and tooling cost.

When data related to past experience with tool steels for identical or similar applications are not available, a tool steel selection procedure may be followed, based on information in this Handbook section as follows:

1) Identify the AISI category that contains the sought type of steel by consulting the Quick Reference Table on starting on page 455.

Within the defined category

a) find from the listed applications of the most frequently used types of tool steels the particular type that corresponds to the job on hand; or

b) evaluate from the table of property ratings the best compromise between any conflicting properties (e.g., compromising on wear resistance to obtain better toughness).

For those willing to refine even further the first choice or to improve on it when there is not entirely satisfactory experience in one or more meaningful respects, the identifying analyses of the different types of tool steels within each general category may provide additional guidance. In this procedure, the general discussion of the effects of different alloying elements on the properties of tool steels, in a previous section, will probably be found useful.

The following two examples illustrate the procedure for refining an original choice with the purpose of adopting a tool steel grade best suited to a particular set of conditions:

Table 6. Classification, Approximate Compositions, and Properties Affecting Selection of Tool andDie Steels

(From SAE Recommended Practice)

Type of Tool Steel	Chemical Composition[a]								Non-warping Prop.	Safety in Harden-ing	Tough-ness	Depth of Hardening	Wear Resis-tance
	C	Mn	Si	Cr	V	W	Mo	Co					
Water Hardening													
0.80 Carbon	70–0.85	[b]	[b]	[b]	…	…	…	…	Poor	Fair	Good[c]	Shallow	Fair
0.90 Carbon	0.85–0.95	[b]	[b]	[b]	…	…	…	…	Poor	Fair	Good[c]	Shallow	Fair
1.00 Carbon	0.95–1.10	[b]	[b]	[b]	…	…	…	…	Poor	Fair	Good[c]	Shallow	Good
1.20 Carbon	1.10–1.30	[b]	[b]	[b]	…	…	…	…	Poor	Fair	Good[c]	Shallow	Good
0.90 Carbon–V	0.85–0.95	[b]	[b]	[b]	0.15–0.35	…	…	…	Poor	Fair	Good	Shallow	Fair
1.00 Carbon–V	0.95–1.10	[b]	[b]	[b]	0.15–0.35	…	…	…	Poor	Fair	Good	Shallow	Good
1.00 Carbon–VV	0.90–1.10	[b]	[b]	[b]	0.35–0.50	…	…	…	Poor	Fair	Good	Shallow	Good
Oil Hardening													
Low Manganese	0.90	1.20	0.25	0.50	0.20[d]	0.50	…	…	Good	Good	Fair	Deep	Good
High Manganese	0.90	1.60	0.25	0.35[d]	0.20[d]	…	0.30[d]	…	Good	Good	Fair	Deep	Good
High-Carbon, High-Chromium[e]	2.15	0.35	0.35	12.00	0.80[d]	0.75[d]	0.80[d]	…	Good	Good	Poor	Through	Best
Chromium	1.00	0.35	0.25	1.40	…	…	0.40	…	Fair	Good	Fair	Deep	Good
Molybdenum Graphitic	1.45	0.75	1.00	…	…	…	0.25	…	Fair	Good	Fair	Deep	Good
Nickel–Chromium[f]	0.75	0.70	0.25	0.85	0.25[d]	…	0.50[d]	…	Fair	Good	Fair	Deep	Fair
Air Hardening													
High-Carbon, High-Chromium	1.50	0.40	0.40	12.00	0.80[d]	…	0.90	0.60[d]	Best	Best	Fair	Through	Best
5 Per Cent Chromium	1.00	0.60	0.25	5.25	0.40[d]	…	1.10	…	Best	Best	Fair	Through	Good
High-Carbon, High-Chromium–Cobalt	1.50	0.40	0.40	12.00	0.80[d]	…	0.90	3.10	Best	Best	Fair	Through	Best
Shock-Resisting													
Chromium–Tungsten	0.50	0.25	0.35	1.40	0.20	2.25	0.40[d]	…	Fair	Good	Good	Deep	Fair
Silicon–Molybdenum	0.50	0.40	1.00	…	0.25[d]	…	0.50	…	Poor[g]	Poor[h]	Best	Deep	Fair
Silicon–Manganese	0.55	0.80	2.00	0.30[d]	0.25[d]	…	0.40[d]	…	Poor[g]	Poor[h]	Best	Deep	Fair
Hot Work													
Chromium–Molybdenum–Tungsten	0.35	0.30	1.00	5.00	0.25[d]	1.25	1.50	…	Good	Good	Good	Through	Fair
Chromium–Molybdenum–V	0.35	0.30	1.00	5.00	0.40	…	1.50	…	Good	Good	Good	Through	Fair
Chromium–Molybdenum–VV	0.35	0.30	1.00	5.00	0.90	…	1.50	…	Good	Good	Good	Through	Fair
Tungsten	0.32	0.30	0.20	3.25	0.40	9.00	…	…	Good	Good	Good	Through	Fair

Table 6. *(Continued)* **Classification, Approximate Compositions, and Properties Affecting Selection of Tool andDie Steels**

(From SAE Recommended Practice)

Type of Tool Steel	Chemical Composition[a]								Non-warping Prop.	Safety in Hardening	Toughness	Depth of Hardening	Wear Resistance
	C	Mn	Si	Cr	V	W	Mo	Co					
High Speed													
Tungsten, 18–4–1	0.70	0.30	0.30	4.10	1.10	18.00	…	…	Good	Good	Poor	Through	Good
Tungsten, 18–4–2	0.80	0.30	0.30	4.10	2.10	18.50	0.80	…	Good	Good	Poor	Through	Good
Tungsten, 18–4–3	1.05	0.30	0.30	4.10	3.25	18.50	0.70	…	Good	Good	Poor	Through	Best
Cobalt–Tungsten, 14–4–2–5	0.80	0.30	0.30	4.10	2.00	14.00	0.80	5.00	Good	Fair	Poor	Through	Good
Cobalt–Tungsten, 18–4–1–5	0.75	0.30	0.30	4.10	1.00	18.00	0.80	5.00	Good	Fair	Poor	Through	Good
Cobalt–Tungsten, 18–4–2–8	0.80	0.30	0.30	4.10	1.75	18.50	0.80	8.00	Good	Fair	Poor	Through	Good
Cobalt–Tungsten, 18–4–2–12	0.80	0.30	0.30	4.10	1.75	20.00	0.80	12.00	Good	Fair	Poor	Through	Good
Molybdenum, 8–2–1	0.80	0.30	0.30	4.00	1.15	1.50	8.50	…	Good	Fair	Poor	Through	Good
Molybdenum–Tungsten, 6–6–2	0.83	0.30	0.30	4.10	1.90	6.25	5.00	…	Good	Fair	Poor	Through	Good
Molybdenum–Tungsten, 6–6–3	1.15	0.30	0.30	4.10	3.25	5.75	5.25	…	Good	Fair	Poor	Through	Best
Molybdenum–Tungsten, 6–6–4	1.30	0.30	0.30	4.25	4.25	5.75	5.25	…	Good	Fair	Poor	Through	Best
Cobalt–Molybdenum–Tungsten, 6–6–2–8	0.85	0.30	0.30	4.10	2.00	6.00	5.00	8.00	Good	Fair	Poor	Through	Good

[a] C = carbon; Mn = manganese; Si = silicon; Cr = chromium; V = vanadium; W = tungsten; Mo = molybdenum; Co = cobalt.

[b] Carbon tool steels are usually available in four grades or qualities: *Special (Grade 1)*—The highest quality water-hardening carbon tool steel, controlled for hardenability, chemistry held to closest limits, and subject to rigid tests to ensure maximum uniformity in performance; *Extra (Grade 2)*—A high-quality water-hardening carbon tool steel, controlled for hardenability, subject to tests to ensure good service; *Standard (Grade 3)*—A good-quality water-hardening carbon tool steel, not controlled for hardenability, recommended for application where some latitude with respect to uniformity is permissible; *Commercial (Grade 4)*—A commercial-quality water-hardening carbon tool steel, not controlled for hardenability, not subject to special tests. On *special* and *extra* grades, limits on manganese, silicon, and chromium are not generally required if Shepherd hardenability limits are specified. For *standard* and *commercial* grades, limits are 0.35 max. each for Mn and Si; 0.15 max. Cr for standard; 0.20 max. Cr for commercial.

[c] Toughness decreases somewhat when increasing depth of hardening.

[d] Optional element. Steels have found satisfactory application either with or without the element present. In silicon–manganese steel listed under Shock-Resisting Steels, if chromium, vanadium, and molybdenum are not present, then hardenability will be affected.

[e] This steel may have 0.50 per cent nickel as an optional element. The steel has been found to give satisfactory application either with or without the element present.

[f] Approximate nickel content of this steel is 1.50 per cent.

[g] Poor when water quenched, fair when oil quenched.

[h] Poor when water quenched, good when oil quenched.

Table 7. Quick Reference Guide for Tool Steel Selection

Application Areas	Tool Steel Categories and AISI Letter Symbol						
	High-Speed Tool Steels, M and T	Hot-Work Tool Steels, H	Cold-Work Tool Steels, D, A, and O	Shock-Resisting Tool Steels, S	Mold Steels, P	Special-Purpose Tool Steels, L and F	Water-Hardening Tool Steels, W
Examples of Typical Applications							
Cutting Tools Single-point types (lathe, planer, boring) Milling cutters Drills Reamers Taps Threading dies Form cutters	General-purpose production tools: M2, T1 For increased abrasion resistance: M3, M4, and M10 Heavy-duty work calling for high hot hardness: T5, T15 Heavy-duty work calling for high abrasion resistance: M42, M44		Tools with keen edges (knives, razors) Tools for operations where no high-speed is involved, yet stability in heat treatment and substantial abrasion resistance are needed	Pipe cutter wheels			Uses that do not require hot hardness or high abrasion resistance. Examples with carbon content of applicable group: Taps (1.05⁄1.10% C) Reamers (1.10⁄1.15% C) Twist drills (1.20⁄1.25% C) Files (1.35⁄1.40% C)
Hot Forging Tools and Dies Dies and inserts Forging machine plungers and pierces	For combining hot hardness with high abrasion resistance: M2, T1	Dies for presses and hammers: H20, H21 For severe conditions over extended service periods: H22 to H26, also H43	Hot trimming dies: D2	Hot trimming dies Blacksmith tools Hot swaging dies			Smith's tools (1.65⁄0.70% C) Hot chisels (0.70⁄0.75% C) Drop forging dies (0.90⁄1.00% C) Applications limited to short-run production
Hot Extrusion Tools and Dies Extrusion dies and mandrels, Dummy blocks Valve extrusion tools	Brass extrusion dies: T1	Extrusion dies and dummy blocks: H20 to H26 For tools that are exposed to less heat: H10 to H19		Compression molding: S1			

Table 7. *(Continued)* Quick Reference Guide for Tool Steel Selection

Application Areas	Tool Steel Categories and AISI Letter Symbol						
	High-Speed Tool Steels, M and T	Hot-Work Tool Steels, H	Cold-Work Tool Steels, D, A, and O	Shock-Resisting Tool Steels, S	Mold Steels, P	Special-Purpose Tool Steels, L and F	Water-Hardening Tool Steels, W
Examples of Typical Applications							
Cold-Forming Dies Bending, forming, drawing, and deep drawing dies and punches	Burnishing tools: M1, T1	Cold heading: die casting dies: H13	Drawing dies: 01 Coining tools: O1, D2 Forming and bending dies: A2 Thread rolling dies: D2	Hobbing and short-run applications: S1, S7 Rivet sets and rivet busters		Blanking, forming, and trimmer dies when toughness has precedence over abrasion resistance: L6	Cold-heading dies: W1 or W2 (C ≅ 1.00%) Bending dies: W1 (C ≅ 1.00%)
Shearing Tools Dies for piercing, punching, and trimming Shear blades	Special dies for cold and hot work: T1 For work requiring high abrasion resistance: M2, M3	For shearing knives: H11, H12 For severe hot shearing applications: M21, M25	Dies for medium runs: A2, A6 also O1 and O4 Dies for long runs: D2, D3 Trimming dies (also for hot trimming): A2	Cold and hot shear blades Hot punching and piercing tools Boilermaker's tools		Knives for work requiring high toughness: L6	Trimming dies (0.90⁄0.95% C) Cold blanking and punching dies (1.00% C)
Die Casting Dies and Plastics Molds		For zinc and lead: H11 For aluminum: H13 For brass: H21	A2 and A6 O1		Plastics molds: P2 to P4, and P20		
Structural Parts for Severe Service Conditions	Roller bearings for high-temperature environment: T1 Lathe centers: M2 and T1	For aircraft components (landing gear, arrester hooks, rocket cases): H11	Lathe centers: D2, D3 Arbors: O1 Bushings: A4 Gages: D2	Pawls Clutch parts		Spindles, clutch parts (where high toughness is needed): L6	Spring steel (1.10⁄1.15% C)
Battering Tools for Hand and Power Tool Use				Pneumatic chisels for cold work: S5 For higher performance: S7			For intermittent use: W1 (0.80% C)

Example 1, Workpiece—Trimming Dies: For the manufacture of a type of trimming die, the first choice was grade A2, because for the planned medium rate of production, the lower material cost was considered an advantage.

A subsequent rise in the production rate indicated the use of a higher-alloy tool steel, such as D2, whose increased abrasion resistance would permit longer runs between regrinds.

A still further increase in the abrasion-resistant properties was then sought, which led to the use of D7, the high carbon and high chromium content of which provided excellent edge retainment, although at the cost of greatly reduced grindability. Finally, it became a matter of economic appraisal, whether the somewhat shorter tool regrind intervals (for D2) or the more expensive tool sharpening (for D7) constituted the lesser burden.

Example 2, Workpiece—Circular form cutter made of high-speed tool steel for use on multiple-spindle automatic turning machines: The first choice from the Quick Reference Guide may be the classical tungsten-base high-speed tool steel T1, because of its good performance and ease of heat treatment, or its alternate in the molybdenum high-speed tool steel category, the type M2.

In practice, neither of these grades provided a tool that could hold its edge and profile over the economical tool change time, because of the abrasive properties of the work material and the high cutting speeds applied in the cycle. An overrating of the problem resulted in reaching for the top of the scale, making the tool from T15, a high-alloy high-speed tool steel (high vanadium and high cobalt).

Although the performance of the tools made of T15 was excellent, the cost of this steel type was rather high, and the grinding of the tool, both for making it and in the regularly needed resharpening, proved to be very time-consuming and expensive. Therefore, an intermediate tool steel type was tried, the M3 that provided added abrasion resistance (due to increased carbon and vanadium content), and was less expensive and much easier to grind than the T15.

High-Speed Tool Steels

The primary application of high-speed steels is to tools used for the working of metals at high cutting speeds. Cutting metal at high speed generates heat, the penetration of the cutting tool edge into the work material requires great hardness and strength, and the continued frictional contact of the tool with both the parent material and the detached chips can only be sustained by an abrasion-resistant tool edge.

Accordingly, the dominant properties of high-speed steel are B) resistance to the softening effect of elevated temperature; C) great hardness penetrating to substantial depth from the surface; and D) excellent abrasion resistance.

High-speed tool steels are listed in the AISI specifications in two groups: molybdenum types and tungsten types, these designations expressing the dominant alloying element of the respective group.

Molybdenum-Type High-Speed Tool Steels.— Unlike the traditional tungsten-base high-speed steels, the tool steels listed in this category are considered to have molybdenum as the principal alloying constituent, this element also being used in the designation of the group. Other significant elements like tungsten and cobalt might be present in equal, or even greater amounts in several types listed in this category. The available range of types also includes high-speed tool steels with higher than usual carbon and vanadium content. Amounts of these alloying elements have been increased to obtain better abrasion resistance although such a change in composition may adversely affect the machinability and the grindability of the steel. The series in whose AISI identification numbers the number 4 is the first digit was developed to attain exceptionally high hardness in heat treatment that, for these types, usually requires triple tempering rather than the double tempering generally applied for high-speed tool steels.

Properties and Applications of Frequently Used Molybdenum Types: AISI M1: This alloy was developed as a substitute for the classical T1 to save on the alloying element tungsten by replacing most of it with molybdenum. In most uses, this steel is an acceptable substitute, although it requires greater care or more advanced equipment for its heat treatment than the tungsten alloyed type it replaces. The steel is often selected for cutting tools like drills, taps, milling cutters, reamers, lathe tools used for lighter cuts, and for shearing dies.

AISI M2: Similar to M1, yet with substantial tungsten content replacing a part of the molybdenum. This is one of the general-purpose high-speed tool steels, combining the economic advantages of the molybdenum-type steels with greater ease of hardening, excellent wear resistance, and improved toughness. It is a preferred steel type for the manufacture of general-purpose lathe tools; of most categories of multiple-edge cutting tools, like milling cutters, taps, dies, reamers, and for form tools in lathe operations.

AISI M3: A high-speed tool steel with increased vanadium content for improved wear resistance, yet still below the level where vanadium would interfere with the ease of grinding. This steel is preferred for cutting tools requiring improved wear resistance, like broaches, form tools, milling cutters, chasers, and reamers.

AISI M7: The chemical composition of this type is similar to that of M1, except for the higher carbon and vanadium content that raises the cutting efficiency without materially reducing the toughness. Because of sensitivity to decarburization, heat treatment in a salt bath or a controlled atmosphere is advisable. Used for blanking and trimming dies, shear blades, lathe tools, and thread rolling dies.

AISI M10: Although the relatively high vanadium content assures excellent wear and cutting properties, the only slightly increased carbon does not cause brittleness to an extent that is harmful in many applications. Form cutters and single-point lathe tools, broaches, planer tools, punches, blanking dies, and shear blades are examples of typical uses.

AISI M42: In applications where high hardness both at regular and at elevated temperatures is needed, this type of high-speed steel with high cobalt content can provide excellent service. Typical applications are tool bits, form tools, shaving tools, fly cutters, roll turning tools, and thread rolling dies. Important uses are found for M42, and for other types of the "M40" group in the working of "difficult-to-machine" alloys.

Tungsten-Type High-Speed Tool Steels.—For several decades following their introduction, the tungsten-base high-speed steels were the only types available for cutting operations involving the generation of substantial heat, and are still preferred by users who do not have the kind of advanced heat-treating equipment that efficient hardening of the molybdenum-type high-speed tool steels requires. Most tungsten high-speed steels display excellent resistance to decarburization and can be brought to good hardness by simple heat treatment. However, even with tungsten-type high-speed steels, heat treatment using modern methods and furnaces can appreciably improve the metallurgical qualities of the hardened material and the performance of the cutting tools made from these steels.

Properties and Applications of Frequently Used Tungsten Types: AISI T1: Also mentioned as the 18–4–1 type with reference to the nominal percentage of its principal alloying elements (W–Cr–V), it is considered to be the classical type of high-speed tool steel. The chemical composition of T1 was developed in the early 1900s, and has changed very little since. T1 is still considered to be perhaps the best general-purpose high-speed tool steel because of the comparative ease of its machining and heat treatment. It combines a high degree of cutting ability with relative toughness. T1 steel is used for all types of multiple-edge cutting tools like drills, reamers, milling cutters, threading taps and dies, light- and medium-duty lathe tools, and is also used for punches, dies, and machine knives, as well as for structural parts that are subjected to elevated temperatures, like lathe centers, and certain types of antifriction bearings.

AISI T2: Similar to T1 except for somewhat higher carbon content and twice the vanadium contained in the former grade. Its handling ease, both in machining and heat treating,

Table 8. Molybdenum High-Speed Steels

Identifying Chemical Composition and Typical Heat-Treatment Data																					
Identifying Chemical Elements in Per Cent	AISI Type			M1	M2	M3 Cl. 1	M3 Cl. 2	M4	M6	M7	M10	M30	M33	M34	M36	M41	M42	M43	M44	M46	M47
	C			0.80	0.85; 1.00	1.05	1.20	1.30	0.80	1.00	0.85; 1.00	0.80	0.90	0.90	0.80	1.10	1.10	1.20	1.15	1.25	1.10
	W			1.50	6.00	6.00	6.00	5.50	4.00	1.75	…	2.00	1.50	2.00	6.00	6.75	1.50	2.75	5.25	2.00	1.50
	Mo			8.00	5.00	5.00	5.00	4.50	5.00	8.75	8.00	8.00	9.50	8.00	5.00	3.75	9.50	8.00	6.25	8.25	9.50
	Cr			4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.25	3.75	3.75	4.25	4.00	3.75
	V			1.00	2.00	2.40	3.00	4.00	1.50	2.00	2.00	1.25	1.15	2.00	2.00	2.00	1.15	1.60	2.25	3.20	1.25
	Co			…	…	…	…	…	12.00	…	…	5.00	8.00	8.00	8.00	5.00	8.00	8.25	12.00	8.25	5.00
Heat-Treat. Data	Hardening Temperature Range, °F			2150–2225	2175–2225	2200–2250	2200–2250	2200–2250	2150–2200	2150–2225	2150–2225	2200–2250	2200–2250	2200–2250	2225–2275	2175–2220	2175–2210	2175–2220	2190–2240	2175–2225	2150–2200
	Tempering Temperature Range, °F			1000–1100	1000–1160	1000–1100	1000–1100	1000–1100	1000–1100	1000–1100	1000–1100	1000–1100	1000–1100	1000–1100	1000–1100	1000–1100	950–1100	950–1100	1000–1160	975–1050	975–1100
	Approx. Tempered Hardness, Rc			65–60	65–60	66–61	66–61	66–61	66–61	66–61	65–60	65–60	65–60	65–60	65–60	70–65	70–65	70–65	70–62	69–67	70–65
Relative Ratings of Properties (A = greatest to E = least)																					
Characteristics in Heat Treatment	Safety in Hardening			D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
	Depth of Hardening			A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
	Resistance to Decarburization			C	B	B	B	B	C	C	C	C	C	C	C	C	C	C	C	C	C
	Stability of Shape in Heat Treatment	Quench-ing Medium	Air or Salt	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
			Oil	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
Service Properties	Machinability			D	D	D	D/E	D	D	D	D	D	D	D	D	D	D	D	D	D	D
	Hot Hardness			B	B	B	B	B	A	B	B	A	A	A	A	A	A	A	A	A	A
	Wear Resistance			B	B	B	B	A	B	B	B	B	B	B	B	B	B	B	B	B	B
	Toughness			E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E

is comparable to that of T1, although it should be held at the quenching temperature slightly longer, particularly when the heating is carried out in a controlled atmosphere furnace. The applications are similar to that of T1, however, because of its increased wear resistance T2 is preferred for tools required for finer cuts, and where the form or size retention of the tool is particularly important, such as for form and finishing tools.

AISI T5: The essential characteristic of this type of high-speed steel, its superior red hardness, stems from its substantial cobalt content that, combined with the relatively high amount of vanadium, provides this steel with excellent wear resistance. In heat treatment, the tendency for decarburization must be considered, and heating in a controlled, slightly reducing atmosphere is recommended. This type of high-speed tool steel is mainly used for single-point tools and inserts; it is well adapted for working at high-speeds and feeds, for cutting hard materials and those that produce discontinuous chips, also for nonferrous metals and, in general, for all kinds of tools needed for hogging (removing great bulks of material).

AISI T15: The performance qualities of this high-alloy tool steel surpass most of those found in other grades of high-speed tool steels. The high vanadium content, supported by uncommonly high carbon assures superior cutting ability and wear resistance. The addition of high cobalt increases the “hot hardness,” and therefore tools made of T15 can sustain cutting speeds in excess of those commonly applicable to tools made of steel. The machining and heat treatment of T15 does not cause extraordinary problems, although for best results, heating to high temperature is often applied in its heat treatment, and double or even triple tempering is recommended. On the other hand, T15 is rather difficult to grind because of the presence of large amounts of very hard metallic carbides; therefore, it is considered to have a very low “grindability” index. The main uses are in the field of high-speed cutting and the working of hard metallic materials, T15 being often considered to represent in its application a transition from the regular high-speed tool steels to cemented carbides. Lathe tool bits, form cutters, and solid and inserted blade milling cutters are examples of uses of this steel type for cutting tools; excellent results may also be obtained with such tools as cold-work dies, punches, blanking, and forming dies, etc. The low toughness rating of the T15 steel excludes its application for operations that involve shock or sudden variations in load.

Hot-Work Tool Steels

A family of special tool steels has been developed for tools that in their regular service are in contact with hot metals over a shorter or longer period of time, with or without cooling being applied, and are known as hot-work steels. The essential property of these steels is their capability to sustain elevated temperature without seriously affecting the usefulness of the tools made from them. Depending on the purpose of the tools for which they were developed, the particular types of hot-work tool steels have different dominant properties and are assigned to one of three groups, based primarily on their principal alloying elements.

Hot-Work Tool Steels, Chromium Types.—As referred to in the group designation, the chromium content is considered the characteristic element of these tool steels. Their predominant properties are high hardenability, excellent toughness, and great ductility, even at the cost of wear resistance. Some members of this family are made with the addition of tungsten, and in one type, cobalt as well. These alloying elements improve the resistance to the softening effect of elevated temperatures, but reduce ductility.

Properties and Applications of Frequently Used Chromium Types: AISI H11: This hot-work tool steel of the Chromium–molybdenum–vanadium type has excellent ductility, can be machined easily, and retains its strength at temperatures up to 1000 degrees F.

Table 9. Tungsten High-Speed Tool Steels

Identifying Chemical Composition and Typical Heat-Treatment Data										
	AISI Type			T1	T2	T4	T5	T6	T8	T15
Identifying Chemical Elements in Per Cent	C			0.75	0.80	0.75	0.80	0.80	0.75	1.50
	W			18.00	18.00	18.00	18.00	20.00	14.00	12.00
	Cr			4.00	4.00	4.00	4.00	4.50	4.00	4.00
	V			1.00	2.00	1.00	2.00	1.50	2.00	5.00
	Co			…	…	5.00	…	…	5.00	5.00
Heat-Treat. Data	Hardening Temperature Range, °F			2300–2375	2300–2375	2300–2375	2325–2375	2325–2375	2300–2375	2200–2300
	Tempering Temperature Range, °F			1000–1100	1000–1100	1000–1100	1000–1100	1000–1100	1000–1100	1000–1200
	Approx. Tempered Hardness, R_c			65–60	66–61	66–62	65–60	65–60	65–60	68–63
Relative Ratings of Properties (A = greatest to E = least)										
Characteristics in Heat Treatment	Safety in Hardening			C	C	D	D	D	D	D
	Depth of Hardening			A	A	A	A	A	A	A
	Resistance to Decarburization			A	A	B	C	C	B	B
	Stability of Shape in Heat Treatment	Quenching Medium	Air or Salt	C	C	C	C	C	C	C
			Oil	D	D	D	D	D	D	D
Service Properties	Machinability			D	D	D	D	D/E	D	D/E
	Hot Hardness			B	B	A	A	A	A	A
	Wear Resistance			B	B	B	B	B	B	A
	Toughness			E	E	E	E	E	E	E

These properties, combined with relatively good abrasion and shock resistance, account for the varied fields of application of H11, which include the following typical uses:

E) structural applications where high strength is needed at elevated operating temperatures, as for gas turbine engine components; and F) hot-work tools, particularly of the kind whose service involves shocks and drastic cooling of the tool, such as in extrusion tools, pierce and draw punches, bolt header dies, etc.

AISI H12: The properties of this type of steel are comparable to those of H11, with increased abrasion resistance and hot hardness, resulting from the addition of tungsten, yet in an amount that does not affect the good toughness of this steel type. The applications, based on these properties, are hot-work tools that often have to withstand severe impact, such as various punches, bolt header dies, trimmer dies, and hot shear blades. H12 is also used to make aluminum extrusion dies and die-casting dies.

AISI H13: This type of tool steel differs from the preceding ones particularly in properties related to the addition of about 1 per cent vanadium, which contributes to increased hot hardness, abrasion resistance, and reduced sensitivity to heat checking. Such properties are needed in die casting, particularly of aluminum, where the tools are subjected to drastic heating and cooling at high operating temperatures. Besides die-casting dies, H13 is also widely used for extrusion dies, trimmer dies, hot gripper and header dies, and hot shear blades.

AISI H19: This high-alloyed hot-work tool steel, containing chromium, tungsten, cobalt, and vanadium, has excellent resistance to abrasion and shocks at elevated temperatures. It is particularly well adapted to severe hot-work uses where the tool, to retain its size and shape, must withstand wear and the washing-out effect of molten work material. Typical applications include brass extrusion dies and dummy blocks, inserts for forging and valve extrusion dies, press forging dies, and hot punches.

Hot-Work Tool Steels, Tungsten Types.—Substantial amounts of tungsten, yet very low-carbon content characterize the hot-work tool steels of this group. These tool steels have been developed for applications where the tool is in contact with the hot-work material over extended periods of time; therefore, the resistance of the steel to the softening effect of elevated temperatures is of prime importance. even to the extent of accepting a lower degree of toughness.

Properties and Applications of Frequently Used Tungsten Types: AISI H21: This medium-tungsten alloyed hot-work tool steel has substantially increased abrasion resistance over the chromium alloyed types, yet possesses a degree of toughness that represents a transition between the chromium and the higher-alloyed tungsten-steel types. The principal applications are for tools subjected to continued abrasion, yet to only a limited amount of shock loads, like tools for the extrusion of brass, both dies and dummy blocks, pierces for forging machines, inserts for forging tools, and hot nut tools. Another typical application is dies for the hot extrusion of automobile valves.

AISI H24: The comparatively high tungsten content (about 14 per cent) of this steel results in good hardness, great compression strength, and excellent abrasion resistance, but makes it sensitive to shock loads. By taking these properties into account, the principal applications include extrusion dies for brass in long-run operations, hot-forming and gripper dies with shallow impressions, punches that are subjected to great wear yet only to moderate shocks, and hot shear blades.

AISI H20: The composition of this high-alloyed tungsten-type hot-work steel resembles the tungsten-type high-speed steel AISI T1, except for the somewhat lower carbon content for improved toughness. The high amount of tungsten provides the maximum resistance to the softening effect of elevated temperature and assures excellent wear-resistant properties, including withstanding the washing-out effect of certain processes. However, this steel is less resistant to thermal shocks than the chromium hot-work steels. Typical applications comprise extrusion dies for long production runs, extrusion mandrels operated

Table 10. Hot-Work Tool Steels

Identifying Chemical Composition and Typical Heat-Treatment Data																	
AISI	Group			Chromium Types						Tungsten Types						Molybdenum Types		
	Type			H10	H11	H12	H13	H14	H19	H21	H22	H23	H24	H25	H26	H41	H42	H43
Identifying Chemical Elements in Per Cent	C			0.40	0.35	0.35	0.35	0.40	0.40	0.35	0.35	0.35	0.45	0.25	0.50	0.65	0.60	0.55
	W			…	…	1.50	…	5.00	4.25	9.00	11.00	12.00	15.00	15.00	18.00	1.50	6.00	…
	Mo			2.50	1.50	1.50	1.50	…	…	…	…	…	…	…	…	8.00	5.00	8.00
	Cr			3.25	5.00	5.00	5.00	5.00	4.25	3.50	2.00	12.00	3.00	4.00	4.00	4.00	4.00	4.00
	V			0.40	0.40	0.40	1.00	…	2.00	…	…	…	…	…	1.00	1.00	2.00	2.00
	Co			…	…	…	…	…	4.25	…	…	…	…	…	…	…	…	…
Heat-Treat. Data	Hardening Temperature Range, °F			1850–1900	1825–1875	1825–1875	1825–1900	1850–1950	2000–2200	2000–2200	2000–2200	2000–2300	2000–2250	2100–2300	2150–2300	2000–2175	2050–2225	2000–2175
	Tempering Temperature Range, °F			1000–1200	1000–1200	1000–1200	1000–1200	1100–1200	1000–1300	1100–1250	1100–1250	1200–1500	1050–1200	1050–1250	1050–1250	1050–1200	1050–1200	1050–1200
	Approx. Tempered Hardness, Rc			56–39	54–38	55–38	53–38	47–40	59–40	54–36	52–39	47–30	55–45	44–35	58–43	60–50	60–50	58–45
Relative Ratings of Properties (A = greatest to D = least)																	
Characteristics in Heat Treatment	Safety in Hardening			A	A	A	A	A	B	B	B	B	B	B	B	C	C	C
	Depth of Hardening			A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
	Resistance to Decarburization			B	B	B	B	B	B	B	B	B	B	B	B	C	B	C
	Stability of Shape in Heat Treatment	Quenching Medium	Air or Salt	B	B	B	B	C	C	C	C	…	C	C	C	C	C	C
			Oil	…	…	…	…	…	D	D	D	D	D	D	D	D	D	D
Service Properties	Machinability			C/D	C/D	C/D	C/D	D	D	D	D	D	D	D	D	D	D	D
	Hot Hardness			C	C	C	C	C	C	C	C	B	B	B	B	B	B	B
	Wear Resistance			D	D	D	D	D	C/D	C/D	C/D	C/D	C	D	C	C	C	C
	Toughness			C	B	B	B	C	C	C	C	D	D	C	D	D	D	D

without cooling, hot piercing punches, hot forging dies and inserts. It is also used as special structural steel for springs operating at elevated temperatures.

Hot-Work Tool Steels, Molybdenum Types.—These steels are closely related to certain types of molybdenum high-speed steels and possess excellent resistance to the softening effect of elevated temperature but their ductility is rather low. These steel types are generally available on special orders only.

Properties and Applications of Frequently Used Molybdenum Types: AISI H43: The principal constituents of this hot-work steel, chromium, molybdenum, and vanadium, provide excellent abrasion- and wear-resistant properties at elevated temperatures. H43 has a good resistance to the development of heat checks and a toughness adequate for many different purposes. Applications include tools and operations that tend to cause surface wear in high-temperature work, like hot headers, punch and die inserts, hot heading and hot nut dies, as well as different kinds of punches operating at high temperature in service involving considerable wear.

Cold-Work Tool Steels

Tool steels of the cold-working category are primarily intended for die work, although their use is by no means restricted to that general field. Cold-work tool steels are extensively used for tools whose regular service does not involve elevated temperatures. They are available in chemical compositions adjusted to the varying requirements of a wide range of different applications. According to their predominant properties, characterized either by the chemical composition or by the quenching medium in heat treatment, the cold-work tool steels are assigned to three different groups, as discussed in what follows.

Cold-Work Tool Steels, High-Carbon, High-Chromium Types.—The chemical composition of tool steels of this family is characterized by the very high chromium content, to the order of 12 to 13 per cent, and the uncommonly high carbon content, in the range of about 1.50 to 2.30 per cent. Additional alloying elements that are present in different amounts in some of the steel types of this group are vanadium, molybdenum, and cobalt, each of which contributes desirable properties.

The predominant properties of the whole group are: 1) excellent dimensional stability in heat treatment, where, with one exception, air quench is used; 2) great wear resistance, particularly in the types with the highest carbon content; and 3) rather good machinability.

Properties and Applications of Frequently Used High-Carbon, High-Chromium Types:

AISI D2: An air-hardening die steel with high-carbon, high-chromium content having several desirable tool steel properties, such as abrasion resistance. high hardness, and nondeforming characteristics. The carbon content of this type, although relatively high, is not particularly detrimental to its machining. The ease of working can be further improved by selecting the same basic type with the addition of sulfur. Several steel producers supply the sulfurized version of D2, in which the uniformly distributed sulfide particles substantially improve the machinability and the resulting surface finish. The applications comprise primarily cold-working press tools for shearing (blanking and stamping dies, punches, shear blades), for forming (bending, seaming), also for thread rolling dies, solid gages, and wear-resistant structural parts. Dies for hot trimming of forgings are also made of D2 which is then heated treated to a lower hardness for the purpose of increasing toughness.

AISI D3: The high carbon content of this high-chromium tool steel type results in excellent resistance to wear and abrasion and provides superior compressive strength as long as the pressure is applied gradually, without exerting sudden shocks. In hardening, an oil quench is used, without affecting the excellent nondeforming properties of this type. Its deep-hardening properties make it particularly suitable for tools that require repeated regrinding during their service life, such as different types of dies and punches. The more important applications comprise blanking, stamping, and trimming dies and punches for

Table 11. Cold-Work Tool Steels

Identifying Chemical Composition and Typical Heat-Treatment Data																		
AISI	Group	High-Carbon, High-Chromium Types					Medium-Alloy, Air-Hardening Types								Oil-Hardening Types			
	Types	D2	D3	D4	D5	D7	A2	A3	A4	A6	A7	A8	A9	A10	O1	O2	O6	O7
Identifying Chemical Elements in Per Cent	C	1.50	2.25	2.25	1.50	2.35	1.00	1.25	1.00	0.70	2.25	0.55	0.50	1.35	0.90	0.90	1.45	1.20
	Mn	…	…	…	…	…	…	…	2.00	2.00	…	…	…	1.80	1.00	1.60	…	…
	Si	…	…	…	…	…	…	…	…	…	…	…	…	1.25	…	…	1.00	…
	W	…	…	…	…	…	…	…	…	…	1.00	1.25	…	…	0.50	…	…	1.75
	Mo	1.00	…	1.00	1.00	1.00	1.00	1.00	1.00	1.25	1.00	1.25	1.40	1.50	…	…	0.25	…
	Cr	12.00	12.00	12.00	12.00	12.00	5.00	5.00	1.00	1.00	5.25	5.00	5.00	…	0.50	…	…	0.75
	V	1.00	…	…	…	4.00	…	1.00	…	…	4.75	…	1.00	…	…	…	…	…
	Co	…	…	…	3.00	…	…	…	…	…	…	…	…	…	…	…	…	…
Heat-Treatment Data	Ni	…	…	…	…	…	…	…	…	…	…	…	1.50	1.80	…	…	…	…
	Hardening Temperature Range, °F	1800–1875	1700–1800	1775–1850	1800–1875	1850–1950	1700–1800	1750–1850	1500–1600	1525–1600	1750–1800	1800–1850	1800–1875	1450–1500	1450–1500	1400–1475	1450–1500	1550–1525
	Quenching Medium	Air	Oil	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Oil	Oil	Oil	Oil
	Tempering Temperature Range, °F	400–1000	400–1000	400–1000	400–1000	300–1000	350–1000	350–1000	350–800	300–800	300–1000	350–1100	950–1150	350–800	350–500	350–500	350–600	350–550
	Approx. Tempered Hardness, Rc	61–54	61–54	61–54	61–54	65–58	62–57	65–57	62–54	60–54	67–57	60–50	56–35	62–55	62–57	62–57	63–58	64–58
Relative Ratings of Properties (A = greatest to E = least)																		
Characteristics in Heat Treatment	Safety in Hardening	A	C	A	A	A	A	A	A	A	A	A	A	A	B	B	B	B
	Depth of Hardening	A	A	A	A	A	A	A	A	A	A	A	A	A	B	B	B	B
	Resistance to Decarburization	B	B	B	B	B	B	B	A/B	A/B	B	B	B	A/B	A	A	A	A
	Stability of Shape in Heat Treatment	A	B	A	A	A	A	A	A	A	A	A	A	A	B	B	B	B
Service Properties	Machinability	E	E	E	E	E	D	D	D/E	D/E	E	D	D	C/D	C	C	B	C
	Hot Hardness	C	C	C	C	C	C	C	D	D	C	C	C	D	E	E	E	E
	Wear Resistance	B/C	B	B	B/C	A	C	B	C/D	C/D	A	C/D	C/D	C	D	D	D	D
	Toughness	E	E	E	E	E	D	D	D	D	E	C	C	D	D	D	D	C

long production runs; forming, bending and drawing tools; and structural elements like plug and ring gages, and lathe centers, in applications where high wear resistance is important.

Cold-Work Tool Steels, Oil-Hardening Types.—With a relatively low percentage of alloying elements, yet with a substantial amount of manganese, these less expensive types of tool steels attain good depth of hardness in an oil quench, although at the cost of reduced resistance to deformation. Their good machinability supports general-purpose applications, yet because of relatively low wear resistance, they are mostly selected for comparatively short-run work.

Properties and Applications of Frequently Used Oil-Hardening Types: AISI O1: A low-alloy tool steel that is hardened in oil and exhibits only a low tendency to shrinking or warping. It is used for cutting tools, the operation of which does not generate high heat, such as taps and threading dies, reamers, and broaches, and for press tools like blanking, trimming, and forming dies in short- or medium-run operations.

AISI O2: Manganese is the dominant alloying element in this type of oil-hardening tool steel that has good nondeforming properties, can be machined easily, and performs satisfactorily in low-volume production. The low hardening temperature results in good safety in hardening, both with regard to form stability and freedom from cracking. The combination of handling ease, including free-machining properties, with good wear resistance, makes this type of tool steel adaptable to a wide range of common applications such as cutting tools for low- and medium-speed operations; forming tools including thread rolling dies; structural parts such as bushings and fixed gages, and for plastics molds.

AISI O6: This oil-hardening type of tool steel belongs to a group often designated as graphitic because of the presence of small particles of graphitic carbon that are uniformly dispersed throughout the steel. Usually, about one-third of the total carbon is present as free graphite in nodular form, which contributes to the uncommon ease of machining. In the service of parts made of this type of steel, the free graphite acts like a lubricant, reducing wear and galling. The ease of hardening is also excellent, requiring only a comparatively low quenching temperature. Deep hardness penetration is produced and the oil quench causes very little dimensional change. The principal applications of the O6 tool steel are in the field of structural parts, like arbors, bushings, bodies for inserted tool cutters, and shanks for cutting tools, jigs, and machine parts, and fixed gages like plugs, rings, and snap gages. It is also used for blanking, forming, and trimming dies and punches, in applications where the stability of the tool material is more important than high wear resistance.

Cold-Work Tool Steels, Medium-Alloy, Air-Hardening Types.—The desirable nondeforming properties of the high-chromium types are approached by the members of this family, with substantially lower alloy content that, however, is sufficient to permit hardening by air quenching. The machinability is good, and the comparatively low wear resistance is balanced by relatively high toughness, a property that, in certain applications, may be considered of prime importance.

Properties and Applications of Frequently Used Medium-Alloy, Air-Hardening Types:

AISI A2: The lower chromium content, about 5 per cent, makes this air-hardening tool steel less expensive than the high-chromium types, without affecting its nondeforming properties. The somewhat reduced wear resistance is balanced by greater toughness, making this type suitable for press work where the process calls for tough tool materials. The machinability is improved by the addition of about 0.12 percent sulfur, offered as a variety of the basic composition by several steel producers. The prime uses of this tool steel type are punches for blanking and forming, cold and hot trimming dies (the latter heat treated to a lower hardness), thread rolling dies, and plastics molds.

AISI A6: The composition of this type of tool steel makes it adaptable to air hardening from a relatively low temperature, comparable to that of oil-hardening types, yet offering improved stability in heat treating. Its reduced tendency to heat-treatment distortions makes this tool steel type well adapted for die work, forming tools, and gages, which do not require the highest degree of wear resistance.

Shock-Resisting, Mold, and Special-Purpose Tool Steels

There are fields of tool application in which specific properties of the tool steels have dominant significance, determining to a great extent the performance and the service life of tools made of these materials. To meet these requirements, special types of tool steels have been developed. These individual types grew into families with members that, while similar in their major characteristics, provide related properties to different degrees. Originally developed for a specific use, the resulting particular properties of some of these tool steels made them desirable for other uses as well. In the tool steel classification system, they are shown in three groups, as discussed in what follows.

Shock-Resisting Tool Steels.—These steels are made with low-carbon content for increased toughness, even at the expense of wear resistance, which is generally low. Each member of this group also contains alloying elements, different in composition and amount, selected to provide properties particularly adjusted to specific applications. Such varying properties are the degree of toughness (generally, high in all members), hot hardness, abrasion resistance, and machinability.

Properties and Applications of Frequently Used Shock-Resisting Types: AISI S1: This Chromium–tungsten alloyed tool steel combines, in its hardened state, great toughness with high hardness and strength. Although it has a low-carbon content for reasons of good toughness, the carbon-forming alloys contribute to deep hardenability and abrasion resistance. When high wear resistance is also required, this property can be improved by carburizing the surface of the tool while still retaining its shock-resistant characteristics. Primary uses are for battering tools, including hand and pneumatic chisels. The chemical composition, particularly the silicon and tungsten content, provides good hot hardness, too, up to operating temperatures of about 1050 °F, making this tool steel type also adaptable for such hot-work tool applications involving shock loads, as headers, pierces, forming tools, drop forge die inserts, and heavy shear blades.

AISI S2: This steel type serves primarily for hand chisels and pneumatic tools, although it also has limited applications for hot work. Although its wear-resistance properties are only moderate, S2 is sometimes used for forming and thread rolling applications, when the resistance to rupturing is more important than extended service life. For hot-work applications, this steel requires heat treatment in a neutral atmosphere to avoid either carburization or decarburization of the surface. Such conditions make this tool steel type particularly susceptible to failure in hot-work uses.

AISI S5: This composition is essentially a Silicon–manganese type tool steel with small additions of chromium, molybdenum, and vanadium for the purpose of improved deep hardening and refinement of the grain structure. The most important properties of this steel are its high elastic limit and good ductility, resulting in excellent shock-resisting characteristics, when used at atmospheric temperatures. Its recommended quenching medium is oil, although a water quench may also be applied as long as the design of the tools avoids sharp corners or drastic sectional changes. Typical applications include pneumatic tools in severe service, like chipping chisels, also shear blades, heavy-duty punches, and bending rolls. Occasionally, this steel is also used for structural applications, like shanks for carbide tools and machine parts subject to shocks.

Table 12. Shock-Resisting, Mold, and Special-Purpose Tool Steels

Identifying Chemical Composition and Typical Heat-Treatment Data																			
AISI	Category			Shock-Resisting Tool Steels				Mold Steels							Special-Purpose Tool Steels				
	Types			S1	S2	S5	S7	P2	P3	P4	P5	P6	P20	P21[a]	L2[b]	L3[b]	L6	F1	F2
Identifying Elements in Per Cent	C			0.50	0.50	0.55	0.50	0.07	0.10	0.07	0.10	0.10	0.35	0.20	0.50/ 1.10	1.00	0.70	1.00	1.25
	Mn			…	…	0.80	…	…	…	…	…	…	…	…	…	…	…	…	…
	Si			…	1.00	2.00	…	…	…	…	…	…	…	…	…	…	…	…	…
	W			2.50	…	…	…	…	…	…	…	…	…	…	…	…	…	1.25	3.50
	Mo			…	0.50	0.40	1.40	0.20	…	0.75	…	…	0.40	…	…	…	0.25	…	…
	Cr			1.50	…	…	3.25	2.00	0.60	5.00	2.25	1.50	1.25	…	1.00	1.50	0.75	…	…
	V			…	…	…	…	…	…	…	…	…	…	…	0.20	0.20	…	…	…
	Ni			…	…	…	…	0.50	1.25	…	…	3.50	…	4.00	…	…	1.50	…	…
Heat-Treat. Data	Hardening Temperature, °F			1650–1750	1550–1650	1600–1700	1700–1750	1525–1550[c]	1475–1525[c]	1775–1825[c]	1550–1600[c]	1450–1500[c]	1500–1600[c]	Soln. treat.	1550–1700	1500–1600	1450–1550	1450–1600	1450–1600
	Tempering Temp. Range, °F			400–1200	350–800	350–800	400–1150	350–500	350–500	350–900	350–500	350–450	900–1100	Aged	350–1000	350–600	350–1000	350–500	350–500
	Approx. Tempered Hardness, Rc			58–40	60–50	60–50	57–45	64–58[d]	64–58[d]	64–58[d]	64–58[d]	61–58[d]	37–28[d]	40–30	63–45	63–56	62–45	64–60	65–62
Relative Ratings of Properties (A = greatest to E = least)																			
Characteristics in Heat Treatment	Safety in Hardening			C	E	C	B/C	C	C	C	C	C	C	A	D	D	C	E	E
	Depth of Hardening			B	B	B	A	B[e]	B[e]	B[e]	B[e]	A[e]	B	A	B	B	B	C	C
	Resist. to Decarb.			B	C	C	B	A	A	A	A	A	A	A	A	A	A	A	A
	Stability of Shape in Heat Treatment	Quench. Med.	Air	…	…	…	A	…	…	B	…	B	C	A	…	…	…	…	…
			Oil	D	…	D	C	C	C	…	C	C	…	A	D	D	C	…	…
			Water[f]	…	E	…	…	…	…	…	E	…	…	…	E	E	…	E	E
Service Properties	Machinability			D	C/D	C/D	D	C/D	D	D/E	D	D	C/D	D	C	C	D	C	D
	Hot Hardness			D	E	E	C	E	E	D	E	E	E	D	E	E	E	E	E
	Wear Resistance			D/E	D/E	D/E	D/E	D	D	C	D	D	D/E	D	D/E	D	D	D	B/C
	Toughness			B	A	A	B	C	C	C	C	C	C	D	B	D	B	E	E

[a] Contains also about 1.20 per cent A1. Solution treated in hardening.

[b] Quenched in oil.

[c] After carburizing.

[d] Carburized case.

[e] Core hardenability.

[f] Sometimes brine is used.

Mold Steels.—These materials differ from all other types of tool steels by their very low-carbon content, generally requiring carburizing to obtain a hard operating surface. A special property of most steel types in this group is the adaptability to shaping by impression (hobbing) instead of by conventional machining. They also have high resistance to decarburization in heat treatment and dimensional stability, characteristics that obviate the need for grinding following heat treatment. Molding dies for plastics materials require an excellent surface finish, even to the degree of high luster; the generally high-chromium content of these types of tool steels greatly aids in meeting this requirement.

Properties and Applications of Frequently Used Mold Steel Types: AISI P3 and P4:

Essentially, both types of tool steels were developed for the same special purpose, that is, the making of plastics molds. The application conditions of plastics molds require high core strength, good wear resistance at elevated temperature, and excellent surface finish. Both types are carburizing steels that possess good dimensional stability. Because hobbing, that is, sinking the cavity by pressing a punch representing the inverse replica of the cavity into the tool material, is the process by which many plastics mold cavities are produced, good “hobbability” of the tool steels used for this purpose is an important requirement. The different chemistry of these two types of mold steels is responsible for the high core hardness of the P4, which makes it better suited for applications requiring high strength at elevated temperature.

AISI P6: This nickel–chromium-type plastics mold steel has exceptional core strength and develops a deep carburized case. Due to the high nickel–chromium content, the cavities of molds made of this steel type are produced by machining rather than by hobbing. An outstanding characteristic of this steel type is the high luster that is produced by polishing of the hard case surface.

AISI P20: This general-type mold steel is adaptable to both through hardening and carburized case hardening. In through hardening, an oil quench is used and a relatively lower, yet deeply penetrating hardness is obtained, such as is needed for zinc die-casting dies and injection molds for plastics. After the direct quenching and tempering, carburizing produces a very hard case and comparatively high core hardness. When thus heat treated, this steel is particularly well adapted for making compression, transfer, and plunger-type plastics molds.

Special-Purpose Tool Steels.—These steels include several low-alloy types of tool steels that were developed to provide transitional types between the more commonly used basic types of tool steels, and thereby contribute to the balancing of certain conflicting properties such as wear resistance and toughness; to offer intermediate depth of hardening; and to be less expensive than the higher-alloyed types of tool steels.

Properties and Applications of Frequently Used Special-Purpose Types: AISI L6: This material is a low-alloy-type special-purpose tool steel. The comparatively safe hardening and the fair nondeforming properties, combined with the service advantage of good toughness in comparison to most other oil-hardening types, explains the acceptance of this steel with a rather special chemical composition. The uses of L6 are for tools whose toughness requirements prevail over abrasion-resistant properties, such as forming rolls and forming and trimmer dies in applications where combinations of moderate shock- and wear-resistant properties are sought. The areas of use also include structural parts, like clutch members, pawls, and knuckle pins, that must withstand shock loads and still display good wear properties.

AISI F2: This carbon–tungsten type is one of the most abrasion-resistant of all water-hardening tool steels. However, it is sensitive to thermal changes, such as are involved in heat treatment and it is also susceptible to distortions. Consequently, its use is limited to tools of simple shape in order to avoid cracking in hardening. The shallow hardening characteristics of F2 result in a tough core and are desirable properties for certain tool types that, at the same time, require excellent wear-resistant properties.

Water-Hardening Tool Steels.—Steel types in this category are made without, or with only a minimum amount of alloying elements and, their heat treatment needs the harsh quenching action of water or brine, hence the general designation of the category.

Water-hardening steels are usually available with different percentages of carbon, to provide properties required for different applications; the classification system lists a carbon range of 0.60 to 1.40 per cent. In practice, however, the steel mills produce these steels in a few varieties of differing carbon content, often giving proprietary designations to each particular group. Typical carbon content limits of frequently used water-hardening tool steels are 0.70–0.90, 0.90–1.10, 1.05–1.20, and 1.20–1.30 per cent. The appropriate group should be chosen according to the intended use, as indicated in the steel selection guide for this category, keeping in mind that whereas higher carbon content results in deeper hardness penetration, it also reduces toughness.

The general system distinguishes the following four grades: 1) special; 2) extra;

3) standard; and 4) commercial.

listed in the order of decreasing quality. The differences between these grades, which are not offered by all steel mills, are defined in principle only. The distinguishing characteristics are purity and consistency, resulting from different degrees of process refinement and inspection steps applied in making the steel. Higher qualities are selected for assuring dependable uniformity and performance of the tools made from the steel.

The groups with higher carbon content are more sensitive to heat-treatment defects and are generally used for the more demanding applications, so the better grades are usually chosen for the high-carbon types and the lower grades for applications where steels with lower carbon content only are needed.

Water-hardening tool steels, although the least expensive, have several drawbacks, but these are quite acceptable in many types of applications. Some limiting properties are the tendency to deformation in heat treatment due to harsh effects of the applied quenching medium, the sensitivity to heat during the use of the tools made of these steels, the only fair degree of toughness, and the shallow penetration of hardness. However, this last-mentioned property may prove a desirable characteristic in certain applications, such as cold-heading dies, because the relatively shallow hard case is supported by the tough, although softer core.

The AISI designation for water-hardening tool steels is W, followed by a numeral indicating the type, primarily defined by the steel's chemical composition, as shown in the Table 13.

Recommended Applications of Water-Hardening Type W1 (Plain Carbon) Tool Steels:

Group I (C-0.70 to 0.90%): This group is relatively tough and therefore preferred for tools that are subjected to shocks or abusive treatment. Used for such applications as: hand tools, chisels, screwdriver blades, cold punches, and nail sets, and fixture elements, vise jaws, anvil faces, and chuck jaws.

Group II (C-0.90 to 1.10%): This group combines greater hardness with fair toughness, resulting in improved cutting capacity and moderate ability to sustain shock loads. Used for such applications as: hand tools, knives, center punches, pneumatic chisels, cutting tools, reamers, hand taps, and threading dies, wood augers; die parts, drawing and heading dies, shear knives, cutting and forming dies; and fixture elements, drill bushings, lathe centers, collets, and fixed gages.

Group III (C-1.05 to 1.20%): The higher carbon content of this group increases the depth of hardness penetrations, yet reduces toughness, thus the resistance to shock loads. Preferred for applications where wear resistance and cutting ability are the prime considerations. Used for such applications as: hand tools, woodworking chisels, paper knives, cutting tools (for low-speed applications), milling cutters, reamers, planer tools, thread chasers, center drills, die parts, cold blanking, coining, bending dies.

Group IV (C-1.20 to 1–30%): The high carbon content of this group produces a hard case of considerable depth with improved wear resistance yet sensitive to shock and concentrated stresses. Selected for applications where the capacity to withstand abrasive wear is needed, and where the retention of a keen edge or the original shape of the tool is important. Used for such applications as: cutting tools for finishing work, like cutters and reamers, and for cutting chilled cast iron and forming tools, for ferrous and nonferrous metals, and burnishing tools.

By adding small amounts of alloying elements to W-steel types 2 and 5, certain characteristics that are desirable for specific applications are improved. The vanadium in type 2 contributes to retaining a greater degree of fine-grain structure after heat treating. Chromium in type 5 improves the deep-hardening characteristics of the steel, a property needed for large sections, and assists in maintaining the keen cutting edge that is desirable in cutting tools like broaches, reamers, threading taps, and dies.

Table 13. Water-Hardening Tool Steels—Identifying Chemical Composition and Heat-Treatment Data

Chemical Composition in Per Cent	AISI Types		
	W1	W2	W5
C	0.60–1.40	0.60–1.40	1.10
	Varying carbon content may be available		
V	…	0.25	…
Cr	These elements are adjusted to satisfy the hardening requirements		0.50
Mn			
Si			

Heat-Treatment Data		
Hardening Temperature Ranges, °F Varying with Carbon Content	0.60–0.80%	1450–1500
	0.85–1.05%	1425–1550
	1.10–1.40%	1400–1525
Quenching Medium		Brine or Water
Tempering Temperature Range, °F		350–650
Approx. Tempered Hardness, Rc		64–50

Relative Ratings of Properties (A = greatest to E = least)							
Characteristics in Heat Treatment				Service Properties			
Safety in Hardening	Depth of Hardening	Resistance to Decarburization	Stability of Shape in Heat Treatment	Machinability	Hot Hardness	Wear Resistance	Toughness
D	C	A	E	A	E	D/E	C/D

Mill Production Forms of Tool Steels

Tool steels are produced in many different forms, although not all those listed in the following are always readily available; certain forms and shapes are made for special orders only.

Hot-Finished Bars and Cold-Finished Bars.—These bars are the most commonly produced forms of tool steels. Bars can be furnished in many different cross-sections, the round shape being the most common. Sizes can vary over a wide range, with a more limited number of standard stock sizes. Various conditions may also be available, however, technological limitations prevent all conditions applying to every size, shape, or type of steel. Tool steel bars may be supplied in one of the following conditions and surface finishes:

Conditions: Hot-rolled or forged (natural); hot-rolled or forged and annealed; hot-rolled or forged and heat-treated; cold- or hot-drawn (as drawn); and cold- or hot-drawn and annealed.

Finishes: Hot-rolled finish (scale not removed); pickled or blast-cleaned; cold-drawn; turned or machined; rough ground; centerless ground or precision flat ground; and polished (rounds only).

Other forms in which tool steels are supplied are the following:

Rolled or Forged Special Shapes: These shapes are usually produced on special orders only, for the purpose of reducing material loss and machining time in the large-volume manufacture of certain frequently used types of tools.

Forgings: All types of tool steels may be supplied in the form of forgings, which are usually specified for special shapes and for dimensions that are beyond the range covered by bars.

Wires: Tool steel wires are produced either by hot or cold drawing and are specified when special shapes, controlled dimensional accuracy, improved surface finish, or special mechanical properties are required. Round wire is commonly produced within an approximate size range of 0.015 to 0.500 inch, and these dimensions also indicate the limits within which other shapes of tool steel wires, like oval, square, or rectangular, may be produced.

Drill Rods: Rods are produced in round, rectangular, square, hexagonal, and octagonal shapes, usually with tight dimensional tolerances to eliminate subsequent machining, thereby offering manufacturing economies for the users.

Hot-Rolled Plates and Sheets, and Cold-Rolled Strips: Such forms of tool steel are generally specified for the high-volume production of specific tool types.

Tool Bits: These pieces are semifinished tools and are used by clamping in a tool holder or shank in a manner permitting ready replacement. Tool bits are commonly made of high-speed types of tool steels, mostly in square, but also in round, rectangular, andother shapes. Tool bits are made of hot rolled bars and are commonly, yet not exclusively, supplied in hardened and ground form, ready for use after the appropriate cutting edges are ground, usually in the user's plant.

Hollow Bars: These bars are generally produced by trepanning, boring, or drilling of solid round rods and are used for making tools or structural parts of annular shapes, like rolls, ring gages, bushings, etc.

Tolerances of Dimensions.—Such tolerances have been developed and published by the American Iron and Steel Institute (AISI) as a compilation of available industry experience that, however, does not exclude the establishment of closer tolerances, particularly for hot rolled products manufactured in large quantities. The tolerances differ for various categories of production processes (e.g., forged, hot-rolled, cold-drawn, centerless ground) and of general shapes.

Allowances for Machining.—These allowances provide freedom from soft spots and defects of the tool surface, thereby preventing failures in heat treatment or in service. After a layer of specific thickness, known as the allowance, has been removed, the bar or other form of tool steel material should have a surface without decarburization and other surface defects, such as scale marks or seams. The industry wide accepted machining allowance values for tool steels in different conditions, shapes, and size ranges are spelled out in AISI specifications and are generally also listed in the tool steel catalogs of the producer companies.

Decarburization Limits.—Heating of steel for production operation causes the oxidation of the exposed surfaces resulting in the loss of carbon. That condition, called decarburization, penetrates to a certain depth from the surface, depending on the applied process, the shape and the dimensions of the product. Values of tolerance for decarburization must be considered as one of the factors for defining the machining allowances, which must also compensate for expected variations of size and shape, the dimensional effects of heat treatment, and so forth. Decarburization can be present not only in hot-rolled and forged, but also in rough turned and cold-drawn conditions.

Advances in Tool Steel Making Technology.—Significant advances in processes for tool steel production have been made that offer more homogeneous materials of greater density and higher purity for applications where such extremely high quality is required. Two of these methods of tool steel production are of particular interest.

Vacuum-melted tool steels: These steels are produced by the consumable electrode method, which involves remelting of the steel originally produced by conventional processes. Inside a vacuum-tight shell that has been evacuated, the electrode cast of tool steel of the desired chemical analysis is lowered into a water-cooled copper mold where it strikes a low-voltage, high-amperage arc causing the electrode to be consumed by gradual melting. The undesirable gases and volatiles are drawn off by the vacuum, and the inclusions float on the surface of the pool, accumulating on the top of the produced ingot, to be removed later by cropping. In the field of tool steels, the consumable-electrode vacuum-melting (CVM) process is applied primarily to the production of special grades of hot-work and high-speed tool steels.

High-speed tool steels produced by powder metallurgy: The steel produced by conventional methods is reduced to a fine powder by a gas atomization process. The powder is compacted by a hot isostatic method with pressures in the range of 15,000 to 17,000 psi. The compacted billets are hot-rolled to the final bar size, yielding a tool-steel material which has 100 per cent theoretical density. High-speed tool steels produced by the P/M method offer a tool material providing increased tool wear life and high impact strength, of particular advantage in interrupted cuts.

Physical Properties

Physical Properties of Heat-Treated Steels.—Steels that have been "fully hardened" to the same hardness when quenched will have about the same tensile and yield strengths regardless of composition and alloying elements. When the hardness of such a steel is known, it is also possible to predict its reduction of area and tempering temperature. The accompanying figures illustrating these relationships have been prepared by the Society of Automotive Engineers.

Fig. 1 gives the range of Brinell hardnesses that could be expected for any particular tensile strength or it may be used to determine the range of tensile strengths that would correspond to any particular hardness. Fig. 2 shows the relationship between the tensile strength or hardness and the yield point. The solid line is the normal-expectancy curve. The dotted-line curves give the range of the variation of scatter of the plotted data. Fig. 3 shows the relationship that exists between the tensile strength (or hardness) and the reduction of area. The curve to the left represents the alloy steels and that on the right the carbon steels. Both are normal-expectancy curves and the extremities of the perpendicular lines that intersect them represent the variations from the normal-expectancy curves that may be caused by quality differences and by the magnitude of parasitic stresses induced by quenching. Fig. 4 shows the relationship between the hardness (or approximately equivalent tensile strength) and the tempering temperature. Three curves are given, one for fully hardened steels with a carbon content between 0.40 and 0.55 per cent, one for fully hardened steels with a carbon content between 0.30 and 0.40 per cent, and one for steels that are not fully hardened.

From Fig. 1, it can be seen that for a tensile strength of, say, 200,000 pounds per square inch, the Brinell hardness could range between 375 and 425. By taking 400 as the mean hardness value and using Fig. 4, it can be seen that the tempering temperature of fully hardened steels of 0.40 to 0.55 per cent carbon content would be 990 degrees F and that of fully hardened steels of 0.30 to 0.40 per cent carbon would be 870 degrees F. This chart also shows that the tempering temperature for a steel not fully hardened would approach 520 degrees F. A yield point of 0.9 × 200,000, or 180,000, pounds per square inch is indicated (Fig. 2) for the fully hardened steel with a tensile strength of 200,000 pounds per square inch. Most alloy steels of 200,000 pounds per square inch tensile strength would probably have a reduction in area of close to 44 per cent (Fig. 3) but some would have values in the range of 35 to 53 per cent. Carbon steels of the same tensile strength would probably have a reduction in area of close to 24 per cent but could possibly range from 17 to 31 per cent.

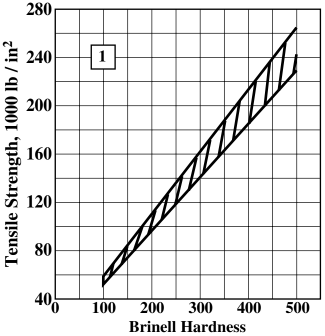


Fig. 1.

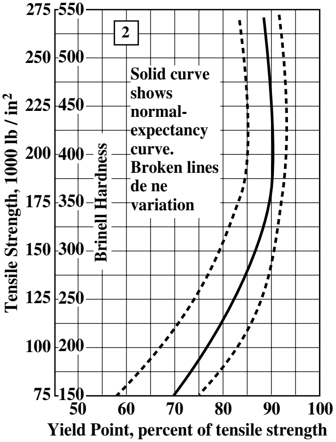


Fig. 2.

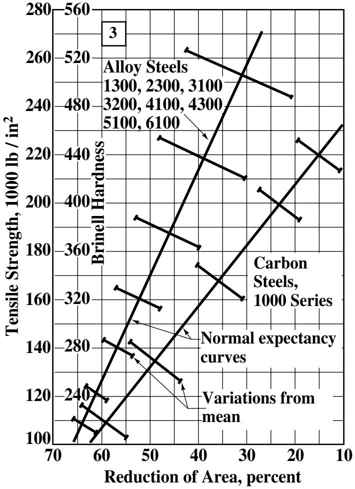


Fig. 3.

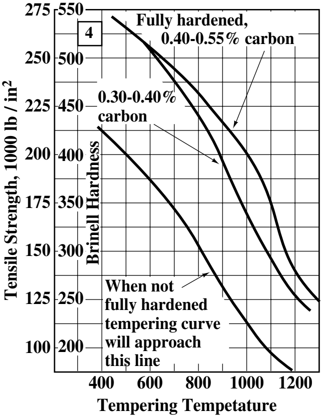


Fig. 4.

Figs. 2 and 3 represent steel in the quenched and tempered condition and Fig. 1 represents steel in the hardened and tempered, as-rolled, annealed, and normalized conditions.

These charts give a good general indication of mechanical properties; however, more exact information when required should be obtained from tests on samples of the individual heats of steel under consideration.

Strength Data for Ferrous Metals.—The accompanying Table 1 gives ultimate strengths, yield points, and moduli of elasticity for various ferrous metals. Values are given as ranges, minimum values, and average values. Ranges of values are due to differences in size and shape of sections, heat treatments undergone, and composition, where several slightly different materials are listed under one general classification. The values in the table are meant to serve as a guide in the selection of ferrous materials and should not be used to write specifications. More specific data should be obtained from the supplier.

Strength Data for Nonferrous Metals.—The ultimate tensile, shear, and yield strengths and moduli of elasticity of many nonferrous metals are given in Table 2. Values for the most part are given in ranges rather than as single values because of differences in composition, forms, sizes, and shapes for the aluminum alloys plus differences in heat treatments undergone for the other nonferrous metals. The values in the table are meant to serve as a guide, not as specifications. More specific data should be obtained from the supplier.

Effect of Temperature on Strength and Elasticity of Metals.—Most ferrous metals have a maximum strength at approximately 400 degrees F, whereas the strength of nonferrous alloys is a maximum at about room temperature. The table on page 478 gives general data for variation in metal strength with temperature.

The modulus of elasticity of metals decreases regularly with increasing temperatures above room temperature until at some elevated temperature it falls off rapidly and reaches zero at the melting point.

Table 1. Strength Data for Iron and Steel

Material	Ultimate Strength			Yield Point, Thousands of Pounds per Square Inch	Modulus of Elasticity	
	Tension, Thousands of Pounds per Square Inch, *T*	Compression, in terms of *T*	Shear, in terms of *T*		Tension, Millions of psi, *E*	Shear,[a] in terms of *E*
Cast iron, gray, class 20	20[b]	3.6*T* to 4.4*T*	1.6*T*	…	11.6	0.40*E*
class 25	25[b]	3.6*T* to 4.4*T*	1.4*T*	…	14.2	0.40*E*
class 30	30[b]	3.7*T*	1.4*T*	…	14.5	0.40*E*
class 35	35[b]	3.2*T* to 3.9*T*	1.4*T*	…	16.0	0.40*E*
class 40	40[b]	3.1*T* to 3.4*T*	1.3*T*	…	17	0.40*E*
class 50	50[b]	3.0*T* to 3.4*T*	1.3*T*	…	18	0.40*E*
class 60	60[b]	2.8*T*	1.0*T*	…	19.9	0.40*E*
malleable	40 to 100[c]	…	…	30 to 80[c]	25	0.43*E*
nodular (ductile iron)	60 to 120[d]	…	…	40 to 90[d]	23	…
Cast steel, carbon	60 to 100	*T*	0.75*T*	30 to 70	30	0.38*E*
low-alloy	70 to 200	*T*	0.75*T*	45 to 170	30	0.38*E*
Steel, SAE 950 (low-alloy)	65 to 70	*T*	0.75*T*	45 to 50	30	0.38*E*
1025 (low-carbon)	60 to 103	*T*	0.75*T*	40 to 90	30	0.38*E*
1045 (medium-carbon)	80 to 182	*T*	0.75*T*	50 to 162	30	0.38*E*
1095 (high-carbon)	90 to 213	*T*	0.75*T*	20 to 150	30	0.39*E*
1112 (free-cuttting)*	60 to 100	*T*	0.75*T*	30 to 95	30	0.38*E*
1212 (free-cuttting)	57 to 80	*T*	0.75*T*	25 to 72	30	0.38*E*
1330 (alloy)	90 to 162	*T*	0.75*T*	27 to 149	30	0.38*E*
2517 (alloy)[e]	88 to 190	*T*	0.75*T*	60 to 155	30	0.38*E*
3140 (alloy)	93 to 188	*T*	0.75*T*	62 to 162	30	0.38*E*
3310 (alloy)[e]	104 to 172	*T*	0.75*T*	56 to 142	30	0.38*E*
4023 (alloy)[e]	105 to 170	*T*	0.75*T*	60 to 114	30	0.38*E*
4130 (alloy)	81 to 179	*T*	0.75*T*	46 to 161	30	0.38*E*
4340 (alloy)	109 to 220	*T*	0.75*T*	68 to 200	30	0.38*E*
4640 (alloy)	98 to 192	*T*	0.75*T*	62 to 169	30	0.38*E*
4820 (alloy)[e]	98 to 209	*T*	0.75*T*	68 to 184	30	0.38*E*
5150 (alloy)	98 to 210	*T*	0.75*T*	51 to 190	30	0.38*E*
52100 (alloy)	100 to 238	*T*	0.75*T*	81 to 228	30	0.38*E*
6150 (alloy)	96 to 228	*T*	0.75*T*	59 to 210	30	0.38*E*
8650 (alloy)	110 to 228	*T*	0.75*T*	69 to 206	30	0.38*E*
8740 (alloy)	100 to 179	*T*	0.75*T*	60 to 165	30	0.38*E*
9310 (alloy)[e]	117 to 187	*T*	0.75*T*	63 to 162	30	0.38*E*
9840 (alloy)	120 to 285	*T*	0.75*T*	45 to 50	30	0.38*E*
Steel, stainless, SAE						
30302[f]	85 to 125	*T*	…	35 to 95	28	0.45*E*
30321[f]	85 to 95	*T*	…	30 to 60	28	…
30347[f]	90 to 100	*T*	…	35 to 65	28	…
51420[g]	95 to 230	*T*	…	50 to 195	29	0.40*E*
51430[h]	75 to 85	*T*	…	40 to 70	29	…
51446[h]	80 to 85	*T*	…	50 to 70	29	…
51501[g]	70 to 175	*T*	…	30 to 135	29	…
Steel, structural						
common	60 to 75	*T*	0.75*T*	33[b]	29	0.41*E*
rivet	52 to 62	*T*	0.75*T*	28[b]	29	…
rivet, high-strength	68 to 82	*T*	0.75*T*	38[b]	29	…
Wrought iron	34 to 54	*T*	0.83*T*	23 to 32	28	…

[a] Synonymous in other literature to the modulus of elasticity in torsion and the modulus of rigidity, *G*.

[b] Minimum specified value of the American Society for Testing and Materials. The specifications for the various materials are as follows: Cast iron, ASTM A48; structural steel for bridges and structures, ASTM A7; structural rivet steel, ASTM A141; high-strength structural rivet steel, ASTM A195.

[c] Range of minimum specified values of the ASTM (ASTM A47, A197, and A220).

[d] Range of minimum specified values of the ASTM (ASTM A339) and the Munitions Board Standards Agency (MIL-I-17166A and MIL-I-11466).

[e] Carburizing grades of steel.

[f] Nonhardenable nickel–chromium and Chromium–nickel–manganese steel (austenitic).

[g] Hardenable chromium steel (martensitic).

[h] Nonhardenable chromium steel (ferritic).

Table 2. Strength Data for Nonferrous Metals

	Ultimate Strength, Thousands of Pounds per Square Inch		Yield Strength (0.2 per cent offset), Thousands of Pounds per Square Inch	Modulus of Elasticity, Millions of Pounds per Square Inch	
Material	in Tension	in Shear		in Tension, *E*	in Shear, *G*
Aluminum alloys, cast,					
sand-cast	19 to 35	14 to 26	8 to 25	10.3	…
heat-treated	20 to 48	20 to 34	16 to 40	10.3	…
permanent-mold-cast,	23 to 35	16 to 27	9 to 24	10.3	…
heat-treated	23 to 48	15 to 36	8.5 to 43	10.3	…
die-cast	30 to 46	19 to 29	16 to 27	10.3	…
Aluminum alloys, wrought,					
annealed	10 to 42	7 to 26	4 to 22	10.0 to 10.6	…
cold-worked	12 to 63	8 to 34	11 to 59	10.0 to 10.3	…
heat-treated	22 to 83	14 to 48	13 to 73	10.0 to 11.4	…
Aluminum bronze, cast,	62 to 90	…	25 to 37	15 to 18	…
heat-treated	80 to 110	…	32 to 65	15 to 18	…
Aluminum bronze, wrought,					
annealed	55 to 80	…	20 to 40	16 to 19	…
cold-worked	71 to 110	…	62 to 66	16 to 19	…
heat-treated	101 to 151	…	48 to 94	16 to 19	…
Brasses, leaded, cast	32 to 40	29 to 31	12 to 15	12 to 14	…
flat products, wrought	46 to 85	31 to 45	14 to 62	14 to 17	5.3 to 6.4
wire, wrought	50 to 88	34 to 46	…	15	5.6
Brasses, nonleaded,					
flat products, wrought	34 to 99	28 to 48	10 to 65	15 to 17	5.6 to 6.4
wire, wrought	40 to 130	29 to 60	…	15 to 17	5.6 to 6.4
Copper, wrought,					
flat products	32 to 57	22 to 29	10 to 53	17	6.4
wire	35 to 66	24 to 33	…	17	6.4
Inconel, cast	70 to 95	…	30 to 45	23	…
flat products, wrought	80 to 170	…	30 to 160	31	11
wire, wrought	80 to 185	…	25 to 175	31	11
Lead	2.2 to 4.9	…	…	0.8 to 2.0	…
Magnesium, cast,					
sand & permanent mold	22 to 40	17 to 22	12 to 23	6.5	2.4
die-cast	33	20	22	6.5	2.4
Magnesium, wrought,					
sheet and plate	35 to 42	21 to 23	20 to 32	6.5	2.4
bars, rods, and shapes	37 to 55	19 to 27	26 to 44	6.5	2.4
Monel, cast	65 to 90	…	32 to 40	19	…
flat products, wrought	70 to 140	…	25 to 130	26	9.5
wire, wrought	70 to 170	…	25 to 160	26	9.5
Nickel, cast,	45 to 60	…	20 to 30	21.5	…
flat products, wrought	55 to 130	…	15 to 115	30	11
wire, wrought	50 to 165	…	10 to 155	30	11
Nickel silver, cast	40 to 50	…	24 to 25	…	…
flat products, wrought	49 to 115	41 to 59	18 to 90	17.5 to 18	6.6 to 6.8
wire, wrought	50 to 145	…	25 to 90	17.5 to 18	6.6 to 6.8
Phosphor bronze, wrought,					
flat products	40 to 128	…	14 to 80	15 to 17	5.6 to 6.4
wire	50 to 147	…	20 to 80	16 to 17	6 to 6.4
Silicon bronze, wrought,					
flat products	56 to 110	42 to 63	21 to 62	15	5.6
wire	50 to 145	36 to 70	25 to 70	15 to 17	5.6 to 6.4
Tin bronze, leaded, cast	21 to 38	23 to 43	15 to 18	10 to 14.5	…
Titanium	50 to 135	…	40 to 120	15.0 to 16.5	…
Zinc, commercial rolled	19.5 to 31	…	…	…	…
Zirconium	22 to 83	…	…	9 to 14.5	4.8

Consult the index for data on metals not listed and for more data on metals listed.

Average Ultimate Strength of Common Materials other than Metals (pounds per square inch)

Material	Compression	Tension
Bricks, best hard	12,000	400
Bricks, light red	1,000	40
Brickwork, common	1,000	50
Brickwork, best	2,000	300
Cement, Portland, 1 month old	2,000	400
Cement, Portland, 1 year old	3,000	500
Concrete, Portland	1,000	200
Concrete, Portland, 1 year old	2,000	400
Granite	19,000	700
Limestone and sandstone	9,000	300
Trap rock	20,000	800
Slate	14,000	500
Vulcanized fiber	39,000	13,000

Influence of Temperature on the Strength of Metals

Material	Degrees Fahrenheit							
	210	400	570	750	930	1100	1300	1475
	Strength in Per Cent of Strength at 70 Degrees F							
Wrought iron	104	112	116	96	76	42	25	15
Cast iron	…	100	99	92	76	42	…	…
Steel castings	109	125	121	97	57	…	…	…
Structural steel	103	132	122	86	49	28	…	…
Copper	95	85	73	59	42	…	…	…
Bronze	101	94	57	26	18	…	…	…

Strength of Copper–Zinc–Tin Alloys (U.S. Government Tests)

Percentage of			Tensile Strength, lb/in^2	Percentage of			Tensile Strength, lb/in^2	Percentage of			Tensile Strength, lb/in^2
Copper	Zinc	Tin		Copper	Zinc	Tin		Copper	Zinc	Tin	
45	50	5	15,000	60	20	20	10,000	75	20	5	45,000
50	45	5	50,000	65	30	5	50,000	75	15	10	45,000
50	40	10	15,000	65	25	10	42,000	75	10	15	43,000
55	43	2	65,000	65	20	15	30,000	75	5	20	41,000
55	40	5	62,000	65	15	20	18,000	80	15	5	45,000
55	35	10	32,500	65	10	25	12,000	80	10	10	45,000
55	30	15	15,000	70	25	5	45,000	80	5	15	47,500
60	37	3	60,000	70	20	10	44,000	85	10	5	43,500
60	35	5	52,500	70	15	15	37,000	85	5	10	46,500
60	30	10	40,000	70	10	20	30,000	90	5	5	42,000

HARDENING, TEMPERING, AND ANNEALING

Heat Treatment Of Standard Steels

Heat-Treating Definitions.—This glossary of heat-treating terms has been adopted by the American Foundrymen's Association, the American Society for Metals, the American Society for Testing and Materials, and the Society of Automotive Engineers. Since it is not intended to be a specification but is strictly a set of definitions, temperatures have purposely been omitted.

Aging: Describes a time–temperature-dependent change in the properties of certain alloys. Except for strain aging and age softening, it is the result of precipitation from a solid solution of one or more compounds whose solubility decreases with decreasing temperature. For each alloy susceptible to aging, there is a unique range of time–temperature combinations to which it will respond.

Annealing: A term denoting a treatment, consisting of heating to and holding at a suitable temperature followed by cooling at a suitable rate, used primarily to soften but also to simultaneously produce desired changes in other properties or in microstructure. The purpose of such changes may be, but is not confined to, improvement of machinability; facilitation of cold working; improvement of mechanical or electrical properties; or increase in stability of dimensions. The time–temperature cycles used vary widely both in maximum temperature attained and in cooling rate employed, depending on the composition of the material, its condition, and the results desired. When applicable, the following more specific process names should be used: Black Annealing, Blue Annealing, Box Annealing, Bright Annealing, Cycle Annealing, Flame Annealing, Full Annealing, Graphitizing, Intermediate Annealing, Isothermal Annealing, Process Annealing, Quench Annealing, and Spheroidizing. When the term is used without qualification, full annealing is implied. When applied only for the relief of stress, the process is properly called stress relieving.

Black Annealing: Box annealing or pot annealing, used mainly for sheet, strip, or wire.

Blue Annealing: Heating hot-rolled sheet in an open furnace to a temperature within the transformation range and then cooling in air, to soften the metal. The formation of a bluish oxide on the surface is incidental.

Box Annealing: Annealing in a sealed container under conditions that minimize oxidation. In box annealing, the charge is usually heated slowly to a temperature below the transformation range, but sometimes above or within it, and is then cooled slowly; this process is also called “close annealing” or “pot annealing.”

Bright Annealing: Annealing in a protective medium to prevent discoloration of the bright surface.

Cycle Annealing: An annealing process employing a predetermined and closely controlled time–temperature cycle to produce specific properties or microstructure.

Flame Annealing: Annealing in which the heat is applied directly by a flame.

Full Annealing: Austenitizing and then cooling at a rate such that the hardness of the product approaches a minimum.

Graphitizing: Annealing in such a way that some or all of the carbon is precipitated as graphite.

Intermediate Annealing: Annealing at one or more stages during manufacture and before final thermal treatment.

Isothermal Annealing: Austenitizing and then cooling to and holding at a temperature at which austenite transforms to a relatively soft ferrite-carbide aggregate.

Process Annealing: An imprecise term used to denote various treatments that improve workability. For the term to be meaningful, the condition of the material and the time–temperature cycle used must be stated.

Quench Annealing: Annealing an austenitic alloy by *Solution Heat Treatment*.

Spheroidizing: Heating and cooling in a cycle designed to produce a spheroidal or globular form of carbide.

Austempering: Quenching from a temperature above the transformation range, in a medium having a rate of heat abstraction high enough to prevent the formation of high-temperature transformation products, and then holding the alloy, until transformation is complete, at a temperature below that of pearlite formation and above that of martensite formation.

Austenitizing: Forming austenite by heating into the transformation range (partial austenitizing) or above the transformation range (complete austenitizing). When used without qualification, the term implies complete austenitizing.

Baking: Heating to a low temperature in order to remove entrained gases.

Bluing: A treatment of the surface of iron-base alloys, usually in the form of sheet or strip, on which, by the action of air or steam at a suitable temperature, a thin blue oxide film is formed on the initially scale-free surface, as a means of improving appearance and resistance to corrosion. This term is also used to denote a heat treatment of springs after fabrication, to reduce the internal stress created by coiling and forming.

Carbon Potential: A measure of the ability of an environment containing active carbon to alter or maintain, under prescribed conditions, the carbon content of the steel exposed to it. In any particular environment, the carbon level attained will depend on such factors as temperature, time, and steel composition.

Carbon Restoration: Replacing the carbon lost in the surface layer from previous processing by carburizing this layer to substantially the original carbon level.

Carbonitriding: A case-hardening process in which a suitable ferrous material is heated above the lower transformation temperature in a gaseous atmosphere of such composition as to cause simultaneous absorption of carbon and nitrogen by the surface and, by diffusion, create a concentration gradient. The process is completed by cooling at a rate that produces the desired properties in the workpiece.

Carburizing: A process in which carbon is introduced into a solid iron-base alloy by heating above the transformation temperature range while in contact with a carbonaceous material that may be a solid, liquid, or gas. Carburizing is frequently followed by quenching to produce a hardened case.

Case: 1) The surface layer of an iron-base alloy that has been suitably altered in composition and can be made substantially harder than the interior or core by a process of case hardening; and 2) the term case is also used to designate the hardened surface layer of a piece of steel that is large enough to have a distinctly softer core or center.

Cementation: The process of introducing elements into the outer layer of metal objects by means of high-temperature diffusion.

Cold Treatment: Exposing to suitable subzero temperatures for the purpose of obtaining desired conditions or properties, such as dimensional or microstructural stability. When the treatment involves the transformation of retained austenite, it is usually followed by a tempering treatment.

Conditioning Heat Treatment: A preliminary heat treatment used to prepare a material for a desired reaction to a subsequent heat treatment. For the term to be meaningful, the treatment used must be specified.

Controlled Cooling: A term used to describe a process by which a steel object is cooled from an elevated temperature, usually from the final hot-forming operation in a predetermined manner of cooling to avoid hardening, cracking, or internal damage.

Core: 1) The interior portion of an iron-base alloy that after case hardening is substantially softer than the surface layer or case; and 2) the term core is also used to designate the relatively soft central portion of certain hardened tool steels.

Critical Range or Critical Temperature Range: Synonymous with *Transformation Range*, which is preferred.

Cyaniding: A process of case hardening an iron-base alloy by the simultaneous absorption of carbon and nitrogen by heating in a cyanide salt. Cyaniding is usually followed by quenching to produce a hard case.

Decarburization: The loss of carbon from the surface of an iron-base alloy as the result of heating in a medium that reacts with the carbon.

Drawing: Drawing, or drawing the temper, is synonymous with *Tempering*, which is preferable.

Eutectic Alloy: The alloy composition that freezes at constant temperature similar to a pure metal. The lowest melting (or freezing) combination of two or more metals. The alloy structure (homogeneous) of two or more solid phases formed from the liquid eutectically.

Hardenability: In a ferrous alloy, the property that determines the depth and distribution of hardness induced by quenching.

Hardening: Any process of increasing hardness of metal by suitable treatment, usually involving heating and cooling. See also *Aging*.

Hardening, Case: A process of surface hardening involving a change in the composition of the outer layer of an iron-base alloy followed by appropriate thermal treatment. Typical case-hardening processes are *Carburizing*, *Cyaniding*, *Carbonitriding*, and *Nitriding*.

Hardening, Flame: A process of heating the surface layer of an iron-base alloy above the transformation temperature range by means of a high-temperature flame, followed by quenching.

Hardening, Precipitation: A process of hardening an alloy in which a constituent precipitates from a supersaturated solid solution. See also *Aging*.

Hardening, Secondary: An increase in hardness following the normal softening that occurs during the tempering of certain alloy steels.

Heating, Differential: A heating process by which the temperature is made to vary throughout the object being heated so that on cooling, different portions may have such different physical properties as may be desired.

Heating, Induction: A process of local heating by electrical induction.

Heat Treatment: A combination of heating and cooling operations applied to a metal or alloy in the solid state to obtain desired conditions or properties. Heating for the sole purpose of hot working is excluded from the meaning of this definition.

Heat Treatment, Solution: A treatment in which an alloy is heated to a suitable temperature and held at this temperature for a sufficient length of time to allow a desired constituent to enter into solid solution, followed by rapid cooling to hold the constituent in solution. The material is then in a supersaturated, unstable state, and may subsequently exhibit *Age Hardening*.

Homogenizing: A high-temperature heat-treatment process intended to eliminate or to decrease chemical segregation by diffusion.

Isothermal Transformation: A change in phase at constant temperature.

Malleablizing: A process of annealing white cast iron in which the combined carbon is wholly or in part transformed to graphitic or free carbon and, in some cases, part of the carbon is removed completely. See *Temper Carbon*.

Maraging: A precipitation hardening treatment applied to a special group of iron-base alloys to precipitate one or more intermetallic compounds in a matrix of essentially carbon-free martensite.

Martempering: A hardening procedure in which an austenitized ferrous workpiece is quenched into an appropriate medium whose temperature is maintained substantially at the M_s of the workpiece, held in the medium until its temperature is uniform throughout but not long enough to permit bainite to form, and then cooled in air. The treatment is followed by tempering.

Nitriding: A process of case hardening in which an iron-base alloy of special composition is heated in an atmosphere of ammonia or in contact with nitrogenous material. Surface hardening is produced by the absorption of nitrogen without quenching.

Normalizing: A process in which an iron-base alloy is heated to a temperature above the transformation range and subsequently cooled in still air at room temperature.

Overheated: A metal is said to have been overheated if, after exposure to an unduly high temperature, it develops an undesirably coarse grain structure but is not permanently damaged. The structure damaged by overheating can be corrected by suitable heat treatment or by mechanical work or by a combination of the two. In this respect it differs from a Burnt structure.

Patenting: A process of heat treatment applied to medium- or high-carbon steel in wire making prior to the wire drawing or between drafts. It consists in heating to a temperature above the transformation range, followed by cooling to a temperature below that range in air or in a bath of molten lead or salt maintained at a temperature appropriate to the carbon content of the steel and the properties required of the finished product.

Preheating: Heating to an appropriate temperature immediately prior to austenitizing when hardening high-hardenability constructional steels, many of the tool steels, and heavy sections.

Quenching: Rapid cooling. When applicable, the following more specific terms should be used: Direct Quenching, Fog Quenching, Hot Quenching, Interrupted Quenching, Selective Quenching, Slack Quenching, Spray Quenching, and Time Quenching.

Direct Quenching: Quenching carburized parts directly from the carburizing operation.

Fog Quenching: Quenching in a mist.

Hot Quenching: An imprecise term used to cover a variety of quenching procedures in which a quenching medium is maintained at a prescribed temperature above 160 degrees F (71 degrees C).

Interrupted Quenching: A quenching procedure in which the workpiece is removed from the first quench at a temperature substantially higher than that of the quenchant and is then subjected to a second quenching system having a different cooling rate than the first.

Selective Quenching: Quenching only certain portions of a workpiece.

Slack Quenching: The incomplete hardening of steel due to quenching from the austenitizing temperature at a rate slower than the critical cooling rate for the particular steel, resulting in the formation of one or more transformation products in addition to martensite.

Spray Quenching: Quenching in a spray of liquid.

Time Quenching: Interrupted quenching in which the duration of holding in the quenching medium is controlled.

Soaking: Prolonged heating of a metal at a selected temperature.

Stabilizing Treatment: A treatment applied to stabilize the dimensions of a workpiece or the structure of a material such as 1) before finishing to final dimensions, heating a workpiece to or somewhat beyond its operating temperature and then cooling to room temperature a sufficient number of times to ensure stability of dimensions in service; 2) transforming retained austenite in those materials that retain substantial amounts when quench hardened (see cold treatment); and 3) heating a solution-treated austenitic stainless steel that contains controlled amounts of titanium or niobium plus tantalum to a temperature below the solution heat-treating temperature to cause precipitation of finely divided, uniformly distributed carbides of those elements, thereby substantially reducing the amount of carbon available for the formation of chromium carbides in the grain boundaries on subsequent exposure to temperatures in the sensitizing range.

Stress Relieving: A process to reduce internal residual stresses in a metal object by heating the object to a suitable temperature and holding for a proper time at that temperature. This treatment may be applied to relieve stresses induced by casting, quenching, normalizing, machining, cold working, or welding.

Temper Carbon: The free or graphitic carbon that comes out of solution usually in the form of rounded nodules in the structure during *Graphitizing* or *Malleablizing*.

Tempering: Heating a quench-hardened or normalized ferrous alloy to a temperature below the transformation range to produce desired changes in properties.

Double Tempering: A treatment in which quench hardened steel is given two complete tempering cycles at substantially the same temperature for the purpose of ensuring completion of the tempering reaction and promoting stability of the resulting microstructure.

Snap Temper: A precautionary interim stress-relieving treatment applied to high hardenability steels immediately after quenching to prevent cracking because of delay in tempering them at the prescribed higher temperature.

Temper Brittleness: Brittleness that results when certain steels are held within, or are cooled slowly through, a certain range of temperatures below the transformation range. The brittleness is revealed by notched-bar impact tests at or below room temperature.

Transformation Ranges or Transformation Temperature Ranges: Those ranges of temperature within which austenite forms during heating and transforms during cooling. The two ranges are distinct, sometimes overlapping but never coinciding. The limiting temperatures of the ranges depend on the composition of the alloy and on the rate of change of temperature, particularly during cooling.

Transformation Temperature: The temperature at which a change in phase occurs. The term is sometimes used to denote the limiting temperature of a transformation range. The following symbols are used for iron and steels:

Ac_{cm} = In hypereutectoid steel, the temperature at which the solution of cementite in austenite is completed during heating

Ac_1 = The temperature at which austenite begins to form during heating

Ac_3 = The temperature at which transformation of ferrite to austenite is completed during heating

Ac_4 = The temperature at which austenite transforms to delta ferrite during heating

$Ae_1, Ae_3, Ae_{cm}, Ae_4$ = The temperatures of phase changes at equilibrium

Ar_{cm} = In hypereutectoid steel, the temperature at which precipitation of cementite starts during cooling

Ar_1 = The temperature at which transformation of austenite to ferrite or to ferrite plus cementite is completed during cooling

Ar_3 = The temperature at which austenite begins to transform to ferrite during cooling

Ar_4 = The temperature at which delta ferrite transforms to austenite during cooling

M_s = The temperature at which transformation of austenite to martensite starts during cooling

M_f = The temperature, during cooling, at which transformation of austenite to martensite is substantially completed

All these changes except the formation of martensite occur at lower temperatures during cooling than during heating, and depend on the rate of change of temperature.

Structure of Fully Annealed Carbon Steel.—In carbon steel that has been fully annealed, there are normally present, apart from such impurities as phosphorus and sulfur, two constituents: the element iron in a form metallurgically known as *ferrite* and the chemical compound iron carbide in the form metallurgically known as *cementite*. This latter constituent consists of 6.67 per cent carbon and 93.33 per cent iron. A certain proportion of these two constituents will be present as a mechanical mixture. This mechanical mixture, the amount of which depends on the carbon content of the steel, consists of alternate bands or layers of ferrite and cementite. Under the microscope, the matrix frequently has the appearance of mother-of-pearl and hence has been named *pearlite*. Pearlite contains about 0.85 per cent carbon and 99.15 per cent iron, neglecting impurities. A fully annealed steel containing 0.85 per cent carbon would consist entirely of pearlite. Such a steel is known as *eutectoid* steel and has a laminated structure characteristic of a eutectic alloy. Steel that has less than 0.85 per cent carbon (*hypoeutectoid* steel) has an excess of ferrite above that required to mix with the cementite present to form pearlite; hence, both ferrite and pearlite are present in the fully annealed state. Steel having a carbon content greater than 0.85 per cent (*hypereutectoid* steel) has an excess of cementite over that required to mix with the ferrite to form pearlite; hence, both cementite and pearlite are present in the fully annealed state. The structural constitution of carbon steel in terms of ferrite, cementite, pearlite and austenite for different carbon contents and at different temperatures is shown by the accompanying figure, *Phase Diagram of Carbon Steel*.

Effect of Heating Fully Annealed Carbon Steel.—When carbon steel in the fully annealed state is heated above the lower critical point, which is some temperature in the range of 1335 to 1355 degrees F (depending on the carbon content), the alternate bands or layers of ferrite and cementite that make up the pearlite begin to merge into each other. This process continues until the pearlite is thoroughly "dissolved," forming what is known as *austenite*. If the temperature of the steel continues to rise and there is present, in addition to the pearlite, any excess ferrite or cementite, this also will begin to dissolve into the austenite until finally only austenite will be present. The temperature at which the excess ferrite or cementite is completely dissolved in the austenite is called the *upper critical point*. This temperature varies with the carbon content of the steel much more widely than the lower critical point (see Fig. 1).

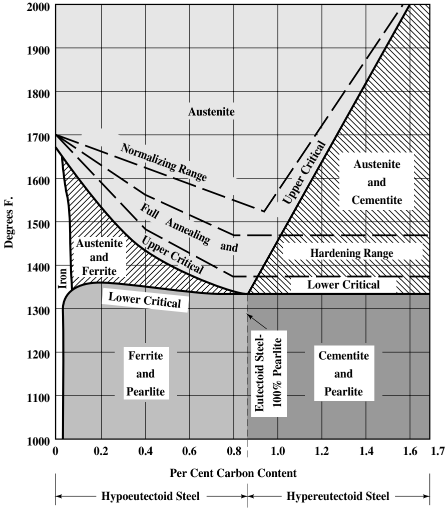


Fig. 1. Phase Diagram of Carbon Steel

Effect of Slow Cooling on Carbon Steel.—If carbon steel that has been heated to the point where it consists entirely of austenite is slowly cooled, the process of transformation that took place during the heating will be reversed, but the upper and lower critical points will occur at somewhat lower temperatures than they do on heating. Assuming that the steel was originally fully annealed, its structure on returning to atmospheric temperature after slow cooling will be the same as before in terms of the proportions of ferrite or cementite and pearlite present. The austenite will have entirely disappeared.

Effect of Rapid Cooling or Quenching on Carbon Steel.—Observations have shown that as the rate at which carbon steel is cooled from an austenitic state is increased, the temperature at which the austenite begins to change into pearlite drops more and more below the slow cooling transformation temperature of about 1300 degrees F. (For example, a 0.80 per cent carbon steel that is cooled at such a rate that the temperature drops 500 degrees in one second will show transformation of austenite beginning at 930 degrees F.) As the cooling rate is increased, the laminations of the pearlite formed by the transformation of the austenite become finer and finer up to the point where they cannot be detected under a high-power microscope, while the steel itself increases in hardness and tensile strength. As the rate of cooling is still further increased, this transformation temperature suddenly drops to around 500 degrees F or lower, depending on the carbon content of the steel. The cooling rate at which this sudden drop in transformation temperature takes place is called the *critical cooling rate*. When a piece of carbon steel is quenched at this rate or faster, a new structure is formed. The austenite is transformed into *martensite*, which is characterized by an angular needlelike structure and a very high hardness.

If carbon steel is subjected to a severe quench or to extremely rapid cooling, a small percentage of the austenite, instead of being transformed into martensite during the quenching operation, may be retained. Over a period of time, however, this remaining austenite tends to be gradually transformed into martensite even though the steel is not subjected to further heating or cooling. Martensite has a lower density than austenite, and such a change, or "aging" as it is called, often results in an appreciable increase in volume or "growth" and the setting up of new internal stresses in the steel.

Steel Heat-Treating Furnaces.—Various types of furnaces heated by gas, oil, or electricity are used for the heat treatment of steel. These furnaces include the oven or box type in various modifications for "in-and-out" or for continuous loading and unloading; the retort type; the pit type; the pot type; and the salt-bath electrode type.

Oven or Box Furnaces: This type of furnace has a box or oven-shaped heating chamber. The "in-and-out" oven furnaces are loaded by hand or by a track-mounted car that, when rolled into the furnace, forms the bottom of the heating chamber. The car type is used where heavy or bulky pieces must be handled. Some oven-type furnaces are provided with a full muffle or a semimuffle, which is an enclosed refractory chamber into which the parts to be heated are placed. The full-muffle, being fully enclosed, prevents any flames or burning gases from coming in contact with the work and permits a special atmosphere to be used to protect or condition the work. The semimuffle, which is open at the top, protects the work from direct impingement of the flame although it does not shut off the work from the hot gases. In the direct-heat-type oven furnace, the work is open to the flame. In the electric oven furnace, a retort is provided when gas atmospheres are to be employed to confine the gas and prevent it from attacking the heating elements. Where muffles are used, they must be replaced periodically, and a greater amount of fuel is required than in a direct-heat type of oven furnace.

For continuous loading and unloading, there are several types of furnaces such as rotary hearth car; roller-, furnace belt-, walking-beam, or pusher-conveyor; and a continuous-kiln-type through which track-mounted cars are run. In the continuous type of furnace, the work may pass through several zones that are maintained at different temperatures for preheating, heating, soaking, and cooling.

Retort Furnace: This is a vertical type of furnace provided with a cylindrical metal retort into which the parts to be heat-treated are suspended either individually, if large enough, or in a container of some sort. The use of a retort permits special gas atmospheres to be employed for carburizing, nitriding, etc.

Pit-Type Furnace: This is a vertical furnace arranged for the loading of parts in a metal basket. The parts within the basket are heated by convection, and when the basket is lowered into place, it fits into the furnace chamber in such a way as to provide a dead-air space to prevent direct heating.

Pot-Type Furnace: This furnace is used for the immersion method of heat treating small parts. A cast-alloy pot is employed to hold a bath of molten lead or salt in which the parts are placed for heating.

Salt Bath Electrode Furnace: In this type of electric furnace, heating is accomplished by means of electrodes suspended directly in the salt bath. The patented grouping and design of electrodes provide an electromagnetic action that results in an automatic stirring action. This stirring tends to produce an even temperature throughout the bath.

Vacuum Furnace: Vacuum heat treatment is a relatively new development in metallurgical processing, with a vacuum substituting for the more commonly used protective gas atmospheres. The most often used furnace is the “cold wall” type, consisting of a water-cooled vessel that is maintained near ambient temperature during operation. During quenching, the chamber is backfilled up to or above atmospheric pressure with an inert gas, which is circulated by an internal fan. When even faster cooling rates are needed, furnaces are available with capability for liquid quenching, performed in an isolated chamber.

Fluidized-Bed Furnace: Fluidized-bed techniques are not new; however, new furnace designs have extended the technology into the temperature ranges required for most common heat treatments. In fluidization, a bed of dry, finely divided particles, typically aluminum oxide, is made to behave like a liquid by feeding gas upward through the bed. An important characteristic of the bed is high-efficiency heat transfer. Applications include continuous or batch-type units for all general heat treatments.

Hardening

Basic Steps in Hardening.—The operation of hardening steel consists fundamentally of two steps. The first step is to heat the steel to some temperature above (usually at least 100 degrees F above) its transformation point so that it becomes entirely austenitic in structure. The second step is to quench the steel at some rate faster than the critical rate (which depends on the carbon content, the amounts of alloying elements present other than carbon, and the grain size of the austenite) to produce a martensitic structure. The hardness of a martensitic steel depends on its carbon content and ranges from about 460 Brinell at 0.20 per cent carbon to about 710 Brinell above 0.50 carbon. In comparison, ferrite has a hardness of about 90 Brinell, pearlite about 240 Brinell, and cementite around 550 Brinell.

Critical Points of Decalescence and Recalescence.—The critical or transformation point at which pearlite is transformed into austenite as it is being heated is also called the *decalescence point*. If the temperature of the steel was observed as it passed through the decalescence point, it would be noted that it would continue to absorb heat without appreciably rising in temperature, although the immediate surroundings were hotter than the steel. Similarly, the critical or transformation point at which austenite is transformed back into pearlite on cooling is called the *recalescence point*. When this point is reached, the steel will give out heat so that its temperature instead of continuing to fall, will momentarily increase.

The recalescence point is lower than the decalescence point by anywhere from 85 to 215 degrees F, and the lower of these points does not manifest itself unless the higher one has first been fully passed. These critical points have a direct relation to the hardening of steel. Unless a temperature sufficient to reach the decalescence point is obtained, so that the pearlite is changed into austenite, no hardening action can take place; and unless the steel is cooled suddenly before it reaches the recalescence point, thus preventing the changing back again from austenite to pearlite, no hardening can take place. The critical points vary for different kinds of steel and must be determined by tests. This variation in the critical points makes it necessary to heat different steels to different temperatures when hardening.

Hardening Temperatures.—The maximum temperature to which a steel is heated before quenching to harden it is called the hardening temperature. Hardening temperatures vary for different steels and different classes of service, although, in general, it may be said that the hardening temperature for any given steel is above the lower critical point of that steel.

Just how far above this point the hardening temperature lies for any particular steel depends on three factors: 1) the chemical composition of the steel; 2) the amount of excess ferrite (if the steel has less than 0.85 per cent carbon content) or the amount of excess cementite (if the steel has more than 0.85 per cent carbon content) that is to be dissolved in the austenite; and 3) the maximum grain size permitted, if desired.

The general range of full-hardening temperatures for carbon steels is shown by the diagram. This range is merely indicative of general practice and is not intended to represent absolute hardening temperature limits. It can be seen that for steels of less than 0.85 per cent carbon content, the hardening range is above the upper critical point — that is, above the temperature at which all the excess ferrite has been dissolved in the austenite. On the other hand, for steels of more than 0.85 per cent carbon content, the hardening range lies somewhat below the upper critical point. This indicates that in this hardening range, some of the excess cementite still remains undissolved in the austenite. If steel of more than 0.85 per cent carbon content were heated above the upper critical point and then quenched, the resulting grain size would be excessively large.

At one time, it was considered desirable to heat steel only to the minimum temperature at which it would fully harden, one of the reasons being to avoid grain growth that takes place at higher temperature. It is now realized that no such rule as this can be applied generally since there are factors other than hardness that must be taken into consideration. For example, in many cases, toughness can be impaired by too low a temperature just as much as by too high a temperature. It is true, however, that too high hardening temperatures result in warpage, distortion, increased scale, and decarburization.

Hardening Temperatures for Carbon Tool Steels.—The best hardening temperatures for any given tool steel are dependent on the type of tool and the intended class of service. Wherever possible, the specific recommendations of the tool steel manufacturer should be followed. General recommendations for hardening temperatures of carbon tool steels based on carbon content are as follows: For steel of 0.65 to 0.80 per cent carbon content, 1450 to 1550 degrees F; for steel of 0.80 to 0.95 per cent carbon content, 1410 to 1460 degrees F; for steel of 0.95 to 1.10 per cent carbon content, 1390 to 1430 degrees F; and for steels of 1.10 per cent and over carbon content, 1380 to 1420 degrees F. For a given hardening temperature range, the higher temperatures tend to produce deeper hardness penetration and increased compressional strength, whereas the lower temperatures tend to result in shallower hardness penetration but increased resistance to splitting or bursting stresses.

Determining Hardening Temperatures.—A hardening temperature can be specified directly or it may be specified indirectly as a certain temperature rise above the lower critical point of the steel. Where the temperature is specified directly, a pyrometer of the type that indicates the furnace temperature or a pyrometer of the type that indicates the work temperature may be employed. If the pyrometer shows furnace temperature, care must be taken to allow sufficient time for the work to reach the furnace temperature after the pyrometer indicates that the required hardening temperature has been attained. If the pyrometer indicates work temperature, then, where the workpiece is large, time must be allowed for the interior of the work to reach the temperature of the surface, which is the temperature indicated by the pyrometer.

Where the hardening temperature is specified as a given temperature rise above the critical point of the steel, a pyrometer that indicates the temperature of the work should be used. The critical point, as well as the given temperature rise, can be more accurately determined with this type of pyrometer. As the work is heated, its temperature, as indicated by the pyrometer, rises steadily until the lower critical or decalescence point of the steel is reached. At this point, the temperature of the work ceases to rise and the pyrometer indicating or recording pointer remains stationary or fluctuates slightly. After a certain elapsed period, depending on the heat input rate, the internal changes in structure of the steel that take place at the lower critical point are completed and the temperature of the work again begins to rise. A small fluctuations in temperature may occur in the interval during which structural changes are taking place, so for uniform practice, the critical point may be considered as the temperature at which the pointer first becomes stationary.

Heating Steel in Liquid Baths.—The liquid bath commonly used for heating steel tools preparatory to hardening are molten lead, sodium cyanide, barium chloride, a mixture of barium and potassium chloride, and other metallic salts. The molten substance is retained in a crucible or pot and the heat required may be obtained from gas, oil, or electricity. The principal advantages of heating baths are as follows: No part of the work can be heated to a temperature above that of the bath; the temperature can be easily maintained at whatever degree has proved, in practice, to give the best results; the submerged steel can be heated uniformly, and the finished surfaces are protected against oxidation.

Salt Baths.—Molten baths of various salt mixtures or compounds are used extensively for heat-treating operations such as hardening and tempering; they are also utilized for annealing ferrous and nonferrous metals. Commercial salt-bath mixtures are available that meet a wide range of temperature and other metallurgical requirements. For example, there are neutral baths for heating tool and die steels without carburizing the surfaces; baths for carburizing the surfaces of low-carbon steel parts; baths adapted for the usual tempering temperatures of, say, 300 to 1100 degrees F; and baths that may be heated to temperatures up to approximately 2400 degrees F for hardening high-speed steels. Salt baths are also adapted for local or selective hardening, the type of bath being selected to suit the requirements. For example, a neutral bath may be used for annealing the ends of tubing or other parts, or an activated cyanide bath for carburizing the ends of shafts or other parts. Surfaces that are not to be carburized are protected by copper plating. When the work is immersed, the unplated surfaces are subjected to the carburizing action.

Baths may consist of a mixture of sodium, potassium, barium, and calcium chlorides or nitrates of sodium, potassium, barium, and calcium in varying proportions, to which sodium carbonate and sodium cyanide are sometimes added to prevent decarburization. Various proportions of these salts provide baths of different properties. Potassium cyanide is seldom used as sodium cyanide costs less. The specific gravity of a salt bath is not as high as that of a lead bath; consequently, the work may be suspended in a salt bath and does not have to be held below the surface as in a lead bath.

The Lead Bath.—The lead bath is extensively used, but is not adapted to the high temperatures required for hardening high-speed steel, as it begins to vaporize at about 1190 degrees F. As the temperature increases, the lead volatilizes and gives off poisonous vapors; hence, lead furnaces should be equipped with hoods to carry away the fumes. Lead baths are generally used for temperatures below 1500 or 1600 degrees F. They are often employed for heating small pieces that must be hardened in quantities. It is important to use pure lead that is free from sulfur. The work should be preheated before plunging it into the molten lead.

Defects in Hardening.—Uneven heating is the cause of most of the defects in hardening. Cracks of a circular form, from the corners or edges of a tool, indicate uneven heating in hardening. Cracks of a vertical nature and dark-colored fissures indicate that the steel has been burned and should be put on the scrap heap. Tools that have hard and soft places have been either unevenly heated, unevenly cooled, or "soaked," a term used to indicate prolonged heating. A tool not thoroughly moved about in the hardening fluid will show hard and soft places, and have a tendency to crack. Tools that are hardened by dropping them to the bottom of the tank sometimes have soft places, owing to contact with the floor or sides.

Scale on Hardened Steel.—The formation of scale on the surface of hardened steel is due to the contact of oxygen with the heated steel; hence, to prevent scale, the heated steel must not be exposed to the action of the air. When using an oven heating furnace, the flame should be so regulated that it is not visible in the heating chamber. The heated steel should be exposed to the air as little as possible, when transferring it from the furnace to the quenching bath. An old method of preventing scale and retaining a fine finish on dies used in jewelry manufacture, small taps, etc., is as follows: Fill the die impression with powdered boracic acid and place near the fire until the acid melts; then add a little more acid to ensure covering all the surfaces. The die is then hardened in the usual way. If the boracic acid does not come off entirely in the quenching bath, immerse the work in boiling water. Dies hardened by this method are said to be as durable as those heated without the acid.

Hardening or Quenching Baths.—The purpose of a quenching bath is to remove heat from the steel being hardened at a rate that is faster than the critical cooling rate. Generally speaking, the more rapid the rate of heat extraction above the cooling rate, the higher will be the resulting hardness. To obtain the different rates of cooling required by different classes of work, baths of various kinds are used. These include plain or fresh water, brine, caustic soda solutions, oils of various classes, oil–water emulsions, baths of molten salt or lead for high-speed steels, and air cooling for some high-speed steel tools when a slow rate of cooling is required. To minimize distortion and cracking where such tendencies are present, without sacrificing depth-of-hardness penetration, a quenching medium should be selected that will cool rapidly at the higher temperatures and more slowly at the lower temperatures, that is below 750 degrees F. Oil quenches in general meet this requirement.

Oil Quenching Baths: Oil is used very extensively as a quenching medium as it results in a good proportion of hardness, toughness, and freedom from warpage when used with standard steels. Oil baths are used extensively for alloy steels. Various kinds of oils are employed, such as prepared mineral oils and vegetable, animal, and fish oils, either singly or in combination. Prepared mineral quenching oils are widely used because they have good quenching characteristics, are chemically stable, do not have an objectionable odor, and are relatively inexpensive. Special compounded oils of the soluble type are used in many plants instead of such oils as fish oil, linseed oil, cottonseed oil, etc. The soluble properties enable the oil to form an emulsion with water.

Oil cools steel at a slower rate than water, but the rate is fast enough for alloy steel. Oils have different cooling rates, however, and this rate may vary through the initial and final stages of the quenching operation. Faster cooling in the initial stage and slower cooling at lower temperatures are preferable because there is less danger of cracking the steel. The temperature of quenching oil baths should range ordinarily between 90 and 130 degrees F. A fairly constant temperature may be maintained either by circulating the oil through cooling coils or by using a tank provided with a cold-water jacket.

A good quenching oil should possess a flash and fire point sufficiently high to be safe under the conditions used and 350 degrees F should be about the minimum point. The specific heat of the oil regulates the hardness and toughness of the quenched steel; and the greater the specific heat, the higher will be the hardness produced. Specific heats of quenching oils vary from 0.20 to 0.75, the specific heats of fish, animal, and vegetable oils usually being from 0.2 to 0.4, and of soluble and mineral oils from 0.5 to 0.7. The efficient temperature range for quenching oil is from 90 to 140 degrees F.

Quenching in Water.—Many carbon tool steels are hardened by immersing them in a bath of fresh water, but water is not an ideal quenching medium. Contact between the water and work and the cooling of the hot steel are impaired by the formation of gas bubbles or an insulating vapor film especially in holes, cavities, or pockets. The result is uneven cooling and sometimes excessive strains which may cause the tool to crack; in fact, there is greater danger of cracking in a fresh-water bath than in one containing salt water or brine.

In order to secure more even cooling and reduce danger of cracking, either rock salt (8 or 9 per cent) or caustic soda (3 to 5 per cent) may be added to the bath to eliminate or prevent the formation of a vapor film or gas pockets, thus promoting rapid early cooling. Brine is commonly used and ¾ pound of rock salt per gallon of water is equivalent to about 8 per cent of salt. Brine is not inherently a more severe or drastic quenching medium than plain water, although it may seem to be because the brine makes better contact with the heated steel and, consequently, cooling is more effective. In still-bath quenching, a slow up-and-down movement of the tool is preferable to a violent swishing around.

The temperature of water-base quenching baths should preferably be kept around 70 degrees F, but 70 to 90 or 100 degrees F is a safe range. The temperature of the hardening bath has a great deal to do with the hardness obtained. The higher the temperature of the quenching water, the more nearly does its effect approach that of oil; and if boiling water is used for quenching, it will have an effect even more gentle than that of oil — in fact, it would leave the steel nearly soft. Parts of irregular shape are sometimes quenched in a water bath that has been warmed somewhat to prevent sudden cooling and cracking.

When water is used, it should be "soft" because unsatisfactory results will be obtained with "hard" water. Any contamination of water-base quenching liquids by soap tends to decrease their rate of cooling. A water bath having 1 or 2 inches of oil on the top is sometimes employed to advantage for quenching tools made of high-carbon steel as the oil through which the work first passes reduces the sudden quenching action of the water.

The bath should be amply large to dissipate the heat rapidly and the temperature should be kept about constant so that successive pieces will be cooled at the same rate. Irregularly shaped parts should be immersed so that the heaviest or thickest section enters the bath first. After immersion, the part to be hardened should be agitated in the bath; the agitation reduces the tendency of the formation of a vapor coating on certain surfaces, and a more uniform rate of cooling is obtained. The work should never be dropped to the bottom of the bath until quite cool.

Flush or Local Quenching by Pressure-Spraying: When dies for cold heading, drawing, extruding, etc., or other tools, require a hard working surface and a relatively soft but tough body, the quenching may be done by spraying water under pressure against the interior or other surfaces to be hardened. Special spraying fixtures are used to hold the tool and apply the spray where the hardening is required. The pressure spray prevents the formation of gas pockets previously referred to in connection with the fresh-water quenching bath; hence, fresh water is effective for flush quenching and there is no advantage in using brine.

Quenching in Molten Salt Bath.—A molten salt bath may be used in preference to oil for quenching high-speed steel. The object in using a liquid salt bath for quenching (instead of an oil bath) is to obtain maximum hardness with minimum cooling stresses and distortion that might result in cracking expensive tools, especially if there are irregular sections. The temperature of the quenching bath may be around 1100 or 1200 degrees F. Quenching is followed by cooling to room temperature and then the tool is tempered or drawn in a bath having a temperature range of 950 to 1100 degrees F. In many cases, the tempering temperature is about 1050 degrees F.

Tanks for Quenching Baths.—The main point to be considered in a quenching bath is to keep it at a uniform temperature, so that successive pieces quenched will be subjected to the same heat treatment. The next consideration is to keep the bath agitated, so that it will not be of different temperatures in different places; if thoroughly agitated and kept in motion, as the case with the bath shown in Fig. 1, it is not even necessary to keep the pieces in motion in the bath, as steam will not be likely to form around the pieces quenched. Experience has proved that if a piece is held still in a thoroughly agitated bath, it will come out much straighter than if it has been moved around in an unagitated bath, an important consideration, especially when hardening long pieces. It is, besides, no easy matter to keep heavy and long pieces in motion unless it be done by mechanical means.

In Fig. 1 is shown a water or brine tank for quenching baths. Water is forced by a pump or other means through the supply pipe into the intermediate space between the outer and inner tank. From the intermediate space, it is forced into the inner tank through holes as indicated. The water returns to the storage tank by overflowing from the inner tank into the outer one and then through the overflow pipe as indicated. In Fig. 3 is shown another water or brine tank of a more common type. In this case, the water or brine is pumped from the storage tank and continuously returned to it. If the storage tank contains a large volume of water, there is no need for a special means for cooling. Otherwise, arrangements must be made for cooling the water after it has passed through the tank. The bath is agitated by the force with which the water is pumped into it. The holes at A are drilled at an angle, so as to throw the water toward the center of the tank. In Fig. 2 is shown an oil-quenching tank in which water is circulated in an outer surrounding tank to keep the oil bath cool. Air is forced into the oil bath to keep it agitated. Fig. 4 shows the ordinary type of quenching tank cooled by water forced through a coil of pipe. This arrangement can be used for oil, water, or brine. Fig. 5 shows a similar type of quenching tank, but with two coils of pipe. Water flows through one of these and steam through the other. By these means, it is possible to keep the bath at a constant temperature.

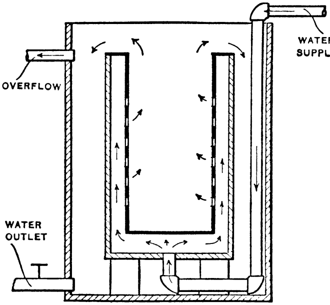


Fig. 1.

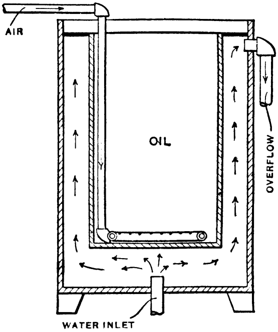


Fig. 2.

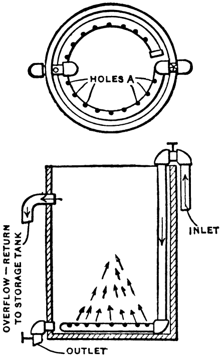


Fig. 3.

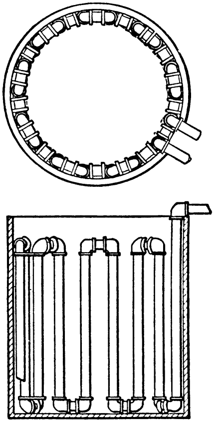


Fig. 4.

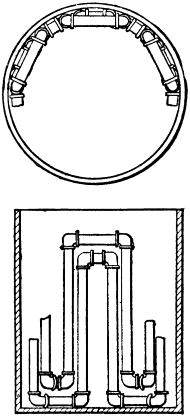


Fig. 5.

Interrupted Quenching.—*Austempering, martempering, and isothermal quenching* are three methods of interrupted quenching that have been developed to obtain greater toughness and ductility for given hardnesses and to avoid the difficulties of quench cracks, internal stresses, and warpage, frequently experienced when the conventional method of quenching steel directly and rapidly from above the transformation point to atmospheric temperature is employed. In each of these three methods, quenching is begun when the work has reached some temperature above the transformation point and is conducted at a rate faster than the critical rate. The rapid cooling of the steel is interrupted, however, at some temperature above that at which martensite begins to form. The three methods differ in the temperature range at which interruption of the rapid quench takes place, the length of time that the steel is held at this temperature, and whether the subsequent cooling to atmospheric temperature is rapid or slow, and is or is not preceded by a tempering operation.

One of the reasons for maintaining the steel at a constant temperature for a definite period of time is to permit the inside sections of the piece to reach the same temperature as the outer sections so that when transformation of the structure does take place, it will occur at about the same rate and period of time throughout the piece. In order to maintain the constant temperature required in interrupted quenching, a quenching arrangement for absorbing and dissipating a large quantity of heat without increase in temperature is needed. Molten salt baths equipped for water spray or air cooling around the exterior of the bath container have been used for this purpose.

Austempering: This is a heat-treating process in which steels are quenched in a bath maintained at some constant temperature in the range of 350 to 800 degrees F, depending on the analysis of the steel and the characteristics to be obtained. On immersion in the quenching bath, the steel is cooled more rapidly than the critical quenching rate. When the temperature of the steel reaches that of the bath, however, the quenching action is interrupted. If the steel is now held at this temperature for a predetermined length of time, say, from 10 to 60 minutes, the austenitic structure of the steel is gradually changed into a new structure, called *bainite*. The structure of bainite is acicular (needlelike) and resembles that of tempered martensite such as is usually obtained by quenching in the usual manner to atmospheric temperature and tempering at 400 degrees F or higher.

Hardnesses ranging up to 60 Rockwell C, depending on the carbon and alloy content of the steel, are obtainable and compare favorably with those obtained for the respective steels by a conventional quench and tempering to above 400 degrees F. Much greater toughness and ductility are obtained in an austempered piece, however, as compared with a similar piece quenched and tempered in the usual manner.

Two factors are important in austempering. First, the steel must be quenched rapidly enough to the specified subtransformation temperature to avoid any formation of pearlite, and, second, it must be held at this temperature until the transformation from austenite to bainite is completed. Time and temperature transformation curves (called S-curves because of their shape) have been developed for different steels and these curves provide important data governing the conduct of austempering, as well as the other interrupted quenching methods.

Austempering has been applied chiefly to steels having 0.60 per cent or more carbon content with or without additional low-alloy content, and to pieces of small diameter or section, usually under 1 inch, but varying with the composition of the steel. Case-hardened parts may also be austempered.

Martempering: In this process the steel is first rapidly quenched from some temperature above the transformation point down to some temperature (usually about 400 degrees F) just above that at which martensite begins to form. It is then held at this temperature for a length of time sufficient to equalize the temperature throughout the part, after which it is removed and cooled in air. As the temperature of the steel drops below the transformation point, martensite begins to form in a matrix of austenite at a fairly uniform rate throughout the piece. The soft austenite acts as a cushion to absorb some of the stresses which develop as the martensite is formed. The difficulties presented by quench cracks, internal stresses, and dimensional changes are largely avoided, thus a structure of high hardness can be obtained. If greater toughness and ductility are required, conventional tempering may follow. In general, heavier sections can be hardened more easily by the martempering process than by the austempering process. The martempering process is especially suited to the higher-alloyed steels.

Isothermal Quenching: This process resembles austempering in that the steel is first rapidly quenched from above the transformation point down to a temperature that is above that at which martensite begins to form and is held at this temperature until the austenite is completely transformed into bainite. The constant temperature to which the piece is quenched and then maintained is usually 450 degrees F or above. The process differs from austempering in that after transformation to a bainite structure has been completed, the steel is immersed in another bath and is brought up to some higher temperature, depending on the characteristics desired, and is maintained at this temperature for a definite period of time, followed by cooling in air. Thus, tempering to obtain the desired toughness or ductility takes place immediately after the structure of the steel has changed to bainite and before it is cooled to atmospheric temperature.

Tempering

The object of *tempering* or *drawing* is to reduce the brittleness in hardened steel and to remove the internal strains caused by the sudden cooling in the quenching bath. The tempering process consists in heating the steel by various means to a certain temperature and then cooling it. When steel is in a fully hardened condition, its structure consists largely of *martensite*. On reheating to a temperature of from about 300 to 750 degrees F, a softer and tougher structure known as *troostite* is formed. If the steel is reheated to a temperature of from 750 to 1290 degrees F, a structure known as *sorbite* is formed that has somewhat less strength than troostite but much greater ductility.

Tempering Temperatures.—If steel is heated in an oxidizing atmosphere, a film of oxide forms on the surface that changes color as the temperature increases. These oxide colors (see table) have been used extensively in the past as a means of gaging the correct amount of temper; but since these colors are affected to some extent by the composition of the metal, the method is not dependable.

The availability of reliable pyrometers in combination with tempering baths of oil, salt, or lead make it possible to heat the work uniformly and to a given temperature within close limits.

Suggested temperatures for tempering various tools are given in the accompanying table.

Tempering in Oil.—Oil baths are extensively used for tempering tools (especially in quantity), the work being immersed in oil heated to the required temperature, which is indicated by a thermometer. It is important that the oil have a uniform temperature throughout and that the work be immersed long enough to acquire this temperature. Cold steel should not be plunged into a bath heated for tempering, owing to the danger of cracking. The steel should either be preheated to about 300 degrees F, before placing it in the bath, or the latter should be at a comparatively low temperature before immersing the steel, and then be heated to the required degree. A temperature of from 650 to 700 degrees F can be obtained with heavy tempering oils; for higher temperatures, either a bath of nitrate salts or a lead bath may be used.

In tempering, the best method is to immerse the pieces to be tempered before starting to heat the oil, so that they are heated with the oil. After the pieces tempered are taken out of the oil bath, they should be immediately dipped in a tank of caustic soda, and after that in a tank of hot water. This will remove all oil that might adhere to the tools. The following tempering oil has given satisfactory results: mineral oil, 94 per cent; saponifiable oil, 6 per cent; specific gravity, 0.920; flash point, 550 degrees F; fire test, 625 degrees F.

Tempering in Salt Baths.—Molten salt baths may be used for tempering or drawing operations. Nitrate baths are particularly adapted for the usual drawing temperature range of, say, 300 to 1100 degrees F. Tempering in an oil bath usually is limited to temperatures of 500 to 600 degrees F, and some heat-treating specialists recommend the use of a salt bath for temperatures above 350 or 400 degrees F, as it is considered more efficient and economical. Tempering in a bath (salt or oil) has several advantages, such as ease in controlling the temperature range and maintenance of a uniform temperature. The work is also heated much more rapidly in a molten bath. A gas- or oil-fired muffle or semimuffle furnace may be used for tempering, but a salt bath or oil bath is preferable. A salt bath is recommended for tempering high-speed steel, although furnaces may also be used. The bath or furnace temperature should be increased gradually, say, from 300 to 400 degrees F up to the tempering temperature, which may range from 1050 to 1150 degrees F for high-speed steel.

Tempering in a Lead Bath.—The lead bath is commonly used for heating steel in connection with tempering, as well as for hardening. The bath is first heated to the temperature at which the steel should be tempered; the preheated work is then placed in the bath long enough to acquire this temperature, after which it is removed and cooled. As the melting temperature of pure lead is about 620 degrees F, tin is commonly added to it to lower the temperature sufficiently for tempering. Reductions in temperature can be obtained by varying the proportions of lead and tin, as shown by the table, "Temperatures of Lead Bath Alloys."

Temperatures of Lead Bath Alloys

Parts Lead	Parts Tin	Melting Temp., Deg. F	Parts Lead	Parts Tin	Melting Temp., Deg. F	Parts Lead	Parts Tin	Melting Temp., Deg. F
200	8	560	39	8	510	19	8	460
100	8	550	33	8	500	17	8	450
75	8	540	28	8	490	16	8	440
60	8	530	24	8	480	15	8	430
48	8	520	21	8	470	14	8	420

To Prevent Lead from Sticking to Steel.—To prevent hot lead from sticking to parts heated in it, mix common whiting with wood alcohol, and paint the part that is to be heated. Water can be used instead of alcohol, but in that case, the paint must be thoroughly dry, as otherwise the moisture will cause the lead to "fly." Another method is to make a thick paste according to the following formula: Pulverized charred leather, 1 pound; fine wheat flour, 1½ pounds; fine table salt, 2 pounds. Coat the tool with this paste and heat slowly until dry, then proceed to harden. Still another method is to heat the work to a blue color, or about 600 degrees F, and then dip it in a strong solution of salt water, prior to heating in the lead bath. The lead is sometimes removed from parts having fine projections or teeth, by using a stiff brush just before immersing in the cooling bath. Removal of lead is necessary to prevent the formation of soft spots.

Tempering in Sand.—The sand bath is used for tempering certain classes of work. One method is to deposit the sand on an iron plate or in a shallow box that has burners beneath it. With this method of tempering, tools such as boiler punches, etc., can be given a varying temper by placing them endwise in the sand. As the temperature of the sand bath is higher toward the bottom, a tool can be so placed that the color of the lower end will become a deep dark blue when the middle portion is a very dark straw, and the working end or top a light straw color, the hardness gradually increasing from the bottom up.

Double Tempering.—In tempering high-speed steel tools, it is common practice to repeat the tempering operation or "double temper" the steel. Double tempering is done by heating the steel to the tempering temperature (say, 1050 degrees F) and holding it at that temperature for two hours. It is then cooled to room temperature, reheated to 1050 degrees F for another two-hour period, and again cooled to room temperature. After the first tempering operation, some untempered martensite remains in the steel. This martensite is not only tempered by a second tempering operation but is relieved of internal stresses, thus improving the steel for service conditions. The hardening temperature for the higher-alloy steels may affect the hardness after tempering. For example, molybdenum high-speed steel when heated to 2100 degrees F had a hardness of 61 Rockwell C after tempering, whereas a temperature of 2250 degrees F resulted in a hardness of 64.5 Rockwell C after tempering.

Temperatures as Indicated by the Color of Plain Carbon Steel

Degrees Centigrade	Degrees Fahrenheit	Color of Steel	Degrees Centigrade	Degrees Fahrenheit	Color of Steel
221.1	430	Very pale yellow	265.6	510	Spotted red-brown
226.7	440	Light yellow	271.1	520	Brown-purple
232.2	450	Pale straw-yellow	276.7	530	Light purple
237.8	460	Straw-yellow	282.2	540	Full purple
243.3	470	Deep straw-yellow	287.8	550	Dark purple
248.9	480	Dark yellow	293.3	560	Full blue
254.4	490	Yellow-brown	298.9	570	Dark blue
260.0	500	Brown-yellow	337.8	640	Light blue

Tempering Temperatures for Various Plain Carbon Steel Tools

Degrees F	Class of Tool
495 to 500	Taps ½ inch or over, for use on automatic screw machines
495 to 500	Nut taps ½ inch and under
515 to 520	Taps ¼ inch and under, for use on automatic screw machines
525 to 530	Thread dies to cut thread close to shoulder
500 to 510	Thread dies for general work
495	Thread dies for tool steel or steel tube
525 to 540	Dies for bolt threader threading to shoulder
460 to 470	Thread rolling dies
430 to 435	Hollow mills (solid type) for roughing on automatic screw machines
485	Knurls
450	Twist drills for hard service
450	Centering tools for automatic screw machines
430	Forming tools for automatic screw machines
430 to 435	Cut-off tools for automatic screw machines
440 to 450	Profile cutters for milling machines
430	Formed milling cutters
435 to 440	Milling cutters
430 to 440	Reamers
460	Counterbores and countersinks
480	Cutters for tube- or pipe-cutting machines
460 to 520	Snaps for pneumatic hammers — harden full length, temper to 460 degrees, then bring point to 520 degrees

Annealing, Spheroidizing, and Normalizing

Annealing of steel is a heat-treating process in which the steel is heated to some elevated temperature, usually in or near the critical range, is held at this temperature for some period of time, and is then cooled, usually at a slow rate. Spheroidizing and normalizing may be considered as special cases of annealing.

The *full annealing* of carbon steel consists in heating it slightly above the *upper* critical point for hypoeutectoid steels (steels of less than 0.85 per cent carbon content) and slightly above the *lower* critical point for hypereutectoid steels (steels of more than 0.85 per cent carbon content), holding it at this temperature until it is uniformly heated and then slowly cooling it to 1000 degrees F or below. The resulting structure is layerlike, or lamellar, in character due to the pearlite that is formed during the slow cooling.

Anealing is employed 1) to soften steel for machining, cutting, stamping, etc., or for some particular service; 2) to alter ductility, toughness, electrical or magnetic characteristics or other physical properties; 3) to refine the crystal structure; 4) to produce grain reorientation; and 5) to relieve stresses and hardness resulting from cold working.

The *spheroidizing* of steel, according to the American Society of Metals, is "any process of heating and cooling that produces a rounded or globular form of carbide." High-carbon steels are spheroidized to improve their machinability especially in continuous cutting operations such as are performed by lathes and screw machines. In low-carbon steels, spheroidizing may be employed to meet certain strength requirements before subsequent heat treatment. Spheroidizing also tends to increase resistance to abrasion.

The *normalizing* of steel consists in heating it to some temperature above that used for annealing, usually about 100 degrees F above the upper critical range, and then cooling it in still air at room temperature. Normalizing is intended to put the steel into a uniform, unstressed condition of proper grain size and refinement so that it will properly respond to further heat treatments. It is particularly important in the case of forgings that are to be later heat treated. Normalizing may or may not (depending on the composition) leave steel in a sufficiently soft state for machining with available tools. Annealing for machinability is often preceded by normalizing and the combined treatment — frequently called a *double anneal* — produces a better result than a simple anneal.

Annealing Practice.—For carbon steels, the following annealing temperatures are recommended by the American Society for Testing and Materials: Steels of less than 0.12 per cent carbon content, 1600 to 1700 degrees F; steels of 0.12 to 0.29 per cent carbon content, 1550 to 1600 degrees F, steels of 0.30 to 0.49 per cent carbon content, 1500 to 1550 degrees F; and for 0.50 to 1.00 per cent carbon steels, from 1450 to 1500 degrees F. Slightly lower temperatures are satisfactory for steels having more than 0.75 per cent manganese content. Heating should be uniform to avoid the formation of additional stresses. In the case of large workpieces, the heating should be slow enough so that the temperature of the interior does not lag too far behind that of the surface.

It has been found that in annealing steel, the higher the temperature to which it is heated to produce an austenitic structure, the greater the tendency of the structure to become lamellar (pearlitic) in cooling. On the other hand, the closer the austenitizing temperature to the critical temperature, the greater is the tendency of the annealed steel to become spheroidal.

Rate of Cooling: After heating the steel to some temperature within the annealing range, it should be cooled slowly enough to permit the development of the desired softness and ductility. In general, the slower the cooling rate, the greater the resulting softness and ductility. Steel of a high-carbon content should be cooled more slowly than steel of a low-carbon content; and the higher the alloy content, the slower is the cooling rate usually required. Where extreme softness and ductility are not required. the steel may be cooled in the annealing furnace to some temperature well below the critical point, say, to about 1000 degrees F and then removed and cooled in air.

Annealing by Constant-Temperature Transformation.—It has been found that steel that has been heated above the critical point so that it has an austenitic structure can be transformed into a lamellar (pearlitic) or a spheroidal structure by holding it for a definite period of time at some constant subcritical temperature. In other words, it is feasible to anneal steel by means of a constant-temperature transformation as well as by the conventional continuous cooling method. When the constant-temperature transformation method is employed, the steel, after being heated to some temperature above the critical and held at this temperature until it is austenitized, is cooled as rapidly as feasible to some relatively high subcritical transformation temperature. The selection of this temperature is governed by the desired microstructure and hardness required and is taken from a transformation time and temperature curve (often called a TTT curve). As drawn for a particular steel, such a curve shows the length of time required to transform that steel from an austenitic state at various subcritical temperatures. After being held at the selected sub-critical temperature for the required length of time, the steel is cooled to room temperature — again, as rapidly as feasible. This rapid cooling down to the selected transformation temperature and then down to room temperature has a negligible effect on the structure of the steel and often produces a considerable saving in time over the conventional slow cooling method of annealing.

The softest condition in steel can be developed by heating it to a temperature usually less than 100 degrees F above the lower critical point and then cooling it to some temperature, usually less than 100 degrees, below the critical point, where it is held until the transformation is completed. Certain steels require a very lengthy period of time for transformation of the austenite when held at a constant temperature within this range. For such steels, a practical procedure is to allow most of the transformation to take place in this temperature range where a soft product is formed and then to finish the transformation at a lower temperature where the time for the completion of the transformation is short.

Spheroidizing Practice.—A common method of spheroidizing steel consists in heating it to or slightly below the lower critical point, holding it at this temperature for a period of time, and then cooling it slowly to about 1000 degrees F or below. The length of time for which the steel is held at the spheroidizing temperature largely governs the degree of spheroidization. High-carbon steel may be spheroidized by subjecting it to a temperature that alternately rises and falls between a point within and a point without the critical range. Tool steel may be spheroidized by heating to a temperature slightly above the critical range and then, after being held at this temperature for a period of time, cooling without removal from the furnace.

Normalizing Practice.—When using the lower-carbon steels, simple normalizing is often sufficient to place the steel in its best condition for machining and will lessen distortion in carburizing or hardening. In the medium- and higher-carbon steels, combined normalizing and annealing constitutes the best practice. For unimportant parts, the normalizing may be omitted entirely or annealing may be practiced only when the steel is otherwise difficult to machine. Both processes are recommended in the following heat treatments (for SAE steels) as representing the best metallurgical practice. The temperatures recommended for normalizing and annealing have been made indefinite in many instances because of the many different types of furnaces used in various plants and the difference in results desired.

Case Hardening

In order to harden low-carbon steel, it is necessary to increase the carbon content of the surface of the steel so that a thin outer "case" can be hardened by heating the steel to the hardening temperature and then quenching it. The process, therefore, involves two separate operations. The first is the *carburizing* operation for impregnating the outer surface with sufficient carbon, and the second operation is that of heat treating the carburized parts so as to obtain a hard outer case and, at the same time, give the "core" the required physical properties. The term "case hardening" is ordinarily used to indicate the complete process of carburizing and hardening.

Carburization.—Carburization is the result of heating iron or steel to a temperature below its melting point in the presence of a solid, liquid, or gaseous material that decomposes so as to liberate carbon when heated to the temperature used. In this way, it is possible to obtain by the gradual penetration, diffusion, or absorption of the carbon by the steel, a "zone" or "case" of higher-carbon content at the outer surfaces than that of the original object. When a carburized object is rapidly cooled or quenched in water, oil, brine, etc., from the proper temperature, this case becomes hard, leaving the inside of the piece soft, but of great toughness.

Use of Carbonaceous Mixtures.—When carburizing materials of the solid class are used, the case-hardening process consists in packing steel articles in metal boxes or pots, with a carbonaceous compound surrounding the steel objects. The boxes or pots are sealed and placed in a carburizing oven or furnace maintained usually at a temperature of from about 1650 to 1700 degrees F for a length of time depending on the extent of the carburizing action desired. The carbon from the carburizing compound will then be absorbed by the steel on the surfaces desired, and the low-carbon steel is converted into high-carbon steel at these portions. The internal sections and the insulated parts of the object retain practically their original low-carbon content. The result is a steel of a dual structure, a high-carbon and a low-carbon steel in the same piece. The carburized steel may now be heat treated by heating and quenching, in much the same way as high-carbon steel is hardened, in order to develop the properties of hardness and toughness; but as the steel is, in reality, two steels in one, one high-carbon and one low-carbon, the correct heat treatment after carburizing includes two distinct processes, one suitable for the high-carbon portion or the "case," as it is generally called, and one suitable for the low-carbon portion or core. The method of heat treatment varies according to the kind of steel used. Usually, an initial heating and slow cooling is followed by reheating to 1400–1450 degrees F, quenching in oil or water, and a final tempering. More definite information is given in the following section on S.A.E. steels.

Carburizers: There are many commercial carburizers on the market in which the materials used as the generator may be hard and soft wood charcoal, animal charcoal, coke, coal, beans and nuts, bone and leather, or various combinations of these. The energizers may be barium, cyanogen, and ammonium compounds, various salts, soda ash, or lime and oil hydrocarbons.

Pack-Hardening.—When cutting tools, gages, and other parts made from high-carbon steels are heated for hardening while packed in some carbonaceous material in order to protect delicate edges, corners, or finished surfaces, the process usually is known as pack-hardening. Thus, the purpose is to protect the work, prevent scale formation, ensure uniform heating, and minimize the danger of cracking and warpage. The work is packed, as in carburizing, and in the same type of receptacle. Common hardwood charcoal often is used, especially if it has had an initial heating to eliminate shrinkage and discharge its more impure gases. The lowest temperature required for hardening should be employed for pack-hardening — usually 1400 to 1450 degrees F for carbon steels. Pack-hardening has also been applied to high-speed steels, but modern developments in heat-treating salts have made it possible to harden high-speed steel without decarburization, injury to sharp edges, or marring the finished surfaces. See paragraph on Salt Baths.

Cyanide Hardening.—When low-carbon steel requires a very hard outer surface but does not need high shock-resisting qualities, the cyanide-hardening process may be employed to produce what is known as superficial hardness. This superficial hardening is the result of carburizing a very thin outer skin (which may be only a few thousandths inch thick) by immersing the steel in a bath containing sodium cyanide. The temperatures usually vary from 1450 to 1650 degrees F and the percentage of sodium cyanide in the bath extends over a wide range, depending on the steel used and properties required.

Nitriding Process.—Nitriding is a process for surface hardening certain alloy steels by heating the steel in an atmosphere of nitrogen (ammonia gas) at approximately 950 degrees F. The steel is then cooled slowly. Finish machined surfaces hardened by nitriding are subject to minimum distortion. The physical properties, such as toughness, high impact strength, etc., can be imparted to the core by previous heat treatments and are unaffected by drawing temperatures up to 950 degrees F. The "Nitralloy" steels suitable for this process may be readily machined in the heat-treated as well as in the annealed state, and they forge as easily as alloy steels of the same carbon content. Certain heat treatments must be applied prior to nitriding, the first being annealing to relieve rolling, forging, or machining strains. Parts or sections not requiring heat treating should be machined or ground to the exact dimensions required. Close tolerances must be maintained in finish machining, but allowances for growth due to adsorption of nitrogen should be made, and this usually amounts to about 0.0005 inch for a case depth of 0.02 inch. Parts requiring heat treatment for definite physical properties are forged or cut from annealed stock, heat treated for the desired physical properties, rough machined, normalized, and finish machined. If quenched and drawn parts are normalized afterwards, the drawing and normalizing temperatures should be alike. The normalizing temperature may be below but should never be above the drawing temperature.

Ion Nitriding.—Ion nitriding, also referred to as glow discharge nitriding, is a process for case hardening of steel parts such as tool spindles, cutting tools, extrusion equipment, forging dies, gears, and crankshafts. An electrical potential ionizes low-pressure nitrogen gas, and the ions produced are accelerated to and impinge on the workpiece, heating it to the appropriate temperature for diffusion to take place. Therefore, there is no requirement for a supplemental heat source. The inward diffusion of the nitrogen ions forms the iron and alloy nitrides in the case. White layer formation, familiar in conventional gas nitriding, is readily controlled by this process.

Liquid Carburizing.—Activated liquid salt baths are now used extensively for carburizing. Sodium cyanide and other salt baths are used. The salt bath is heated by electrodes immersed in it, the bath itself acting as the conductor and resistor. One or more groups of electrodes, with two or more electrodes per group, may be used. The heating is accompanied by a stirring action to ensure uniform temperature and carburizing activity throughout the bath. The temperature may be controlled by a thermocouple immersed in the bath and connecting with a pyrometer designed to provide automatic regulation. The advantages of liquid baths include rapid action; uniform carburization; minimum distortion; and elimination of the packing and unpacking required when carbonaceous mixtures are used. In selective carburizing, the portions of the work that are not to be carburized are copper-plated and the entire piece is then immersed in an activated cyanide bath. The copper inhibits any carburizing action on the plated parts, and this method offers a practical solution for selectively carburizing any portion of a steel part.

Gas Carburizing.—When carburizing gases are used, the mixture varies with the type of case and quality of product desired. The gaseous hydrocarbons most widely used are methane (natural gas), propane, and butane. These carbon-bearing gases are mixed with air, with manufactured gases of several types, with flue gas, or with other specially prepared "diluent" gases. It is necessary to maintain a continuous fresh stream of carburizing gases to the carburizing retort or muffle, as well as to remove the spent gases from the muffle continuously, in order to obtain the correct mixture of gases inside the muffle. A slight pressure is maintained on the muffle to exclude unwanted gases.

The horizontal rotary type of gas carburizing furnace has a retort or muffle that revolves slowly. This type of furnace is adapted to small parts such as ball and roller bearings, chain links, small axles, bolts, etc. With this type of furnace, very large pieces such as gears, for example, may be injured by successive shocks due to tumbling within the rotor.

The vertical pit type of gas carburizer has a stationary workholder that is placed vertically in a pit. The work, instead of circulating in the gases as with the rotary type, is stationary and the gases circulate around it. This type is applicable to long large shafts or other parts or shapes that cannot be rolled in a rotary type of furnace.

There are three types of continuous gas furnaces that may be designated as 1) direct quench and manually operated; 2) direct quench and mechanically operated; and 3) cooling-zone type.

Where production does not warrant using a large continuous-type furnace, a horizontal muffle furnace of the batch type may be used, especially if the quantities of work are varied and the production not continuous.

Vacuum Carburizing.—Vacuum carburizing is a high-temperature gas carburizing process that is performed at pressures below atmospheric. The furnace atmosphere usually consists solely of an enriching gas, such as natural gas, pure methane, or propane; nitrogen is sometimes used as a carrier gas. Vacuum carburizing offers several advantages such as combining of processing operations and reduced total processing time.

Carburizing Steels.—A low-carbon steel containing, say, from 0.10 to 0.20 per cent of carbon is suitable for carburized case hardening. In addition to straight-carbon steels, the low-carbon alloy steels are employed. The alloys add to case-hardened parts the same advantageous properties that they give to other classes of steel. Various steels suitable for case hardening will be found in the section on SAE steels.

To Clean Work after Case Hardening.—To clean work, especially if knurled, where dirt is likely to stick into crevices after case hardening, wash it in caustic soda (1 part soda to 10 parts water). In making this solution, the soda should be put into hot water gradually, and the mixture stirred until the soda is thoroughly dissolved. A still more effective method of cleaning is to dip the work into a mixture of 1 part sulfuric acid and 2 parts water. Leave the pieces in this mixture about three minutes; then wash them off immediately in a soda solution.

Flame Hardening.—This method of hardening is especially applicable to the selective hardening of large steel forgings or castings that must be finish-machined prior to heat-treatment, or that because of size or shape cannot be heat treated by using a furnace or bath. An oxyacetylene torch is used to heat quickly the surface to be hardened; this surface is then quenched to secure a hardened layer that may vary in depth from a mere skin to ¼ inch and with hardness ranging from 400 to 700 Brinell. A multiflame torchhead may be equipped with quenching holes or a spray nozzle back of the flame. This is not a carburizing or a case-hardening process as the torch is only a heating medium. Most authorities recommend tempering or drawing of the hardened surface at temperatures between 200 and 350 degrees F. This treatment may be done in a standard furnace, an oil bath, or with a gas flame. It should follow the hardening process as closely as possible. Medium-carbon and many low-alloy steels are suitable for flame hardening. Plain carbon steels ranging from 0.35 to 0.60 per cent carbon will give hardnesses of from 400 to 700 Brinell. Steels in the 0.40 to 0.45 per cent carbon range are preferred, as they have excellent core properties and produce hardnesses of from 400 to 500 Brinell without checking or cracking. Higher-carbon steels will give greater hardnesses, but extreme care must be taken to prevent cracking. Careful control of the quenching operation is required.

Spinning Method of Flame Hardening: This method is employed on circular objects that can be rotated or spun past a stationary flame. It may be subdivided according to the speed of rotation, as where the part is rotated slowly in front of a stationary flame and the quench is applied immediately after the flame. This method is used on large circular pieces such as track wheels and bearing surfaces. There will be a narrow band of material with lower hardness between adjacent torches if more than one path of the flame is required to harden the surface. There will also be an area of lower hardness where the flame is extinguished. A second method is applicable to small rollers or pinions. The work is spun at a speed of 50 to 150 rpm in front of the flame until the entire piece has reached the proper temperature; then it is quenched as a unit by a cooling spray or by ejecting it into a cooling bath.

The Progressive Method: With this method the torch travels along the face of the work while the work remains stationary. It is used to harden lathe ways, gear teeth, and track rails.

The Stationary or Spot-hardening Method: When this method is employed, the work and torch are both stationary. When the spot to be hardened reaches the quenching temperature, the flame is removed and the quench applied.

The Combination Method: This approach is a combination of the spinning and progressive methods, and is used for long bearing surfaces. The work rotates slowly past the torch as the torch travels longitudinally across the face of the work at the rate of the torch width per revolution of the work.

Equipment for the stationary method of flame hardening consists merely of an acetylene torch, an oxyacetylene supply, and a suitable means of quenching; but when the other methods are employed, work-handling tools are essential and specialty designed torches are desirable. A lathe is ideally suited for the spinning or combination hardening method, whereas a planer is easily adapted for progressive hardening. Production jobs, such as the hardening of gears, require specially designed machines. These machines reduce handling and hardening time, as well as assuring consistent results.

Induction Hardening.—The hardening of steel by means of induction heating and subsequent quenching in either liquid or air is particularly applicable to parts that require localized hardening or controlled depth of hardening and to irregularly shaped parts, such as cams that require uniform surface hardening around their contour.

Advantages offered by induction hardening are: 1) a short heating cycle that may range from a fraction of a second to several seconds (heat energy can be induced in a piece of steel at the rate of 100 to 250 Btu per square inch per minute by induction heating, as compared with a rate of 3 Btu per square inch per minute for the same material at room temperature when placed in a furnace with a wall temperature of 2000 degrees F); 2) absence of tendency to produce oxidation or decarburization; 3) exact control of depth and area of hardening; 4) close regulation of degree of hardness obtained by automatic timing of heating and quenching cycles; 5) minimum amount of warpage or distortion; and 6) possibility of substituting carbon steels for higher-cost alloy steels.

The principal advantage of induction hardening to the designer lies in its application to localized zones. Thus, specific areas in a given part can be heat treated separately to the respective hardnesses required. Parts can be designed so that the stresses at any given point in the finished piece can be relieved by local heating. Parts can be designed in which welded or brazed assemblies are built up prior to heat treating with only internal surfaces or projections requiring hardening.

Types of Induction Heating Equipment.—Induction heating is secured by placing the metal part inside or close to an "applicator" coil of one or more turns, through which alternating current is passed. The coil, formed to suit the general class of workto be heated, is usually made of copper tubing through which water is passed to prevent overheating of the coil itself. The workpiece is held either in a fixed position or is rotated slowly within or close to the applicator coil. Where the length of work is too great to permit heating in a fixed position, progressive heating may be employed. Thus, a rod or tube of steel may be fed through an applicator coil of one or more turns so that the heating zone travels progressively along the entire length of the workpiece.

The frequency of the alternating current used and the type of generator employed to supply this current to the applicator coil depend on the character of the work to be done.

There are three types of equipment used commercially to produce high-frequency current for induction heating: 1) motor generator sets that deliver current at frequencies of approximately 1000, 2000, 3000, and 10,000 cycles; 2) spark gap oscillator units that produce frequencies ranging from 80,000 to 300,000 cycles; and 3) vacuum tube oscillator sets, which produce currents at frequencies ranging from 350,000 to 15,000,000 cycles or more.

Depth of Heat Penetration.—Generally speaking, the higher the frequency used, the shallower the depth of heat penetration. For heating clear through, for deep hardening and for large workpieces, low power concentrations and low frequencies are usually employed. For very shallow and closely controlled depths of heating, as in surface hardening, and in localized heat treating of small workpieces, currents at high frequencies are employed.

For example, a $\frac{1}{2}$-inch round bar of hardenable steel will be heated through its entire structure quite rapidly by an induced current of 2000 cycles. After quenching, the bar would show through hardness with a decrease in hardness from surface to center. The same piece of steel could be readily heated and surface hardened to a depth of 0.100 inch with current at 9600 cycles, and to an even shallower depth with current at 100,000 cycles. A $\frac{1}{4}$-inch bar, however, would not reach a sufficiently high temperature at 2000 cycles to permit hardening, but at 9600 cycles through hardening would be accomplished. Current at over 100,000 cycles would be needed for surface hardening such a bar.

Types of Steel for Induction Hardening.—Most of the standard types of steels can be hardened by induction heating, providing the carbon content is sufficient to produce the desired degree of hardness by quenching. Thus, low-carbon steels with a carburized case, medium- and high-carbon steels (both plain and alloy), and cast iron with a portion of the carbon in combined form, may be used for this purpose. Induction heating of alloy steels should be limited primarily to the shallow hardening type, that is those of low alloy content, otherwise the severe quench usually required may result in a highly stressed surface with consequent reduced load-carrying capacity and danger of cracking.

Through Hardening, Annealing, and Normalizing by Induction.—For through hardening, annealing, and normalizing by induction, low power concentrations are desirable to prevent too great a temperature differential between the surface and the interior of the work. A satisfactory rate of heating is obtained when the total power input to the work is slightly greater than the radiation losses at the desired temperature. If possible, as low a frequency should be used as is consistent with good electrical coupling. A number of applicator coils may be connected in a series so that several workpieces can be heated simultaneously, thus reducing the power input to each. Widening the spacing between work and applicator coil also will reduce the amount of power delivered to the work.

Induction Surface Hardening.—As indicated earlier in “Depth of Heat Penetration,” currents at much higher frequencies are required in induction surface hardening than in through hardening by induction. In general, the smaller the workpiece, the thinner the section, or the shallower the depth to be hardened, the higher will be the frequency required. High power concentrations are also needed to make possible a short heating period so that an undue amount of heat will not be conducted to adjacent or interior areas, where a change in hardness is not desired. Generators of large capacity and applicator coils of but a few turns, or even a single turn, provide the necessary concentration of power in the localized area to be hardened.

Induction heating of internal surfaces, such as the interior of a hollow cylindrical part or the inside of a hole, can be accomplished readily with applicator coils shaped to match the cross-section of the opening, which may be round, square, elliptical or other form. If the internal surface is of short length, a multiturn applicator coil extending along its entire length may be employed. Where the power available is insufficient to heat the entire internal surface at once, progressive heating is used. For this purpose, an applicator coil of few turns — often but a single turn — is employed, and either coil or work is moved so that the heated zone passes progressively from one end of the hole or opening to the other. For bores of small diameter, a hairpin-shaped applicator, extending the entire length of the hole, may be employed and the work rotated about the axis of the hole to ensure even heating.

Quenching After Induction Heating.—After induction heating, quenching may be by immersion in a liquid bath (usually oil), by liquid spray (usually water), or by self-quenching. (The term "self-quenching" is used when there is no quenching medium and hardening of the heated section is due chiefly to rapid absorption of heat by the mass of cool metal adjacent to it.) Quenching by immersion offers the advantage of even cooling and is particularly satisfactory for through heated parts. Spray quenching may be arranged so that the quenching ring and applicator coil are in the same or adjacent units, permitting the quenching cycle to follow the heating cycle immediately without removal of the work from the holding fixture. Automatic timing to a fraction of a second may also be employed for both heating and quenching with this arrangement to secure the exact degree of hardness desired. Self-quenching is applicable only in thin-surface hardening where the mass of adjacent cool metal in the part is great enough to conduct the heat rapidly out of the surface layer that is being hardened. It has been recommended that for adequate self-quenching, the mass of the unheated section should be at least ten times that of the heated shell. It has been found difficult to use the self-quenching technique to produce hardened shells of much more than about 0.060 inch thickness. Close to this limit, self-quenching can only be accomplished with the easily hardenable steels. By using a combination of self-quench and liquid quench, however, it is possible to produced hardened shells on work too thin to self-quench completely. In general, self-quenching is confined chiefly to relatively small parts and simple shapes.

Induction Hardening of Gear Teeth.—Several advantages are claimed for the induction hardening of gear teeth. One advantage is that the gear teeth can be completely machined, including shaving, when in the soft-annealed or normalized condition, and then hardened, because when induction heating is used, distortion is held to a minimum. Another advantage claimed is that bushings and inserts can be assembled in the gears before hardening. A wide latitude in choice of built-up webs and easily machined hubs is afforded because the hardness of neither web nor hub is affected by the induction-hardening operation although slight dimensional changes may occur in certain designs. Regular carbon steels can be used in place of alloy steels for a wide variety of gears, and a steel with a higher carbon content can frequently be substituted for a carburizing steel so that the carburizing operation can be eliminated. Another saving in time is the elimination of cleaning after hardening.

In heating spur gear teeth by induction, the gear is usually placed inside a circular unit that combines the applicator coil and quenching ring. An automatic timing device controls both the heating and quenching cycles. During the heating cycle, the gear is rotated at 25 to 35 rpm to ensure uniform heating.

In hardening bevel gears, the applicator coil is wound to conform to the face angle of the gear. In some spiral-bevel gears, there is a tendency to obtain more heat on one side of the tooth than on the other. In some sizes of spiral-bevel gears, this tendency can be overcome by applying slightly more heat to ensure hardening of the concave side. In some forms of spiral-bevel gears, it has been the practice to carburize that part of the gear surface which is to be hardened, after the teeth have been rough-cut. Carburizing is followed by the finish-cutting operation, after which the teeth can be induction heated, using a long enough period to heat the entire tooth. When the gear is quenched, only the carburized surface will become hardened.

Table 1a. Typical Heat Treatments for SAE Carbon Steels (Carburizing Grades)

SAE No.	Normalize, Deg. F	Carburize, Deg. F	Cool[a]	Reheat, Deg. F	Cool[a]	2nd Reheat, Deg. F	Cool[a]	Temper,[b] Deg. F
1010 to 1022	…	1650–1700	A	…	…	…	…	250–400
	…	1650–1700	B	1400–1450	A	…	…	250–400
	…	1650–1700	C	1400–1450	A	…	…	250–400
	…	1650–1700	C	1650–1700	B	1400–1450	A	250–400
	…	1500–1650^{cd}	B	…	…	…	…	Optional
	…	1350–1575^{ed}	D	…	…	…	…	Optional
1024	1650–1750^{f}	1650–1700	E	……	…	…	…	250–400
	…	1350–1575^{ed}	D	…	…	…	…	Optional
1025 1026	…	1650–1700	A	…	…	…	…	250–400
	…	1500–1650^{cd}	B	…	…	…	…	Optional
1027	…	1350–1575^{ed}	D	…	…	…	…	Optional
1030	…	1500–1650^{cd}	B	…	…	…	…	Optional
	…	1350–1575^{ed}	D	…	…	…	…	Optional
1111 1112 1113	…	1500–1650^{cd}	B	…	…	…	…	Optional
	…	1350–1575^{ed}	D	…	…	…	…	Optional
1109 to 1120	…	1650–1700	A	…	…	…	…	250–400
	…	1650–1700	B	1400–1450	A	…	…	250–400
	…	1650–1700	C	1400–1450	A	…	…	250–400
	…	1650–1700	C	1650–1700	B	1400–1450	A	250–400
	…	1500–1650^{cd}	B	…	…	…	…	Optional
	…	1350–1575^{ed}	D	…	…	…	…	Optional
1126	…	1500–1650^{cd}	B	…	…	…	…	Optional
	…	1350–1575^{ed}	D	…	…	…	…	Optional

[a] Symbols: A = water or brine; B = water or oil; C = cool slowly; D = air or oil; E = oil; F = water, brine, or oil.

[b] Even where tempering temperatures are shown, tempering is not mandatory in many applications. Tempering is usually employed for partial stress relief and improves resistance to grinding cracks.

[c] Activated or cyanide baths.

[d] May be given refining heat as in other processes.

[e] Carbonitriding atmospheres

[f] Normalizing temperatures at least 50 deg. F above the carburizing temperature are sometimes recommended where minimum heat-treatment distortion is of vital importance.

Table 1b. Typical Heat Treatments for SAE Carbon Steels (Heat-Treating Grades)

SAE Number	Normalize, Deg. F		Anneal, Deg. F	Harden, Deg. F	Quench[a]	Temper, Deg. F
1025 & 1030	…		…	1575–1650	A	To Desired Hardness
1033 to 1035	…		…	1525–1575	B	
1036	1600–1700		…	1525–1575	B	
	…		…	1525–1575	B	
1038 to 1040	1600–1700		…	1525–1575	B	
	…		…	1525–1575	B	
1041	1600–1700	and/or	1400–1500	1475–1550	E	
1042 to 1050	1600–1700		…	1475–1550	B	
1052 & 1055	1550–1650	and/or	1400–1500	1475–1550	E	
1060 to 1074	1550–1650	and/or	1400–1500	1475–1550	E	
1078	…		1400–1500[a]	1450–1500	A	
1080 to 1090	1550–1650	and/or	1400–1500[a]	1450–1500	E[b]	
1095	…		1400–1500[a]	1450–1500	F	
	…		1400–1500[a]	1500–1600	E	
1132 & 1137	1600–1700	and/or	1400–1500	1525–1575	B	
1138 & 1140	…		…	1500–1550	B	
	1600–1700		…	1500–1550	B	
1141 & 1144	…		1400–1500	1475–1550	E	
	1600–1700		1400–1500	1475–1550	E	
1145 to 1151	…		…	1475–1550	B	
	1600–1700		…	1475–1550	B	

[a] Slow cooling produces a spheroidal structure in these high-carbon steels that is sometimes required for machining purposes.

[b] May be water- or brine-quenched by special techniques such as partial immersion or time quenched; otherwise they are subject to quench cracking.

Table 2a. Typical Heat Treatments for SAE Alloy Steels (Carburizing Grades)

SAE No.	Normalize[a]	Cycle Anneal[b]	Carburized, Deg. F	Cool[c]	Reheat, Deg. F	Cool[c]	Temper,[d] Deg. F
1320	yes	…	1650–1700	E	1400–1450[e]	E	250–350
	yes	…	1650–1700	E	1475–1525[f]	E	250–350
	yes	…	1650–1700	C	1400–1450[e]	E	250–350
	yes	…	1650–1700	C	1500–1550[f]	E	250–350
	yes	…	1650–1700	E[g]	…	…	250–350
	yes	…	1500–1650[h]	E	…	…	250–350
2317	yes	yes	1650–1700	E	1375–1425[e]	E	250–350
	yes	yes	1650–1700	E	1450–1500[f]	E	250–350
	yes	yes	1650–1700	C	1375–1425[e]	E	250–350
	yes	yes	1650–1700	C	1475–1525[f]	E	250–350
	yes	yes	1650–1700	E[g]	…	…	250–350
	yes	yes	1450–1650[h]	E	…	…	250–350
2512 to 2517	yes[i]	…	1650–1700	C	1325–1375[e]	E	250–350
	yes[i]	…	1650–1700	C	1425–1475[f]	E	250–350
3115 & 3120	yes	…	1650–1700	E	1400–1450[e]	E	250–350
	yes	…	1650–1700	E	1475–1525[f]	E	250–350
	yes	…	1650–1700	C	1400–1450[e]	E	250–350
	yes	…	1650–1700	C	1500–1550[f]	E	250–350
	yes	…	1650–1700	E[g]	…	…	250–350
	yes	……	1500–1650[h]	E	…	…	250–350
3310 & 3316	yes[i]	…	1650–1700	E	1400–1450[e]	E	250–350
	yes[i]	…	1650–1700	C	1475–1500[f]	E	250–350
4017 to 4032	yes	yes	1650–1700	E[g]	…	…	250–350
4119 & 4125	yes	…	1650–1700	E[g]	…	…	250–350
4317 & 4320 4608 to 4621	yes	yes	1650–1700	E	1425–1475[e]	E	250–350
	yes	yes	1650–1700	E	1475–1527[f]	E	250–350
	yes	yes	1650–1700	C	1425–1475[e]	E	250–350
	yes	yes	1650–1700	C	1475–1525[f]	E	250–350
	yes	yes	1650–1700	E[g]	…	…	250–350
	yes	yes	1650–1700	E[g]	…	…	250–350
	yes	…	1500–1650[h]	E	…	…	250–350
4812 to 4820	yes[i]	yes	1650–1700	E	1375–1425[e]	E	250–350
	yes[i]	yes	1650–1700	E	1450–1500[f]	E	250–350
	yes[i]	yes	1650–1700	C	1375–1425[e]	E	250–350
	yes[i]	yes	1650–1700	C	1450–1500[f]	E	250–350
	…	…	1650–1700	E[g]	…	…	250–350
5115 & 5120	yes	…	1650–1700	E	1425–1475[e]	E	250–350
	yes	…	1650–1700	E	1500–1550[f]	E	250–350
	yes	…	1650–1700	C	1425–1475[e]	E	250–350
	yes	…	1650–1700	C	1500–1550[f]	E	250–350
	yes	…	1500–1650[h]	E	…	…	250–350
8615 to 8625 8720	yes	yes	1650–1700	E	1475–1525[e]	E	250–350
	yes	yes	1650–1700	E	1525–1575[f]	E	250–350
	yes	yes	1650–1700	C	1475–1525[e]	E	250–350
	yes	yes	1650–1700	C	1525–1575[f]	E	250–350
	yes	yes	1650–1700	E[g]	…	…	250–350
	yes	yes	1500–1650[h]	E	…	…	250–350
9310 to 9317	yes[i]	…	1650–1700	E	1400–1450[e]	E	250–350
	yes[i]	…	1650–1700	C	1500–1525	E	250–350

[a] Normalizing temperatures should be not less than 50 deg. F higher than the carburizing temperature. Follow by air cooling.

[b] For cycle annealing, heat to normalizing temperature—hold for uniformity—cool rapidly to 1000–1250 deg. F; hold 1 to 3 hours, then air or furnace cool to obtain a structure suitable for machining and finishing.

[c] Symbols: C = cool slowly; E = oil.

[d] Tempering treatment is optional and is generally employed for partial stress relief and improved resistance to cracking from grinding operations.

[e] For use when case hardness only is paramount.

[f] For use when higher core hardness is desired.

[g] Treatment is for fine-grained steels only, when a second reheat is often unnecessary.

[h] Treatment is for activated or cyanide baths. Parts may be given refining heats as indicated for other heat-treating processes.

[i] After normalizing, reheat to temperatures of 1000–1200 deg. F and hold approximately 4 hours.

Table 3a. Typical Heat Treatments for SAE Alloy Steels (Directly Hardenable Grades)

SAE No.	Normalize, Deg. F		Anneal, Deg. F	Harden, Deg. F	Quench[a]	Temper, Deg. F
1330	…		…	1525–1575	B	To desired hardness
	1600–1700	and/or	1500–1600	1525–1575	B	To desired hardness
1335 & 1340	…		…	1500–1550	E	To desired hardness
	1600–1700	and/or	1500–1600	1525–1575	E	To desired hardness
2330	…		…	1450–1500	E	To desired hardness
	1600–1700	and/or	1400–1500	1450–1500	E	To desired hardness
2340 & 2345	…		…	1425–1475	E	To desired hardness
	1600–1700	and/or	1400–1500	1425–1475	E	To desired hardness
3130	1600–1700		…	1500–1550	B	To desired hardness
3135 to 3141	…		…	1500–1550	E	To desired hardness
	1600–1700	and/or	1450–1550	1500–1550	E	To desired hardness
3145 & 3150	…		…	1500–1550	E	To desired hardness
	1600–1700	and/or	1400–1500	1500–1550	E	To desired hardness
4037 & 4042	…		1525–1575	1500–1575	E	Gears, 350–450 To desired hardness
4047 & 4053	…		1450–1550	1500–1575	E	To desired hardness
4063 & 4068	…		1450–1550	1475–1550	E	To desired hardness
4130	1600–1700	and/or	1450–1550	1600–1650	B	To desired hardness
4137 & 4140	1600–1700	and/or	1450–1550	1550–1600	E	To desired hardness
4145 & 4150	1600–1700	and/or	1450–1550	1500–1600	E	To desired hardness
4340	1600–1700	and draw	1100–1225	1475–1525	E	To desired hardness
4640	1600–1700	and/or	1450–1550	1450–1500	E	To desired hardness
	1600–1700	and/or	1450–1500	1450–1500	E	Gears, 350–450
5045 & 5046	1600–1700	and/or	1450–1550	1475–1500	E	250–300
5130 & 5132	1650–1750	and/or	1450–1550	1500–1550	G	To desired hardness
5135 to 5145	1650–1750	and/or	1450–1550	1500–1550	E	To desired hardness Gears, 350–400
5147 to 5152	1650–1750	and/or	1450–1550	1475–1550	E	To desired hardness Gears, 350–400
50100	…		1350–1450	1425–1475	H	To desired hardness
51100 52100	…		1350–1450	1500–1600	E	To desired hardness
6150	1650–1750	and/or	1550–1650	1600–1650	E	To desired hardness
9254 to 9262	…		…	1500–1650	E	To desired hardness
8627 to 8632	1600–1700	and/or	1450–1550	1550–1650	B	To desired hardness
8635 to 8641	1600–1700	and/or	1450–1550	1525–1575	E	To desired hardness
8642 to 8653	1600–1700	and/or	1450–1550	1500–1550	E	To desired hardness
8655 & 8660	1650–1750	and/or	1450–1550	1475–1550	E	To desired hardness
8735 & 8740	1600–1700	and/or	1450–1550	1525–1575	E	To desired hardness
8745 & 8750	1600–1700	and/or	1450–1500	1500–1550	E	To desired hardness
9437 & 9440	1600–1700	and/or	1450–1550	1550–1600	E	To desired hardness
9442 to 9747	1600–1700	and/or	1450–1550	1500–1600	E	To desired hardness
9840	1600–1700	and/or	1450–1550	1500–1550	E	To desired hardness
9845 & 9850	1600–1700	and/or	1450–1550	1500–1550	E	To desired hardness

[a] Symbols: B = water or oil; E = oil; G = water, caustic solution, or oil; H = water.

Table 4a. Typical Heat Treatments for SAE Alloy Steels

(Heat-Treating Grades—Chromium–Nickel Austenitic Steels)

SAE No.	Normalize	Anneal,[a] Deg. F	Harden, Deg. F	Quenching Medium	Temper
30301 to 30347	…	1800–2100	…	Water or Air	…

[a] Quench to produce full austenitic structure using water or air in accordance with thickness of section. Annealing temperatures given cover process and full annealing as used by industry, the lower end of the range being used for process annealing.

Table 5a. Typical Heat Treatments for SAE Alloy Steels

(Heat-Treating Grades — Stainless Chromium Irons and Steels)

SAE No.[a]	Nor-malize	Aub-critical Anneal, Deg. F	Full Anneal Deg. F	Harden Deg. F	Quenching Medium	Temper Deg. F
51410	…	1300–1350[b]	1550–1650[c]	…	Oil or air	To desired hardness
	…	…	…	1750–1850		
51414	…	1200–1250[b]	…	…	Oil or air	To desired hardness
	…	…	…	1750–1850		
51416	…	1300–1350[b]	1550–1650[c]	…	Oil or air	To desired hardness
	…	…	…	1750–1850		
51420 51420F	…	1350–1450[b]	1550–1650[c]	…	Oil or air	To desired hardness
	…	…	…	1800–1850		
51430	…	1400–1500[d]	…	…	…	…
51430F	…	1250–1500[d]	…	…	…	…
51431	…	1150–1225[b]	…	1800–1900	Oil or air	To desired hardness
51440A 51440B 51440C 51440F	…	1350–1440[b]	1550–1650[c]	1850–1950	Oil or air	To desired hardness
51442	…	1400–1500[d]	…	…	…	…
51446	…	1500–1650[d]	…	…	…	…
51501	…	1325–1375[b]	1525–1600[c]	1600–1700	Oil or air	To desired hardness

[a] Suffixes A, B, and C denote three types of steel differing in carbon content only. Suffix F denotes a free-machining steel.

[b] Usually air cooled, but may be furnace cooled.

[c] Cool slowly in furnace.

[d] Cool rapidly in air.

Laser and Electron-Beam Surface Hardening.—Industrial lasers and electron-beam equipment are now available for surface hardening of steels. The laser and electron beams can generate very intense energy fluxes and steep temperature profiles in the workpiece, so that external quench media are not needed. This self-quenching is due to a cold interior with sufficient mass acting as a large heat sink to rapidly cool the hot surface by conducting heat to the interior of a part. The laser beam is a beam of light and does not require a vacuum for operation. The electron beam is a stream of electrons and processing usually takes place in a vacuum chamber or envelope. Both processes may normally be applied to finished machined or ground surfaces, because little distortion results.

HEAT-TREATING HIGH-SPEED STEELS

Heat Treating High-Speed Steels

Cobaltcrom Steel.—A tungstenless alloy steel or high-speed steel that contains approximately 1.5 per cent carbon, 12.5 per cent chromium, and 3.5 per cent cobalt. Tools such as dies and milling cutters, made from cobaltcrom steel can be cast to shape in suitable molds, the teeth of cutters being formed so that it is necessary only to grind them.

Before the blanks can be machined, they must be annealed; this operation is performed by pack annealing at the temperature of 1800 degrees F, for a period of from three to six hours, according to the size of the castings being annealed. The following directions are given for the hardening of blanking and trimming dies, milling cutters, and similar tools made from cobaltcrom steel: Heat slowly in a hardening furnace to about 1830 degrees F, and hold at this temperature until the tools are thoroughly soaked. Reduce the temperature about 50 degrees, withdraw the tools from the furnace, and allow them to cool in the atmosphere. As soon as the red color disappears from the cooling tool, place it in quenching oil until cold. The slight drop of 50 degrees in temperature while the tool is still in the hardening furnace is highly important to obtain proper results. The steel will be injured if the tool is heated above 1860 degrees F. In cooling milling cutters or other rotary tools, it is suggested that they be suspended on a wire to ensure a uniform rate of cooling.

Tools that are to be subjected to shocks or vibration, such as pneumatic rivet sets, shear blades, etc., should be heated slowly to 1650 degrees F, after which the temperature should be reduced to about 1610 degrees F, at which point the tool should be removed from the furnace and permitted to cool in the atmosphere. No appreciable scaling occurs in the hardening of cobaltcrom steel tools.

Preheating Tungsten High-Speed Steel.—Tungsten high-speed steel must be hardened at a very high temperature; consequently, tools made from such steel are seldom hardened without at least one preheating stage to avoid internal strain. This requirement applies especially to milling cutters, taps, and other tools having thin teeth and thick bodies and to forming tools of irregular shape and section. The tools should be heated slowly and carefully to a temperature somewhat below the critical point of the steel, usually in the range of 1500 to 1600 degrees F. Limiting the preheating temperature prevents the operation from being unduly sensitive, and the tool may be safely left in the furnace until it reaches a uniform temperature throughout its length and cross-section.

A single stage of preheating is customary for tools of simple form that are not more than from 1 to $1\frac{1}{2}$ inches in thickness. For large, intricate tools, two stages of preheating are frequently used. The first brings the tool up to a temperature of about 1100 to 1200 degrees F, and the second raises its temperature to 1550 to 1600 degrees F. A preheating time of 5 minutes for each $\frac{1}{4}$ inch in tool thickness has been recommended for a furnace temperature of 1600 degrees F. This is where a single stage of preheating is used and the furnace capacity should be sufficient to maintain practically constant temperature when the tools are changed. To prevent undue chilling, it is common practice to insert a single tool or a small lot in the hardening furnace whenever a tool or lot is removed, rather than to insert a full charge of cold metal at one time.

Preheating is usually done in a simple type of oven furnace heated by gas, electricity, or oil. Atmospheric control is seldom used, although for 18–4–1 steel a slightly reducing atmosphere (2 to 6 per cent carbon monoxide) has been found to produce the least amount of scale and will result in a better surface after final hardening.

Hardening of Tungsten High-Speed Steel.—All tungsten high-speed steels must be heated to a temperature close to their fusion point to develop their maximum efficiency as metal-cutting tools. Hardening temperatures ranging from 2200 to 2500 deg. F may be needed. The effects of changes in the hardening temperature on the cutting efficiency of several of the more common high-speed steels are shown in Table 1. The figures given are ratios, the value 1.00 for each steel being assigned to the highest observed cutting speed for that steel. The figures for different steels, therefore, cannot be directly compared with each other, except to note changes in the point of maximum cutting efficiency.

Table 1. Relation of Hardening Temperature to Cutting Efficiency

Hardening Temperature, Deg. F	Typical Analyses of High-Speed Steels			
	18 – 4 – 1	14 – 4 – 2	18 – 4 –1 Cobalt	14 – 4 – 2 Cobalt
2200	0.86	0.83	0.84	0.85
2250	0.88	0.88	0.86	0.88
2300	0.90	0.93	0.90	0.91
2350	0.95	0.98	0.94	0.94
2400	0.99	0.98	0.98	0.98
2450	1.00	…	0.99	1.00
2500	0.98	…	1.00	0.97

The figures in the table refer to tools heated in an oven-type furnace in which a neutral atmosphere is maintained. The available data indicate that a steel reaches its best cutting qualities at a temperature approximately 50 deg. F lower than the figures in the table if it is hardened in a bath-type furnace. It is, however, desirable to use a hardening temperature approximately 50 deg. F lower than that giving maximum cutting qualities, to avoid the possibility of overheating the tool.

Length of Time for Heating: The cutting efficiency of a tool is affected by the time that it is kept at the hardening temperature, almost as much as by the hardening temperature itself. It has been common practice to heat a tool for hardening until a "sweat" appeared on its surface. This sweat is presumably a melting of the oxide film on the surface of a tool heated in an oxidizing atmosphere. It does not appear when the tool is heated in an inert atmosphere. This method of determining the proper heating time is at best an approximation and indicates only the temperature on the outside of the tool rather than the condition of the interior. As such, it cannot be relied upon to give consistent results.

The only safe method is to heat the tool for a definite predetermined time, based on the size and the thickness of metal that the heat must penetrate to reach the interior. The values given in Table 2 are based on a series of experiments to determine the relative cutting efficiency of a group of tools hardened in an identical manner, except for variations in the time the tools were kept at the hardening temperature. The time given is based on that required to harden throughout a tool resting on a conducting hearth; the tool receives heat freely from three sides, on its large top surface and its smaller side surfaces. (The table does not apply to a disk lying flat on the hearth.) For a tool having a projecting cutting edge, such as a tap, the thickness or depth of the projecting portion on which the cutting edge is formed should be used when referring to the table.

Table 2. Length of Heating Time for Through Hardening

High-Speed Steel Tool Thickness, in Inches	Time in Furnace at High Heat, in Minutes	High-Speed Steel Tool Thickness, in Inches	Time in Furnace at High Heat, in Minutes	High-Speed Steel Tool Thickness, in Inches	Time in Furnace at High Heat, in Minutes
¼	2	1½	7	5	18
½	3	2	8	6	20
¾	4	3	12	8	25
1	5	4	15	10	30

The time periods given in Table 2 are based on complete penetration of the hardening effect. For very thick tools, the practical procedure is to harden to a depth sufficient to produce an adequate cutting edge, leaving the interior of the tool relatively soft.

Where atmosphere control is not provided, it often will be found impracticable to use both the temperature for maximum cutting efficiency, given in Table 1, and the heating time, given in Table 2, because abnormal scaling, grain growth, and surface decarburization of the tool will result. The principal value of an accurate control of the furnace atmosphere appears to lie in the fact that its use makes possible the particular heat treatment that produces the best structure in the tool without destruction of the tool surface or grain.

Quenching Tungsten High-Speed Steel.—High-speed steel is usually quenched in oil. The oil bath offers a convenient quench; it calls for no unusual care in handling and brings about a uniform and satisfactory rate of cooling, which does not vary appreciably with the temperature of the oil. Some authorities believe it desirable to withdraw the tool from the oil bath for a few seconds after it has reached a dull red. It is also believed desirable to move the tool around in the quenching oil, particularly immediately after it has been placed in it, to prevent the formation of a gas film on the tool. Such a film is usually a poor conductor of heat and slows the rate of cooling.

Salt Bath: Quenching in a lead or salt bath at from 1000 to 1200 deg. F has the advantage that cooling of the tool from hardening to room temperature is accomplished in two stages, thus reducing the possibility of setting up internal strains that may tend to crack the tool. The quenching temperature is sufficiently below the lower critical point for a tool so quenched to be allowed to cool to room temperature in still air. This type of quench is particularly advantageous for tools of complicated section that would easily develop hardening cracks. The salt quench has the advantage that the tool sinks and requires only a support, whereas the same tool will float in the lead bath and must be held under the surface. It is believed that the lead quench gives a somewhat higher matrix hardness, and is of advantage for tools that tend to fail by nose abrasion. Tools treated as described are brittle unless given a regular tempering treatment, because the 1000-deg. F quenching temperature is not a substitute for later tempering at the same temperature, after the tool has cooled to room temperature.

Air Cooling: Many high-speed steel tools are quenched in air, either in a stream of dry compressed air or in still air. Small sections harden satisfactorily in still air, but heavier sections should be subjected to air under pressure. One advantage of air cooling is that the tool can be kept straight and free from distortion, although it is likely that there will be more scale on a tool thus quenched than when oil, lead, or salt is used. Cooling between steel plates may help to keep thin flat tools straight and flat.

Straightening High-Speed Tools when Quenching.—The final straightness required in a tool must be considered when it is quenched. When several similar tools are to be hardened, a jig can be used to advantage for holding the tools while quenching. When long slender tools are quenched without holders, they frequently warp and must be straightened later. The best time for this straightening is during the first few minutes after the tools have been quenched, as the steel is then quite pliable and may be straightened without difficulty. The straightening must be done at once, as the tools become hard in a few minutes.

Anneal Before Rehardening.—Tools that are too soft after hardening must be annealed before rehardening. A quick anneal, such as previously described, is all that is required to put such a tool into the proper condition for rehardening. This treatment is absolutely essential. For milling cutters and forming tools of irregular section, a full anneal should be used.

Tempering or Drawing Tungsten High-Speed Steel.—The tempering or drawing temperature for high-speed steel tools usually varies from 900 to 1200 deg. F. This temperature is higher for turning and planing tools than for such tools as milling cutters, forming tools, etc. If the temperature is below 800 deg. F, the tool is likely to be too brittle. The general idea is to temper tools at the highest temperature likely to occur in service. Because this temperature ordinarily would not be known, the general practice is to temper at whatever temperature experience with that particular steel and tool has proved to be the best.

The furnace used for tempering usually is kept at a temperature of from 1000 to 1100 deg. F for ordinary high-speed steels and from 1200 to 1300 deg. F for steels of the cobalt type. These furnace temperatures apply to tools of the class used on lathes and planers. Such tools, in service, frequently heat to the point of visible redness. Milling cutters, forming tools, or any other tools for lighter duty may be tempered as low as 850 or 900 deg. F. When the tool has reached the temperature of the furnace, it should be held at this temperature for from one to several hours until it has been heated evenly throughout. It should then be allowed to cool gradually in the air and in a place that is dry and free from air drafts. In tempering, the tool should not be quenched, because quenching tends to produce strains that may result later in cracks.

Annealing Tungsten High-Speed Steel.—The following method of annealing high-speed steel has been used extensively. Use an iron box or pipe of sufficient size to allow at least $\frac{1}{2}$ inch of packing between the pieces of steel to be annealed and the sides of the box or pipe. It is not necessary that each piece of steel be kept separate from every other piece, but only that the steel be prevented from touching the sides of the annealing pipe or box. Pack carefully with powdered charcoal, fine dry lime, or mica (preferably charcoal), and cover with an airtight cap or lute with fire clay; heat slowly to 1600 to 1650 deg. F and keep at this heat from 2 to 8 hours, depending on the size of the pieces to be annealed. A piece measuring 2 by 1 by 8 inches requires about 3 hours. Cool as slowly as possible, and do not expose to the air until cold, because cooling in air is likely to cause partial hardening. A good method is to allow the box or pipe to remain in the furnace until cold.

Hardening Molybdenum High-Speed Steels.—Table 3 gives the compositions of several molybdenum high-speed steels that are widely used for general commercial tool applications. The general method of hardening molybdenum high-speed steels resembles that used for 18–4–1 tungsten high-speed steel except that the hardening temperatures are lower and more precautions must be taken to avoid decarburization, especially on tools made from Type I or Type II steels, when the surface is not ground after hardening. Either salt baths or atmosphere-controlled furnaces are recommended for hardening molybdenum high-speed steels.

Table 3. Compositions of Molybdenum High-Speed Steels

	Molybdenum–Tungsten		Molybdenum–Vanadium	Tungsten–Molybdenum
Element	Type Ia (Per Cent)	Type Ib[a] (Per Cent)	Type II (Per Cent)	Type III (Per Cent)
Carbon	0.70–0.85	0.76–0.82	0.70–0.90	0.75–0.90
Tungsten	1.25–2.00	1.60–2.30	…	5.00–6.00
Chromium	3.00–5.00	3.70–4.20	3.00–5.00	3.50–5.00
Vanadium	0.90–1.50	1.05–1.35	1.50–2.25	1.25–1.75
Molybdenum	8.00–9.50	8.00–9.00	7.50–9.50	3.50–5.50
Cobalt	See footnote	4.50–5.50	See footnote	See footnote

[a] Cobalt may be used in any of these steels in varying amounts up to 9 per cent, and the vanadium content may be as high as 2.25 percent. When cobalt is used in Type III steel, the vanadium content may be as high as 2.25 per cent. When cobalt is used in Type III steel, this steel becomes susceptible to decarburization. As an illustration of the use of cobalt, Type Ib steel is included. This is steel T10 in the U.S. Navy Specification 46S37, dated November 1, 1939.

The usual method is to preheat uniformly in a separate furnace to 1250 to 1550 deg. F then transfer to a high-heat furnace maintained within the hardening temperature range given in Table 4. Single-point cutting tools, in general, should be hardened at the upper end of the temperature range indicated by Table 4. Slight grain coarsening is not objectionable in such tools when they are properly supported in service and are not subjected to chattering; however, when these tools are used for intermittent cuts, it is better to use the middle of the temperature range. All other cutting tools, such as drills, countersinks, taps, milling cutters, reamers, broaches, and form tools, should be hardened in the middle of the range shown. For certain tools, such as slender taps, cold punches, and blanking and trimming dies, where greater toughness to resist shocks is required, the lower end of the hardening temperature range should be used.

Table 4. Heat Treatment of Molybdenum High-Speed Steels

Heat-Treating Operation	Molybdenum–Tungsten	Molybdenum–Vanadium	Tungsten–Molybdenum
	Types Ia and Ib[a] (Temp., in Deg. F)	Type II (Temp., in Deg. F)	Type III (Temp., in Deg. F)
Forging	1850–2000	1850–2000	1900–2050
Not below	1600	1600	1600
Annealing	1450–1550	1450–1550	1450–1550
Strain relief	1150–1350	1150–1350	1150–1350
Preheating	1250–1500	1250–1500	1250–1550
Hardening[b]	2150–2250[a]	2150–2250	2175–2275
Salt	2150–2225	2150–2225	2150–2250
Tempering	950–1100	950–1100	950–1100

[a] For similar working conditions, Type Ib steel requires a slightly higher hardening heat than Type Ia.

[b] The higher side of the hardening range should be used for large sections, and the lower side for small sections.

Molybdenum high-speed steels can be pack-hardened following the same practice as is used for tungsten high-speed steels, but keeping on the lower side of the hardening range (approximately 1850 degrees F). Special surface treatments such as nitriding by immersion in molten cyanide that are used for tungsten high-speed steels are also applicable to molybdenum high-speed tools.

When heated in an open fire or in furnaces without atmosphere control, these steels do not sweat like 18–4–1 steels; consequently, determining the proper time in the high-heat chamber is a matter of experience. This time approximates that used with 18–4–1 steels, although it may be slightly longer when the lower part of the hardening range is used. Much can be learned by preliminary hardening of test pieces and checking on the hardness fracture and structure. It is difficult to give the exact heating time, because it is affected by temperature, type of furnace, size and shape, and furnace atmosphere. Rate of heat transfer is most rapid in salt baths, and slowest in controlled-atmosphere furnaces with high carbon monoxide content.

Quenching and Tempering of Molybdenum High-Speed Tools.—Quenching may be done in oil, air, or molten bath. To reduce the possibility of breakage and undue distortion of intricately shaped tools, it is advisable to quench in a molten bath at approximately 1100 degrees F. The tool also may be quenched in oil and removed while still red, or at approximately 1100 degrees F. The tool is then cooled in air to room temperature, and tempered immediately to avoid cracking.

When straightening is necessary, it should be done after quenching and before cooling to room temperature prior to tempering.

To temper, the tools should be reheated slowly and uniformly to 950 to 1100 degrees F. For general work, 1050 degrees F is most common. The tools should be held at this temperature at least 1 hour. Two hours is a safer minimum, and 4 hours is maximum. The time and temperature depend on the hardness and toughness required. Where tools are subjected to more or less shock, multiple temperings are suggested.

Protective Coatings for Molybdenum Steels.—To protect the surface from oxidation during heat treatment, borax may be applied by sprinkling it lightly over the steel when the latter is heated in a furnace to a low temperature (1200 to 1400 deg. F). Small tools may be rolled in a box of borax before heating. Another method more suitable for finished tools is to apply the borax or boric acid in the form of a supersaturated water solution. The tools are then immersed in the solution at 180 to 212 deg. F, or the solution may be applied with a brush or spray. Pieces so treated are heated as usual, taking care in handling to ensure good adherence of the coating. Special protective coatings or paints, when properly applied, have been found extremely useful. These materials do not fuse or run at the temperatures used, and therefore do not affect the furnace hearth. When applying these coatings, it is necessary to have a surface free from scale or grease to ensure good adherence. Coatings may be sprayed or brushed on, and usually one thin coat is sufficient. Heavy coats tend to pit the surface of the tool and are difficult to remove. Tools covered with these coatings should be allowed to dry before they are charged into the preheat furnace. After hardening and tempering, the coating can be easily removed by light blasting with sand or steel shot. When tools are lightly ground, these coatings come off immediately. Protection may also be obtained by wrapping pieces in stainless steel foil.

Nitriding High-Speed Steel Tools.—Nitriding is applied to high-speed steel for the purpose of increasing tool life by producing a very hard skin or case, the thickness of which ordinarily is from 0.001 to 0.002 inch. Nitriding is done after the tool has been fully heat treated and finish-ground. (The process differs entirely from that which is applied to surface harden certain alloy steels by heating in an atmosphere of nitrogen or ammonia gas.) The temperature of the high-speed steel nitriding bath, which is a mixture of sodium and potassium cyanides, is equal to or slightly lower than the tempering temperature. For ordinary tools, this temperature usually varies from about 1025 to 1050 deg. F; but if the tools are exceptionally fragile, the range may be reduced to 950 or 1000 deg. F. Accurate temperature control is essential to prevent exceeding the final tempering temperature. The nitriding time may vary from 10 or 15 minutes to 30 minutes or longer, and should be determined by experiment. The shorter periods are applied to tools for iron or steel, or any shock-resisting tools, and the longer periods are for tools used in machining nonferrous metals and plastics. This nitriding process is applied to tools such as hobs, reamers, taps, box tools, form tools, and milling cutters. Nitriding may increase tool life 50 to 200 per cent, or more, but it should always be preceded by correct heat treatment.

Nitriding Bath Mixtures and Temperatures: A mixture of 60 per cent sodium cyanide and 40 per cent potassium cyanide is commonly used for nitriding. This mixture has a melting point of 925 deg. F, which is gradually reduced to 800 deg. F as the cyanate content of the bath increases. A more economical mixture of 70 per cent sodium cyanide and 30 per cent potassium cyanide may be used if the operating temperature of the bath is only 1050 deg. F. Nitriding bath temperatures should not exceed 1100 deg. F because higher temperatures accelerate the formation of carbonate at the expense of the essential cyanide. A third mixture suitable for nitriding consists of 55 per cent sodium cyanide, 25 per cent potassium chloride, and 20 per cent sodium carbonate. This mixture melts at 930 deg. F.

Equipment for Hardening High-Speed Steel.—Equipment for hardening high-speed steel consists of a hardening furnace capable of maintaining a temperature of 2350 to 2450 deg. F; a preheating furnace capable of maintaining a temperature of 1700 to 1800 deg. F, and of sufficient size to hold a number of pieces of the work; a tempering (drawing) furnace capable of maintaining a temperature of 1000 to 1200 deg. F as a general rule; and a water-cooled tank of quenching oil.

High-speed steels usually are heated for hardening either in some type of electric furnace or in a gas-fired furnace of the muffle type. The small furnaces used for high-speed steel seldom are oil-fired. It is desirable to use automatic temperature control and, where an oven type of furnace is employed, a controlled atmosphere is advisable because of the variations in cutting qualities caused by hardening under uncontrolled conditions. Some furnaces of both electric and fuel-fired types are equipped with a salt bath suitable for high-speed steel hardening temperatures. Salt baths have the advantage of providing protection against the atmosphere during the heating period. A type of salt developed for commercial use is water-soluble, so that all deposits from the hardening bath may be removed by immersion in water after quenching in oil or salt, or after air cooling. One type of electric furnace heats the salt bath internally by electrodes immersed in it. The same type of furnace is also applied to various heat-treating operations, such as cyanide hardening, liquid carburizing, tempering, and annealing.

An open-forge fire has many disadvantages, especially in hardening cutters or other tools that cannot be ground all over after hardening. The air blast decarburizes the steel and lack of temperature control makes it impossible to obtain uniform results. Electric and gas furnaces provide continuous uniform heat, and the temperature may be regulated accurately, especially when pyrometers are used. In shops equipped with only one furnace for carbon steel and one for high-speed steel, the tempering can be done in the furnace used for hardening carbon steel after the preheating is finished and the steel has been removed for hardening.

Heating High-Speed Steel for Forging.—Care should be taken not to heat high-speed steel for forging too abruptly. In winter, the steel may be extremely cold when brought into the forge shop. If the steel is put directly into the hot forge fire, it is likely to develop cracks that will show up later in the finished tool. The steel, therefore, should be warmed gradually before heating for forging.

Subzero Treatment of Steel

Subzero treatment consists of subjecting the steel, after hardening and either before or after tempering, to a subzero temperature (that usually ranges from −100 to −120 deg. F) and for a period of time varying with the size or volume of the tool, gage, or other part. Commercial equipment is available for obtaining these low temperatures.

The subzero treatment is employed by most gage manufacturers to stabilize precision gages and prevent subsequent changes in size or form. Subzero treatment is also applied to some high-speed steel cutting tools. The object here is to increase the durability or life of the tools; however, up to the present time, the results of tests by metallurgists and tool engineers often differ considerably and in some instances are contradictory. Methods of procedure also vary, especially with regard to the order and number of operations in the complete heat-treating and cooling cycle.

Changes Resulting From Subzero Treatment.—When steel is at the hardening temperature it contains a solid solution of carbon and iron known as *austenite*. When the steel is hardened by sudden cooling, most of the austenite, which is relatively soft, tough, and ductile even at room temperatures, is transformed into martensite, a hard and strong constituent. If all the austenite were changed to martensite upon reaching room temperature, this process would be an ideal hardening operation, but many steels retain some austenite. In general, the higher the carbon and alloy contents and the higher the hardening temperature, the greater the tendency to retain austenite. When steel is cooled to subzero temperatures, the stability of the retained austenite is reduced so that it is more readily transformed. To obtain more complete transformation, the subzero treatment may be repeated. The ultimate transformation of austenite to martensite may take place in carbon steel without the aid of subzero treatment, but this natural transformation might require 6 months or longer, whereas by refrigeration this change occurs in a few hours.

The thorough, uniform heating that is always recommended in heat-treating operations should be accompanied by thorough, uniform cooling when the subzero treatment is applied. To ensure uniform cooling, the subzero cooling period should be increased for the larger tools and it may range from 2 to 6 hours. The tool or other part is sometimes surrounded by one or more layers of heavy wrapping or asbestos paper to delay the cooling somewhat and ensure uniformity. After the cooling cycle is started, it should continue without interruption.

Subzero treatment may sometimes cause cracking. Normally, the austenite in steel provides a cushioning effect that may prevent cracking or breakage resulting from treatments involving temperature and dimensional changes; but if this cushioning effect is removed, particularly at very low temperatures as in subzero treatments, there may be danger of cracking, especially with tools having large or irregular sections and sharp corners offering relatively low resistance to stresses. This effect is one reason why subzero treatments may differ in regard to the cooling and tempering cycle.

Stabilizing Dimensions of Gages or Precision Parts by Subzero Cooling.—Transformation of austenite into martensite is accompanied by an increase in volume; consequently, the transformation of austenite, that may occur naturally over a period of months or years, tends to change the dimensions and form of steel parts, and such changes may be serious in the case of precision gages, close-fitting machine parts, etc. To prevent such changes, the subzero treatment has proved effective. Gage-blocks, for example, may be stabilized by hardening followed by repeated cycles of chilling and tempering, to transform a large percentage of the austenite into martensite.

Order of Operations for Stabilizing Precision Gages: If precision gages and sine-bars, are heat-treated in the ordinary manner and then are finished without some stabilizing treatment, dimensional changes and warpage are liable to occur. Sub-zero cooling provides a practical and fairly rapid method of obtaining the necessary stabilization by transforming the austenite into martensite. In stabilization treatments of this kind, tempering is the final operation. One series of treatments that has been recommended after hardening and rough-grinding is as follows:

A) Cool to −120 degrees F. (This cooling period may require from one to six hours, depending on the size and form of the gage.)

B) Place gage in boiling water for two hours (oil or salt bath may also be used).

Note: Steps (a) and (b) may be repeated from two to six times, depending on the size and form of the gage. These repeated cycles will eventually transform practically all the austenite into martensite. Two or three cooling and drawing operations usually are sufficient for such work as thread gages and gage-blocks.

C) Follow with regular tempering or drawing operation and finish gage by lapping.

Series of Stabilizing Treatments for Chromium Steel: The following series of treatments has proved successful in stabilizing precision gage-blocks made from SAE 52100 chromium steel.

A) Preheat to 600 degrees F and then heat to 1575 degrees F for a period of four minutes.

B) Quench in oil at 85 degrees F. (Uniform quenching is essential.)

C) Temper at 275 degrees F for one hour.

D) Cool in tempering furnace to room temperature.

E) Continue cooling in atmosphere of industrial refrigerator for six hours with temperature of atmosphere at −120 degrees F.

F) Allow gage-blocks to return to room temperature and again temper.

Note: The complete treatment consists of six subzero cooling periods, each followed by a tempering operation. The transformation to martensite is believed to be complete even after the fifth cooling period. The hardness is about 66 Rockwell C. Transformation is checked by magnetic tests based upon the magnetism of martensite and the nonmagnetic qualities of austenite.

Stabilizing Dimensions of Close-Fitting Machine Parts.—Subzero treatment will always cause an increase in size. Machine parts subjected to repeated and perhaps drastic changes in temperature, as in aircraft, may eventually cause trouble due to growth or warpage as the austenite gradually changes to martensite. In some instances, the sizes of close-fitting moving parts have increased sufficiently to cause seizure. Such treatment, for example, may be applied to precision bearings made from SAE 52100 or alloy carburizing steels for stabilizing or aging them. *Time* aging of 52100 steels after hardening has been found to cause changes as large as 0.0025 inch in medium size sections. A practical remedy is to apply the subzero treatment before the final grinding or other machining operation.

Subzero Treatment of Carburized Parts to Improve Physical Properties.—The subzero treatment has been applied to carburized machine parts. For example, the amount of retained austenite in carburized gears may be sufficient to reduce the life of the gears. In one component, the Rockwell hardness was increased from 55 C to 65 C without loss of impact resistance qualities; in fact, impact and fatigue resistance may be increased in some examples.

Application of Subzero Treatments to High-Speed Steel.—The subzero treatment has been applied to such tools as milling cutters, hobs, taps, broaches, and drills. It is applicable to different classes of high-speed steels, such as the 18–4–1 tungsten, 18–4–14 cobalt, and the molybdenum high-speed steels. This *cold* treatment is applied preferably in conjunction with the heat treatment, both being combined in a continuous cycle of operations. The general procedure is either to harden the steel, cool it to a subzero temperature, and then temper; or, especially if there is more than one tempering operation, the first one may *precede* subzero cooling. The cooling and tempering cycle may be repeated two or more times. The number and order of the operations, or the complete cycle, may be varied to suit the class of work and, to minimize the danger of cracking, particularly if the tool has large or irregular sections, sharp corners or edges, or a high cobalt content. A subzero treatment of some kind with a final tempering operation for stress relief, is intended to increase strength and toughness without much loss in hardness; consequently, if there is greater strength at a given hardness, tools subjected to subzero treatment can operate with a higher degree of hardness than those heat treated in the ordinary manner, or, if greater toughness is preferred, it can be obtained by tempering to the original degree of hardness.

Order of Cooling and Tempering Periods for High-speed Steel.—The order or cycle for the cooling and tempering periods has not been standardized. The methods that follow have been applied to high-speed steel tools. They are given as examples of procedure and are subject to possible changes due to subsequent developments. The usual ranges of preheating and hardening temperatures are given; but for a particular steel, the recommended temperatures should be obtained from the manufacturer.

1) *Double Subzero Treatment:* (For rugged simple tool forms without irregular sections, sharp corners or edges where cracks might develop during the subzero treatment).

a) Preheat between 1400 and 1600 degrees F (double preheating is preferable, the first preheating ranging from 700 to 1000 degrees F).

b) Heat to the hardening temperature. (*Note:* Tests indicate that the effect of subzero treatment on high-speed steel may be influenced decidedly by the hardening temperature. If this temperature is near the lower part of the range, the results are unsatisfactory. Effective temperatures for ordinary high-speed steels appear to range from 2300 to 2350 degrees F).

c) Quench in oil, salt, lead, or air, down to a workpiece temperature of 150–200 degrees F. (*Note:* One method is to quench in oil; a second method is to quench in oil to about 200–225 degrees F and then air cool; a third method is to quench in salt bath at 1050–1100 degrees F and then air cool.)

d) Cool in refrigerating unit to temperature of −100 to −120 degrees F *right after quenching*. (*Note:* Tests have shown that a delay of one hour has a detrimental effect, and in ten hours the efficiency of the subzero treatment is reduced 50 per cent. This is because the austenite becomes more and more stabilized when the subzero treatment is delayed; consequently, the austenite is more difficult to transform into martensite.) The refrigerating period usually varies from two to six hours, depending on the size of the tool. Remove the tool from the refrigerating unit and allow it to return to room temperature.

e) Temper to required hardness for a period of two and one-half to three hours. The tempering temperature usually varies from a minimum of 1000 to 1100 degrees F for ordinary high-speed steels. Tests indicate that if this first tempering is less than two and one-half hours at 1050 degrees F, there will not be sufficient precipitation of carbides at the tempering temperature to allow complete transformation of the retained austenite on cooling, whereas more than three hours causes some loss in room temperature hardness, hot hardness, strength, and toughness.

f) Repeat subzero treatment, step (d).

g) Repeat the tempering operation, step (e). (*Note:* The time for the second tempering operation is sometimes reduced to about one-half the time required for the first tempering.)

2) *Single Subzero Treatment:* This treatment is the same as procedure No. 1 except that a second subzero cooling is omitted; hence, the cycle consists of hardening, subzero cooling, and double tempering. Procedure No. 3, which follows, also has one subzero cooling period in the cycle, but this *follows* the first tempering operation.

3) *Tempering Followed by Subzero Treatment:*(This treatment is for tools having irregular sections, sharp corners, or edges where cracks might develop if the hardening operation were followed immediately by subzero cooling.)

a) Preheat and heat for hardening.
b) Preheat and heat for hardening.
c) Quench as described under Procedure No. I.
d) Temper to required hardness.
e) Cool to subzero temperature –100 to –120 degrees F and then allow the tool to return to room temperature.
f) Repeat tempering operation.

Testing the Hardness of Metals

Brinell Hardness Test.—The Brinell test for determining the hardness of metallic materials consists in applying a known load to the surface of the material to be tested through a hardened steel ball of known diameter. The diameter of the resulting permanent impression in the metal is measured and the Brinell Hardness Number (BHN) is then calculated from the following formula in which D = diameter of ball in millimeters, d = measured diameter at the rim of the impression in millimeters, and P = applied load in kilograms.

$$\text{BHN} = \frac{\text{load on indenting tool in kilograms}}{\text{surface area of indentation in sq. mm.}} = \frac{P}{\frac{\pi D}{2}\left(D - \sqrt{D^2 - d^2}\right)}$$

If the steel ball were not deformed under the applied load and if the impression were truly spherical, then the preceding formula would be a general one, and any combination of applied load and size of ball could be used. The impression, however, is not quite a spherical surface because there must always be some deformation of the steel ball and some recovery of form of the metal in the impression; hence, for a standard Brinell test, the size and characteristics of the ball and the magnitude of the applied load must be standardized. In the standard Brinell test, a ball 10 millimeters in diameter and a load of 3000, 1500, or 500 kilograms is used. It is desirable, although not mandatory, that the test load be of such magnitude that the diameter of the impression be in the range of 2.50 to 4.75 millimeters. The following test loads and approximate Brinell numbers for this range of impression diameters are: 3000 kg, 160 to 600 BHN; 1500 kg, 80 to 300 BHN; 500 kg, 26 to 100 BHN. In making a Brinell test, the load should be applied steadily and without a jerk for at least 15 seconds for iron and steel, and at least 30 seconds in testing other metals. A minimum period of 2 minutes, for example, has been recommended for magnesium and magnesium alloys. (For the softer metals, loads of 250, 125, or 100 kg are sometimes used.)

According to the American Society for Testing and Materials Standard E10-66, a steel ball may be used on material having a BHN not over 450, a Hultgren ball on material not over 500, or a carbide ball on material not over 630. The Brinell hardness test is not recommended for material having a BHN over 630.

Rockwell Hardness Test.—The Rockwell hardness tester is essentially a machine that measures hardness by determining the depth of penetration of a penetrator into the specimen under certain fixed conditions of test. The penetrator may be either a steel ball or a diamond spheroconical penetrator. The hardness number is related to the depth of indentation and the number is higher the harder the material. A minor load of 10 kg is first applied, causing an initial penetration; the dial is set at zero on the black-figure scale, and the major load is applied. This major load is customarily 60 or 100 kg when a steel ball is used as a penetrator, but other loads may be used when necessary. The ball penetrator is 1⁄16 inch in diameter normally, but other penetrators of larger diameter, such as 1⁄8 inch, may be employed for soft metals. When a diamond spheroconical penetrator is employed, the load usually is 150 kg. Experience decides the best combination of load and penetrator for use. After the major load is applied and removed, according to standard procedure, the reading is taken while the minor load is still applied.

The Rockwell Hardness Scales.—The various Rockwell scales and their applications are shown in the following table. The type of penetrator and load used with each are shown in Tables and , which give comparative hardness values for different hardness scales.

Scale	Testing Application
A	For tungsten carbide and other extremely hard materials. Also for thin, hard sheets.
B	For materials of medium hardness such as low- and medium-carbon steels in the annealed condition.
C	For materials harder than Rockwell B-100.
D	Where a somewhat lighter load is desired than on the C scale, as on case-hardened pieces.
E	For very soft materials such as bearing metals.
F	Same as the E scale but using a 1⁄16-inch ball.
G	For metals harder than tested on the B scale.
H & K	For softer metals.
15–N; 30–N; 45–N	Where a shallow impression or a small area is desired. For hardened steel and hard alloys.
15–T; 30–T; 45-T	Where a shallow impression or a small area is desired for materials softer than hardened steel.

Shore's Scleroscope.—The scleroscope is an instrument that measures the hardness of the work in terms of elasticity. A diamond-tipped hammer is allowed to drop from a known height on the metal to be tested. As this hammer strikes the metal, it rebounds, and the harder the metal, the greater the rebound. The extreme height of the rebound is recorded, and an average of a number of readings taken on a single piece will give a good indication of the hardness of the work. The surface smoothness of the work affects the reading of the instrument. The readings are also affected by the contour and mass of the work and the depth of the case, in carburized work, the soft core of light-depth carburizing, pack-hardening, or cyanide hardening, absorbing the force of the hammer fall and decreasing the rebound. The hammer weighs about 40 grains, the height of the rebound of hardened steel is in the neighborhood of 100 on the scale, or about 6¼ inches, and the total fall is about 10 inches or 255 millimeters.

Vickers Hardness Test.—The Vickers test is similar in principle to the Brinell test. The standard Vickers penetrator is a square-based diamond pyramid having an included point angle of 136 degrees. The numerical value of the hardness number equals the applied load in kilograms divided by the area of the pyramidal impression: A smooth, firmly supported, flat surface is required. The load, which usually is applied for 30 seconds, may be 5, 10, 20, 30, 50, or 120 kilograms. The 50-kilogram load is the most usual. The hardness number is based upon the diagonal length of the square impression. The Vickers test is considered to be very accurate, and may be applied to thin sheets as well as to larger sections with proper load regulation.

Knoop Hardness Numbers.—The Knoop hardness test is applicable to extremely thin metal, plated surfaces, exceptionally hard and brittle materials, very shallow carburized or nitrided surfaces, or whenever the applied load must be kept below 3600 grams. The Knoop indentor is a diamond ground to an elongated pyramidal form and it produces an indentation having long and short diagonals with a ratio of approximately 7 to 1. The longitudinal angle of the indentor is 172 degrees, 30 minutes, and the transverse angle 130 degrees. The Tukon Tester in which the Knoop indentor is used is fully automatic under electronic control. The Knoop hardness number equals the load in kilograms divided by the projected area of indentation in square millimeters. The indentation number corresponding to the long diagonal and for a given load may be determined from a table computed for a theoretically perfect indentor. The load, which may be varied from 25 to 3600 grams, is applied for a definite period and always normal to the surface tested. Lapped plane surfaces free from scratches are required.

Monotron Hardness Indicator.—With this instrument, a diamond-ball impressor point $\frac{3}{4}$ mm in diameter is forced into the material to a depth of $\frac{9}{5000}$ inch and the pressure required to produce this constant impression indicates the hardness. One of two dials shows the pressure in kilograms and pounds, and the other shows the depth of the impression in millimeters and inches. Readings in Brinell numbers may be obtained by means of a scale designated as *M*–1.

Keep's Test.—With this apparatus, a standard steel drill is caused to make a definite number of revolutions while it is pressed with standard force against the specimen to be tested. The hardness is automatically recorded on a diagram on which a dead soft material gives a horizontal line, and a material as hard as the drill itself gives a vertical line, intermediate hardness being represented by the corresponding angle between 0 and 90 degrees.

Comparison of Hardness Scales.—Tables and show comparisons of various hardness scales. All such tables are based on the assumption that the metal tested is homogeneous to a depth several times that of the indentation. To the extent that the metal being tested is not homogeneous, errors are introduced because different loads and different shapes of penetrators meet the resistance of metal of varying hardness, depending on the depth of indentation. Another source of error is introduced in comparing the hardness of different materials as measured on different hardness scales. This error arises from the fact that in any hardness test, metal that is severely cold-worked actually supports the penetrator, and different metals, different alloys, and different analyses of the same type of alloy have different cold-working properties. In spite of the possible inaccuracies introduced by such factors, it is of considerable value to be able to compare hardness values in a general way.

The data shown in Table are for hardness measurements of unhardened steel, steel of soft temper, grey and malleable cast iron, and most nonferrous metals. Again these hardness comparisons are not as accurate for annealed metals of high Rockwell B hardness such as austenitic stainless steel, nickel and high nickel alloys, and cold-worked metals of low B-scale hardness such as aluminum and the softer alloys.

The data shown in Table are based on extensive tests on carbon and alloy steels mostly in the heat-treated condition, but have been found to be reliable on constructional alloy steels and tool steels in the as-forged, annealed, normalized, quenched, and tempered conditions, providing they are homogeneous. These hardness comparisons are not as accurate for special alloys such as high manganese steel, 18–8 stainless steel and other austenitic steels, nickel-base alloys, constructional alloy steels, and nickel-base alloys in the cold-worked condition.

Table 1. Comparative Hardness Scales for Steel

Rockwell C-Scale Hardness Number	Diamond Pyramid Hardness Number Vickers	Brinell Hardness Number 10-mm Ball, 3000-kgf Load			Rockwell Hardness Number		Rockwell Superficial Hardness Number Superficial Diam. Penetrator			Shore Scleroscope Hardness Number
		Standard Ball	Hultgren Ball	Tungsten Carbide Ball	A-Scale 60-kgf Load Diam. Penetrator	D-Scale 100-kgf Load Diam. Penetrator	15-N Scale 15-kgf Load	30-N Scale 30-kgf Load	45-N Scale 45-kgf Load	
68	940	…	…	…	85.6	76.9	93.2	84.4	75.4	97
67	900	…	…	…	85.0	76.1	92.9	83.6	74.2	95
66	865	…	…	…	84.5	75.4	92.5	82.8	73.3	92
65	832	…	…	739	83.9	74.5	92.2	81.9	72.0	91
64	800	…	…	722	83.4	73.8	91.8	81.1	71.0	88
63	772	…	…	705	82.8	73.0	91.4	80.1	69.9	87
62	746	…	…	688	82.3	72.2	91.1	79.3	68.8	85
61	720	…	…	670	81.8	71.5	90.7	78.4	67.7	83
60	697	…	613	654	81.2	70.7	90.2	77.5	66.6	81
59	674	…	599	634	80.7	69.9	89.8	76.6	65.5	80
58	653	…	587	615	80.1	69.2	89.3	75.7	64.3	78
57	633	…	575	595	79.6	68.5	88.9	74.8	63.2	76
56	613	…	561	577	79.0	67.7	88.3	73.9	62.0	75
55	595	…	546	560	78.5	66.9	87.9	73.0	60.9	74
54	577	…	534	543	78.0	66.1	87.4	72.0	59.8	72
53	560	…	519	525	77.4	65.4	86.9	71.2	58.6	71
52	544	500	508	512	76.8	64.6	86.4	70.2	57.4	69
51	528	487	494	496	76.3	63.8	85.9	69.4	56.1	68
50	513	475	481	481	75.9	63.1	85.5	68.5	55.0	67
49	498	464	469	469	75.2	62.1	85.0	67.6	53.8	66
48	484	451	455	455	74.7	61.4	84.5	66.7	52.5	64
47	471	442	443	443	74.1	60.8	83.9	65.8	51.4	63
46	458	432	432	432	73.6	60.0	83.5	64.8	50.3	62
45	446	421	421	421	73.1	59.2	83.0	64.0	49.0	60
44	434	409	409	409	72.5	58.5	82.5	63.1	47.8	58
43	423	400	400	400	72.0	57.7	82.0	62.2	46.7	57
42	412	390	390	390	71.5	56.9	81.5	61.3	45.5	56
41	402	381	381	381	70.9	56.2	80.9	60.4	44.3	55
40	392	371	371	371	70.4	55.4	80.4	59.5	43.1	54
39	382	362	362	362	69.9	54.6	79.9	58.6	41.9	52
38	372	353	353	353	69.4	53.8	79.4	57.7	40.8	51
37	363	344	344	344	68.9	53.1	78.8	56.8	39.6	50
36	354	336	336	336	68.4	52.3	78.3	55.9	38.4	49
35	345	327	327	327	67.9	51.5	77.7	55.0	37.2	48
34	336	319	319	319	67.4	50.8	77.2	54.2	36.1	47
33	327	311	311	311	66.8	50.0	76.6	53.3	34.9	46
32	318	301	301	301	66.3	49.2	76.1	52.1	33.7	44
31	310	294	294	294	65.8	48.4	75.6	51.3	32.5	43
30	302	286	286	286	65.3	47.7	75.0	50.4	31.3	42
29	294	279	279	279	64.7	47.0	74.5	49.5	30.1	41
28	286	271	271	271	64.3	46.1	73.9	48.6	28.9	41
27	279	264	264	264	63.8	45.2	73.3	47.7	27.8	40
26	272	258	258	258	63.3	44.6	72.8	46.8	26.7	38
25	266	253	253	253	62.8	43.8	72.2	45.9	25.5	38
24	260	247	247	247	62.4	43.1	71.6	45.0	24.3	37
23	254	243	243	243	62.0	42.1	71.0	44.0	23.1	36
22	248	237	237	237	61.5	41.6	70.5	43.2	22.0	35

Table 1. *(Continued)* **Comparative Hardness Scales for Steel**

Rockwell C-Scale Hardness Number	Diamond Pyramid Hardness Number Vickers	Brinell Hardness Number 10-mm Ball, 3000-kgf Load			Rockwell Hardness Number		Rockwell Superficial Hardness Number Superficial Diam. Penetrator			Shore Scleroscope Hardness Number
		Standard Ball	Hultgren Ball	Tungsten Carbide Ball	A-Scale 60-kgf Load Diam. Penetrator	D-Scale 100-kgf Load Diam. Penetrator	15-N Scale 15-kgf Load	30-N Scale 30-kgf Load	45-N Scale 45-kgf Load	
21	**243**	**231**	**231**	**231**	**61.0**	**40.9**	**69.9**	**42.3**	**20.7**	35
20	**238**	**226**	**226**	**226**	**60.5**	**40.1**	**69.4**	**41.5**	**19.6**	34
(18)	230	219	219	219	…	…	…	…	…	33
(16)	222	212	212	212	…	…	…	…	…	32
(14)	213	203	203	203	…	…	…	…	…	31
(12)	204	194	194	194	…	…	…	…	…	29
(10)	196	187	187	187	…	…	…	…	…	28
(8)	188	179	179	179	…	…	…	…	…	27
(6)	180	171	171	171	…	…	…	…	…	26
(4)	173	165	165	165	…	…	…	…	…	25
(2)	166	158	158	158	…	…	…	…	…	24
(0)	160	152	152	152	…	…	…	…	…	24

Note: The values in this table shown in **boldface** type correspond to those shown in American Society for Testing and Materials Specification E140-67.

Values in ( ) are beyond the normal range and are given for information only.

Turner's Sclerometer.—In making this test a weighted diamond point is drawn, once forward and once backward, over the smooth surface of the material to be tested. The hardness number is the weight in grams required to produce a standard scratch.

Mohs's Hardness Scale.—Hardness, in general, is determined by what is known as Mohs's scale, a standard for hardness that is applied mainly to nonmetallic elements and minerals. In this hardness scale, there are ten degrees or steps, each designated by a mineral, the difference in hardness of the different steps being determined by the fact that any member in the series will scratch any of the preceding members.

This scale is as follows: 1) talc; 2) gypsum; 3) calcite; 4) fluor spar; 5) apatite;

6) orthoclase; 7) quartz; 8) topaz; 9) sapphire or corundum; and 10) diamond.

These minerals, arbitrarily selected as standards, are successively harder, from talc, the softest of all minerals, to diamond, the hardest. This scale, which is now universally used for nonmetallic minerals, is not applied to metals.

Relation Between Hardness and Tensile Strength.—The approximate relationship between the hardness and tensile strength is shown by the following formula:

Tensile strength $= Bhn \times 515$ (for Brinell numbers up to 175).

Tensile strength $= Bhn \times 490$ (for Brinell numbers larger than 175).

The above formulas give the tensile strength in pounds per square inch for steels. These approximate relationships between hardness and tensile strength do not apply to nonferrous metals with the possible exception of certain aluminum alloys.

Durometer Tests.—The durometer is a portable hardness tester for measuring hardness of rubber, plastics, and some soft metals. The instrument is designed to apply pressure to the specimen and the hardness is read from a scale while the pressure is maintained. Various scales can be used by changing the indentor and the load applied.

Table 2. Comparative Hardness Scales for Unhardened Steel, Soft-Temper Steel, Grey and Malleable Cast Iron, and Nonferrous Alloys

Rockwell Hardness Number			Rockwell Superficial Hardness Number			Rockwell Hardness Number			Brinell Hardness Number	
Rockwell B scale 1/16″ Ball Penetrator 100-kg Load	Rockwell F scale 1/16″ Ball Penetrator 60-kg Load	Rockwell G scale 1/16″ Ball Penetrator 150-kg Load	Rockwell Superficial 15-T scale 1/16″ Ball Penetrator	Rockwell Superficial 30-T scale 1/16″ Ball Penetrator	Rockwell Superficial 45-T scale 1/16″ Ball Penetrator	Rockwell E scale 1/8″ Ball Penetrator 100-kg Load	Rockwell K scale 1/8″ Ball Penetrator 150-kg Load	Rockwell A scale “Brale” Penetrator 60-kg Load	Brinell Scale 10-mm Standard Ball 500-kg Load	Brinell Scale 10-mm Standard Ball 3000-kg Load
100	…	82.5	93.0	82.0	72.0	…	…	61.5	201	240
99	…	81.0	92.5	81.5	71.0	…	…	61.0	195	234
98	…	79.0	…	81.0	70.0	…	…	60.0	189	228
97	…	77.5	92.0	80.5	69.0	…	…	59.5	184	222
96	…	76.0	…	80.0	68.0	…	…	59.0	179	216
95	…	74.0	91.5	79.0	67.0	…	…	58.0	175	210
94	…	72.5	…	78.5	66.0	…	…	57.5	171	205
93	…	71.0	91.0	78.0	65.5	…	…	57.0	167	200
92	…	69.0	90.5	77.5	64.5	…	100	56.5	163	195
91	…	67.5	…	77.0	63.5	…	99.5	56.0	160	190
90	…	66.0	90.0	76.0	62.5	…	98.5	55.5	157	185
89	…	64.0	89.5	75.5	61.5	…	98.0	55.0	154	180
88	…	62.5	…	75.0	60.5	…	97.0	54.0	151	176
87	…	61.0	89.0	74.5	59.5	…	96.5	53.5	148	172
86	…	59.0	88.5	74.0	58.5	…	95.5	53.0	145	169
85	…	57.5	…	73.5	58.0	…	94.5	52.5	142	165
84	…	56.0	88.0	73.0	57.0	…	94.0	52.0	140	162
83	…	54.0	87.5	72.0	56.0	…	93.0	51.0	137	159
82	…	52.5	…	71.5	55.0	…	92.0	50.5	135	156
81	…	51.0	87.0	71.0	54.0	…	91.0	50.0	133	153
80	…	49.0	86.5	70.0	53.0	…	90.5	49.5	130	150
79	…	47.5	…	69.5	52.0	…	89.5	49.0	128	147
78	…	46.0	86.0	69.0	51.0	…	88.5	48.5	126	144
77	…	44.0	85.5	68.0	50.0	…	88.0	48.0	124	141
76	…	42.5	…	67.5	49.0	…	87.0	47.0	122	139
75	99.5	41.0	85.0	67.0	48.5	…	86.0	46.5	120	137
74	99.0	39.0	…	66.0	47.5	…	85.0	46.0	118	135
73	98.5	37.5	84.5	65.5	46.5	…	84.5	45.5	116	132
72	98.0	36.0	84.0	65.0	45.5	…	83.5	45.0	114	130
71	97.5	34.5	…	64.0	44.5	100	82.5	44.5	112	127
70	97.0	32.5	83.5	63.5	43.5	99.5	81.5	44.0	110	125
69	96.0	31.0	83.0	62.5	42.5	99.0	81.0	43.5	109	123
68	95.5	29.5	…	62.0	41.5	98.0	80.0	43.0	107	121
67	95.0	28.0	82.5	61.5	40.5	97.5	79.0	42.5	106	119
66	94.5	26.5	82.0	60.5	39.5	97.0	78.0	42.0	104	117
65	94.0	25.0	…	60.0	38.5	96.0	77.5	…	102	116
64	93.5	23.5	81.5	59.5	37.5	95.5	76.5	41.5	101	114
63	93.0	22.0	81.0	58.5	36.5	95.0	75.5	41.0	99	112
62	92.0	20.5	…	58.0	35.5	94.5	74.5	40.5	98	110
61	91.5	19.0	80.5	57.0	34.5	93.5	74.0	40.0	96	108
60	91.0	17.5	…	56.5	33.5	93.0	73.0	39.5	95	107
59	90.5	16.0	80.0	56.0	32.0	92.5	72.0	39.0	94	106
58	90.0	14.5	79.5	55.0	31.0	92.0	…	71.0	38.5	92
57	89.5	13.0	…	54.5	30.0	91.0	…	70.5	38.0	91
56	89.0	11.5	79.0	54.0	29.0	90.5	…	69.5	…	90
55	88.0	10.0	78.5	53.0	28.0	90.0	…	68.5	37.5	89
54	87.5	8.5	…	52.5	27.0	89.5	…	68.0	37.0	87
53	87.0	7.0	78.0	51.5	26.0	89.0	…	67.0	36.5	86
52	86.5	5.5	77.5	51.0	25.0	88.0	…	66.0	36.0	85
51	86.0	4.0	…	50.5	24.0	87.5	…	65.0	35.5	84
50	85.5	2.5	77.0	49.5	23.0	87.0	…	64.5	35.0	83
50	85.5	2.5	77.0	49.5	23.0	87.0	…	64.5	35.0	83
49	85.0	1.0	76.5	49.0	22.0	86.5	…	63.5	…	82

Table 2. *(Continued)* **Comparative Hardness Scales for Unhardened Steel, Soft-Temper Steel, Grey and Malleable Cast Iron, and Nonferrous Alloys**

Rockwell Hardness Number			Rockwell Superficial Hardness Number			Rockwell Hardness Number			Brinell Hardness Number	
Rockwell B scale 1/16″ Ball Penetrator 100-kg Load	Rockwell F scale 1/16″ Ball Penetrator 60-kg Load	Rockwell G scale 1/16″ Ball Penetrator 150-kg Load	Rockwell Superficial 15-T scale 1/16″ Ball Penetrator	Rockwell Superficial 30-T scale 1/16″ Ball Penetrator	Rockwell Superficial 45-T scale 1/16″ Ball Penetrator	Rockwell E scale 1/8″ Ball Penetrator 100-kg Load	Rockwell K scale 1/8″ Ball Penetrator 150-kg Load	Rockwell A scale "Brale" Penetrator 60-kg Load	Brinell Scale 10-mm Standard Ball 500-kg Load	Brinell Scale 10-mm Standard Ball 3000-kg Load
48	84.5	…	…	48.5	20.5	85.5	…	62.5	34.5	81
47	84.0	…	76.0	47.5	19.5	85.0	…	61.5	34.0	80
46	83.0	…	75.5	47.0	18.5	84.5	…	61.0	33.5	…
45	82.5	…	…	46.0	17.5	84.0	…	60.0	33.0	79
44	82.0	…	75.0	45.5	16.5	83.5	…	59.0	32.5	78
43	81.5	…	74.5	45.0	15.5	82.5	…	58.0	32.0	77
42	81.0	…	…	44.0	14.5	82.0	…	57.5	31.5	76
41	80.5	…	74.0	43.5	13.5	81.5	…	56.5	31.0	75
40	79.5	…	73.5	43.0	12.5	81.0	…	55.5	…	…
39	79.0	…	…	42.0	11.0	80.0	…	54.5	30.5	74
38	78.5	…	73.0	41.5	10.0	79.5	…	54.0	30.0	73
37	78.0	…	72.5	40.5	9.0	79.0	…	53.0	29.5	72
36	77.5	…	…	40.0	8.0	78.5	100	52.0	29.0	…
35	77.0	…	72.0	39.5	7.0	78.0	99.5	51.5	28.5	71
34	76.5	…	71.5	38.5	6.0	77.0	99.0	50.5	28.0	70
33	75.5	…	…	38.0	5.0	76.5	…	49.5	…	69
32	75.0	…	71.0	37.5	4.0	76.0	98.5	48.5	27.5	…
31	74.5	…	…	36.5	3.0	75.5	98.0	48.0	27.0	68
30	74.0	…	70.5	36.0	2.0	75.0	…	47.0	26.5	67
29	73.5	…	70.0	35.5	1.0	74.0	97.5	46.0	26.0	…
28	73.0	…	…	34.5	…	73.5	97.0	45.0	25.5	66
27	72.5	…	69.5	34.0	…	73.0	96.5	44.5	25.0	…
26	72.0	…	69.0	33.0	…	72.5	…	43.5	24.5	65
25	71.0	…	…	32.5	…	72.0	96.0	42.5	…	64
24	70.5	…	68.5	32.0	…	71.0	95.5	41.5	24.0	…
23	70.0	…	68.0	31.0	…	70.5	…	41.0	23.5	63
22	69.5	…	…	30.5	…	70.0	95.0	40.0	23.0	…
21	69.0	…	67.5	29.5	…	69.5	94.5	39.0	22.5	62
20	68.5	…	…	29.0	…	68.5	…	38.0	22.0	…
19	68.0	…	67.0	28.5	…	68.0	94.0	37.5	21.5	61
18	67.0	…	66.5	27.5	…	67.5	93.5	36.5	…	…
17	66.5	…	…	27.0	…	67.0	93.0	35.5	21.0	60
16	66.0	…	66.0	26.0	…	66.5	…	35.0	20.5	…
15	65.5	…	65.5	25.5	…	65.5	92.5	34.0	20.0	59
14	65.0	…	…	25.0	…	65.0	92.0	33.0	…	…
13	64.5	…	65.0	24.0	…	64.5	…	32.0	…	58
12	64.0	…	64.5	23.5	…	64.0	91.5	31.5	…	…
11	63.5	…	…	23.0	…	63.5	91.0	30.5	…	…
10	63.0	…	64.0	22.0	…	62.5	90.5	29.5	…	57
9	62.0	…	…	21.5	…	62.0	…	29.0	…	…
8	61.5	…	63.5	20.5	…	61.5	90.0	28.0	…	…
7	61.0	…	63.0	20.0	…	61.0	89.5	27.0	…	56
6	60.5	…	…	19.5	…	60.5	…	26.0	…	…
5	60.0	…	62.5	18.5	…	60.0	89.0	25.5	…	55
4	59.5	…	62.0	18.0	…	59.0	88.5	24.5	…	…
3	59.0	…	…	17.0	…	58.5	88.0	23.5	…	…
2	58.0	…	61.5	16.5	…	58.0	…	23.0	…	54
1	57.5	…	61.0	16.0	…	57.5	87.5	22.0	…	…
0	57.0	…	…	15.0	…	57.0	87.0	21.0	…	53

Not applicable to annealed metals of high B-scale hardness such as austenitic stainless steels, nickel and high-nickel alloys nor to cold-worked metals of low B-scale hardness such as aluminum and the softer alloys.

(Compiled by Wilson Mechanical Instrument Co.)

Creep.—Continuing changes in dimensions of a stressed material over time is called creep, and it varies with different materials and periods under stress, also with temperature. Creep tests may take some time as it is necessary to apply a constant tensile load to a specimen under a selected temperature. Measurements are taken to record the resulting elongation at time periods sufficiently long for a relationship to be established. The data are then plotted as elongation against time. The load is applied to the specimen only after it has reached the testing temperature, and causes an initial elastic elongation that includes some plastic deformation if the load is above the proportional limit for the material.

Some combinations of stress and temperature may cause failure of the specimen. Others show initial high rates of deformation, followed by decreasing, then constant, rates over long periods. Generally testing times to arrive at the constant rate of deformation are over 1000 hours.

Creep Rupture.—Tests for creep rupture are similar to creep tests but are prolonged until the specimen fails. Further data to be obtained from these tests include time to rupture, amount of elongation, and reduction of area. Stress-rupture tests are performed without measuring the elongation, so that no strain data are recorded, time to failure, elongation and reduction of area being sufficient. Sometimes, a V-notch is cut in the specimen to allow measurement of notch sensitivity under the testing conditions.

Stress Analysis.—Stresses, deflections, strains, and loads may be determined by application of strain gages or lacquers to the surface of a part, then applying loads simulating those to be encountered in service. Strain gages are commercially available in a variety of configurations and are usually cemented to the part surface. The strain gages are then calibrated by application of a known moment, load, torque, or pressure. The electrical characteristics of the strain gages change in proportion to the amount of strain, and the magnitude of changes in these characteristics under loads to be applied in service indicate changes caused by stress in the shape of the components being tested.

Lacquers are compounded especially for stress analysis and are applied to the entire part surface. When the part is loaded, and the lacquer is viewed under light of specific wavelength, stresses are indicated by color shading in the lacquer. The presence and intensity of the strains can then be identified and measured on the part(s) or on photographs of the setup. From such images, it is possible to determine the need for thicker walls, strengthening ribs and other modifications to component design that will enable the part to withstand stresses in service.

Most of these tests have been standardized by the American Society for Testing and Materials (ASTM), and are published in their *Book of Standards* in separate sections for metals, plastics, rubber, and wood. Many of the test methods are also adopted by the American National Standards Institute (ANSI).

Identifying Metals.—When it is necessary to sort materials, several rough methods may be used without elaborate chemical analysis. The most obvious of these is by using a magnet to pick out those materials that contain magnetic elements. To differentiate various levels of carbon and other elements in a steel bar, hold the bar in contact with a grinding wheel and observe the sparks. With high levels of carbon, for instance, sparks are produced that appear to split into several bright tracers. Patterns produced by several other elements, including small amounts of aluminum and titanium, for instance, can be identified with the aid of Data Sheet 13, issued by the American Society for Metals (ASM), Metals Park, OH.

NONFERROUS ALLOYS

Copper and Copper Alloys

Pure copper is a reddish, highly malleable metal, and was one of the first to be found and utilized. Copper and its alloys are widely used because of their excellent electrical and thermal conductivities, outstanding resistance to corrosion, ease of fabrication, and broad ranges of obtainable strengths and special properties. Almost 400 commercial copper and copper-alloy compositions are available from mills as wrought products (rod, plate, sheet, strip, tube, pipe, extrusions, foil, forgings, and wire) and from foundries as castings.

Copper alloys are grouped into several general categories according to composition:

coppers and high-copper alloys; brasses; bronzes; copper nickels; copper–nickel–zinc alloys (nickel silvers); leaded coppers; and special alloys.

The designation system originally developed by the U.S. copper and brass industry for identifying copper alloys used a three-digit number preceded by the letters CA. These designations have now been made part of the Unified Numbering System (UNS) simply by expanding the numbers to five digits preceded by the letter C. Because the old numbers are embedded in the new UNS numbers, no confusion results. UNS C10000 to C79999 are assigned to wrought compositions, and UNS C80000 to C99999 are assigned to castings. The designation system is not a specification, but a method for identifying the composition of mill and foundry products. The precise technical and quality assurance requirements to be satisfied are defined in relevant standard specifications issued by the federal government, the military, and the ASTM.

Classification of Copper and Copper Alloys

Family	Principal Alloying Element	UNS Numbers[a]
Coppers, high-copper alloys		C1xxxx
Brasses	Zn	C2xxxx, C3xxxx, C4xxxx, C66400 to C69800
Phosphor bronzes	Sn	C5xxxx
Aluminum bronzes	Al	C60600 to C64200
Silicon bronzes	Si	C64700 to C66100
Copper nickels, nickel silvers	Ni	C7xxxx

[a] Wrought alloys.

Cast Copper Alloys.—Generally, casting permits greater latitude in the use of alloying elements than in the fabrication of wrought products, which requires either hot or cold working. The cast compositions of coppers and high-copper alloys have a designated minimum copper content and may include other elements to impart special properties. The cast brasses comprise copper–zinc–tin alloys (red, semired, and yellow brasses); manganese bronze alloys (high-strength yellow brasses); leaded manganese bronze alloys (leaded high-strength yellow brasses); and copper–zinc–silicon alloys (silicon brasses and bronzes).

The cast bronze alloys have four main families: copper–tin alloys (tin bronzes); copper–tin–lead alloys (leaded and high leaded tin bronzes); copper–tin–nickel alloys (nickel–tin bronzes); and copper–aluminum alloys (aluminum bronzes).

The cast copper–nickel alloys contain nickel as the principal alloying element. The leaded coppers are cast alloys containing 20 per cent or more lead.

Table lists the properties and applications of common cast copper alloys.

Table 1. Properties and Applications of Cast Coppers and Copper Alloys

		Typical Mechanical Properties, as Cast or Heat Treated[a]				
UNS Designation	Nominal Composition (%)	Tensile Strength (ksi)	Yield Strength (ksi)	Elongation in 2 in. (%)	Machinability Rating[b]	Typical Applications
Copper Alloys						
C80100	99.95 Cu + Ag min, 0.05 others max	25	9	40	10	Electrical and thermal conductors; corrosion and oxidation-resisant applications.
C80300	99.95 Cu + Ag min, 0.034 Ag min, 0.05 others max	25	9	40	10	Electrical and thermal conductors; corrosion and oxidation-resistant applications.
C80500	99.75 Cu + Ag min, 0.034 Ag min, 0.02 B max, 0.23 others max	25	9	40	10	Electrical and thermal conductors; corrosion and oxidation-resistant applications.
C80700	99.75 Cu + Ag min, 0.02 B max, 0.23 others max	25	9	40	10	Electrical and thermal conductors; corrosion and oxidation-resistant applications.
C80900	99.70 Cu + Ag min, 0.034 Ag min, 0.30 others max	25	9	40	10	Electrical and thermal conductors; corrosion and oxidation-resistant applications.
C81100	99.70 Cu + Ag min, 0.30 others max	25	9	40	10	Electrical and thermal conductors; corrosion and oxidation resstant applications.
High-Copper Alloys						
C81300	98.5 Cu min, 0.06 Be, 0.80 Co, 0.40 others max	(53)	(36)	(11)	20	Higher hardness electrical and thermal conductors.
C81400	98.5 Cu min, 0.06 Be, 0.80 Cr, 0.40 others max	(53)	(36)	(11)	20	Higher hardness electrical and thermal conductors.
C81500	98.0 Cu min, 1.0 Cr, 0.50 others max	(51)	(40)	(17)	20	Electrical and/or thermal conductors used as structural members where strength and hardness greater than that of C80100–81100 are required.

Table 1. *(Continued)* **Properties and Applications of Cast Coppers and Copper Alloys**

UNS Designation	Nominal Composition (%)	Typical Mechanical Properties, as Cast or Heat Treated[a]				Typical Applications
		Tensile Strength (ksi)	Yield Strength (ksi)	Elongation in 2 in. (%)	Machinability Rating[b]	
C81700	94.2 Cu min, 1.0 Ag, 0.4 Be, 0.9 Co, 0.9 Ni	(92)	(68)	(8)	30	Electrical and/or thermal conductors used as structural members where strength and hardness greater than that of C80100–81100 are required. Also used in place of C81500 where electrical and/or thermal conductivities can be sacrificed for hardness and strength.
C81800	95.6 Cu min,1.0 Ag, 0.4 Be,1.6 Co	50 (102)	25 (75)	20 (8)	20	Resistance-welding electrodes, dies.
C82000	96.8 Cu, 0.6 Be, 2.6 Co	50 (100)	20 (75)	20 (8)	20	Current-carrying parts, contact and switch blades, bushings and bearings, and soldering iron and resistance-welding tips.
C82100	97.7 Cu, 0.5 Be, 0.9 Co, 0.9 Ni	(92)	(68)	(8)	30	Electrical and/or thermal conductors used as structural members where strength and hardness greater than that of C80100–81100 are required. Also used in place of C81500 where electrical and/or thermal conductivities can be sacrificed for hardness and strength.
C82200	96.5 Cu min, 0.6 Be, 1.5 Ni	57 (95)	30 (75)	20 (8)	20	Clutch rings, brake drums, seam-welder electrodes, projection welding dies, spot-welding tips, beam-welder shapes, bushings, water-cooled holders.
C82400	96.4 Cu min, 1.70 Be, 0.25 Co	72 (150)	37 (140)	20 (1)	20	Safety tools, molds for plastic parts, cams, bushings, bearings, valves, pump parts, gears.
C82500	97.2 Cu, 2.0 Be, 0.5 Co, 0.25 Si	80 (160)	45	20 (1)	20	Safety tools, molds for plastic parts, cams, bushings, bearings, valves, pump parts.
C82600	95.2 Cu min,2.3 Be, 0.5 Co, 0.25 Si	82 (165)	47 (155)	20 (1)	20	Bearings and molds for plastic parts.
C82700	96.3 Cu, 2.45 Be,1.25 Ni	(155)	(130)	(0)	20	Bearings and molds for plastic parts.
C82800	96.6 Cu, 2.6 Be, 0.5 Co, 0.25 Si	97 (165)	55 (145)	20 (1)	10	Molds for plastic parts, cams, bushings, bearings, valves, pump parts, sleeves.
Red Brasses and Leaded Red Brasses						
C83300	93 Cu, 1.5 Sn,1.5 Pb, 4 Zn	32	10	35	35	Terminal ends for electrical cables.
C83400	90 Cu, 10 Zn	35	10	30	60	Moderate strength, moderate conductivity castings; rotating bands.

Table 1. *(Continued)* **Properties and Applications of Cast Coppers and Copper Alloys**

UNS Designation	Nominal Composition (%)	Typical Mechanical Properties, as Cast or Heat Treated[a]				Typical Applications
		Tensile Strength (ksi)	Yield Strength (ksi)	Elongation in 2 in. (%)	Machinability Rating[b]	
C83600	85 Cu, 5 Sn, 5 Pb, 5 Zn	37	17	30	84	Valves, flanges, pipe fittings, plumbing goods, pump castings, water pump impellers and housings, ornamental fixtures, small gears.
C83800	83 Cu, 4 Sn, 6 Pb,7 Zn	35	16	25	90	Low-pressure valves and fittings, plumbing supplies and fittings, general hardware, air–gas–water fittings, pump components, railroad catenary fittings.
Semired Brasses and Leaded Semired Brasses						
C84200	80 Cu, 5 Sn,2.5 Pb, 12.5 Zn	35	14	27	80	Pipe fittings, elbows, T's, couplings, bushings, locknuts, plugs, unions.
C84400	81 Cu, 3 Sn, 7 Pb,9 Zn	34	15	26	90	General hardware, ornamental castings, plumbing supplies and fixtures, low-pressure valves and fittings.
C84500	78 Cu, 3 Sn, 7 Pb,12 Zn	35	14	28	90	Plumbing fixtures, cocks, faucets, stops, waste, air and gas fittings, low-pressure valve fittings.
C84800	76 Cu, 3 Sn, 6 Pb,15 Zn	36	14	30	90	Plumbing fixtures, cocks, faucets, stops, waste, air, and gas, general hardware, and low-pressure valve fittings.
Yellow Brasses and Leaded Yellow Brasses						
C85200	72 Cu, 1 Sn, 3 Pb,24 Zn	38	13	35	80	Plumbing fittings and fixtures, ferrules, valves, hardware, ornamental brass, chandeliers, and-irons.
C85400	67 Cu, 1 Sn, 3 Pb,29 Zn	34	12	35	80	General-purpose yellow casting alloy not subject to high internal pressure. Furniture hardware, ornamental castings, radiator fittings, ship trimmings, battery clamps, valves, and fittings.
C85500	61 Cu, 0.8 Al, bal Zn	60	23	40	80	Ornamental castings.
C85700	63 Cu, 1 Sn, 1 Pb, 34.7 Zn, 0.3 Al	50	18	40	80	Bushings, hardware fittings, ornamental castings.
C85800	58 Cu, 1 Sn, 1 Pb, 40 Zn	55	30	15	80	General-purpose die-casting alloy having moderate strength.
Manganese and Leaded Manganese Bronze Alloys						
C86100	67 Cu, 21 Zn, 3 Fe, 5 Al, 4 Mn	95	50	20	30	Marine castings, gears, gun mounts, bushings and bearings, marine racing propellers.
C86200	64 Cu, 26 Zn, 3 Fe, 4 Al, 3 Mn	95	48	20	30	Marine castings, gears, gun mounts, bushings and bearings.

Table 1. *(Continued)* Properties and Applications of Cast Coppers and Copper Alloys

		Typical Mechanical Properties, as Cast or Heat Treated[a]				
UNS Designation	Nominal Composition (%)	Tensile Strength (ksi)	Yield Strength (ksi)	Elongation in 2 in. (%)	Machinability Rating[b]	Typical Applications
C86300	63 Cu, 25 Zn, 3 Fe, 6 Al, 3 Mn	115	83	15	8	Extra-heavy duty, high-strength alloy. Large valve stems, gears, cams, slow-speed heavy-load bearings, screwdown nuts, hydraulic cylinder-parts.
C86400	59 Cu, 1 Pb, 40 Zn	65	25	20	65	Free-machining manganese bronze. Valve stems, marine fittings, lever arms, brackets, light-duty gears.
C86500	58 Cu, 0.5 Sn, 39.5 Zn, 1 Fe, 1 Al	71	28	30	26	Machinery parts requiring strength and toughness, lever arms, valve stems, gears.
C86700	58 Cu, 1 Pb, 41 Zn	85	42	20	55	High strength, free-machining manganese bronze. Valve stems.
C86800	55 Cu, 37 Zn, 3 Ni, 2 Fe, 3 Mn	82	38	22	30	Marine fittings, marine propellers.
Silicon Bronzes and Silicon Brasses						
C87200	89 Cu min, 4 Si	55	25	30	40	Bearings, bells, impellers, pump and valve components, marine fittings, corrosion-resistant castings.
C87400	83 Cu, 14 Zn, 3 Si	55	24	30	50	Bearings, gears, impellers, rocker arms, valve stems, clamps.
C87500	82 Cu, 14 Zn, 4 Si	67	30	21	50	Bearings, gears, impellers, rocker arms, valve stems, small boat proellers.
C87600	90 Cu, 5.5 Zn,4.5 Si	66	32	20	40	Valve stems.
C87800	82 Cu, 14 Zn, 4 Si	85	50	25	40	High-strength, thin-wall die castings; brush holders, lever arms, brackets, clamps, hexagonal nuts.
C87900	65 Cu, 34 Zn, 1 Si	70	35	25	80	General-purpose die-casting alloy having moderate strength.
Tin Bronzes						
C90200	93 Cu, 7 Sn	38	16	30	20	Bearings and bushings.
C90300	88 Cu, 8 Sn, 4 Zn	45	21	30	30	Bearings, bushings, pump impellers, piston rings, valve components, seal rings, steam fittings, gears.
C90500	88 Cu, 10 Sn, 2 Zn	45	22	25	30	Bearings, bushings, pump impellers, piston rings, valve components, steam fittings, gears.
C90700	89 Cu, 11 Sn	44 (55)	22 (30	20 (16)	20	Gears, bearings, bushings.

Table 1. *(Continued)* **Properties and Applications of Cast Coppers and Copper Alloys**

UNS Designation	Nominal Composition (%)	Typical Mechanical Properties, as Cast or Heat Treated[a]				Typical Applications
		Tensile Strength (ksi)	Yield Strength (ksi)	Elongation in 2 in. (%)	Machinability Rating[b]	
C90900	87 Cu, 13 Sn	40	20	15	20	Bearings and bushings.
C91000	85 Cu, 14 Sn, 1 Zn	32	25	2	20	Piston rings and bearings.
C91100	84 Cu, 16 Sn	35	25	2	10	Piston rings, bearings, bushings, bridge plates.
C91300	81 Cu, 19 Sn	35	30	0.5	10	Piston rings, bearings, bushings, bridge plates, bells.
C91600	88 Cu, 10.5 Sn,1.5 Ni	44 (60)	22 (32)	16 (16)	20	Gears.
C91700	86.5 Cu, 12 Sn,1.5 Ni	44 (60)	22 (32)	16 (16)	20	Gears.
Leaded Tin Bronzes						
C92200	88 Cu, 6 Sn,1.5 Pb, 4.5 Zn	40	20	30	42	Valves, fittings, and pressure-containing parts for use up to 550°F.
C92300	87 Cu, 8 Sn, 4 Zn	40	20	25	42	Valves, pipe fittings, and high-pressure steam castings. Superior machinability to C90300.
C92500	87 Cu, 11 Sn,1 Pb, 1 Ni	44	20	20	30	Gears, automotive synchronizer rings.
C92600	87 Cu, 10 Sn,1 Pb, 2 Zn	44	20	30	40	Bearings, bushings, pump impellers, piston rings, valve components, steam fittings, and gears. Superior machinability to C90500.
C92700	88 Cu, 10 Sn,2 Pb	42	21	20	45	Bearings, bushings, pump impellers, piston rings, and gears. Superior machinability to C90500.
C92800	79 Cu, 16 Sn, 5 Pb	40	30	1	70	Piston rings.
C92900	82 Cu min, 9 Sn min, 2 Pb min,2.8 Ni min	47 (47)	26 (26)	20 (20)	40	Gears, wear plates, guides, cams, parts requiring machinability superior to that of C91600 or 91700.
High-Leaded Tin Bronzes						
C93200	83 Cu, 6.3 Sn min,7 Pb, 3 Zn	35	18	20	70	General-utility bearings and bushings.
C93400	84 Cu, 8 Sn, 8 Pb	32	16	20	70	Bearings and bushings.
C93500	85 Cu, 5 Sn, 9 Pb	32	16	20	70	Small bearings and bushings, bronze backing for babbit-lined automotive bearings.
C93700	80 Cu, 10 Sn,10 Pb	35	18	20	80	Bearings for high speed and heavy pressures, pumps, impellers, corrosion-resistant applications, pressure tight castings.

Table 1. *(Continued)* Properties and Applications of Cast Coppers and Copper Alloys

UNS Designation	Nominal Composition (%)	Typical Mechanical Properties, as Cast or Heat Treated[a] Tensile Strength (ksi)	Yield Strength (ksi)	Elongation in 2 in. (%)	Machinability Rating[b]	Typical Applications
C93800	78 Cu, 7 Sn, 15 Pb	30	16	18	80	Bearings for general service and moderate pressure, pump impellers, and bodies for use in acid mine water.
C93900	79 Cu, 6 Sn, 15 Pb	32	22	7	80	Continuous castings only. Bearings for general service, pump bodies, and impellers for mine waters.
C94300	70 Cu, 5 Sn, 25 Pb	27	13	15	80	High-speed bearings for light loads.
C94400	81 Cu, 8 Sn, 11 Pb,0.35 P	32	16	18	80	General-utility alloy for bushings and bearings.
C94500	73 Cu, 7 Sn, 20 Pb	25	12	12	80	Locomotive wearing parts; high-low, low-speed bearings.
Nickel–Tin Bronzes						
C94700	88 Cu, 5 Sn, 2 Zn,5 Ni	50 (85)	23 (60)	35 (10)	30 (20)	Valve stems and bodies, bearings, wear guides, shift forks, feeding mechanisms, circuit breaker parts, gears, piston cylinders, nozzles.
C94800	87 Cu, 5 Sn, 5 Ni	45 (60)	23 (30)	35 (8)	50 (40)	Structural castings, gear components, motion-translation devices, machinery parts, bearings.
Aluminum Bronzes						
C95200	88 Cu, 3 Fe, 9 Al	80	27	35	50	Acid-resisting pumps, bearing, gears, valve seats, guides, plungers, pump rods, bushings.
C95300	89 Cu, 1 Fe, 10 Al	75 (85)	27 (42)	25 (15)	55	Pickling baskets, nuts, gears, steel mill slippers, marine equipment, welding jaws.
C95400	85 Cu, 4 Fe, 11 Al	85 (105)	35 (54)	18 (8)	60	Bearings, gears, worms, bushings, valve seats and guides, pickling hooks.
C95500	81 Cu, 4 Ni, 4 Fe, 11 Al	100 (120)	44 (68)	12 (10)	50	Valve guides and seats in aircraft engines, corrosion-resistant parts, bushings, gears, worms, pickling hooks and baskets, agitators.
C95600	91 Cu, 7 Al, 2 Si	75	34	18	60	Cable connectors, terminals, valve stems, marine hardware, gears, worms, pole-line hardware.
C95700	75 Cu, 2 Ni, 3 Fe, 8 Al, 12 Mn	95	45	26	50	Propellers, impellers, stator clamp segments, safety tools, welding rods, valves, pump casings.
C95800	81 Cu, 5 Ni, 4 Fe, 9 Al, 1 Mn	95	38	25	50	Propeller hubs, blades, and other parts in contact with salt water.

Table 1. *(Continued)* **Properties and Applications of Cast Coppers and Copper Alloys**

UNS Designation	Nominal Composition (%)	Typical Mechanical Properties, as Cast or Heat Treated[a]				Typical Applications
		Tensile Strength (ksi)	Yield Strength (ksi)	Elongation in 2 in. (%)	Machinability Rating[b]	
Copper–Nickels						
C96200	88.6 Cu, 10 Ni,1.4 Fe	45 min	25 min	20 min	10	Components of items being used for seawater corrosion resistance.
C96300	79.3 Cu, 20 Ni,0.7 Fe	75 min	55 min	10 min	15	Centrifugally cast tailshaft sleeves.
C96400	69.1 Cu, 30 Ni,0.9 Fe	68	37	28	20	Valves, pump bodies, flanges, elbows used for seawater corrosion resistance.
C96600	68.5 Cu, 30 Ni, 1 Fe, 0.5 Be	(110)	(70)	(7)	20	High-strength constructional parts for seawater corrosion resistance.
Nickel Silvers						
C97300	56 Cu, 2 Sn,10 Pb, 12 Ni,20 Zn	35	17	20	70	Hardware fittings, valves and valve trim, statuary, ornamental castings.
C97400	59 Cu, 3 Sn, 5 Pb,17 Ni, 16 Zn	38	17	20	60	Valves, hardware, fittings, ornamental castings.
C97600	64 Cu, 4 Sn, 4 Pb, 20 Ni, 8 Zn	45	24	20	70	Marine castings, sanitary fittings, ornamental hardware, valves,pumps.
C97800	66 Cu, 5 Sn, 2 Pb, 25 Ni, 2 Zn	55	30	15	60	Ornamental and sanitary castings, valves and valve seats, musical instrument components.
Special Alloys						
C99300	71.8 Cu,15 Ni,0.7 Fe, 11 Al,1.5 Co	95	55	2	20	Glass-making molds, plate glass rolls, marine hardware.
C99400	90.4 Cu, 2.2 Ni, 2.0 Fe, 1.2 Al,1.2 Si, 3.0 Zn	66 (79)	34 (54)	25	50	Valve stems, marine and other uses requiring resistance to dezincification and dealuminification, propeller wheels, electrical parts, mining equipment gears.
C99500	87.9 Cu, 4.5 Ni, 4.0 Fe, 1.2 Al,1.2 Si, 1.2 Zn	70 min	40 min	12 min	50	Same as C99400, but where higher yield strength is required.
C99700	56.5 Cu, Al,1.5 Pb, 12 Mn,5 Ni, 24 Zn	55	25	25	80	…
C99750	58 Cu,1 Al,1 Pb, 20 Mn, 20 Zn	65 (75)	32 (40)	30 (20)	…	…

[a] Values in parentheses are for heat-treated condition.

[b] Free cutting brass = 100.

Source: Copper Development Association, New York.

Wrought Copper Alloys.—Wrought copper alloys can be utilized in the annealed, cold-worked, stress-relieved, or hardened-by-heat-treatment conditions, depending on composition and end use. The “temper designation” for copper alloys is defined in ASTM Standard Recommended Practice B601, which is applicable to all product forms.

Wrought copper and high-copper alloys, like cast alloys, have a designated minimum copper content and may include other elements to impart special properties. Wrought brasses have zinc as the principal alloying element and may have other designated elements. They comprise the copper–zinc alloys; copper–zinc–lead alloys (leaded brasses); and copper–zinc–tin alloys (tin brasses).

Wrought bronzes comprise four main groups:; copper–tin–phosphorus alloys (phosphor bronze); copper–tin–lead–phosphorus alloys (leaded phosphor bronze); copper–aluminum alloys (aluminum bronzes); and copper–silicon alloys (silicon bronze).

Wrought copper–nickel alloys, like the cast alloys, have nickel as the principal alloying element. The wrought copper–nickel–zinc alloys are known as “nickel silvers” because of their color.

Table 2 lists the nominal composition, properties, and applications of common wrought copper alloys.

Table 2. Properties and Applications of Wrought Coppers and Copper Alloys

Name and Number	Nominal Composition (%)	Strength (ksi)		Elongation in 2 in. (%)	Machinability Rating[a]	Fabricating Characteristics and Typical Applications
		Tensile	Yield			
C10100 Oxygen-free electronic	99.99 Cu	32 –66	10 –53	55	20	Excellent hot and cold workability; good forgeability. Fabricated by blanking, coining, coppersmithing, drawing and upsetting, hot forging and pressing, spinning, swaging, stamping. Uses: busbars, bus conductors, waveguides, hollow conductors, lead-in wires and anodes for vacuum tubes, vacuum seals, transistor components, glass to metal seals, coaxial cables and tubes, klystrons, microwave tubes, rectifiers.
C10200 Oxygen-free copper	99.95 Cu	32–66	10–53	55	20	Fabricating characteristics same as C10100. Uses: busbars, waveguides.
C10300 Oxygen-free, extra-low phosphorus	99.95 Cu, 0.003 P	32–55	10–50	50	20	Fabricating characteristics same as C10100. Uses: busbars, electrical conductors, tubular bus, and applications requiring good conductivity and welding or brazing properties.
C10400, C10500, C10700 Oxygen-free, silver-bearing	99.95 Cu	32–66	10–53	55	20	Fabricating characteristics same as C10100. Uses: auto gaskets, radiators, busbars, conductivity wire, contacts, radio parts, winding, switches, terminals, commutator segments; chemical process equipment, printing rolls, clad metals, printed-circuit foil.
C10800 Oxygen-free, low phosphorus	99.95 Cu, 0.009 P	32–55	10–50	50	20	Fabricating characteristics same as C10100. Uses: refrigerators, air conditioners, gas and heater lines, oil burner tubes, plumbing pipe and tube, brewery tubes, condenser and heat-exchanger tubes, dairy and distiller tubes, pulp and paper lines, tanks; air, gasoline, and hydraulic lines.
C11000 Electrolytic tough pitch copper	99.90 Cu, 0.04 O	32–66	10–53	55	20	Fabricating characteristics same as C10100. Uses: downspouts, gutters, roofing, gaskets, auto radiators, busbars, nails, printing rolls, rivets, radio parts.
C11000 Electrolytic tough pitch, anneal-resistant	99.90 Cu, 0.04 O, 0.01 Cd	66	…	…	20	Fabricated by drawing and stranding, stamping. Uses: electrical power transmission where resistance to softening under overloads is desired.
C11300, C11400, C11500, C11600 Silver- bearing tough pitch copper	99.90 Cu, 0.04 O, Ag	32–66	10–53	55	20	Fabricating characteristics same as C10100. Uses: gaskets, radiators, busbars, windings, switches, chemical process equipment, clad metals, printed-circuit foil.

Table 2. *(Continued)* **Properties and Applications of Wrought Coppers and Copper**

Name and Number	Nominal Composition (%)	Strength (ksi)		Elongation in 2 in. (%)	Machinability Rating[a]	Fabricating Characteristics and Typical Applications
		Tensile	Yield			
C12000, C12100 Phosphorus deoxidized, low residual phosphorus	99.9 Cu	32–57	10–53	55	20	Fabricating characteristics same as C10100. Uses: busbars, electrical conductors, tubular bus, and applications requiring welding or brazing.
C12200, C12210 Phosphorus deoxidized copper, high residual phosphorus	99.90 Cu, 0.02 P	32–55	10–53	55	20	Fabricating characteristics same as C10100. Uses: gas and heater lines; oil burner tubing; plumbing pipe and tubing; condenser, evaporator, heat exchanger, dairy, and distiller tubing; steam and water lines; air, gasoline, and hydraulic lines.
C12500,C12700, C12800, C12900, C13000 Fire-refined tough pitch with silver	99.88 Cu	32–66	10–53	55	20	Fabricating characteristics same as C10100. Uses: same as C11000, Electrolytic tough pitch copper.
C14200 Phosphorus deoxidized, arsenical	99.68 Cu, 0.3 As, 0.02 P	32–55	10–50	45	20	Fabricating characteristics same as C10100. Uses: staybolts, heat-exchanger and condenser tubes.
C14300, C14310 Cadmium copper, deoxidized	99.9 Cu, 0.1 Cd	32–58	11–56	42	20	Fabricating characteristics same as C10100. Uses: anneal-resistant electrical applications requiring thermal softening and embrittlement resistance, lead frames, contacts, terminals, solder-coated and solder-fabricated parts, furnace-brazed assemblies and welded components, cable wrap.
C14500, C14510, C14520 Tellurium bearing	99.5 Cu, 0.50 Te, 0.008 P	32–56	10–51	50	85	Fabricating characteristics same as C10100. Uses: Forgings and screw-machine products, and parts requiring high conductivity, extensive machining, corrosion resistance, copper color, or a combination of these; electrical connectors, motor and switch parts, plumbing fittings, soldering coppers, welding torch tips, transistor bases, and furnace-brazed articles.
C14700, C14710, C14720 Sulfur bearing	99.6 Cu, 0.40 S	32–57	10–55	52	85	Fabricating characteristics same as C10100. Uses: screw-machine products and parts requiring high conductivity, extensive machining, corrosion resistance, copper color, or a combination of these; electrical connectors, motor and switch components, plumbing fittings, cold-headed and machined parts, cold forgings, furnace-brazed articles, screws, soldering coppers, rivets and welding torch tips.
C15000 Zirconium copper	99.8 Cu, 0.15 Zr	29–76	6–72	54	20	Fabricating characteristics same as C10100. Uses: switches, high-temperature circuit breakers, commutators, stud bases for power transmitters, rectifiers, soldering welding tips.
C15500	99.75 Cu, 0.06 P, 0.11 Mg, Ag	40–80	18–72	40	20	Fabricating characteristics same as C10100. Uses: high-conductivity light-duty springs, electrical contacts, fittings, clamps, connectors, diahragms, electronic components, resistance-welding electrodes.
C15715	99.6 Cu, 0.13 Al_2O_3	52–88	44–84	27	20	Excellent cold workability. Fabricated by extrusion, drawing, rolling, heading, swaging, machining, blanking, roll threading. Uses: integrated-circuit lead frames, diode leads; vacuum, microwave, and x-ray tube components; electrical components; brush springs; commutators, electric generator and motor components.
C15720	99.5 Cu, 0.18 Al_2O_3	64–98	54–96	25	…	Excellent cold workability, Fabricated by extrusion, drawing, rolling, heading, swaging, machining, blanking. Uses: relay and switch springs, lead frames, contact supports, heat sinks, circuit breaker parts, rotor bars, resistance-welding electrodes and wheels, connectors, soldering gun tips.

Table 2. *(Continued)* **Properties and Applications of Wrought Coppers and Copper**

Name and Number	Nominal Composition (%)	Strength (ksi)		Elongation in 2 in. (%)	Machinability Rating[a]	Fabricating Characteristics and Typical Applications
		Tensile	Yield			
C15760	98.8 Cu, 0.58 Al_2O_3	70–90	65–87	22	…	Excellent cold workability. Fabricated by extrusion and drawing. Uses: resistance-welding electrodes, soldering gun tips, MIG welding contact tips, continuous-casting molds.
C16200, C16210 Cadmium copper	99.0 Cu, 1.0 Cd	35–100	7–69	57	20	Excellent cold workability; good hot formability. Uses: trolley wires, heating pads, electric-blanket elements, spring contacts, railbands, high-strength transmission lines, connectors, cable wrap, switchgear components, and waveguide cavities.
C16500	98.6 Cu, 0.8 Cd, 0.6 Sn	40–95	14–71	53	20	Fabricating characteristics same as C16200. Uses: electrical springs and contacts, trolley wire, clips, flat cable, resistance-welding electrodes.
C17000 Beryllium copper	98.3 Cu, 1.7 Be, 0.20 Co	70–190	32–170	45	20	Fabricating characteristics same as C16200. Commonly fabricated by blanking, forming and bending, turning, drilling, tapping. Uses: bellows, Bourdon tubing, diaphragms, fuse clips, fasteners, lock-washers, springs, switch parts, roll pins, valves, welding equipment.
C17200 Beryllium copper	98.1 Cu, 1.9 Be, 0.20 Co	68–212	25–195	48	20	Similar to C17000, particularly for its nonsparking characteristics.
C17300 Beryllium copper	98.1 Cu, 1.9 Be, 0.40 Pb	68–212	25–195	48	50	Combines superior machinability with good fabricating characteristics of C17200.
C17500, C17510 Beryllium copper	96.9 Cu, 2.5 Co, 0.6 Be	45–115	25–110	28	…	Fabricating characteristics same as C16200. Uses: fuse clips, fasteners, springs, switch and relay parts, electrical conductors, welding equipment.
C18200, C18400, C18500 Chromium copper	99.2 Cu	34–86	14–77	40	20	Excellent cold workability, good hot workability. Uses: resistance-welding electrodes, seam-welding wheels, switch gear, electrode holder jaws, cable connectors, current-carrying arms and shafts, circuit-breaker parts, molds, spot-welding tips, flash-welding electrodes, electrical and thermal conductors requiring strength, switch contacts.
C18700 Leaded copper	99.0 Cu, 1.0 Pb	32–55	10–50	45	85	Good cold workability; poor hot formability. Uses: connectors, motor and switch parts, screw-machine parts requiring high conductivity.
C18900	98.7 Cu, 0.8 Sn, 0.3 Si, 0.20 Mn	38–95	9–52	48	20	Fabricating characteristics same as C10100. Uses: welding rod and wire for inert gas tungsten arc and metal arc welding and oxyacetylene welding of copper.
C19000 Copper–nickel–phosphorus alloy	98.6 Cu, 1.1 Ni, 0.3 P	38–115	20–81	50	30	Fabricating characteristics same as C10100. Uses: springs, clips, electrical connectors, power tube and electron tube components, high-strength electrical conductors, bolts, nails, screws, cotter pins, and parts requiring some combination of high strength, high electrical or thermal conductivity, high resistance to fatigue and creep, and good workability.
C19100 Copper– nickel– phosphorus– tellurium alloy	98.2 Cu, 1.1 Ni, 0.5 Te, 0.2 P	36–104	10–92	27	75	Good hot and cold workability. Uses: forgings and screw-machine parts requiring high strength, hardenability, extensive machining, corrosion resistance, copper color, good conductivity, or a combination of these; bolts, bushings, electrical connectors, gears, marine hardware, nuts, pinions, tie rods, turnbuckle barrels, welding torch tips.

Table 2. *(Continued)* Properties and Applications of Wrought Coppers and Copper

Name and Number	Nominal Composition (%)	Strength (ksi)		Elongation in 2 in. (%)	Machinability Rating[a]	Fabricating Characteristics and Typical Applications
		Tensile	Yield			
C19200	99 Cu, 1.0 Fe, 0.03 P	37–77	11–74	40	20	Excellent hot and cold workability. Uses: automotive hydraulic brake lines, flexible hose, electrical terminals, fuse clips, gaskets, gift hollow ware, applications requiring resistance to softening and stress corrosion, air-conditioning and heat-exchanger tubing.
C19400	97.4 Cu, 2.4 Fe, 0.13 Zn, 0.04 P	45–76	24–73	32	20	Excellent hot and cold workability. Uses: circuit-breaker components, contact springs, electrical clamps, electrical springs, electrical terminals, flexible hose, fuse clips, gaskets, gift hollow ware, plug contacts, rivets, and welded condenser tubes.
C19500	97.0 Cu, 1.5 Fe, 0.6 Sn, 0.10 P, 0.80 Co	80–97	65–95	15	20	Excellent hot and cold workability. Uses: electrical springs, sockets, terminals, connectors, clips, and other current-carrying parts requiring strength.
C21000 Gilding, 95%	95.0 Cu, 5.0 Zn	34–64	10–58	45	20	Excellent cold workability, good hot workability for blanking, coining, drawing, piercing and punching, shearing, spinning, squeezing and swaging, stamping. Uses: coins, medals, bullet jackets, fuse caps, primers, plaques, jewelry base for gold plate.
C22000 Commercial bronze, 90%	90.0 Cu, 10.0 Zn	37–72	10–62	50	20	Fabricating characteristics same as C21000, plus heading and up-setting, roll threading and knurling, hot forging and pressing. Uses: etching bronze, grillwork, screen cloth, weatherstripping, lipstick cases, compacts, marine hardware, screws, rivets.
C22600 Jewelry bronze, 87.5%	87.5 Cu, 12.5 Zn	39–97	11–62	46	30	Fabricating characteristics same as C21000, plus heading and up-setting, roll threading and knurling. Uses: angles, channels, chain, fasteners, costume jewelry, lipstick cases, powder compacts, base for gold plate.
C23000 Red brass, 85%	85.0 Cu, 15.0 Zn	39–105	10–63	55	30	Excellent cold workability; good hot formability. Uses: weather-stripping, conduit, sockets, fasteners, fire extinguishers, condenser and heat-exchanger tubing, plumbing pipe, radiator cores.
C24000 Low brass, 80%	80.0 Cu, 20.0 Zn	42–125	12–65	55	30	Excellent cold workability. Fabricating characteristics same as C23000. Uses: battery caps, bellows, musical instruments, clock dials, pump lines, flexible hose.
C26000, C26100, C26130, C26200 Cartridge brass, 70%	70.0 Cu, 30.0 Zn	44 – 130	11–65	66	…	Excellent cold workability. Uses: radiator cores and tanks, flashlight shells, lamp fixtures, fasteners, screws, springs, grillwork, stencils, plumbing accessories, plumbing brass goods, locks, hinges, ammunition components, plumbing accessories, pins, rivets.
C26800, C27000 Yellow brass	65.0 Cu, 35.0 Zn	46–128	14–62	65	30	Excellent cold workability. Fabricating characteristics same as C23000. Uses: same as C26000 except not used for ammunition.
C28000 Muntz metal, 60%	60.0 Cu, 40.0 Zn	54–74	21–55	52	40	Excellent hot formability and forgeability for blanking, forming and bending, hot forging and pressing, hot heading and upsetting, shearing. Uses: architectural, large nuts and bolts, brazing rod, condenser plates, heat-exchanger and condenser tubing, hot forgings.
C31400 Leaded commercial bronze	89.0 Cu, 1.9 Pb, 0.1 Zn	37–60	12–55	45	80	Excellent machinability. Uses: screws, machine parts, pickling crates.

Table 2. *(Continued)* **Properties and Applications of Wrought Coppers and Copper**

Name and Number	Nominal Composition (%)	Strength (ksi)		Elongation in 2 in. (%)	Machinability Rating[a]	Fabricating Characteristics and Typical Applications
		Tensile	Yield			
C31600 Leaded commercial bronze, nickel-bearing	89.0 Cu, 1.9 Pb, 1.0 Ni, 8.1 Zn	37–67	12–59	45	80	Good cold workability; poor hot formability. Uses: electrical connectors, fasteners, hardware, nuts, screws, screw-machine parts.
C33000 Low-leaded brass tube	66.0 Cu, 0.5 Pb, 33.5 Zn	47–75	15–60	60	60	Combines good machinability and excellent cold workability. Fabricated by forming and bending, machining, piercing and punching. Uses: pump and power cylinders and liners, ammunition primers, plumbing accessories.
C33200 High-leaded brass tube	66.0 Cu, 2.0 Pb, 32.0 Zn	47–75	15–60	50	80	Excellent machinability. Fabricated by piercing, punching, and machining. Uses: general-purpose screw-machine parts.
C33500 Low-leaded brass	63.5 Cu, 0.5 Pb, 36 Zn	46–74	14–60	65	60	Similar to C33200. Commonly fabricated by blanking, drawing, machining, piercing and punching, stamping. Uses: butts, hinges, watch backs.
C34000 Medium-leaded brass	63.5 Cu, 1.0 Pb, 35.5 Zn	47–88	15–60	60	70	Similar to C33200. Fabricated by blanking, heading and upsetting, machining, piercing and punching, roll threading and knurling, stamping. Uses: butts, gears, nuts, rivets, screws, dials, engravings, instrument plates.
C34200 High-leaded brass	63.5 Cu, 2.0 Pb, 34.5 Zn	49–85	17–62	52	90	Combines excellent machinability with moderate cold workability. Uses: clock plates and nuts, clock and watch backs, gears, wheels and channel plate.
C35000 Medium-leaded brass	62.5 Cu, 1.1 Pb, 36.4 Zn	45–95	13–70	66	70	Fair cold workability; poor hot formability. Uses: bearing cages, book dies, clock plates, gears, hinges, hose couplings, keys, lock parts, lock tumblers, meter parts, nuts, sink strainers, strike plates, templates, type characters, washers, wear plates.
C35300 High-leaded brass	61.5 Cu, 2.8 Pb, 36.5 Zn	49–85	17–62	52	90	Similar to C34200.
C35600 Extra-high-leaded brass	61.5 Cu, 2.5 Pb, 36 Zn	47–97	17–87	60	100	Excellent machinability. Fabricated by blanking, machining, piercing and punching, stamping. Uses: clock plates and nuts, clock and watch backs, gears, wheels, and channel plate.
C36000 Free-cutting brass	61.5 Cu, 3.1 Pb, 35.4 Zn	49–68	18–45	53	100	Excellent machinability. Fabricated by machining, roll threading, and knurling. Uses: gears, pinions, automatic high-speed screw-machine parts.
C36500 to C36800 Leaded Muntz metal	59.5 Cu, 0.5 Pb, 40.0 Zn	54 (As hot rolled)	20	45	60	Combines good machinability with excellent hot formability. Uses: condenser-tube plates.
C37000 Free-cutting Muntz metal	60.0 Cu, 1.0 Pb, 39.0 Zn	54–80	20–60	40	70	Fabricating characteristics similar to C36500 to 36800. Uses: automatic screw-machine parts.
C37700 Forging brass	59.5 Cu, 2.0 Pb, 38.0 Zn	52 (As extruded)	20	45	80	Excellent hot workability. Fabricated by heading and upsetting, hot forging and pressing, hot heading and upsetting, machining. Uses: forgings and pressings of all kinds.
C38500 Architectural bronze	57.0 Cu, 3.0 Pb, 40.0 Zn	60 (As extruded)	20	30	90	Excellent machinability and hot workability. Fabricated by hot forging and pressing, forming, bending, and machining. Uses: architectural extrusions, store fronts, thresholds, trim, butts, hinges, lock bodies, and forgings.
C40500	95 Cu, 1 Sn, 4 Zn	39–78	12–70	49	20	Excellent cold workability. Fabricated by blanking, forming, and drawing. Uses: meter clips, terminals, fuse clips, contact and relay springs, washers.

Table 2. *(Continued)* **Properties and Applications of Wrought Coppers and Copper**

Name and Number	Nominal Composition (%)	Strength (ksi)		Elongation in 2 in. (%)	Machinability Rating[a]	Fabricating Characteristics and Typical Applications
		Tensile	Yield			
C40800	95 Cu, 2 Sn, 3 Zn	42–79	13–75	43	20	Excellent cold workability. Fabricated by blanking, stamping, and shearing. Uses: electrical connectors.
C41100	91 Cu, 0.5 Sn, 8.5 Zn	39–106	11–72	43	20	Excellent cold workability, good hot formability. Fabricated by blanking, forming and bending, drawing, piercing and punching, shearing, spinning, and stamping. Uses: bushings, bearing sleeves, thrust washers, flexible metal hose.
C41300	90.0 Cu, 1.0 Sn, 9.0 Zn	41–105	12–82	45	20	Excellent cold workability; good hot formability. Uses: plater bar for jewelry products, flat springs for electrical switchgear.
C41500	91 Cu, 1.8 Sn, 7.2 Zn	46–81	17–75	44	30	Excellent cold workability. Fabricated by blanking, drawing, bending, forming, shearing, and stamping. Uses: spring applications for electrical switches.
C42200	87.5 Cu, 1.1 Sn, 11.4 Zn	43–88	15–75	46	30	Excellent cold workability; good hot formability. Fabricated by blanking, piercing, forming, and drawing. Uses: sash chains, fuse clips, terminals, spring washers, contact springs, electrical connectors.
C42500	88.5 Cu, 2.0 Sn, 9.5 Zn	45–92	18–76	49	30	Excellent cold workability. Fabricated by blanking, piercing, forming, and drawing. Uses: electrical switches, springs, terminals, connectors, fuse clips, pen clips, weather stripping.
C43000	87.0 Cu, 2.2 Sn, 10.8 Zn	46–94	18–73	55	30	Excellent cold workability; good hot formability. Fabricated by blanking, coining, drawing, forming, bending, heading, and upsetting. Uses: same as C42500.
C43400	85.0 Cu, 0.7 Sn, 14.3 Zn	45–90	15–75	49	30	Excellent cold workability. Fabricated by blanking, drawing, bonding, forming, stamping, and shearing. Uses: electrical switch parts, blades, relay springs, contacts.
C43500	81.0 Cu, 0.9 Sn, 18.1 Zn	46–80	16–68	46	30	Excellent cold workability for fabrication by forming and bending. Uses: Bourdon tubing and musical instruments.
C44300, C44400, C44500 Inhibited admiralty	71.0 Cu, 28.0 Zn, 1.0 Sn	48–55	18–22	65	30	Excellent cold workability for forming and bending. Uses: condenser, evaporator and heat-exchanger tubing, condenser tubing plates, distiller tubing, ferrules.
C46400 to C46700 Naval brass	60.0 Cu, 39.2 Zn, 0.8 Sn	55–88	25–66	50	30	Excellent hot workability and hot forgeability. Fabricated by blanking, drawing, bending, heading and upsetting, hot forging, pressing. Uses: aircraft turnbuckle barrels, balls, bolts, marine hardware, nuts, propeller shafts, rivets, valve stems, condenser plates, welding rod.
C48200 Naval brass, medium-leaded	60.5 Cu, 0.7 Pb, 0.8 Sn, 38.0 Zn	56–75	25–53	43	50	Good hot workability for hot forging, pressing, and machining operations. Uses: marine hardware, screw-machine products, valve stems.
C48500 Leaded naval brass	60.0 Cu, 1.8 Pb, 37.5 Zn, 0.7 Sn	57–75	25–53	40	70	Combines good hot forgeability and machinability. Fabricated by hot forging and pressing, machining. Uses: marine hardware, screw-machine parts, valve stems.
C50500 Phosphor bronze, 1.25% E	98.7 Cu, 1.3 Sn, trace P	40–79	14–50	48	20	Excellent cold workability; good hot formability. Fabricated by blanking, bending, heading and upsetting, shearing and swaging. Uses: electrical contacts, flexible hose, pole-line hardware.

Table 2. *(Continued)* **Properties and Applications of Wrought Coppers and Copper**

Name and Number	Nominal Composition (%)	Strength (ksi)		Elongation in 2 in. (%)	Machinability Rating[a]	Fabricating Characteristics and Typical Applications
		Tensile	Yield			
C51000 Phosphor bronze, 5% A	94.8 Cu, 5.0 Sn, trace P	47–140	19–80	64	20	Excellent cold workability. Fabricated by blanking, drawing, bending, heading and upsetting, roll threading and knurling, shearing, stamping. Uses: bellows, Bourdon tubing, clutch discs, cotter pins, diaphragms, fasteners, lock washers, wire brushes, chemical hardware, textile machinery, welding rod.
C51100	95.6 Cu, 4.2 Sn, 0.2 P	46–103	50–80	48	20	Excellent cold workability. Uses: bridge bearing plates, locator bars, fuse clips, sleeve bushings, springs, switch parts, truss wire, wire brushes, chemical hardware, perforated sheets, textile machinery.
C52100 Phosphor bronze, 8% C	92.0 Cu, 8.0 Sn, trace P	55–140	24–80	70	20	Good cold workability for blanking, drawing, forming and bending, shearing, stamping. Uses: generally for more severe service conditions than C51000.
C52400 Phosphor bronze, 10% D	90.0 Cu, 10.0 Sn, trace P	66–147	28	70	20	Good cold workability for blanking, forming and bending, shearing. Uses: heavy bars and plates for severe compression, bridge and expansion plates and fittings, articles requiring good spring qualities, resilience, fatigue resistance, good wear and corrosion resistance.
C54400	88.0 Cu, 4.0 Pb, 4.0 Zn, 4.0 Sn	44–75	19–63	50	80	Excellent machinability; good cold workability. Fabricated by blanking, drawing, bending, machining, shearing, stamping. Uses: bearings, bushings, gears, pinions, shafts, thrust washers, valve parts.
C60800	95.0 Cu, 5.0 Al	60	27	55	20	Good cold workability; fair hot formability. Uses: condenser, evaporator and heat-exchanger tubes, distiller tubes, ferrules.
C61000	92.0 Cu, 8.0 Al	52–60	17–27	45	20	Good hot and cold workability. Uses: bolts, pump parts, shafts, tie rods, overlay on steel for wearing surfaces.
C61300	90.3 Cu, 0.35 Sn, 6.8 Al, 0.35 Sn	70–85	30–58	42	30	Good hot and cold formability. Uses: nuts, bolts, corrosion resistant vessels and tanks, structural components, machine parts, condenser tube and piping systems, marine protective sheathing and fasteners, munitions mixing troughs and blending chambers.
C61400 Aluminum bronze, D	91.0 Cu, 7.0 Al, 2.0 Fe	76–89	33–60	45	20	Similar to C61300.
C61500	90.0 Cu, 8.0 Al, 2.0 Ni	70–145	22–140	55	30	Good hot and cold workability. Fabricating characteristics similar to C52100. Uses: hardware, decorative metal trim, interior furnishings and other articles requiring high tarnish resistance.
C61800	89.0 Cu, 1.0 Fe, 10.0 Al	80–85	39–42.5	28	40	Fabricated by hot forging and hot pressing. Uses: bushings, bearings, corrosion-resistant applications, welding rods.
C61900	86.5 Cu, 4.0 Fe, 9.5 Al	92–152	49–145	30	…	Excellent hot formability for fabricating by blanking, forming, bending, shearing, and stamping. Uses: springs, contacts, and switch components.
C62300	87.0 Cu, 3.0 Fe, 10.0 Al	75–98	35–52	35	50	Good hot and cold formability. Fabricated by bending, hot forging, hot pressing, forming, and welding. Uses: bearings, bushings, valve guides, gears, valve seats, nuts, bolts, pump rods, worm gears, and cams.
C62400	86.0 Cu, 3.0 Fe, 11.0 Al	90–105	40–52	18	50	Excellent hot formability for fabrication by hot forging and hot bending. Uses: bushings, gears, cams, wear strips, nuts, drift pins, tie rods.

Table 2. *(Continued)* Properties and Applications of Wrought Coppers and Copper

Name and Number	Nominal Composition (%)	Strength (ksi)		Elongation in 2 in. (%)	Machinability Rating[a]	Fabricating Characteristics and Typical Applications
		Tensile	Yield			
C62500	82.7 Cu, 4.3 Fe, 13.0 Al	100 (As extruded)	55	1	20	Excellent hot formability for fabrication by hot forging and machining. Uses: guide bushings, wear strips, cams, dies, forming rolls.
C63000	82.0 Cu, 3.0 Fe, 10.0 Al, 5.0 Ni	90–118	50–75	20	30	Good hot formability. Fabricated by hot forming and forging. Uses: nuts, bolts, valve seats, plunger tips, marine shafts, valve guides, aircraft parts, pump shafts, structural members.
C63200	82.0 Cu, 4.0 Fe, 9.0 Al, 5.0 Ni	90–105	45–53	25	30	Good hot formability. Fabricated by hot forming and welding. Uses: nuts, bolts, structural pump parts, shafting requiring corrosion resistance.
C63600	95.5 Cu, 3.5 Al, 1.0 Si	60–84	…	64	40	Excellent cold workability; fair hot formability. Fabricated by cold heading. Uses: components for pole-line hardware, cold-headed nuts for wire and cable connectors, bolts and screw products.
C63800	95.0 Cu, 2.8 Al, 1.8 Si, 0.40 Co	82–130	54–114	36	…	Excellent cold workability and hot formability. Uses: springs, switch parts, contacts, relay springs, glass sealing, and porcelain enameling.
C64200	91.2 Cu, 7.0 Al, 1.8 Si	75–102	35–68	32	60	Excellent hot formability. Fabricated by hot forming, forging, machining. Uses: valve stems, gears, marine hardware, pole-line hardware, bolts, nuts, valve bodies, and components.
C65100 Low-silicon bronze, B	98.5 Cu, 1.5 Si	40–105	15–71	55	30	Excellent hot and cold workability. Fabricated by forming and bending, heading and upsetting, hot forging and pressing, roll threading and knurling, squeezing and swaging. Uses: hydraulic pressure lines, anchor screws, bolts, cable clamps, cap screws, machine screws, marine hardware, nuts, pole-line hardware, rivets, U-bolts, electrical conduits, heat-exchanger tubing, welding rod.
C65500 High-silicon bronze, A	97.0 Cu, 3.0 Si	56–145	21–71	63	30	Excellent hot and cold workability. Fabricated by blanking, drawing, forming and bending, heading and upsetting, hot forging and pressing, roll threading and knurling, shearing, squeezing and swaging. Uses: similar to C65100 including propeller shafts.
C66700 Manganese brass	70.0 Cu, 28.8 Zn, 1.2 Mn	45.8–100	12–92.5	60	30	Excellent cold formability. Fabricated by blanking, bending, forming, stamping, welding. Uses: brass products resistance welded by spot, seam, and butt welding.
C67400	58.5 Cu, 36.5 Zn, 1.2 Al, 2.8 Mn, 1.0 Sn	70–92	34–55	28	25	Excellent hot formability. Fabricated by hot forging and pressing, machining. Uses: bushings, gears, connecting rods, shafts, wear plates.
C67500 Manganese bronze, A	58.5 Cu, 1.4 Fe, 39.0 Zn, 1.0 Sn, 0.1 Mn	65–84	30–60	33	30	Excellent hot workability. Fabricated by hot forging and pressing, hot heading and upsetting. Uses: clutch discs, pump rods, shafting, balls, valve stems and bodies.
C68700 Aluminum brass, arsenical	77.5 Cu, 20.5 Zn, 2.0 Al, trace As	60	27	55	30	Excellent cold workability for forming and bending. Uses: condenser, evaporator- and heat-exchanger tubing, condenser tubing plates, distiller tubing, ferrules.
C68800	73.5 Cu, 22.7 Zn, 3.4 Al, 0.40 Co	82–129	55–114	36	…	Excellent hot and cold formability. Fabricated by blanking, drawing, forming and bending, shearing and stamping. Uses: springs, switches, contacts, relays, drawn parts.

Table 2. *(Continued)* **Properties and Applications of Wrought Coppers and Copper**

Name and Number	Nominal Composition (%)	Strength (ksi)		Elongation in 2 in. (%)	Machinability Rating[a]	Fabricating Characteristics and Typical Applications
		Tensile	Yield			
C69000	73.3 Cu, 3.4 Al, 0.6 Ni, 22.7 Zn	82–130	52–117	35	…	Fabricating characteristics same as C68800. Uses: contacts, relays, switches, springs, drawn parts.
C69400 Silicon red brass	81.5 Cu, 14.5 Zn, 4.0 Si	80–100	40–57	25	30	Excellent hot formability for fabrication by forging, screw-machine operations. Uses: valve stems where corrosion resistance and high strength are critical.
C70400 Copper nickel, 5%	92.4 Cu, 1.5 Fe, 5.5 Ni, 0.6 Mn	38–77	40–76	46	20	Excellent cold workability; good hot formability. Fabricated by forming, bending, and welding. Uses: condensers, evaporators, heat exchangers, ferrules, salt water piping, lithium bromide absorption tubing, shipboard condenser intake systems.
C70600 Copper nickel, 10%	88.6 Cu, 1.4 Fe, 10.0 Ni	44–60	16–57	42	20	Good hot and cold workability. Fabricated by forming and bending, welding. Uses: condensers, condenser plates, distiller tubing, evaporator and heat-exchanger tubing, ferrules.
C71000 Copper nickel, 20%	79.0 Cu, 21.0 Ni	49–95	13–85	40	20	Good hot and cold formability. Fabricated by blanking, forming and bending, welding. Uses: communication relays, condensers, condenser plates, electrical springs, evaporator and heat-exchanger tubes, ferrules, resistors.
C71500 Copper nickel, 30%	69.5 Cu, 30.0 Ni, 0.5 Fe	54–75	20–70	45	20	Similar to C70600.
C72200	82.2 Cu, 16.5 Ni, 0.8 Fe, 0.5 Cr	46–70	18–66	46	…	Good hot and cold formability. Fabricated by forming, bending, and welding. Uses: condenser tubing, heat-exchanger tubing, salt water piping.
C72500	88.2 Cu, 9.5 Ni, 2.3 Sn	55–120	22–108	35	20	Excellent cold and hot formability. Fabricated by blanking, brazing, coining, drawing, etching, forming and bending, heading and upsetting, roll threading and knurling, shearing, spinning, squeezing, stamping, and swaging. Uses: relay and switch springs, connectors, brazing alloy, lead frames, control and sensing bellows.
C73500	72.0 Cu, 10.0 Zn, 18.0 Ni	50–100	15–84	37	20	Fabricating characteristics same as C74500. Uses: hollow ware, medallions, jewelry, base for silver plate, cosmetic cases, musical instruments, name plates, contacts.
C74500 Nickel silver, 65–10	65.0 Cu, 25.0 Zn, 10.0 Ni	49–130	18–76	50	20	Excellent cold workability. Fabricated by blanking, drawing, etching, forming and bending, heading and upsetting, roll threading and knurling, shearing, spinning, squeezing, and swaging. Uses: rivets, screws, slide fasteners, optical parts, etching stock, hollow ware, nameplates, platers' bars.
C75200 Nickel silver, 65–18	65.0 Cu, 17.0 Zn, 18.0 Ni	56–103	25–90	45	20	Fabricating characteristics similar to C74500. Uses: rivets, screws, table flatware, truss wire, zippers, bows, camera parts, core bars, temples, base for silver plate, costume jewelry, etching stock, hollow ware, nameplates, radio dials.
C75400 Nickel silver, 65–15	65.0 Cu, 20.0 Zn, 15.0 Ni	53–92	18–79	43	20	Fabricating characteristics similar to C74500. Uses: camera parts, optical equipment, etching stock, jewelry.
C75700 Nickel silver, 65–12	65.0 Cu, 23.0 Zn, 12.0 Ni	52–93	18–79	48	20	Fabricating characteristics similar to C74500. Uses: slide fasteners, camera parts, optical parts, etching stock, name plates.

Table 2. *(Continued)* **Properties and Applications of Wrought Coppers and Copper**

Name and Number	Nominal Composition (%)	Strength (ksi)		Elongation in 2 in. (%)	Machinability Rating[a]	Fabricating Characteristics and Typical Applications
		Tensile	Yield			
C76390	61 Cu, 13 Zn, 24.5 Ni, 1 Pb, 0.5 Sn	90	85	6	40	Fabricated by machining, roll threading, and knurling. Uses: hardware, fasteners, connectors for electronic applications.
C77000 Nickel silver, 55–18	55.0 Cu, 27.0 Zn, 18.0 Ni	60–145	27–90	40	30	Good cold workability. Fabricated by blanking, forming and bending, and shearing. Uses: optical goods, springs, and resistance wire.
C78200	65.0 Cu, 2.0 Pb, 25.0 Zn, 8.0 Ni	53–91	23–76	40	60	Good cold formability. Fabricated by blanking, milling, and drilling. Uses: key blanks, watch plates, watch parts.

[a] Free-cutting brass = 100.

Source: Copper Development Association, New York.

Aluminum and Aluminum Alloys

Pure aluminum is a silver-white metal characterized by a slightly bluish cast. It has a specific gravity of 2.70, resists the corrosive effects of many chemicals, and has a malleability approaching that of gold. When alloyed with other metals, numerous properties are obtained that make these alloys useful over a wide range of applications.

Aluminum alloys are light in weight compared with steel, brass, nickel, or copper; can be fabricated by all common processes; are available in a wide range of sizes, shapes, and forms; resist corrosion; readily accept a wide range of surface finishes; have good electrical and thermal conductivities; and are highly reflective to both heat and light.

Characteristics of Aluminum and Aluminum Alloys.—Aluminum and its alloys lose part of their strength at elevated temperatures, although some alloys retain good strength at temperatures from 400 to 500 degrees F. At subzero temperatures, however, their strength increases without loss of ductility so that aluminum is a particularly useful metal for low-temperature applications.

When aluminum surfaces are exposed to the atmosphere, a thin invisible oxide skin forms immediately that protects the metal from further oxidation. This self-protecting characteristic gives aluminum its high resistance to corrosion. Unless exposed to some substance or condition that destroys this protective oxide coating, the metal remains protected against corrosion. Aluminum is highly resistant to weathering, even in industrial atmospheres. It is also corrosion resistant to many acids. Alkalis are among the few substances that attack the oxide skin and therefore are corrosive to aluminum. Although the metal can safely be used in the presence of certain mild alkalis with the aid of inhibitors, in general, direct contact with alkaline substances should be avoided. Direct contact with certain other metals should be avoided in the presence of an electrolyte; otherwise, galvanic corrosion of the aluminum may take place in the contact area. Where other metals must be fastened to aluminum, the use of a bituminous paint coating or insulating tape is recommended.

Aluminum is one of the two common metals having an electrical conductivity high enough for use as an electric conductor. The conductivity of electric-conductor (EC) grade is about 62 per cent that of the International Annealed Copper Standard. Because aluminum has less than one-third the specific gravity of copper, however, a pound of aluminum will go almost twice as far as a pound of copper when used as a conductor. Alloying lowers the conductivity somewhat so that wherever possible the EC grade is used in electric conductor applications. However, aluminum takes a set, which often results in loosening of screwed connectors, leading to arcing and fires. Special clamping designs are therefore required when aluminum is used for electrical wiring, especially in buildings.

Aluminum has nonsparking and nonmagnetic characteristics that make the metal useful for electrical shielding purposes such as in bus bar housings or enclosures for other electrical equipment and for use around inflammable or explosive substances.

Aluminum can be cast by any method known. It can be rolled to any desired thickness down to foil thinner than paper and in sheet form can be stamped, drawn, spun, or roll-formed. The metal also may be hammered or forged. Aluminum wire, drawn from rolled rod, may be stranded into cable of any desired size and type. The metal may be extruded into a variety of shapes. It may be turned, milled, bored, or otherwise machined in equipment often operating at their maximum speeds. Aluminum rod and bar may readily be employed in the high-speed manufacture of parts made on automatic screw-machine.

Almost any method of joining is applicable to aluminum—riveting, welding, or brazing. A wide variety of mechanical aluminum fasteners simplifies the assembly of many products. Resin bonding of aluminum parts has been successfully employed, particularly in aircraft components.

For the majority of applications, aluminum needs no protective coating. Mechanical finishes such as polishing, sandblasting, or wire brushing meet the majority of needs. When additional protection is desired, chemical, electrochemical, and paint finishes are all used. Vitreous enamels have been developed for aluminum, and the metal may also be electroplated.

Temper Designations for Aluminum Alloys.—The temper designation system adopted by the Aluminum Association and used in industry pertains to all forms of wrought and cast aluminum and aluminum alloys except ingot. It is based on the sequences of basic treatments used to produce the various tempers. The temper designation follows the alloy designation, being separated by a dash.

Basic temper designations consist of letters. Subdivisions of the basic tempers, where required, are indicated by one or more digits following the letter. These digits designate specific sequences of basic treatments, but only operations recognized as significantly influencing the characteristics of the product are indicated. Should some other variation of the same sequence of basic operations be applied to the same alloy, resulting in different characteristics, then additional digits are added.

The basic temper designations and subdivisions are as follows:

–F, as fabricated: Applies to products that acquire some temper from shaping processes not having special control over the amount of strain-hardening or thermal treatment. For wrought products, there are no mechanical property limits.

–O, annealed, recrystallized (wrought products only): Applies to the softest temper of wrought products.

–H, strain-hardened (wrought products only): Applies to products that have their strength increased by strain-hardening with or without supplementary thermal treatments to produce partial softening.

The –H is always followed by two or more digits. The first digit indicates the specific combination of basic operations, as follows:

–H1, strain-hardened only: Applies to products that are strain-hardened to obtain the desired mechanical properties without supplementary thermal treatment. The number following this designation indicates the degree of strain-hardening.

–H2, strain-hardened and then partially annealed: Applies to products that are strain-hardened more than the desired final amount and then reduced in strength to the desired level by partial annealing. For alloys that age-soften at room temperature, the –H2 tempers have approximately the same ultimate strength as the corresponding –H3 tempers. For other alloys, the –H2 tempers have approximately the same ultimate strengths as the corresponding –H1 tempers and slightly higher elongations.The number following this desig-

nation indicates the degree of strain-hardening remaining after the product has been partially annealed.

–H3, strain-hardened and then stabililized: Applies to products which are strain-hardened and then stabilized by a low-temperature heating to slightly lower their strength and increase ductility. This designation applies only to the magnesium-containing alloys that, unless stabilized, gradually age-soften at room temperature.The number following this designation indicates the degree of strain-hardening remaining after the product has been strain-hardened a specific amount and then stabilized.

The second digit following the designations –H1, –H2, and –H3 indicates the final degree of strain-hardening. Numeral 8 has been assigned to indicate tempers having a final degree of strain-hardening equivalent to that resulting from approximately 75 per cent reduction of area. Tempers between –O (annealed) and 8 (full hard) are designated by numerals 1 through 7. Material having an ultimate strength about midway between that of the –O temper and that of the 8 temper is designated by the numeral 4 (half hard); between –O and 4 by the numeral 2 (quarter hard); and between 4 and 8 by the numeral 6 (three-quarter hard). (*Note:* For two-digit –H tempers whose second figure is odd, the standard limits for ultimate strength are exactly midway between those for the adjacent two-digit –H tempers whose second figures are even.) Numeral 9 designates extra-hard tempers.

The third digit, when used, indicates a variation of a two-digit –H temper, and is used when the degree of control of temper or the mechanical properties are different from but close to those for the two-digit –H temper designation to which it is added. (*Note:* The minimum ultimate strength of a three-digit –H temper is at least as close to that of the corresponding two-digit –H temper as it is to the adjacent two-digit –H tempers.) Numerals 1 through 9 may be arbitrarily assigned and registered with the Aluminum Association for an alloy and product to indicate a specific degree of control of temper or specific mechanical property limits. Zero has been assigned to indicate degrees of control of temper or mechanical property limits negotiated between the manufacturer and purchaser that are not used widely enough to justify registration with the Aluminum Association.

The following three-digit –H temper designations have been assigned for wrought products in all alloys:

–H111: Applies to products that are strain-hardened less than the amount required for a controlled H11 temper.

–H112: Applies to products that acquire some temper from shaping processes not having special control over the amount of strain-hardening or thermal treatment, but for which there are mechanical property limits, or mechanical property testing is required.

The following three-digit H temper designations have been assigned for wrought products in alloys containing more than a normal 4 per cent magnesium.

–H311: Applies to products that are strain-hardened less than the amount required for a controlled H31 temper.

–H321: Applies to products that are strain-hardened less than the amount required for a controlled H32 temper.

–H323: Applies to products that are specially fabricated to have acceptable resistance to stress-corrosion cracking.

–H343: Applies to products that are specially fabricated to have acceptable resistance to stress-corrosion cracking.

The following three-digit –H temper designations have been assigned for

Patterned or Embossed Sheet	Fabricated Form
–H114	–O temper
–H124, –H224, –H324	–H11, –H21, –H31 temper, respectively
–H134, –H234, –H334	–H12, –H22, –H32 temper, respectively
–H144, –H244, –H344	–H13, –H23, –H33 temper, respectively
–H154, –H254, –H354	–H14, –H24, –H34 temper, respectively
–H164, –H264, –H364	–H15, –H25, –H35 temper, respectively

Patterned or Embossed Sheet	Fabricated Form
–H174, –H274, –H374	–H16, –H26, –H36 temper, respectively
–H184, –H284, –H384	–H17, –H27, –H37 temper, respectively
–H194, –H294, –H394	–H18, –H28, –H38 temper, respectively
–H195, –H395	–H19, –H39 temper, respectively

–W, solution heat-treated: An unstable temper applicable only to alloys that spontaneously age at room temperature after solution heat treatment. This designation is specific only when the period of natural aging is indicated.

–T, thermally treated to produce stable tempers other than –F, –O, or –H: Applies to products that are thermally treated, with or without supplementary strain-hardening, to produce stable tempers.The –T is always followed by one or more digits. Numerals 2 through 10 have been assigned to indicate specific sequences of basic treatments, as follows:

–T1, naturally aged to a substantially stable condition: Applies to products for which the rate of cooling from an elevated temperature-shaping process, such as casting or extrusion, is such that their strength is increased by room-temperature aging.

–T2, annealed (cast products only): Designates a type of annealing treatment used to improve ductility and increase dimensional stability of castings.

–T3, solution heat-treated and then cold-worked: Applies to products that are cold-worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in applicable specifications.

–T4, solution heat-treated and naturally aged to a substantially stable condition: Applies to products that are not cold-worked after solution heat treatment, or in which the effect of cold work in flattening or straightening may not be recognized in applicable specifications.

–T5, artificially aged only: Applies to products that are artificially aged after an elevated-temperature rapid-cool fabrication process, such as casting or extrusion, to improve mechanical properties or dimensional stability, or both.

–T6, solution heat-treated and then artificially aged: Applies to products that are not cold-worked after solution heat-treatment, or in which the effect of cold work in flattening or straightening may not be recognized in applicable specifications.

–T7, solution heat-treated and then stabilized: Applies to products that are stabilized to carry them beyond the point of maximum hardness, providing control of growth or residual stress or both.

–T8, solution heat-treated, cold-worked, and then artificially aged: Applies to products that are cold-worked to improve strength, or in which the effect of cold work in flattening or straightening is recognized in applicable specifications.

–T9, solution heat-treated, artificially aged, and then cold-worked: Applies to products that are cold-worked to improve strength.

–T10, artificially aged and then cold-worked: Applies to products that are artificially aged after an elevated-temperature rapid-cool fabrication process, such as casting or extrusion, and then cold-worked to improve strength.

Additional digits may be added to designations –T1 through –T10 to indicate a variation in treatment that significantly alters the characteristics of the product. These may be arbitrarily assigned and registered with The Aluminum Association for an alloy and product to indicate a specific treatment or specific mechanical property limits.

These additional digits have been assigned for wrought products in all alloys:

–T__51, stress-relieved by stretching: Applies to products that are stress-relieved by stretching the following amounts after solution heat-treatment:

Plate	1½ to 3 per cent permanent set
Rod, Bar and Shapes	1 to 3 per cent permanent set
Drawn tube	0.5 to 3 per cent permanent set

Applies directly to plate and rolled or cold-finished rod and bar.

These products receive no further straightening after stretching.

Applies to extruded rod and bar shapes and tube when designated as follows:

–T__510 : Products that receive no further straightening after stretching.

–T__511: Products that receive minor straightening after stretching to comply with standard tolerances.

–T__52, stress-relieved by compressing: Applies to products that are stress-relieved by compressing after solution heat-treatment, to produce a nominal permanent set of 2<FmNumerator>1/<FmDenominator>2 per cent.

–T__54, stress-relieved by combined stretching and compressing: applies to die forgings that are stress relieved by restriking cold in the finish die.

The following two-digit –T temper designations have been assigned for wrought products in all alloys:

–T42: Applies to products solution heat-treated and naturally aged that attain mechanical properties different from those of the –T4 temper.

–T62: Applies to products solution heat-treated and artificially aged that attain mechanical properties different from those of the –T6 temper.

Aluminum Alloy Designation Systems.—Aluminum casting alloys are listed in many specifications of various standardizing agencies. The numbering systems used by each differ and are not always correlatable. Casting alloys are available from producers who use a commercial numbering system and this numbering system is the one used in the tables of aluminum casting alloys given further along in this section.

A system of four-digit numerical designations for wrought aluminum and wrought aluminum alloys was adopted by the Aluminum Association in 1954. This system is used by the commercial producers and is similar to the one used by the SAE; the difference being the addition of two prefix letters.

The first digit of the designation identifies the alloy type: 1) indicating an aluminum of 99.00 per cent or greater purity; 2) copper; 3) manganese; 4) silicon; 5) magnesium;

6) magnesium and silicon; 7) zinc; 8) some element other than those aforementioned;

and 9) unused (not assigned at present).

If the second digit in the designation is zero, it indicates that there is no special control on individual impurities; integers 1 through 9 indicate special control on one or more individual impurities.

In the 1000 series group for aluminum of 99.00 per cent or greater purity, the last two of the four digits indicate to the nearest hundredth the amount of aluminum above 99.00 per cent. Thus designation 1030 indicates 99.30 per cent minimum aluminum. In the 2000 to 8000 series groups the last two of the four digits have no significance but are used to identify different alloys in the group. At the time of adoption of this designation system most of the existing commercial designation numbers were used for these last two digits, as for example, 14S became 2014, 3S became 3003, and 75S became 7075. When new alloys are developed and are commercially used these last two digits are assigned consecutively beginning with –01, skipping any numbers previously assigned at the time of initial adoption.

Experimental alloys are also designated in accordance with this system but they are indicated by the prefix X. The prefix is dropped upon standardization.

Table 3 lists the nominal composition of commonly used aluminum casting alloys, and Tables 4a and 4b list the typical tensile properties of separately cast bars. Table shows the product forms and nominal compositions of common wrought aluminum alloys, and Table lists their typical mechanical properties.

Heat-treatability of Wrought Aluminum Alloys.—In high-purity form, aluminum is soft and ductile. Most commercial uses, however, require greater strength than pure aluminum affords. This extra strength is achieved in aluminum first by the addition of other elements to produce various alloys, which singly or in combination impart strength to the metal. Further strengthening is possible by means that classify the alloys roughly into two categories, non-heat-treatable and heat-treatable.

Non-heat-treatable alloys: The initial strength of alloys in this group depends upon the hardening effect of elements such as manganese, silicon, iron and magnesium, singly or in various combinations. The non-heat-treatable alloys are usually designated, therefore, in the 1000, 3000, 4000, or 5000 series. These alloys are work-hardenable, so further strengthening is made possible by various degrees of cold working, denoted by the "H" series of tempers. Alloys containing appreciable amounts of magnesium when supplied in strain-hardened tempers are usually given a final elevated-temperature treatment called *stabilizing* for property stability.

Heat-treatable alloys: The initial strength of alloys in this group is enhanced by the addition of alloying elements such as copper, magnesium, zinc, and silicon. These elements singly or in various combinations show increasing solid solubility in aluminum with increasing temperature, so it is possible to subject them to thermal treatments that will impart pronounced strengthening.

The first step, called *heat-treatment* or *solution heat-treatment,* is an elevated-temperature process designed to put the soluble element in solid solution. This step is followed by rapid quenching, usually in water, which momentarily "freezes" the structure and for a short time renders the alloy very workable. Some fabricators retain this more workable structure by storing the alloys at below freezing temperatures until they can be formed. At room or elevated temperatures the alloys are not stable after quenching, however, and precipitation of the constituents from the supersaturated solution begins. After a period of several days at room temperature, termed *aging* or *room-temperature precipitation,* the alloy is considerably stronger. Many alloys approach a stable condition at room temperature, but some alloys, particularly those containing magnesium and silicon or magnesium and zinc, continue to age-harden for long periods of time at room temperature.

Heating for a controlled time at slightly elevated temperatures provides even further strengthening and properties are stabilized. This process is called *artificial aging* or *precipitation hardening.* By application of the proper combination of solution heat-treatment, quenching, cold working and artificial aging, the highest strengths are obtained.

Clad Aluminum Alloys.—The heat-treatable alloys in which copper or zinc are major alloying constituents are less resistant to corrosive attack than the majority of non-heat-treatable alloys. To increase the corrosion resistance of these alloys in sheet and plate form they are often clad with high-purity aluminum, a low magnesium-silicon alloy, or an alloy containing 1 per cent zinc. The cladding, usually from 2½ to 5 per cent of the total thickness on each side, not only protects the composite due to its own inherently excellent corrosion resistance but also exerts a galvanic effect that further protects the core material.

Special composites may be obtained such as clad non-heat-treatable alloys for extra corrosion protection, for brazing purposes, or for special surface finishes. Some alloys in wire and tubular form are clad for similar reasons and on an experimental basis extrusions also have been clad.

Table 3. Nominal Compositions (in per cent) of Common Aluminum Casting Alloys (AA/ANSI)

Alloy Designation)	Product	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Others	
											Each	Total
201.0	S	0.10	0.15	4.0–5.2	0.20–0.50	0.15–0.55	…	…	…	0.15–0.35	0.05[a]	0.10
204.0	S&P	0.20	0.35	4.2–5.0	0.10	0.15–0.35	…	0.05	0.10	0.15–0.30	0.05[b]	0.15
208.0	S&P	2.5–3.5	1.2	3.5–4.5	0.50	0.10	…	0.35	1.0	0.25	…	0.50
222.0	S&P	2.0	1.5	9.2–10.7	0.50	0.15–0.35	…	0.50	0.8	0.25	…	0.35
242.0	S&P	0.7	1.0	3.5–4.5	0.35	1.2–1.8	0.25	1.7–2.3	0.35	0.25	0.05	0.15
295.0	S	0.7–1.5	1.0	4.0–5.0	0.35	0.03	…	…	0.35	0.25	0.05	0.15
308.0	P	5.0–6.0	1.0	4.0–5.0	0.50	0.10	…	…	1.0	0.25	…	0.50
319.0	S&P	5.5–6.5	1.0	3.0–4.0	0.50	0.10	…	0.35	1.0	0.25	…	0.50
328.0	S	7.5–8.5	1.0	1.0–2.0	0.20–0.6	0.20–0.6	0.35	0.25	1.5	0.25	…	0.50
332.0	P	8.5–10.5	1.2	2.0–4.0	0.50	0.50–1.5	…	0.50	1.0	0.25	…	0.50
333.0	P	8.0–10.0	1.0	3.0–4.0	0.50	0.05–0.50	…	0.50	1.0	0.25	…	0.50
336.0	P	11.0–13.0	1.2	0.50–1.5	0.35	0.7–1.3	…	2.0–3.0	0.35	0.25	0.05	…
355.0	S&P	4.5–5.5	0.6[c]	1.0–1.5	0.50[c]	0.40–0.6	0.25	…	0.35	0.25	0.05	0.15
C355.0	S&P	4.5–5.5	0.20	1.0–1.5	0.10	0.40–0.6	…	…	0.10	0.20	0.05	0.15
356.0	S&P	6.5–7.5	0.6[c]	0.25	0.35[c]	0.20–0.45	…	…	0.35	0.25	0.05	0.15
356.0	S&P	6.5–7.5	0.20	0.20	0.10	0.25–0.45	…	…	0.10	0.20	0.05	0.15
357.0	S&P	6.5–7.5	0.15	0.05	0.03	0.45–0.6	…	…	0.05	0.20	0.05	0.15
A357.0	S&P	6.5–7.5	0.20	0.20	0.10	0.40–0.7	…	…	0.10	0.04–0.20	0.05[d]	0.15
443.0	S&P	4.5–6.0	0.8	0.6	0.50	0.05	0.25	…	0.50	0.25	…	0.35
B443.0	S&P	4.5–6.0	0.8	0.15	0.35	0.05	…	…	0.35	0.25	0.05	0.15
A444.0	P	6.5–7.5	0.20	0.10	0.10	0.05	…	…	0.10	0.20	0.05	0.15
512.0	S	1.4–2.2	0.6	0.35	0.8	3.5–4.5	0.25	…	0.35	0.25	0.05	0.15
513.0	P	0.30	0.40	0.10	0.30	3.5–4.5	…	…	1.4–2.2	0.20	0.05	0.15
514.0	S	0.35	0.50	0.15	0.35	3.5–4.5	…	…	0.15	0.25	0.05	0.15
520.0	S	0.25	0.30	0.25	0.15	9.5–10.6	…	…	0.15	0.25	0.05	0.15
705.0	S&P	0.20	0.8	0.20	0.40–0.6	1.4–1.8	0.20–0.40	…	2.7–3.3	0.25	0.05	0.15
707.0	S&P	0.20	0.8	0.20	0.40–0.6	1.8–2.4	0.20–0.40	…	4.0–4.5	0.25	0.05	0.15
710.0	S	0.15	0.50	0.35–0.65	0.05	0.6–0.8	…	…	6.0–7.0	0.25	0.05	0.15
711.0	P	0.30	0.7–1.4	0.35–0.65	0.05	0.25–0.45	…	…	6.0–7.0	0.20	0.05	0.15
712.0	S	0.30	0.50	0.25	0.10	0.50–0.65	0.40–0.6	…	5.0–6.5	0.15–0.25	0.05	0.20
850.0	S&P	0.7	0.7	0.7–1.3	0.10	0.10	…	0.7–1.3	…	0.20	__[e]	0.30
851.0	S&P	2.0–3.0	0.7	0.7–1.3	0.10	0.10	…	0.30–0.7	…	0.20	__[e]	0.30

[a] Also contains 0.40–1.0 per cent silver.

[b] Also contains 0.05 max. per cent tin.

[c] If iron exceeds 0.45 per cent, manganese content should not be less than one-half the iron content.

[d] Also contains 0.04-0.07 per cent beryllium.

[e] Also contains 5.5–7.0 per cent tin.

S = sand cast; P = permanent mold cast. The sum of those “Others” metallic elements 0.010 per cent or more each, expressed to the second decimal before determining the sum. *Source:* Standards for Aluminum Sand and Permanent Mold Castings. Courtesy of the Aluminum Association.

Characteristics of Principal Aluminum Alloy Series Groups.— *1000 series:* These alloys are characterized by high corrosion resistance, high thermal and electrical conductivity, low mechanical properties and good workability. Moderate increases in strength may be obtained by strain-hardening. Iron and silicon are the major impurities.

2000 series: Copper is the principal alloying element in this group. These alloys require solution heat-treatment to obtain optimum properties; in the heat-treated condition mechanical properties are similar to, and sometimes exceed, those of mild steel. In some instances artificial aging is employed to further increase the mechanical properties. This treatment materially increases yield strength, with attendant loss in elongation; its effect on tensile (ultimate) strength is not as great. The alloys in the 2000 series do not have as good corrosion resistance as most other aluminum alloys and under certain conditions they may be subject to intergranular corrosion. Therefore, these alloys in the form of sheet are usually clad with a high-purity alloy or a magnesium-silicon alloy of the 6000 series which provides galvanic protection to the core material and thus greatly increases resistance to corrosion. Alloy 2024 is perhaps the best known and most widely used aircraft alloy.

3000 series: Manganese is the major alloying element of alloys in this group, which are generally non-heat-treatable. Because only a limited percentage of manganese, up to about 1.5 per cent, can be effectively added to aluminum, it is used as a major element in only a few instances. One of these, however, is the popular 3003, used for moderate-strength applications requiring good workability.

4000 series: The major alloying element of this group is silicon, which can be added in sufficient quantities to cause substantial lowering of the melting point without producing brittleness in the resulting alloys. For these reasons aluminum-silicon alloys are used in welding wire and as brazing alloys where a lower melting point than that of the parent metal is required. Most alloys in this series are non-heat-treatable, but when used in welding heat-treatable alloys they will pick up some of the alloying constituents of the latter and so respond to heat-treatment to a limited extent. The alloys containing appreciable amounts of silicon become dark gray when anodic oxide finishes are applied, and hence are in demand for architectural applications.

5000 series: Magnesium is one of the most effective and widely used alloying elements for aluminum. When it is used as the major alloying element or with manganese, the result is a moderate to high strength non-heat-treatable alloy. Magnesium is considerably more effective than manganese as a hardener, about 0.8 per cent magnesium being equal to 1.25 per cent manganese, and it can be added in considerably higher quantities. Alloys in this series possess good welding characteristics and good resistance to corrosion in marine atmospheres. However, certain limitations should be placed on the amount of cold work and the safe operating temperatures permissible for the higher magnesium content alloys (over about 3½ per cent for operating temperatures over about 150 deg. F) to avoid susceptibility to stress corrosion.

6000 series: Alloys in this group contain silicon and magnesium in approximate proportions to form magnesium silicide, thus making them capable of being heat-treated. The major alloy in this series is 6061, one of the most versatile of the heat-treatable alloys. Though less strong than most of the 2000 or 7000 alloys, the magnesium-silicon (or magnesium-silicide) alloys possess good formability and corrosion resistance, with medium strength. Alloys in this heat-treatable group may be formed in the –T4 temper (solution heat-treated but not artificially aged) and then reach full –T6 properties by artificial aging.

7000 series: Zinc is the major alloying element in this group, and when coupled with a smaller percentage of magnesium, results in heat-treatable alloys of very high strength. Other elements such as copper and chromium are ussually added in small quantities. A notable member of this group is 7075, which is among the highest strength aluminum alloys available and is used in air-frame structures and for highly stressed parts.

Table 4a. Mechanical Property Limits for Commonly Used Aluminum Sand Casting Alloys

Alloy	Temper[a]	Minimum Properties			Typical Brinell Hardness (500 kgf load, 10-mm ball)
		Tensile Strength (ksi)		Elongation In 2 inches (%)	
		Ultimate	Yield		
201.0	T7	60.0	50.0	3.0	110–140
204.0	T4	45.0	28.0	6.0	…
208.0	F	19.0	12.0	1.5	40–70
222.0	O	23.0	…	…	65–95
222.0	T61	30.0	…	…	100–130
242.0	O	23.0	…	…	55–85
242.0	T571	29.0	…	…	70–100
242.0	T61	32.0	20.0	…	90–120
242.0	T77	24.0	13.0	1.0	60–90
295.0	T4	29.0	13.0	6.0	45–75
295.0	T6	32.0	20.0	3.0	60–90
295.0	T62	36.0	28.0	…	80–110
295.0	T7	29.0	16.0	3.0	55–85
319.0	F	23.0	13.0	1.5	55–85
319.0	T5	25.0	…	…	65–95
319.0	T6	31.0	20.0	1.5	65–95
328.0	F	25.0	14.0	1.0	45–75
328.0	T6	34.0	21.0	1.0	65–95
354.0	[b]	…	…	…	…
355.0	T51	25.0	18.0	…	50–80
355.0	T6	32.0	20.0	2.0	70–105
355.0	T7	35.0	…	…	70–100
355.0	T71	30.0	22.0	…	60–95
C355.0	T6	36.0	25.0	2.5	75–105
356.0	F	19.0	…	2.0	40–70
356.0	T51	23.0	16.0	…	45–75
356.0	T6	30.0	20.0	3.0	55–90
356.0	T7	31.0	29.0	…	60–90
356.0	T71	25.0	18.0	3.0	45–75
A356.0	T6	34.0	24.0	3.5	70–105
443.0	F	17.0	7.0	3.0	25–55
B443.0	F	17.0	6.0	3.0	25–55
512.0	F	17.0	10.0	…	35–65
514.0	F	22.0	9.0	6.0	35–65
520.0	T4[c]	42.0	22.0	12.0	60–90
535.0	F or T5	35.0	18.0	9.0	60–90
705.0	F or T5	30.0	17.0	5.0	50–80
707.0	T5	33.0	22.0	2.0	70–100
707.0	T7	37.0	30.0	1.0	65–95
710.0	F or T5	32.0	20.0	2.0	60–90
712.0	F or T5	34.0	25.0	4.0	60–90
713.0	F or T5	32.0	22.0	3.0	60–90
771.0	T5	42.0	38.0	1.5	85–115
771.0	T51	32.0	27.0	3.0	70–100
771.0	T52	36.0	30.0	1.5	70–100
771.0	T53	36.0	27.0	1.5	…
771.0	T6	42.0	35.0	5.0	75–105
771.0	T71	48.0	45.0	2.0	105–135
850.0	T5	16.0	…	5.0	30–60
851.0	T5	17.0	…	3.0	30–60
852.0	T5	24.0	18.0	…	45–75

[a] F indicates "as cast" condition.

[b] Mechanical properties for these alloys depend on the casting process. For further information consult the individual foundries.

[c] The T4 temper of Alloy 520.0 is unstable; significant room temperature aging occurs within life expectancy of most castings. Elongation may decrease by as much as 80 percent.

For separately cast test bars.

Source: Standards for Aluminum Sand and Permanent Mold Castings. Courtesy of the Aluminum Association.

Table 4b. Mechanical Property Limits for Commonly Used Aluminum Permanent Mold Casting Alloys

Alloy	Temper[a]	Minimum Properties			Typical Brinell Hardness (500 kgf load, 10-mm ball)
		Tensile Strength (ksi)		Elongation In 2 inches (%)	
		Ultimate	Yield		
204.0	T4	48.0	29.0	8.0	…
208.0	T4	33.0	15.0	4.5	60–90
208.0	T6	35.0	22.0	2.0	75–105
208.0	T7	33.0	16.0	3.0	65–95
222.0	T551	30.0	…	…	100–130
222.0	T65	40.0	…	…	125–155
242.0	T571	34.0	…	…	90–120
242.0	T61	40.0	…	…	95–125
296.0	T6	35.0	…	2.0	75–105
308.0	F	24.0	…	…	55–85
319.0	F	28.0	14.0	1.5	70–100
319.0	T6	34.0	…	2.0	75–105
332.0	T5	31.0	…	…	90–120
333.0	F	28.0	…	…	65–100
333.0	T5	30.0	…	…	70–105
333.0	T6	35.0	…	…	85–115
333.0	T7	31.0	…	…	75–105
336.0	T551	31.0	…	…	90–120
336.0	T65	40.0	…	…	110–140
354.0	T61	48.0	37.0	3.0	…
354.0	T62	52.0	42.0	2.0	…
355.0	T51	27.0	…	…	60–90
355.0	T6	37.0	…	1.5	75–105
355.0	T62	42.0	…	…	90–120
355.0	T7	36.0	…	…	70–100
355.0	T71	34.0	27.0	…	65–95
C355.0	T61	40.0	30.0	3.0	75–105
356.0	F	21.0	…	3.0	40–70
356.0	T51	25.0	…	…	55–85
356.0	T6	33.0	22.0	3.0	65–95
356.0	T7	25.0	…	3.0	60–90
356.0	T71	25.0	…	3.0	60–90
A356.0	T61	37.0	26.0	5.0	70–100
357.0	T6	45.0	…	3.0	75–105
A357.0	T61	45.0	36.0	3.0	85–115
359.0	T61	45.0	34.0	4.0	75–105
359.0	T62	47.0	38.0	3.0	85–115
443.0	F	21.0	7.0	2.0	30–60
B443.0	F	21.0	6.0	2.5	30–60
A444.0	T4	20.0	…	20.0	…
513.0	F	22.0	12.0	2.5	45–75
535.0	F	35.0	18.0	8.0	60–90
705.0	T5	37.0	17.0	10.0	55–85
707.0	T7	45.0	35.0	3.0	80–110
711.0	T1	28.0	18.0	7.0	55–85
713.0	T5	32.0	22.0	4.0	60–90
850.0	T5	18.0	…	8.0	30–60
851.0	T5	17.0	…	3.0	30–60
851.0	T6	18.0	…	8.0	…
852.0	T5	27.0	…	3.0	55–85

[a] F indicates "as cast" condition.

For separately cast test bars.

Source: Standards for Aluminum Sand and Permanent Mold Castings. Courtesy of the Aluminum Association.

Table 5. Typical Mechanical Properties of Wrought Aluminum Alloys

Alloy and Temper	Tension				Brinell Hardness Number (500 kg load, 10-mm ball)	Ultimate Shearing Strength (ksi)	Endurance Limit[a] (ksi)
	Strength (ksi)		Elongation in 2 inches (%)				
	Ultimate	Yield	$\frac{1}{16}$-inch Thick Specimen	$\frac{1}{2}$-inch Diameter Specimen			
1060-O	10	4	43	…	19	7	3
1060-H12	12	11	16	…	23	8	4
1060-H14	14	13	12	…	26	9	5
1060-H16	16	15	8	…	30	10	6.5
1060-H18	19	18	6	…	35	11	6.5
1100-O	13	5	35	45	23	9	5
1100-H12	16	15	12	25	28	10	6
1100-H14	18	17	9	20	32	11	7
1100-H16	21	20	6	17	38	12	9
1100-H18	24	22	5	15	44	13	9
1350-O	12	4	…	…[b]	…	8	…
1350-H12	14	12	…	…	…	9	…
1350-H14	16	14	…	…	…	10	…
1350-H16	18	16	…	…	…	11	…
1350-H19	27	24	…	…[c]	…	15	7
2011-T3	55	43	…	15	95	32	18
2011-T8	59	45	…	12	100	35	18
2014-O	27	14	…	18	45	18	13
2014-T4, T451	62	42	…	20	105	38	20
2014-T6, T651	70	60	…	13	135	42	18
Alclad 2014-O	25	10	21	…	…	18	…
Alclad 2014-T3	63	40	20	…	…	37	…
Alclad 2014-T4, T451	61	37	22	…	…	37	…
Alclad 2014-T6, T651	68	60	10	…	…	41	…
2017-O	26	10	…	22	45	18	13
2017-T4, T451	62	40	…	22	105	38	18
2018-T61	61	46	…	12	120	39	17
2024-O	27	11	20	22	47	18	13
2024-T3	70	50	18	…	120	41	20
2024-T4, T351	68	47	20	19	120	41	20
2024-T361[d]	72	57	13	…	130	42	18
Alclad 2024-O	26	11	20	…	…	18	…
Alclad 2024-T3	65	45	18	…	…	40	…
Alclad 2024-T4, T351	64	42	19	…	…	40	…
Alclad 202024-T361[d]	67	53	11	…	…	41	…
Alclad 2024-T81, T851	65	60	6	…	…	40	…
Alclad 2024-T861[d]	70	66	6	…	…	42	…
2025-T6	58	37	…	19	110	35	18
2036-T4	49	28	24	…	…	…	18[e]
2117-T4	43	24	…	27	70	28	14
2218-T72	48	37	…	11	95	30	…
2219-O	25	11	18	…	…	…	…
2219-T42	52	27	20	…	…	…	…
2219-T31, T351	52	36	17	…	…	…	…
2219-T37	57	46	11	…	…	…	…
2219-T62	60	42	10	…	…	…	15
2219-T81, T851	66	51	10	…	…	…	15

Table 5. *(Continued)* **Typical Mechanical Properties of Wrought Aluminum Alloys**

Alloy and Temper	Tension				Brinell Hardness Number (500 kg load, 10-mm ball)	Ultimate Shearing Strength (ksi)	Endurance Limit[a] (ksi)
	Strength (ksi)		Elongation in 2 inches (%)				
	Ultimate	Yield	$\frac{1}{16}$-inch Thick Specimen	$\frac{1}{2}$-inch Diameter Specimen			
2219-T87	69	57	10	…	…	…	15
3003-O	16	6	30	40	28	11	7
3003-H12	19	18	10	20	35	12	8
3003-H14	22	21	8	16	40	14	9
3003-H16	26	25	5	14	47	15	10
3003-H18	29	27	4	10	55	16	10
Alclad 3003-O	16	6	30	40	…	11	…
Alclad 3003-H12	19	18	10	20	…	12	…
Alclad 3003-H14	22	21	8	16	…	14	…
Alclad 3003-H16	26	25	5	14	…	15	…
Alclad 3003-H18	29	27	4	10	…	16	…
3004-O	26	10	20	25	45	16	14
3004-H32	31	25	10	17	52	17	15
3004-H34	35	29	9	12	63	18	15
3004-H36	38	33	5	9	70	20	16
3004-H38	41	36	5	6	77	21	16
Alclad 3004-O	26	10	20	25	…	16	…
Alclad 3004-H32	31	25	10	17	…	17	…
Alclad 3004-H34	35	29	9	12	…	18	…
Alclad 3004-H36	38	33	5	9	…	20	…
Alclad 3004-H38	41	36	5	6	…	21	…
3105-O	17	8	24	…	…	12	…
3105-H12	22	19	7	…	…	14	…
3105-H14	25	22	5	…	…	15	…
3105-H16	28	25	4	…	…	16	…
3105-H18	31	28	3	…	…	17	…
3105-H25	26	23	8	…	…	15	…
4032-T6	55	46	…	9	120	38	16
5005-O	18	6	25	…	28	11	…
5005-H12	20	19	10	…	…	14	…
5005-H14	23	22	6	…	…	14	…
5005-H16	26	25	5	…	…	15	…
5005-H18	29	28	4	…	…	16	…
5005-H32	20	17	11	…	36	14	…
5005-H34	23	20	8	…	41	14	…
5005-H36	26	24	6	…	46	15	…
5005-H38	29	27	5	…	51	16	…
5050-O	21	8	24	…	36	15	12
5050-H32	25	21	9	…	46	17	13
5050-H34	28	24	8	…	53	18	13
5050-H36	30	26	7	…	58	19	14
5050-H38	32	29	6	…	63	20	14
5052-O	28	13	25	30	47	18	16
5052-H32	33	28	12	18	60	20	17
5052-H34	38	31	10	14	68	21	18
5052-H36	40	35	8	10	73	23	19
5052-H38	42	37	7	8	77	24	20
5056-O	42	22	…	35	65	26	20

Table 5. *(Continued)* **Typical Mechanical Properties of Wrought Aluminum Alloys**

Alloy and Temper	Tension				Brinell Hardness Number (500 kg load, 10-mm ball)	Ultimate Shearing Strength (ksi)	Endurance Limit[a] (ksi)
	Strength (ksi)		Elongation in 2 inches (%)				
	Ultimate	Yield	$\frac{1}{16}$-inch Thick Specimen	$\frac{1}{2}$-inch Diameter Specimen			
5056-H18	63	59	…	10	105	34	22
5056-H38	60	50	…	15	100	32	22
5083-O	42	21	…	22	…	25	…
5083-H321, H116	46	33	…	16	…	…	23
5086-O	38	17	22	…	…	23	…
5086-H32, H116	42	30	12	…	…	…	…
5086-H34	47	37	10	…	…	27	…
5086-H112	39	19	14	…	…	…	…
5154-O	35	17	27	…	58	22	17
5154-H32	39	30	15	…	67	22	18
5154-H34	42	33	13	…	73	24	19
5154-H36	45	36	12	…	78	26	20
5154-H38	48	39	10	…	80	28	21
5154-H112	35	17	25	…	63	…	17
5252-H25	34	25	11	…	68	21	…
5252-H38, H28	41	35	5	…	75	23	…
5254-O	35	17	27	…	58	22	17
5254-H32	39	30	15	…	67	22	18
5254-H34	42	33	13	…	73	24	19
5254-H36	45	36	12	…	78	26	20
5254-H38	48	39	10	…	80	28	21
5254-H112	35	17	25	…	63	…	17
5454-O	36	17	22	…	62	23	…
5454-H32	40	30	10	…	73	24	…
5454-H34	44	35	10	…	81	26	…
5454-H111	38	26	14	…	70	23	…
5454-H112	36	18	18	…	62	23	…
5456-O	45	23	…	24	…	…	…
5456-H112	45	24	…	22	…	…	…
5456-H321, H116	51	37	…	16	90	30	…
5457-O	19	7	22	…	32	12	…
5457-H25	26	23	12	…	48	16	…
5457-H38, H28	30	27	6	…	55	18	…
5652-O	28	13	25	30	47	18	16
5652-H32	33	28	12	18	60	20	17
5652-H34	38	31	10	14	68	21	18
5652-H36	40	35	8	10	73	23	19
5652-H38	42	37	7	8	77	24	20
5657-H25	23	20	12	…	40	14	…
5657-H38, H28	28	24	7	…	50	15	…
6061-O	18	8	25	30	30	12	9
6061-T4, T451	35	21	22	25	65	24	14
6061-T6, T651	45	40	12	17	95	30	14
Alclad 6061-O	17	7	25	…	…	11	…
Alclad 6061-T4, T451	33	19	22	…	…	22	…
Alclad 6061-T6, T651	42	37	12	…	…	27	…
6063-O	13	7	…	…	25	10	8
6063-T1	22	13	20	…	42	14	9

Table 5. *(Continued)* **Typical Mechanical Properties of Wrought Aluminum Alloys**

Alloy and Temper	Tension				Brinell Hardness Number (500 kg load, 10-mm ball)	Ultimate Shearing Strength (ksi)	Endurance Limit[a] (ksi)
	Strength (ksi)		Elongation in 2 inches (%)				
	Ultimate	Yield	1/16-inch Thick Specimen	1/2-inch Diameter Specimen			
6063-T4	25	13	22	…	…	…	…
6063-T5	27	21	12	…	60	17	10
6063-T6	35	31	12	…	73	22	10
6063-T83	37	35	9	…	82	22	…
6063-T831	30	27	10	…	70	18	…
6063-T832	42	39	12	…	95	27	…
6066-O	22	12	…	18	43	14	…
6066-T4, T451	52	30	…	18	90	29	…
6066-T6, T651	57	52	…	12	120	34	16
6070-T6	55	51	10	…	…	34	14
6101-H111	14	11	…	…	…	…	…
6101-T6	32	28	15	…	71	20	…
6262-T9	58	55	…	10	120	35	13
6351-T4	36	22	20	…	…	…	…
6351-T6	45	41	14	…	95	29	13
6463-T1	22	13	20	…	42	14	10
6463-T5	27	21	12	…	60	17	10
6463-T6	35	31	12	…	74	22	10
7049-T73	75	65	…	12	135	44	…
7049-T7352	75	63	…	11	135	43	…
7050-T73510, T73511	72	63	…	12	…	…	…
7050-T7451[f]	76	68	…	11	…	44	…
7050-T7651	80	71	…	11	…	47	…
7075-O	33	15	17	16	60	22	…
7075-T6, T651	83	73	11	11	150	48	23
Alclad 7075-O	32	14	17	…	…	22	…
Alclad 7075-T6, T651	76	67	11	…	…	46	…
7178-O	33	15	15	16	…	…	…
7178-T6, T651	88	78	10	11	…	…	…
7178-T76, T7651	83	73	…	11	…	…	…
Alclad 7178-O	32	14	16	…	…	…	…
Alclad 7178-T6, T651	81	71	10	…	…	…	…
8176-H24	17	14	15	…	…	10	…

[a] Based on 500,000,000 cycles of completely reversed stress using the R. R. Moore type of machine and specimen.

[b] 1350-O wire should have an elongation of approximately 23 per cent in 10 inches.

[c] 1350-H19 wire should have an elongation of approximately 1.5 per cent in 10 inches.

[d] Tempers T361 and T861 were formerly designated T36 and T86, respectively.

[e] Based on 10^7 cycles using flexural type testing of sheet specimens.

[f] T7451, although not previously registered, has appeared in the literature and in some specifications as T73651.

The data given in this table are intended only as a basis for comparing alloys and tempers and should not be specified as engineering requirements or used for design purposes. The indicated typical mechanical properties for all except O temper material are higher than the specified minimum properties. For O temper products, typical ultimate and yield values are slightly lower than specified (maximum) values.

Source: Aluminum Standards and Data. Courtesy of the Aluminum Association.

Table 6. Nominal Compositions of Common Wrought Aluminum Alloys

Alloy	Alloying Elements — Aluminum and Normal Impurities Constitute Remainder							
	Si	Cu	Mn	Mg	Cr	Ni	Zn	Ti
1050	…	…	99.50 per cent minimum aluminum			…	…	…
1060	…	…	99.60 per cent minimum aluminum			…	…	…
1100	…	0.12	99.00 per cent minimum aluminum			…	…	…
1145	…	…	99.45 per cent minimum aluminum			…	…	…
1175	…	…	99.75 per cent minimum aluminum			…	…	…
1200	…	…	99.00 per cent minimum aluminum			…	…	…
1230	…	…	99.30 per cent minimum aluminum			…	…	…
1235	…	…	99.35 per cent minimum aluminum			…	…	…
1345	…	…	99.45 per cent minimum aluminum			…	…	…
1350[a]	…	…	99.50 per cent minimum aluminum			…	…	…
2011[b]	…	5.5	…	…	…	…	…	…
2014	0.8	4.4	0.8	0.50	…	…	…	…
2017	0.50	4.0	0.7	0.6	…	…	…	…
2018	…	4.0	…	0.7	…	2.0	…	…
2024	…	4.4	0.6	1.5	…	…	…	…
2025	0.8	4.4	0.8	…	…	…	…	…
2036	…	2.6	0.25	0.45	…	…	…	…
2117	…	2.6	…	0.35	…	…	…	…
2124	…	4.4	0.6	1.5	…	…	…	…
2218	…	4.0	…	1.5	…	2.0	…	…
2219[c]	…	6.3	0.30	…	…	…	…	0.06
2319[c]	…	6.3	0.30	…	…	…	…	0.15
2618[d]	0.18	2.3	…	1.6	…	1.0	…	0.07
3003	…	0.12	1.2	…	…	…	…	…
3004	…	…	1.2	1.0	…	…	…	…
3005	…	…	1.2	0.40	…	…	…	…
4032	12.2	0.9	…	1.0	…	0.9	…	…
4043	5.2	…	…	…	…	…	…	…
4045	10.0	…	…	…	…	…	…	…
4047	12.0	…	…	…	…	…	…	…
4145	10.0	4.0	…	…	…	…	…	…
5005	…	…	…	0.8	…	…	…	…
5050	…	…	…	1.4	…	…	…	…
5052	…	…	…	2.5	0.25	…	…	…
5056	…	…	0.12	5.0	0.12	…	…	…
5083	…	…	0.7	4.4	0.15	…	…	…
5086	…	…	0.45	4.0	0.15	…	…	…
5183	…	…	0.8	4.8	0.15	…	…	…
5252	…	…	…	2.5	…	…	…	…
5254	…	…	…	3.5	0.25	…	…	…
5356	…	…	0.12	5.0	0.12	…	…	0.13
5456	…	…	0.8	5.1	0.12	…	…	…
5457	…	…	0.30	1.0	…	…	…	…
5554	…	…	0.8	2.7	0.12	…	…	0.12

Table 6. *(Continued)* **Nominal Compositions of Common Wrought Aluminum Alloys**

Alloy	Alloying Elements — Aluminum and Normal Impurities Constitute Remainder							
	Si	Cu	Mn	Mg	Cr	Ni	Zn	Ti
5556	…	…	0.8	5.1	0.12	…	…	0.12
5652	…	…	…	2.5	0.25	…	…	…
5654	…	…	…	3.5	0.25	…	…	0.10
6003	0.7	…	…	1.2	…	…	…	…
6005	0.8	…	…	0.50	…	…	…	…
6053	0.7	…	…	1.2	0.25	…	…	…
6061	0.6	0.28	…	1.0	0.20	…	…	…
6066	1.4	1.0	0.8	1.1	…	…	…	…
6070	1.4	0.28	0.7	0.8	…	…	…	…
6101	0.50	…	…	0.6	…	…	…	…
6105	0.8	…	…	0.62	…	…	…	…
6151	0.9	…	…	0.6	0.25	…	…	…
6201	0.7	…	…	0.8	…	…	…	…
6253	0.7	…	…	1.2	0.25	…	2.0	…
6262[e]	0.6	0.28	…	1.0	0.09	…	…	…
6351	1.0	…	0.6	0.6	…	…	…	…
6463	0.40	…	…	0.7	…	…	…	…
7005[f]	…	…	0.45	1.4	0.13	…	4.5	0.04
7008	…	…	…	1.0	0.18	…	5.0	…
7049	…	1.6	…	2.4	0.16	…	7.7	…
7050[g]	…	2.3	…	2.2	6.2	…	…	…
7072	…	…	…	…	…	…	1.0	…
7075	…	1.6	…	2.5	0.23	…	5.6	…
7108[h]	…	…	…	1.0	…	…	5.0	…
7178	…	2.0	…	2.8	0.23	…	6.8	…
8017[i]	…	0.15	…	0.03	…	…	…	…
8030[j]	…	0.22	…	…	…	…	…	…
8177[k]	…	…	…	0.08	…	…	…	…

[a] Formerly designated EC.
[b] Lead and bismuth, 0.40 per cent each.
[c] Vanadium 0.10 per cent; zirconium 0.18 per cent.
[d] Iron 1.1 per cent.
[e] Lead and bismuth, 0.6 per cent each.
[f] Zirconium 0.14 per cent.
[g] Zirconium 0.12 per cent.
[h] Zirconium 0.18 per cent.
[i] Iron 0.7 per cent.
[j] Boron 0.02 per cent.
[k] Iron 0.35 per cent.
Source: Aluminum Standards and Data. Courtesy of the Aluminum Association.

Magnesium Alloys

Magnesium Alloys.—Magnesium is the lightest of all structural metals. Silver-white in color, pure magnesium is relatively soft, so is rarely used for structural purposes in the pure state. Principal metallurgical uses for pure magnesium are as an alloying element for aluminum and other metals; as a reducing agent in the extraction of such metals as titanium, zirconium, hafnium, and uranium; as a nodularizing agent in the manufacture of ductile iron; and as a sulfur removal agent in steel manufacture. Magnesium alloys are made by alloying up to about 10 per cent of other metals and have low density and an excellent combination of mechanical properties, as shown in Table 7a, resulting in high strength-to-weight ratios.

Magnesium alloys are the easiest of all the structural metals to machine, and these alloys have very high weld efficiencies. Magnesium is readily processed by all the standard casting and fabrication techniques used in metalworking, especially by pressure die casting. Because the metal work hardens rapidly, cold forming is limited to mild deformation, but magnesium alloys have excellent working characteristics at temperatures between 300 and 500 degrees F.

These alloys have relatively low elastic moduli, so they will absorb energy with good resistance to dents and high damping capacities. Fatigue strength also is good, particularly in the low-stress, high-cycle range. The alloys can be precipitation hardened, so mechanical properties can be improved by solution heat treatment and aging. Corrosion resistance was greatly improved recently, when methods were found to limit heavy metal impurities to “parts per million.”

Applications of Magnesium Alloys.—Magnesium alloys are used in a wide variety of structural applications including industrial, materials handling, automotive, consumer-durable, and aerospace equipment. In industrial machinery, the alloys are used for parts that operate at high speeds, which must have light weight to allow rapid acceleration and minimize inertial forces. Materials handling equipment applications include hand trucks, dockboards, grain shovels, and gravity conveyors. Automotive applications include wheels, gearboxes, clutch housings, valve covers, and brake pedal and other brackets. Consumer durables include luggage, softball bats, tennis rackets, and housings for cameras and projectors. Their high strength-to-weight ratio suits magnesium alloys to use in a variety of aircraft structures, particularly helicopters. Very intricate shapes that are uneconomical to produce in other materials are often cast in magnesium, sometimes without draft. Wrought magnesium alloys are made in the form of bars, forgings, extrusions, wire, sheet, and plate.

Alloy and Temper Designation.—Magnesium alloys are designated by a standard four-part system established by the ASTM, and now also used by the SAE, that indicates both chemical composition and temper. Designations begin with two letters representing the two alloying elements that are specified in the greatest amount; these letters are arranged in order of decreasing percentage of alloying elements or alphabetically if they are present in equal amounts. The letters are followed by digits representing the respective composition percentages, rounded off to whole numbers, and then by a serial letter indicating some variation in composition of minor constituents. The final part, separated by a hyphen, consists of a letter followed by a number, indicating the temper condition. The letters that designate the more common alloying elements are A, aluminum; E, rare earths; H, thorium; K, zirconium; M, manganese; Q, silver; S, silicon; T, tin; Z, zinc.

The letters and numbers that indicate the temper designation are: F, as fabricated; O, annealed; H10, H11, strain hardened; H23, H24, H26, strain hardened and annealed; T4, solution heat treated; T5, artificially aged; T6, solution heat treated and artificially aged; and T8, solution heat treated, cold-worked, and artificially aged.

The nominal composition and typical properties of magnesium alloys are listed in Table 7a.

Table 7a. Nominal Compositions of Magnesium Alloys

Alloy	Al	Zn	Mn[a]	Si	Zr	Ag	Th	Y	Rare Earth
Sand and Permanent Mold (Gravity Die) Castings									
AM100A-T61	10.0	…	0.10	…	…	…	…	…	…
AZ63A-T6	6.0	3.0	0.15	…	…	…	…	…	…
AZ81A-T4	7.6	0.7	0.13	…	…	…	…	…	…
AZ91C-T6	8.7	0.7	0.13	…	…	…	…	…	…
AZ91E-T6[b]	8.7	0.7	0.17	…	…	…	…	…	…
AZ92A-T6	9.0	2.0	0.10	…	…	…	…	…	…
EZ33A-T5	…	2.6	…	…	0.8	…	…	…	3.3
HK31A-T6	…	0.3	…	…	0.7	…	3.3	…	…
HZ32A-T6	…	2.1	…	…	0.8	…	3.3	…	0.1
K1A-F	…	…	…	…	0.7	…	…	…	…
QE22A-T6	…	…	…	…	0.7	2.5	…	…	2.2
QH21A-T6	…	0.2	…	…	0.7	…	1.1	…	1.1
ZE41A-T5	…	4.3	0.15	…	0.7	…	…	…	1.3
ZE63A-T6	…	5.8	…	…	0.7	…	…	…	2.6
ZH62A-T5	…	5.7	…	…	0.8	…	1.8	…	…
ZK51A-T5	…	4.6	…	…	0.8	…	…	…	…
ZK61A-T6	…	6.0	…	…	0.8	…	…	…	…
WE54A-F	…	…	…	…	0.5	…	…	5.3	3.5
Pressure Die Castings									
AZ91A-F	9.0	0.7	0.13	…	…	…	…	…	…
AZ91B-F[c]	9.0	0.7	0.13	…	…	…	…	…	…
AZ91D-F[b]	9.0	0.7	0.15	…	…	…	…	…	…
AM60A-F	6.0	…	0.13	…	…	…	…	…	…
AM60B-F[b]	6.0	…	0.25	…	…	…	…	…	…
AS41A-F[d]	4.3	…	0.35	1.0	…	…	…	…	…
Extruded Bars and Shapes									
AZ10A-F	1.3	0.4	0.20	…	…	…	…	…	…
AZ31B-F	3.0	1.0	0.20	…	…	…	…	…	…
AZ31C-F	3.0	1.0	0.15	…	…	…	…	…	…
AZ61A-F	6.5	1.0	0.15	…	…	…	…	…	…
AZ80A-T5	8.5	0.5	0.12	…	…	…	…	…	…
HM31A-F	…	…	1.20	…	…	…	3.0	…	…
M1A-F	…	…	1.20	…	…	…	…	…	…
ZK40A-T5	…	4.0	…	…	0.45	…	…	…	…
ZK60A-F	…	5.5	…	…	0.45	…	…	…	…
Sheet and Plate									
AZ31B-H24	3.0	1.0	0.20	…	…	…	…	…	…
AZ31C-H24	3.0	1.0	0.15	…	…	…	…	…	…
HK31A-H24	…	…	…	…	0.7	…	3.3	…	…
HM21A-T8	…	…	0.80	…	…	…	2.0	…	…

[a] All manganese vales are minium.

[b] High-purity alloy, Ni, Fe, and Cu severely restricted.

[c] 0.30 per cent maximum residual copper is allowed.

[d] For battery applications.

Source: Metals Handbook, 9th edition, Vol. 2, American Society for Metals.

Table 7b. Typical Room-Temperature Mechanical Properties of Magnesium Alloys

Alloy	Tensile Strength (ksi)	Yield Strength			Elongation in 2 in. (%)	Shear Strength (ksi)	Hardness Rockwell B[a]
		Tensile (ksi)	Compressive (ksi)	Bearing (ksi)			
Sand and Permanent Mold (Gravity Die) Castings							
AM100A-T61	40	22	22	68	1	…	69
AZ63A-T6	40	14	14	44	12	18	55
AZ81A-T4	40	12	12	35	15	21	55
AZ91C-T6	40	21	21	52	6	21	70
AZ91E-T6[b]	40	21	21	52	6	21	70
AZ92A-T6	40	22	22	65	3	21	81
EZ33A-T5	23	16	16	40	3	20	50
HK31A-T6	32	15	15	40	8	21	55
HZ32A-T6	27	13	13	37	4	20	55
K1A-F	26	8	8	18	19	8	…
QE22A-T6	38	28	28	…	3	…	80
QH21A-T6	40	30	30	…	4	22	…
ZE41A-T5	30	20	20	51	4	23	62
ZE63A-T6	44	28	28	…	10	…	60–85
ZH62A-T5	35	22	22	49	4	23	70
ZK51A-T5	30	20	20	51	4	22	62
ZK61A-T6	45	28	28	…	10	…	…
WE54A-F	40	29	29	…	4	…	…
Pressure Die Castings							
AZ91A-F	34	23	23	…	3	20	63
AZ91B-FAZ91B-F[c]	34	23	23	…	3	20	63
AZ91D-F[b]	34	23	23	…	3	20	63
AM60A-F	32	19	19	…	8	…	…
AM60B-F[b]	32	19	19	…	8	…	…
AS41A-F[d]	31	20	20	…	6	…	…
Extruded Bars and Shapes							
AZ10A-F	35	21	10	…	10	…	…
AZ31B-F	38	29	14	33	15	19	49
AZ31C-F	38	29	14	33	15	19	49
AZ61A-F	45	33	19	41	16	20	60
AZ80A-T5	55	40	35	…	7	24	82
HM31A-F	42	33	27	50	10	22	…
M1A-F	37	26	12	28	12	18	44
ZK40A-T5	40	37	20	…	4	…	…
ZK60A-F	51	41	36	59	11	26	88
Sheet and Plate							
AZ31B-H24	42	32	26	47	15	23	73
AZ31C-H24	42	32	26	47	15	23	73
HK31A-H24	38	30	23	41	9	…	68
HM21A-T8	34	25	19	39	11	18	…

[a] 500 kg load, 10-mm ball.
[b] High-purity alloy, Ni, Fe, and Cu severely restricted.
[c] 0.30 per cent maximum residual copper is allowed.
[d] For battery applications.

Source: Metals Handbook, 9th edition, Vol. 2, American Society for Metals.

Nickel and Nickel Alloys

Nickel is a white metal, similar in some respects to iron but with good oxidation and corrosion resistances. Nickel and its alloys are used in a variety of applications, usually requiring specific corrosion resistance or high strength at high temperature. Some nickel alloys exhibit very high toughness; others have very high strength, high proportional limits, and high moduli compared with steel. Commercially, pure nickel has good electrical, magnetic, and magnetostrictive properties. Nickel alloys are strong, tough, and ductile at cryogenic temperatures, and several of the so-called nickel-based superalloys have good strength at temperatures up to 2000 degrees F.

Most wrought nickel alloys can be hot and cold-worked, machined, and welded successfully; an exception is the most highly alloyed nickel compound—forged nickel-based superalloys—in which these operations are more difficult. The casting alloys can be machined or ground, and many can be welded and brazed.

There are five categories into which the common nickel-based metals and alloys can be separated: the pure nickel and high nickel (over 94 per cent Ni) alloys; the nickel–molybdenum and nickel–molybdenum–chromium superalloys, which are specifically for corrosive or high-temperature, high-strength service; the nickel–molybdenum–chromium–copper alloys, which are also specified for corrosion applications; the nickel–copper (Monel) alloys, which are used in actively corrosive environments; and the nickel–chromium and nickel–chromium–iron superalloys, which are noted for their strength and corrosion resistance at high temperatures.

Descriptions and compositions of some commonly used nickel and high nickel alloys are shown in Table .

Titanium and Titanium Alloys

Titanium is a gray, light metal with a better strength-to-weight ratio than any other metal at room temperature, and is used in corrosive environments or in applications that take advantage of its light weight, good strength, and nonmagnetic properties. Titanium is available commercially in many alloys, but multiple requirements can be met by a single grade of the commercially pure metal. The alloys of titanium are of three metallurgical types: alpha, alpha–beta, and beta, with these designations referring to the predominant phases present in the microstructure.

Titanium has a strong affinity for hydrogen, oxygen, and nitrogen gases, which tend to embrittle the material; carbon is another embrittling agent. Titanium is outstanding in its resistance to strongly oxidizing acids, aqueous chloride solutions, moist chlorine gas, sodium hypochlorite, and seawater and brine solutions. Nearly all nonaircraft applications take advantage of this corrosion resistance. Its uses in aircraft engine compressors and in airframe structures are based on both its high corrosion resistance and high strength-to-weight ratio.

Procedures for forming titanium are similar to those for forming stainless steel. Titanium and its alloys can be machined and abrasive ground; however, sharp tools and continuous feed are required to prevent work hardening. Tapping is difficult because the metal galls.

Titanium castings can be produced by investment or graphite mold methods; however, because of the highly reactive nature of the metal in the presence of oxygen, casting must be done in a vacuum.

Generally, titanium is welded by gas-tungsten arc or plasma arc techniques, and the key to successful welding lies in proper cleaning and shielding. The alpha–beta titanium alloys can be heat treated for higher strength, but they are not easily welded. Beta and alpha–beta alloys are designed for formability; they are formed in the soft state, and then heat treated for high strength.

The properties of some wrought titanium alloys are shown in Table 9.

Table 8. Common Cast and Wrought Nickel and High Nickel Alloys — Designations, Compositions, Typical Properties, and Uses

			Typical Room-Temperature Properties				
UNS Designation	Description and Common Name	Nominal Composition (Weight %)	Tensile (ksi)	0.2% Yield (ksi)	Elong. (%)	Form	Typical Uses
N02200	Commercially pure Ni (Nickel 200)	99.5 Ni	67	22	47	Wrought	Food processing and chemical equipment.
N04400	Nickel–copper alloy (Monel 400)	65 Ni, 32 Cu, 2 Fe	79	30	48	Wrought	Valves, pumps, shafts, marine fixtures and fasteners, electrical and petroleum refining equipment.
N05500	Age-hardened Ni–Cu alloy (Monel K 500)	65 Ni, 30 Cu, 2 Fe, 3 Al + Ti	160	111	24	Wrought	Pump shafts, impellers, springs, fasteners, and electronic and oil well components.
N06002	Ni–Cr Alloy (Hastelloy X)	60 Ni, 22 Cr, 19 Fe, 9 Mo, 0.6 W	114	52	43	Wrought	Turbine and furnace parts, petrochemical equipment.
N06003	Ni–Cr alloy (Nichrome V)	80 Ni, 20 Cr	100	60	30	Wrought	Heating elements, resistors, electronic parts.
N06333	Ni–Cr alloy (RA 333)	48 Ni, 25 Cr, 18 Fe, 3 Mo, 3 W, 3 Co	100	50	50	Wrought	Turbine and furnace parts.
N06600	Ni–Cr alloy (Inconel 600)	75 Ni, 15 Cr, 10 Fe	90	36	47	Wrought	Chemical, electronic, food processing and heat treating equipment; nuclear steam generator tubing.
N06625	Ni–Cr alloy (Inconel 625)	61 Ni, 21 Cr, 2 Fe, 9 Mo, 4 Nb	142	86	42	Wrought	Turbine parts, marine and chemical equipment.
N07001	Age-hardened Ni–Cr alloy (Waspalloy)	58 Ni, 20 Cr, 14 Co, 4 Mo, 3 Al, 1.3 Ti, B, Zr	185	115	25	Wrought	Turbine parts.
N07500	Age-hardened Ni–Cr alloy (Udimet 500)	52 Ni, 18 Cr, 19 Co, 4 Mo, 3 Al, 3 Ti, B, Zr	176	110	16	Wrought & Cast	Turbine parts.

Table 8. *(Continued)* **Common Cast and Wrought Nickel and High Nickel Alloys — Designations, Compositions, Typical Properties, and**

UNS Designation	Description and Common Name	Nominal Composition (Weight %)	Typical Room-Temperature Properties			Form	Typical Uses
			Tensile (ksi)	0.2% Yield (ksi)	Elong. (%)		
N07750	Age-hardened Ni–Cr alloy (Inconel X-750)	73 Ni, 16 Cr, 7 Fe, 2.5 Ti, 1 Al, 1 Nb	185	130	20	Wrought	Turbine parts, nuclear reactor springs, bolts, extrusion dies, forming tools.
N08800	Ni–Cr–Fe alloy (Incoloy 800)	32 Ni, 21 Cr, 46 Fe, 0.4 Ti, 0.4 Al	87	42	44	Wrought	Heat exchangers, furnace parts, chemical and power plant piping.
N08825	Ni–Cr–Fe alloy (Incoloy 825)	42 Ni, 22 Cr, 30 Fe, 3 Mo, 2 Cu, 1 Ti, Al	91	35	50	Wrought	Heat treating and chemical handling equipment.
N09901	Age-hardened Ni–Cr–Fe alloy (Incoloy 901)	43 Ni, 12 Cr, 36 Fe, 6 Mo, 3 Ti + Al, B	175	130	14	Wrought	Turbine parts.
N10001	Ni–Mo alloy (Hastelloy B)	67 Ni, 28 Mo, 5 Fe	121	57	63	Wrought	Chemical handling equipment.
N10004	Ni–Cr–Mo alloy (Hastelloy W)	59 Ni, 5 Cr, 25 Mo, 5 Fe, 0.6 V	123	53	55	Wrought	Weld wire for joining dissimilar metals, engine repair and maintenance.
N10276	Ni–Cr–Mo alloy (Hastelloy C-276)	57 Ni, 15 Cr, 16 Mo, 5 Fe, 4 W, 2 Co	116	52	60	Wrought	Chemical handling equipment.
N13100	Ni–Co alloy (IN 100)	60 Ni, 10 Cr, 15 Co, 3 Mo, 5.5 Al, 5 Ti, 1 V. B, Zr	147	123	9	Cast	Turbine parts.

Table 9. Mechanical Properties of Wrought Titanium Alloys

Nominal Composition (%)	Condition	Tensile Strength (ksi)	Room Temperature		Reduction in Area (%)
			Yield Strength (ksi)	Elongation (%)	
Commercially Pure					
99.5 Ti	Annealed	48	35	30	55
99.2 Ti	Annealed	63	50	28	50
99.1 Ti	Annealed	75	65	25	45
99.0 Ti	Annealed	96	85	20	40
99.2 Ti[a]	Annealed	63	50	28	50
98.9[b]	Annealed	75	65	25	42
Alpha Alloys					
5 Al, 2.5 Sn	Annealed	125	117	16	40
5 Al, 2.5 Sn (low O_2)	Annealed	117	108	16	…
Near Alpha Alloys					
8 Al, 1 Mo, 1 V	Duplex annealed	145	138	15	28
11 Sn, 1 Mo, 2.25 Al, 5.0 Zr, 1 Mo, 0.2 Si	Duplex annealed	160	144	15	35
6 Al, 2 Sn, 4 Zr, 2 Mo	Duplex annealed	142	130	15	35
5 Al, 5 Sn, 2 Zr, 2 Mo, 0.25 Si	975°C (1785°F) (½ h), AC 595°C (1100°F)(2 h), AC	152	140	13	…
6 Al, 2 Nb, 1 Ta, 1 Mo	As rolled 2.5 cm (1 in.) plate	124	110	13	34
6 Al, 2 Sn, 1.5 Zr, 1 Mo, 0.35 Bi, 0.1 Si	Beta forge + duplex anneal	147	137	11	…
Alpha–Beta Alloys					
8 Mn	Annealed	137	125	15	32
3 Al, 2.5 V	Annealed	100	85	20	…
6 Al, 4 V	Annealed	144	134	14	30
	Solution + age	170	160	10	25
6 Al, 4 V (low O_2)	Annealed	130	120	15	35
6 Al, 6 V, 2 Sn	Annealed	155	145	14	30
	Solution + age	185	170	10	20
7 Al, 4 Mo	Solution + age	160	150	16	22
6 Al, 2 Sn, 4 Zr, 6 Mo	Solution + age	184	170	10	23
6 Al, 2 Sn, 2 Zr, 2 Mo, 2 Cr, 0.25 Si	Solution + age	185	165	11	33
10 V, 2 Fe, 3 Al	Solution + age	185	174	10	19
Beta Alloys					
13 V, 11 Cr, 3 Al	Solution + age	177	170	8	…
	Solution + age	185	175	8	…
8 Mo, 8 V, 2 Fe, 3 Al	Solution + age	190	180	8	…
3 Al, 8 V, 6 Cr, 4 Mo, 4 Zr	Solution + age	210	200	7	…
	Annealed	128	121	15	…
11.5 Mo, 6 Zr, 4.5 Sn	Solution + age	201	191	11	…

[a] Also contains 0.2 Pd.

[b] Also contains 0.8 Ni and 0.3 Mo.

Source: Titanium Metals Corp. of America and RMI Co.

Copper–Silicon and Copper–Beryllium Alloys

Everdur.—This copper–silicon alloy is available in five slightly different nominal compositions for applications that require high strength, good fabricating and fusing qualities, immunity to rust, free-machining and a corrosion resistance equivalent to copper. The following table gives the nominal compositions and tensile strengths, yield strengths, and per cent elongations for various tempers and forms.

Table 10. Nominal Composition and Properties of Everdur

Desig. No.	Nominal Composition					Temper[a]	Strength		Elongation (%)
	Cu	Si	Mn	Pb	Al		Tensile (ksi)	Yield (ksi)	
655	95.80	3.10	1.10	…	…	A	52	15	35[b]
						HRA	50	18	40
						CRA	52	18	35
						CRHH	71	40	10
						CRH	87	60	3
						H	70 to 85	38 to 50	17 to 8[b]
651	98.25	1.50	0.25	…	…	AP	38	10	35
						HP	50	40	7
						XHB	75 to 85	45 to 55	8 to 6[b]
661	95.60	3.00	1.00	0.40	…	A	52	15	35[b]
						H	85	50	13 to 8[b]
6552	94.90	4.00	1.10	…	…	AC	45	…	15
637	90.75	2.00	…	…	7.25	A	75 to 90	37.5 to 45	12 to 9[b]

[a] Symbols used are: HRA for hot-rolled and annealed tank plates; CRA for cold-rolled sheets and strips; CRHH for cold-rolled half hard strips; abd CRH for cold-rolled hard strips. For round, square, hexagonal, and octagonal rods: A for anealed; H for hard; and XHB for extra-hard bolt temper (in coils for cold-heading). For pipe and tube: AP for annealed; and HP for hard. For castings: AC for as cast.

[b] Per cent elongation in 4 times the diameter or thickness of the specimen. All other values are per cent elongation in 2 inches.

Designation numbers are those of the American Brass Co.

The values given for the tensile srength, yield strength, and elongation are all minimum values. Where ranges are shown, the first values given are for the largest diameter or largest size specimens. Yield strength values were determined at 0.50 per cent elongation under load.

Copper–Beryllium Alloys.—Alloys of copper and beryllium present health hazards. Particles produced by machining may be absorbed into the body through the skin, the mouth, the nose, or an open wound, resulting in a condition requiring immediate medical attention. Working of these alloys requires protective clothing or other shielding in a monitored environment. Copper–beryllium alloys involved in a fire give off profuse toxic fumes that must not be inhaled.

These alloys contain copper, beryllium, cobalt, and silver, and fall into two groups. One group whose beryllium content is greater than one per cent is characterized by its high strength and hardness and the other, whose beryllium content is less than one per cent, by its high electrical and thermal conductivity. The alloys have many applications in the electrical and aircraft industries or wherever strength, corrosion resistance, conductivity, nonmagnetic and nonsparking properties are essential. Beryllium copper is obtainable in the form of strips, rods and bars, wire, platers, bars, billets, tubes, and casting ingots.

Composition and Properties: Table 11 lists some of the more common wrought alloys and gives some of their mechanical properties.

Table 11. Wrought Copper–Beryllium Properties

Alloy[a]	Form	Temper[b]	Heat Treatment	Tensile Strength (ksi)	Yield Strength 0.2% Offset (ksi)	Elongation in 2 in. (%)
25	Rod, Bar, and Plate	A	…	60–85	20–30	35–60
		½ H or H	…	85–130	75–105	10–20
		AT	3 hr at 600°F or mill heat treated	165–190	145–175	3–10
		½ HT or HT	2 hr at 600°F or mill heat treated	175–215	150–200	2–5
	Wire	A	…	58–78	20–35	35–55
		¼ H	…	90–115	70–95	10–35
		½ H	…	110–135	90–110	5–10
		¾ H	…	130–155	110–135	2–8
		AT	3 hr at 600°F	165–190	145–175	3–8
		¼ HT	2 hr at 600°F	175–205	160–190	2–5
		½ HT	2 hr at 600°F	190–215	175–200	1–3
		¾ HT	2 hr at 600°F	195–220	180–205	1–3
		XHT	Mill heat treated	115–165	95–145	2–8
165	Rod, Bar, and Plate	A	…	60–85	20–30	35–60
		½ H or H	…	85–130	75–105	10–20
		AT	3 hr at 650°F or mill heat treated	150–180	125–155	4–10
		½ HT or HT	2 hr at 650°F or mill heat treated	165–200	135–165	2–5
10	Rod, Bar, and Plate	A	…	35–55	20–30	20–35
		½ H or H	…	65–80	55–75	10–15
		AT	3 hr at 900°F or mill heat treated	100–120	80–100	10–25
		½ HT or HT	2 hr at 900°F or mill heat treated	110–130	100–120	8–20
50	Rod, Bar, and Plate	A	…	35–55	20–30	20–35
		½ H or H	…	65–80	55–75	10–15
		AT	3 hr at 900°F or mill heat treated	100–120	80–100	10–25
		½ HT or HT	2 hr at 900°F or mill heat treated	110–130	100–120	8–20
35	Rod, Bar, and Plate	A	…	35–55	20–30	20–35
		½ H or H	…	65–80	55–75	10–15
		AT	3 hr at 900°F or mill heat treated	100–120	80–100	10–25
		½ HT or HT	2 hr at 900°F or mill heat treated	110–130	100–120	8–20

[a] Composition (in per cent) of alloys is asfollows: alloy 25: 1.80–2.05 Be, 0.20–0.35 Co, balance Cu; alloy 165: 1.6–1.8 Be, 0.20–0.35 Co, balance Cu; alloy 10: 0.4–0.7 Be, 2.35–2.70 Co, balance Cu; alloy 50, 0.25–0.50 Be, 1.4–1.7 Co, 0.9–1.1 Ag, balance Cu; alloy 35, 0.25–0.50 Be, 1.4–1.6 Ni, balance Cu.

[b] Temper symbol designations: A, solution annealed; H, hard; HT, heat-treated from hard; At, heat-treated from solution annealed.

PLASTICS

Properties of Plastics

Characteristics of Important Plastics Families

ABS (acrylonitrile-butadiene-styrene)	Rigid, low-cost thermoplastic, easily machined and thermo-formed.
Acetal	Engineering thermoplastic with good strength, wear resistance, and dimensional stability. More dimensionally stable than nylon under wet and humid conditions.
Acrylic	Clear, transparent, strong, break-resistant thermoplastic with excellent chemical resistance and weatherability.
CPVC (chlorinated PVC)	Thermoplastic with properties similar to PVC, but operates to a 40-60°F higher temperature.
Fiberglass	Thermosetting composite with high strength-to-weight ratio, excellent dielectric properties, and unaffected by corrosion.
Nylon	Thermoplastic with excellent impact resistance, ideal for wear applications such as bearings and gears, self-lubricating under some circumstances.
PEEK (polyetherether-ketone)	Engineering thermoplastic, excellent temperature resistance, suitable for continuous use above 500°F, excellent flexural and tensile properties.
PET (polyethylene-terephthalate)	Dimensionally stable thermoplastic with superior machining characteristics compared to acetal.
Phenolic	Thermosetting family of plastics with minimal thermal expansion, high compressive strength, excellent wear and abrasion resistance, and a low coefficient of friction. Used for bearing applications and molded parts.
Polycarbonate	Transparent tough thermoplastic with high impact strength, excellent chemical resistance and electrical properties, and good dimensional stability.
Polypropylene	Good chemical resistance combined with low moisture absorption and excellent electrical properties, retains strength up to 250°F.
Polysulfone	Durable thermoplastic, good electrical properties, operates at temperatures in excess of 300°F.
Polyurethane	Thermoplastic, excellent impact and abrasion resistance, resists sunlight and weathering.
PTFE (polytetrafluoro-ethylene)	Thermoplastic, low coefficient of friction, withstands up to 500°F, inert to chemicals and solvents, self-lubricating with a low thermal-expansion rate.
PVC (polyvinyl chloride)	Thermoplastic, resists corrosive solutions and gases both acid and alkaline, good stiffness.
PVDF (polyvinylidene-fluoride)	Thermoplastic, outstanding chemical resistance, excellent substitute for PVC or polypropylene. Good mechanical strength and dielectric properties.

Plastics Materials.—Plastics materials, often called resins, are made up of many repeating groups of atoms or molecules linked in long chains (called polymers) that combine such elements as oxygen, hydrogen, nitrogen, carbon, silicon, fluorine, and sulfur. Both the lengths of the chains and the mechanisms that bond the links of the chains together are related directly to the mechanical and physical properties of the materials. There are two main groups: thermoplastics and thermosets.

Thermoplastic materials become soft and moldable when heated, and change back to solids when allowed to cool. Examples of thermoplastics are acetal, acrylic, cellulose acetate, nylon, polyethylene, polystyrene, vinyl, and nylon. Thermoplastic materials that are flexible even when cool are known as thermoplastic elastomers or TPEs. When thermoplastic materials are heated, the linked chains of molecules can move relative to each other, allowing the mass to flow into a different shape. Cooling prevents further flow. Although the heating/cooling cycle can be repeated, recycling reduces mechanical properties and appearance.

Thermoset plastics such as amino, epoxy, phenolic, and unsaturated polyesters, are so named because they are changed chemically during processing and become hard solids. Although the structures of thermoset materials are similar to those of thermoplastic materials, processing develops cross-links between adjacent molecules, forming complex networks that prevent relative movement between the chains at any temperature. Many rubbers that are processed by vulcanizing, such as butyl, latex, neoprene, nitrile, polyurethane, and silicone, also are classified as thermosets. Heating a thermoset degrades the material so that it cannot be reprocessed satisfactorily.

Elastomers are flexible materials that can be stretched up to about double their length at room temperature and can return to their original length when released. Thermoplastic elastomers are often used in place of rubber, and may also be used as additives to improve the impact strength of rigid thermoplastics.

Structures.—Thermoplastics can be classified by their structures into categories such as amorphous (noncrystalline), crystalline, and liquid crystalline polymers (LCP). Amorphous thermoplastics include polycarbonate, polystyrene, ABS (acrylonitrile-butadiene-styrene), SAN (styrene-acrylonitrile), and PVC (polyvinylchloride). Crystalline thermoplastics have polymer chains that are packed together in an organized way, as distinct from the unorganized structures of amorphous plastics, and include acetal, nylon, polyethylene, polypropylene, and polyester. The organized regions in crystalline thermoplastics are joined by noncrystalline (amorphous) zones, and the structures are such that the materials are stronger and stiffer, though less resistant to impact, than completely noncrystalline materials. Crystalline thermoplastics have higher melting temperatures and higher shrinkage and warpage factors than amorphous plastics. Liquid crystalline plastics are polymers with highly ordered rod-like structures and have high mechanical property values, good dimensional stability and chemical resistance, and are easy to process, with melting temperatures similar to those of crystalline plastics. Unlike amorphous and crystalline plastics, liquid crystalline plastics retain significant order in the melt phase. As a result, they have the lowest shrinkage and warpage of the three types of thermoplastics.

Mixtures.—Characteristics of plastics materials can be changed by mixing or combining different types of polymers and by adding nonplastics materials. Particulate fillers such as wood flour, silica, sand, ceramic and carbon powder, tiny glass balls, and powdered metal are added to increase modulus and electrical conductivity, to improve resistance to heat or ultraviolet light, and to reduce cost, for example. Plasticizers may be added to decrease modulus and increase flexibility. Other additives may be used to increase resistance to effects of ultraviolet light and heat or to prevent oxidation, and for a variety of other purposes.

Reinforcing fibers of glass, carbon, or Aramid (aromatic polyamide fibers having high tensile strength, a range of moduli, good toughness, and stress–strain behavior similar to that of metals) are added to improve mechanical properties. Careful design and process selection must be used to position the fibers so that they will provide the required strength where it is needed. Continuous fiber may be positioned carefully in either a thermoplastics or thermoset matrix to produce basic parts generally called composites, which have the highest mechanical properties and cost of the reinforced plastics.

Copolymers embody two or more different polymers and may have properties that are completely different from those of the individual polymers (homopolymers) from which they are made. An approach known as alloying consists of pure mechanical blending of two or more different polymers, often with special additives to make them compatible. These “alloys” are compounded so as to retain the most desirable characteristics of each constituent, especially in impact strength and flame resistance. However, properties usually are intermediate between those of the constituent materials.

Physical Properties.—Almost all proposed uses of plastics require some knowledge of the physical properties of the materials, and this information is generally readily available from manufacturers. Properties such as density, ductility, elasticity and plasticity, homogeneity, uniformity of composition, shrinkage during cooling from the molding temperature, transmittal of light, toughness (resistance to impact), brittleness, notch sensitivity, isotropy (properties that are the same when measured in any direction) and anisotropy (properties that vary when measured in different directions), and lubricity (load-bearing characteristics under relative motion) may all need consideration when a material suitable for a specific application is to be specified.

Most of the terms used to describe the physical characteristics of metals, such as density, ductility, brittleness, elasticity, notch sensitivity, specific gravity, and toughness, have similar meanings when they are applied to plastics, but different measures are often used with plastics. Like cast metals, many plastics are isotropic so that their characteristics are the same measured in any direction. Properties of rolled metals and extruded plastics vary when measured in the longitudinal and transverse directions, so these materials are anisotropic.

Density is a measure of the mass per unit volume, usually expressed in lb/in.^{3} or g/cm^3 at a temperature of 73.4 degrees F (23 degrees C). Density information is used mainly to calculate the amount of material required to make a part of a given volume, the volume being calculated from drawing dimensions.

Specific gravity is the ratio of the mass of a given volume of a material to the mass of the same volume of water, both measured at 73.4 degrees F (23 degrees C). The ratio is dimensionless so is useful for comparing different materials, and is used in cost estimating and quality control.

Shrinkage is the ratio of the dimension of the plastics molding to the corresponding dimension of the mold, expressed in in./in. or cm/cm, both at room temperature. As with a die casting die, the moldmaker uses this ratio to determine mold cavity measurements that will produce a part of the required dimensions. Shrinkage in a given material can vary with wall thickness, direction of flow of the plastics in the mold, and molding conditions. Amorphous and liquid crystalline thermoplastics have lower shrinkage ratios than crystalline thermoplastics. Glass-reinforced and filled materials have lower shrinkage than unfilled materials.

Water absorption is the amount of increase in weight of a material due to absorption of water, expressed as a percentage of the original weight. Standard test specimens are first dried for 24 hr, then weighed before and after immersion in water at 73.4 degrees F (23 degrees C) for various lengths of time. Water absorption affects both mechanical and electrical properties and part dimensions. Parts made from materials with low water absorption rates tend to have greater dimensional stability.

Opacity (or transparency) is a measure of the amount of light transmitted through a given material under specific conditions. Measures are expressed in terms of haze and luminous transmittance. Haze measurements indicate the percentage of light transmitted through a test specimen that is scattered more than 2.5 degrees from the incident beam. Luminous transmittance is the ratio of transmitted light to incident light.

Elasticity is the ability of a material to return to its original size and shape after being deformed. Most plastics have limited elasticity, although rubber and materials classified as thermoplastic elastomers (TPEs) have excellent elasticity.

Plasticity is the inverse of elasticity, and a material that tends to stay in the shape or size to which it has been deformed has high plasticity. Some plastics can be formed cold by being stressed beyond the yield point and such plastics then exhibit plasticity. When thermoplastics are heated to their softening temperature, they have almost perfect plasticity.

Ductility is the ability of a material to be stretched, pulled, or rolled into shape without destroying the integrity of the material.

Toughness is a measure of the ability of a material to absorb mechanical energy without cracking or breaking. Tough material can absorb mechanical energy with either elastic or plastic deformation. High-impact unfilled plastics generally have excellent toughness, and low- or moderate-impact materials may also be tough if their ultimate strength is high enough (see *Typical Stress–Strain Curves* on page 573). The area under the stress–strain curve is often used as the measure of toughness for a particular plastics material.

Brittleness is the lack of toughness. Brittle plastics frequently have low impact and high stiffness properties. Many glass-reinforced and mineral-filled materials are brittle.

Notch sensitivity is a measure of the ease with which a crack progresses through a material from an existing notch, crack, or sharp corner.

Lubricity describes the load-bearing characteristics of a material under relative motion. Plastics with good lubricity have low coefficients of friction with other materials (or sometimes with themselves) and no tendency to gall.

Homogeneous means uniform. The degree of homogeneity indicates the uniformity of composition of a material throughout its mass. In a completely homogeneous body, the smallest sample has the same physical properties as the body. An unfilled thermoplastics is a reasonably homogeneous material.

Heterogeneous means varying. In a heterogeneous body, for example, a glass-reinforced material, the composition varies from point to point. Many heterogeneous materials are treated as homogeneous for design purposes because a small sample of the material has the same properties as the body.

Isotropy means that the properties at any point in a body are the same, regardless of the direction in which they are measured.

Anisotropy means that the physical properties of a material depend on the direction of measurement. Various degrees of anisotropy exist, depending on the amount of symmetry of the material or component shape. For example, cast metals and plastics tend to be isotropic so that samples cut in any direction within a cast body tend to have the same physical properties. However, rolled metals tend to develop crystal orientation in the direction of rolling so that they have different mechanical properties in the rolling and transverse-to-rolling directions.

Extruded plastics film also may have different properties in the extruding and transverse directions so that these materials are oriented biaxially and are anisotropic. Composite materials that have fiber reinforcements carefully oriented in the direction of applied loads, surrounded by a plastics matrix, have a high degree of property orientation with direction at various points in the structure and are anisotropic.

As another example, wood page 375 is an anisotropic material with distinct properties in three directions and is very stiff and strong in the direction of growth. Fair properties are also found in one direction perpendicular to the growth direction, but in a third direction at right angles to the other two directions, the mechanical properties are much lower.

The preceding examples involve mechanical properties, but anisotropy is also used in referring to the way a material shrinks in the mold. Anisotropic shrinkage is important in molding crystalline and glass-fiber-reinforced materials for which shrinkage values are usually listed for the flow direction and the cross-flow direction. These values are of most concern to the tool designer and molder, but the existence of anisotropy and its severity must be considered when a material is chosen for a part having tight tolerances.

Significance of Elasticity, Homogeneity, and Isotropy: Structural analysis during design of components uses two independent constants, Young's modulus (E) and Poisson's ratio (ν), but two constants are sufficient only for elastic, isotropic materials that respond linearly to loads (when load is proportional to deformation). Designers often use the same values for these constants everywhere in the structure, which is correct only if the structure is homogeneous.

Assumptions of linear elasticity, isotropy, and homogeneity are reasonable for many analyses and are a good starting point, but use of these assumptions can lead to significant design errors with plastics, particularly with glass-reinforced and liquid crystalline polymers, which are highly anisotropic. In the following, plastics are assumed to be linearly elastic, homogeneous, and isotropic to allow a simpler presentation of mechanical properties in line with the data provided in plastics manufacturers' marketing data sheets. The standard equations of structural analysis (bending, torsion, pressure in a pipe, etc.) also require these assumptions.

As the degree of anisotropy increases, the number of constants or moduli required to describe the material also increases, up to a maximum of 21. Uncertainty about material properties and the questionable applicability of the simple analysis techniques employed point to the need for extensive end-use testing of plastics parts before approval of a particular application. A partial solution to this problem lies in the use of finite-element-analysis (FEA) methods. The applicability of FEA methods requires good understanding of the anisotropic nature of plastics materials.

Mechanical Properties.—Almost all end-use applications involve some degree of loading, so mechanical properties are of prime importance in designing with plastics. Material selection is usually based on manufacturers' marketing data sheets listing tensile strength, modulus of elasticity (E), elongation, impact strength, stress and strain behavior, and shear strength. Suppliers' data often are generated under standard test conditions so may not be directly transferable to the components produced. Because of the somewhat lower modulus of elasticity of plastics materials (10^5 for plastics compared with 10^6 $\mathrm{lb_f/in^2}$ for metals), different units of measure are used to express the results.

Determination of the true meaning of mechanical properties and their relation to end-use requirements is of vital importance in design. In practical applications, materials are seldom subjected to steady deformation without the influence of other factors such as environment and temperature. A thorough understanding of mechanical properties and tests used to determine such properties, and the effects of adverse or beneficial conditions on mechanical properties over long time periods, is extremely important. Some manufacturers offer design and technical advice to customers who do not possess this understanding.

Stress: A three-dimensional body having a balanced system of external forces F_1 through F_5 acting on it, such that the body is at rest, is shown in Fig. 1. Such a body develops internal forces to transfer and distribute the external loads. If the body is cut at an arbitrary cross-section and one part is removed, as shown at the right in Fig. 1, a new system of forces acting on the cut surface is developed to balance the remaining external forces. Similar forces (stresses) exist within the uncut body.

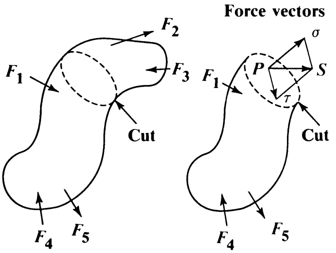


Fig. 1. Internal Forces and Stresses in a Body

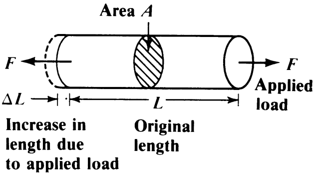


Fig. 2. Simple Tension Load

Stresses must be defined with both magnitude and direction. The stress S acting in the direction shown in Fig. 1, on the point P of the cut surface, has two stress components. One of these components, σ, acts perpendicular to the surface and is called a normal or direct stress. The other stress, τ, acts parallel to the surface and is called a shear stress.

Normal stress is illustrated by the simple tension test shown in Fig. 2, where the direct stress is the ratio of applied load to the original cross-sectional area in $\mathrm{lb_f/in^2}$. In the Système International (SI or metric system, see pages 2520, *Metric Conversion Factors* starting on page 2525, and 2548) the stress, σ, is expressed in newtons/meter^2 ($\mathrm{N/m^2}$).

$$\text{Stress} = \frac{\text{Load}}{\text{Area}} \text{ or } \sigma = \frac{F}{A} \tag{1}$$

If the load is applied as shown in Fig. 2, the test piece is in tension, and if reversed, it is in compression.

Normal strain is also illustrated by the diagram in Fig. 2, where the load or stress applied to the test piece causes it to change its length. If the bar has an original length L, and changes its length by ΔL, the strain, $\in$, is defined as

$$\text{Strain} = \frac{\text{Change of Length}}{\text{Original Length}} \text{ or } \in = \frac{\Delta L}{L} \tag{2}$$

Strain is the ratio between the amount of deformation of the material and its original length and is a dimensionless quantity. Extensions of most materials under load are generally very small. Strain ($\mu\in$ or microstrain in most metals) is measured and expressed in microinches (millionths of an inch) per inch, or 10^{-6} in./in. (10^{-6} cm/cm). Alternatively, strain is expressed as a percentage. The three methods compare as follows:

$$1000\mu\in = 0.001 = 0.1 \text{ per cent strain}$$

$$10000\mu\in = 0.010 = 1 \text{ per cent strain}$$

Modulus of Elasticity: Most metals and plastics have deformations that are proportional to the imposed loads over a range of loads. Stress is proportional to load and strain is proportional to deformation, so stress is proportional to strain and is expressed by Hooke's law:

$$\frac{\text{Stress}}{\text{Strain}} = \text{Constant} = E \tag{3}$$

The constant E is called the modulus of elasticity, Young's modulus, or, in the plastics industry, tensile modulus. Referring to Fig. 2, tensile modulus is given by the formula:

$$E = \frac{\sigma}{\in} = \frac{F/A}{\Delta L/L} = \frac{FL}{A\Delta L} \tag{4}$$

Thus, the modulus is the slope of the initial portion of the stress–strain curve. An elastic material does not necessarily obey Hooke's law, since it is possible for a material to return to its original shape without the stress being proportional to the strain. If a material does obey Hooke's law, however, it is elastic.

The straight portion of the stress–strain curve for many plastics is difficult to locate, and it is necessary to construct a straight line tangent to the initial portion of the curve to use as a modulus. The shape of a line so obtained is called the initial modulus. In some plastics, the initial modulus can be misleading, owing to the nonlinear elasticity of the material. Some suppliers therefore provide the so-called 1 per cent secant modulus, which is the ratio of stress to strain at 1 per cent strain on the stress–strain curve. In the illustration of typical stress–strain curves in Fig. 3, the secant modulus at the point *E* is the slope of the line *OE*.

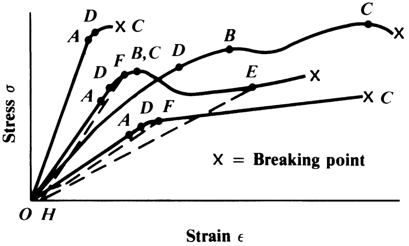


Fig. 3. Typical Stress–Strain Curves

For metals, Young's modulus is expressed in terms of 10^6 $lb_f/in.^2$, N/m^2, or Pa, as convenient (see starting on page 2525). For plastics, tensile modulus is expressed as 10^5 lb_f/in^2 or in GPa (1 GPa = 145,000 $lb_f/in.^2$).

Secant modulus is the ratio of stress to corresponding strain at any point on the stress–strain curve (see *Modulus of Elasticity*).

Proportional limit is the greatest stress at which a material is capable of sustaining the applied load without losing the proportionality of stress to strain. This limit is the point on the stress–strain curve where the slope begins to change, as shown at A on each of the curves in Fig. 3. Proportional limit is expressed in $lb_f/in.^2$ (MPa or GPa).

Yield point is the first point on the stress–strain curve where an increase in strain occurs without an increase in stress, and is indicated by *B* on some of the curves in Fig. 3. The slope of the curve is zero at this point; however, some materials do not have a yield point.

Ultimate strength is the maximum stress a material withstands when subjected to a load, and is indicated by *C* in Fig. 3. Ultimate strength is expressed in $lb_f/in.^2$ (MPa or GPa).

Elastic limit is indicated by the point *D* on the stress–strain curve in Fig. 3, and is the level beyond which the material is permanently deformed when the load is removed.Although many materials can be loaded beyond their proportional limit and still return to zero strain when the load is removed, some plastics have no proportional limit in that no region exists where the stress is proportional to strain (i.e., where the material obeys Hooke's law).

Yield strength is the stress at which a material shows a specified deviation from stress to strain proportionality. Some materials do not show a yield strength clearly, and it may be desirable to choose an arbitrary stress level beyond the elastic limit, especially with plastics that have a very high strain at the yield point, to establish a realistic yield strength. Such a point is seen at F on some of the curves in Fig. 3, and is defined by constructing a line parallel to OA at a specified offset strain, H. The stress at the intersection of the line with the stress–strain curve at F would be the yield strength at H offset. If H were at 2 per cent strain, F would be described as the yield strength at a 2 per cent strain offset.

Poisson's ratio is defined on page 196. Under a tensile load, a rectangular bar of length L, with sides of widths b and d, lengthens by an amount ΔL, producing a longitudinal strain of

$$\in \; = \frac{\Delta L}{L} \tag{5}$$

The bar is reduced in its lateral dimensions and the associated lateral strains will be opposite in sign, resulting in

$$\in \; = -\frac{\Delta b}{b} = -\frac{\Delta d}{d} \tag{6}$$

If the deformation is within the elastic range, the ratio (Poisson's ratio v) of the lateral to the longitudinal strains will be constant. The formula is:

$$v = \frac{\text{Lateral Strain}}{\text{Longitudinal Strain}} = \frac{\Delta d/d}{\Delta L/L} \tag{7}$$

Values of v for most engineering materials lie between 0.20 and 0.40, and these values hold for unfilled rigid thermoplastics. Values of v for filled or reinforced rigid thermoplastics fall between 0.10 and 0.40 and for structural foam between 0.30 and 0.40. Rigid thermoset plastics have Poisson's ratios between 0.20 and 0.40, whether filled or unfilled, and elastomers can approach 0.5.

Shear stress is treated on page 207. Any block of material is subject to a set of equal and opposite shearing forces Q. If the block is envisaged as an infinite number of infinitesimally thin layers as shown diagrammatically in Fig. 4, it is easy to imagine a tendency for one layer subject to a force to slide over the next layer, producing a shear form of deformation or failure. The shear stress τ is defined as

$$\tau = \frac{\text{Shear Load}}{\text{Area Resisting Load}} = \frac{Q}{A} \tag{8}$$

Shear stress is always tangential to the area on which it acts. Shearing strain is the angle of deformation γ and is measured in radians.

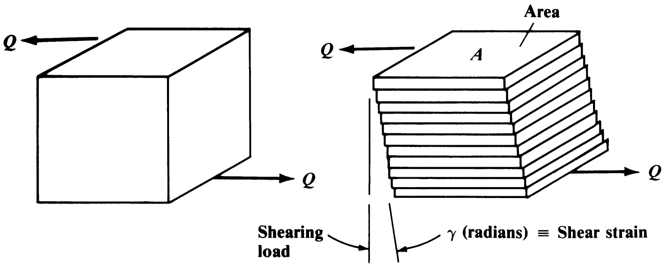


Fig. 4. Shear Stress is Visualized as a Force Q Causing Infinitely Thin Layers of a Component to Slide Past Each Other, Producing a Shear Form of Failure

Shear modulus is a constant G, otherwise called the modulus of rigidity, and, for materials that behave according to Hooke's law, is directly comparable to the modulus of elasticity used in direct stress calculations. The constant is derived from

$$G = \frac{\text{Shear Stress}}{\text{Shear Strain}} = \frac{\tau}{\gamma} \tag{9}$$

Relating Material Constants: Although only two material constants are required to characterize a material that is linearly elastic, homogeneous, and isotropic, three such constants have been introduced here. These three constants are tensile modulus E, Poisson's ratio v, and shear modulus G, and they are related by the following equation, based on elasticity principles:

$$\frac{E}{G} = 2(1 + v) \tag{10}$$

This relationship holds for most metals and is generally applicable to injection-moldable thermoplastics. It must be remembered, however, that most plastics, and particularly fiber-reinforced and liquid crystalline materials, are inherently either nonlinear, or anisotropic, or both.

Direct shear refers to a shear strength test much used in the plastics industry with a setup similar to that shown in Fig. 5, and the results of such tests are often described in manufacturers' marketing data sheets as the shear strength of the material. The shear strength reported from such a test is not a pure shear strength because a considerable part of the load is transferred by bending or compressing, or both, rather than by pure shear, and results can be affected by the susceptibility of the material to the sharpness of the load faces in the test apparatus. Thus, the test cannot be used to develop shear stress–strain curves or to determine the shear modulus.

When analyzing plastics in a pure shear situation or when the maximum shear stress is calculated in a complex stress environment, designers often use a shear strength value of about half the tensile strength, or the direct shear strength obtained from the test referred to above, whichever is least.

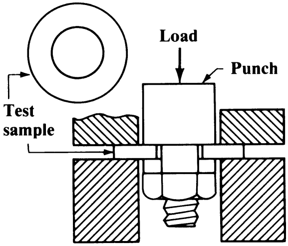


Fig. 5. Direct Shear Test Used in the Plastics Industry

True stress and true strain are terms not in frequent use. In Fig. 2, the stress, sometimes called the engineering stress, is calculated from an increasing load F, acting over a constant area A. Because the cross-sectional area is reduced with most materials, use of that smaller cross-sectional area in the calculation yields what is called the "true stress." In addition, the direct strain referred to earlier, that is, the total change in length divided by the original length, is often called the "engineering strain." The true strain would be the instantaneous deformation divided by the instantaneous length. Therefore, the shape of such a stress–strain curve would not be the same as a simple stress–strain curve. Modulus values and stress–strain curves are almost universally based on engineering stress and strain.

Other Measures of Strength and Modulus.—Tensile and compression properties of many engineering materials, which are treated as linearly elastic, homogeneous, and isotropic, are often considered to be identical, so as to eliminate the need to measure properties in compression. Also, if tension and compression properties are identical, under standard beam bending theory, there is no need to measure the properties in bending. In a concession to the nonlinear, anisotropic nature of most plastics, these properties, particularly flexural properties, are often reported on manufacturers' marketing data sheets.

Compression Strength and Modulus: Because of the relative simplicity of testing in tension the elastic modulus of a material is usually measured and reported as a tension value. For design purposes it often is necessary to know the stress–strain relationship for compression loading. With most elastic materials at low stress levels, the tensile and compressive stress–strain curves are nearly equivalent. At higher stress levels, the compressive strain is less than the tensile strain. Unlike tensile loading, which usually results in a clear-cut failure, stressing in compression produces a slow and indefinite yielding that seldom leads to failure. Because of this phenomenon, compressive strength is customarily expressed as the stress in $lb_f/in.^2$ (Pa) required to deform a standard plastics test specimen to a certain strain. Compression modulus is not always reported, because defining a stress at a given strain is equivalent to reporting a secant modulus. If a compression modulus is given, it is usually an initial modulus.

Bending Strength and Modulus: When material of rectangular cross-section is bent, it is apparent that one surface is stretched in tension and the other side is compressed. Within the material is a line or plane of zero stress called the neutral axis. Simple beam bending theory makes the following assumptions: that the beam is initially straight, unstressed, and symmetric; the material is linearly elastic, homogeneous, and isotropic; the proportional limit is not exceeded; Young's modulus for the material is the same in tension and compression; and all deflections are small so that planar cross-sections remain planar before and after bending.

In these conditions, the formula for bending stress σ is

$$\sigma = \frac{3FL}{2bh^2} \tag{11}$$

the formula for bending or flexural modulus E is

$$E = \frac{FL^3}{4bh^3Y} \tag{12}$$

and the formula for deflection Y is

$$Y = \frac{FL^3}{4Ebh^3} \tag{13}$$

where F, the force in pounds, is centered between the specimen support points, L is the distance in inches between the support points, b and h are the width and thickness of the test specimen in inches, and Y is the deflection in inches at the central load point.

Using the preceding relationships, the flexural strength and flexural modulus (of elasticity) for any material can be determined in the laboratory. The flexural modulus reported is usually the initial modulus from the load deflection curve. Most plastics parts must be analyzed in bending, so use of flexural values should give more accurate results than corresponding tensile values.

Rate Dependence of Mechanical Properties: Tensile and flexural data in manufacturers' literature are measured at specific displacement rates. These rates are usually not consistent with the loading environment encountered in use of the product. The same plastics material, under differing rates or in other environmental conditions, can produce different stress–strain curves. Designers should be aware of the loading rates in specific applications and request the appropriate data. End-use testing must always be considered, but particularly when adequate data are not available.

Time-Related Mechanical Properties.—Mechanical properties discussed previously were related to loads applied gradually and applied for short periods. Long-term and very short-term loading may give somewhat different results. With high-performance thermoplastics it is important to consider creep, impact, fatigue, and related issues. Even the best laboratory test methods do not always predict structural response of production parts accurately, and other factors may also affect results.

Creep is defined as increasing strain over time in the presence of a constant stress when deformation continues without increases in load or stress. The rate of creep for a given material depends on applied stress, temperature, and time.

Creep behavior of a material is important, and a crucial issue with plastics, where parts are to be subjected to loads for extended periods and where the maximum deflection is critical. To determine the creep behavior, test samples may be loaded in tension, compression, or flexure in a constant-temperature environment. Under constant loads, deflection is recorded at regular intervals over suitable periods. Results are generally obtained for four or more stress levels and recorded as creep curves of strain versus time on a logarithmic scale. In general, crystalline materials have lower creep rates than amorphous plastics. Glass reinforcement generally improves the creep resistance.

Apparent or Creep Modulus: If the deflection of a part subjected to continuous loading is calculated by using the modulus of elasticity E, results are likely to be inaccurate because the effects of creep have not been considered. If the stress level and temperature are known and creep curves are available for the temperature in question, an apparent or creep modulus E_{app} can be calculated from the creep curves by the formula: $E_{app} = \sigma/\in_c$, where σ is the calculated stress level and $\in_c$ is the strain from the creep curve at the expected time and temperature.

This value E_{app} can be used instead of E in predicting the maximum deflection, using the methods described subsequently (page 577).

Manufacturers' data often include curves of creep modulus (or log creep modulus) versus log time at either constant stress or constant strain, derived from creep data. This information may also be provided as tables of values at constant stress and temperature for various time periods. Some manufacturers provide creep data in the form of creep modulus figures rather than curves.

Creep rupture data are obtained in the same manner as creep data except that higher stresses are used and time is measured to failure. Such failures may be brittle or ductile with some degree of necking. Results are generally plotted as log stress versus log time to failure.

Stress relaxation occurs when plastics parts are assembled into a permanent deflected condition, as in a press fit, a bolted assembly, or some plastics springs. Under constant strain over a period of time, the stress level decreases due to the same internal molecular movement that produces creep. Stress relaxation is important with such applications as bolt preloading and springs, where loading must be maintained.The relaxation can be assessed by applying a fixed strain to a sample and measuring the load over time. A relaxation modulus similar to the creep modulus can be derived from the relaxation data. Relaxation data are not as readily available as creep data, but the decrease in load due to stress relaxation can be approximated by using the creep modulus E_{app} calculated from the creep curves.

Plastics parts often fail due to imposition of excessive fixed strains over extended periods of time, for example, a plastics tube that is a press fit over a steel shaft. No relaxation rupture equivalent to creep rupture exists, so for initial design purposes a strain limit of 20 per cent of the strain at the yield point or yield strength is suggested for high-elongation plastics. For low-elongation brittle plastics that have no yield point, 20 per cent of the elongation at break is also recommended. These figures should be regarded only as guidelines for development of initial design concepts; prototype parts should be thoroughly tested under end-use conditions to confirm the suitability of the design. Higher or lower property limits may also be indicated in manufacturers' data on specific materials.

Extrapolating creep and relaxation data must be done with caution. When creep and relaxation data are plotted as log property against log time, the curves are generally less pronounced, facilitating extrapolation. This procedure is common practice, particularly with creep modulus and creep rupture data. Extrapolation should not exceed one unit of log time, and the strain limit of 20 per cent of the yield or ultimate strength mentioned above should not be exceeded.

Impact loading describes a situation in which a load is imposed rapidly. Any moving body has kinetic energy and when the motion is stopped by a collision, the energy is dissipated. Ability of a plastics part to absorb energy is determined by the shape, size, thickness, and type of material. Impact testing methods now available do not provide designers with information that can be used analytically. The tests can be used for comparing relative notch sensitivity or relative impact resistance, so can be useful in choosing a series of materials to be evaluated for an application or in grading materials within a series.

Impact testing by the Izod and Charpy methods, in which a pendulum arm is swung from a certain height to impact a notched test specimen, is the most widely used for measuring impact strength. Impact with the test specimen reduces the energy remaining in the arm, and this energy loss is recorded in ft-lb (J). The value of such tests is that they permit comparison of the relative notch toughness of two or more materials under specific conditions.

Tensile impact tests mount the test specimen on the swinging arm. Attached to the test specimen is a cross piece that is arrested by a notched anvil as the bar swings down, allowing the energy stored in the arm to break the specimen under tension as it passes through the notch. Another impact test used for plastics allows a weighted, round-ended cylindrical “dart” to fall on a flat disk of the plastics to be tested. This test is good for ranking materials because it represents conditions that are encountered by actual parts in certain applications.

Fatigue tests are designed to measure the relative ability of plastics materials to withstand repeated stresses or other cyclic phenomena. For example, a snap-action, or snap-fit latch that is continually opened and closed, a gear tooth, a bearing, a structural component subject to vibration or to repeated impacts. Cyclic loading can cause mechanical deterioration and progressive fracture, leading to failure in service. Typical fatigue tests are carried out on machines designed to subject a cantilever test piece to reversing flexural loading cycles at different stress levels. Numbers of cycles before failure are recorded for each stress level. Data are normally presented in plots of log stress versus log cycles called *S-N* curves for specific cycle rates and environmental temperatures. With thermoplastics materials there is the added complication that heat built up by the frequency of the cyclic stress may contribute to failure. Significantly different *S-N* curves can be produced for the same materials by testing at different frequencies, mean stresses, waveforms, and methods, such as testing in tension rather than in bending. Testing usually cannot reproduce the conditions under which components will work. Only tests on the end product can determine whether the design is suitable for the purpose to be served.

Thermal Properties.—Melting temperatures of crystalline thermoplastics are sharp and clearly defined, but amorphous and liquid crystalline materials soften and become more fluid over wider temperature ranges. Melting points have greater significance in molding and assembly operations than in product design, which usually deals with the product's temperatures.

Glass transition temperature is a level at which a plastics material undergoes a significant change in properties. Below this temperature T_g, the material has a stiff, glassy, brittle response to loads. Above T_g the material has a more ductile, rubbery response.

Vicat softening point is the temperature at which a small, circular, lightly gravity-loaded, heated probe penetrates a specific distance into a thermoplastics test specimen. This test measures the ability of a thermoplastics material to withstand a short-term contact with a heated surface, and is most useful for crystalline plastics. Amorphous thermoplastics materials tend to creep during the test, which reduces its usefulness for such materials.

Deflection temperature under load (DTUL) is the temperature at which a test bar of 0.5 in. thickness, loaded to a specified bending stress, will deflect by 0.010 in. This test is run at bending stresses of 66 $\mathrm{lb_f/in.^2}$ or 264 $\mathrm{lb_f/in.^2}$ or both. The value obtained is sometimes referred to as the heat distortion temperature (HDT), and is an indication of the ability of the material to perform at elevated temperatures under load. Both stress and deflection for a specific design of test bar are given so the test may be regarded as establishing the temperature at which the flexural modulus is reduced to particular values, 35,200 $\mathrm{lb_f/in.^2}$ at 66 $\mathrm{lb_f/in.^2}$ stress, and 140,000 $\mathrm{lb_f/in.^2}$ at 264 $\mathrm{lb_f/in.^2}$ stress.

Table 1. Typical Values of Coefficient of Linear Thermal Expansion for Thermoplastics and Other Commonly Used Materials

Material[a]	in./in./deg F $\times 10^{-5}$	cm/cm/deg C $\times 10^{-5}$	Material[b]	in./in./deg F $\times 10^{-5}$	cm/cm/deg C $\times 10^{-5}$
Liquid Crystal—GR	0.3	0.6	ABS—GR	1.7	3.1
Glass	0.4	0.7	Polypropylene—GR	1.8	3.2
Steel	0.6	1.1	Epoxy—GR	2.0	3.6
Concrete	0.8	1.4	Polyphenylene sulfide—GR	2.0	3.6
Copper	0.9	1.6	Acetal—GR	2.2	4.0
Bronze	1.0	1.8	Epoxy	3.0	5.4
Brass	1.0	1.8	Polycarbonate	3.6	6.5
Aluminum	1.2	2.2	Acrylic	3.8	6.8
Polycarbonate—GR	1.2	2.2	ABS	4.0	7.2
Nylon—GR	1.3	2.3	Nylon	4.5	8.1
TP polyester—GR	1.4	2.5	Acetal	4.8	8.5
Magnesium	1.4	2.5	Polypropylene	4.8	8.6
Zinc	1.7	3.1	TP Polyester	6.9	12.4
ABS—GR	1.7	3.1	Polyethylene	7.2	13.0

[a] GR = Typical glass fiber-reinforced material. Other plastics materials shown are unfilled.
[b] GR = Typical glass fiber-reinforced material. Other plastics materials shown are unfilled.

Linear thermal expansion: Like metals, thermoplastic materials expand when heated and contract when cooled. For a given temperature range, most plastics change dimensions much more than metals. The coefficient of linear thermal expansion (CLTE) is the ratio of the change in a linear dimension to the original dimension for a unit change of temperature and is expressed as in./in./degree F, or cm/cm/degree C. Typical average values for common materials are shown in Table 1. These values do not take account of grades, molding conditions, wall thickness, or direction of flow in molding.

Thermal conductivity is the rate at which a material conducts heat energy along its length or through its thickness.

Aging at elevated temperatures may affect physical, mechanical, electrical, or thermal properties of plastics materials. Data from tests on specimens stored at specific temperatures for suitable periods are presented as plots of properties versus aging time at various temperatures, and may be used as an indication of thermal stability of the material.

Temperature index is a rating by Underwriters Laboratories (UL) of electrical and mechanical properties (with and without effects of impacts) of plastics materials used in electrical equipment for certain continuous operating conditions.

Flammability ratings also are produced by Underwriters Laboratories. UL tests measure the ability to continue burning after a flame is removed, and the percentage of oxygen needed for the material to continue burning. Other tests measure combustibility, ignition temperatures, and smoke generation.

Effect of Temperature on Mechanical Properties.—The inverse relationship between strain rate and temperature must be kept in mind when designing with plastics materials. Stress/strain curves for tests performed with one strain rate at several temperatures are similar to those for tests with one temperature and several strain rates. Therefore, very high strain rates and very low temperatures produce similar responses in materials. Conversely, the effects of very low strain rates, that is, creep effects, can be determined more quickly by testing at elevated temperatures. Testing at temperatures near or above the highest values expected in everyday use of a product helps the designer estimate long-term performance of components.

Strength, modulus, and elongation behavior are similar for tensile, compressive, flexural, and shear properties. Generally, strength and modulus decrease with increasing temperature. The effect of temperature increases is shown by the curves in Fig. 6 for crystalline and amorphous materials, where a gradual drop in modulus is seen as the glass transition temperature T_g is approached. Above the glass transition temperature, amorphous materials have a rapid loss of modulus, and even with glass-fiber reinforcement they display a rapid drop in modulus above the glass transition temperature. Crystalline materials maintain a significant usable modulus at temperatures approaching the crystalline melting point, and glass-fiber reinforcement can significantly improve the modulus of crystalline materials between the glass transition and melting temperatures. Generally, strength versus temperature curves are similar to modulus curves and elongation increases with rising temperatures.

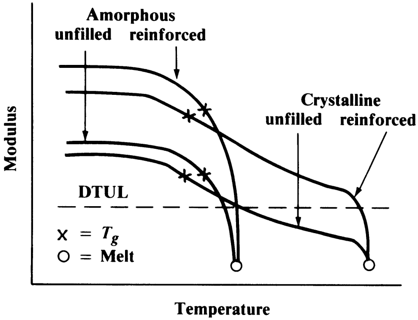


Fig. 6. Modulus Behavior of Crystalline and Amorphous Plastics Showing T_g and Melt Temperatures and the Effect of Reinforcement on Deflection Temperature Under Load (DTUL)

Isochronous stress and isometric stress curves are taken from measurements made at fixed temperatures, although sometimes curves are available for other-than-ambient temperatures. Creep rupture and apparent modulus curves also are often plotted against the log of time, with temperature as a parameter. Refer to sections on creep, creep modulus, and creep rupture beginning on page 577.

As temperatures drop significantly below ambient, most plastics materials lose much of their room temperature impact strength, although a few materials show only a gradual decrease. Plastics reinforced with long glass fibers have relatively high Izod impact values at room temperature, and retain these values at −40 degrees F (− 40 degrees C).

Electrical Properties.—The most notable electrical property of plastics is that they are good insulators, but there are many other electrical properties that must be considered in plastics part design.

Conductivity in solids depends on the availability and mobility of movable charge carriers within the material. Metals are good conductors because the metal atom has a loosely held, outermost electron, and the close proximity of the atoms allows these outer electrons to break free and move within the lattice structure. These free electrons give metals the ability to conduct large currents, even at low voltages. Outer electrons in materials such as glass, porcelain, and plastics are tightly bound to the atoms or molecules so there are no free electrons. Electrical current cannot be conducted and the materials act as insulators.

Volume resistivity is the electrical resistance of a material when a current is applied to it. The resistance is measured in ohm-cm. Materials having values above 10^8 ohm-cm are considered to be insulators, and materials with values between 10^8 and 10^3 ohm-cm are considered to be partial conductors. Most plastics have volume resistivity in the range of 10^{12} to 10^{18} ohm-cm.

Surface resistivity is a measure of the susceptibility of a material to surface contamination, particularly moisture. The tests use electrodes that are placed on the same side of the material.

Dielectric strength is a measure of the voltage required to cause an insulator to break down and allow an electric current to pass and is expressed in volts per 0.001 in. of thickness. Variables that may affect test results include temperature, sample thickness and condition, rate of voltage increase and duration of test, sample contamination, and internal voids.

Dielectric constant or permittivity is a dimensionless constant that indicates how easily a material can become polarized by imposition of an electrical field on an insulator. Reversal of the direction of flow of the current results in reversal of the polarization. The dielectric constant is the ratio of the permittivity of the material in normal ambient conditions to the permittivity of a vacuum. Permittivity is important when plastics are used as insulating materials in high-frequency electrical apparatus. Changes in temperature, moisture levels, electrical frequency, and part thickness may affect the dielectric constant.

Heat dissipation factor is a measure of heat energy dissipated by rapidly repeated reversals of polarization, as with an alternating current. The dissipation factor may also be thought of as the ratio of heat energy lost compared to that transmitted at a given frequency, often 1 MHz (10^6 cycles/sec). Some dielectric constants and heat dissipation factor values are shown in Table 2.

Arc resistance is the length of time required for an electric arc imposed on the surface of an insulating material to develop a conductive path. Materials that resist such a development are preferred for parts of switchgear and other high-voltage apparatus. Tests are used mostly for thermosetting materials because conductive paths can be formed on such materials from the decomposition products resulting from heating by an electric arc.

Table 2. Typical Values of Dielectric Constants and Heat Dissipation Factors for Various Thermoplastics at Room Temperature

Material	Dielectric Constant	Heat Dissipation Factor	Material	Dielectric Constant	Heat Dissipation Factor
Acetal	3.7–3.9	0.001–0.007	Polypropylene	2.3–2.9	0.003–0.014
Acrylic	2.1–3.9	0.001–0.060	Polysulfone	2.7–3.8	0.0008–0.009
ABS	2.9–3.4	0.006–0.021	Modified PPO	2.4–3.1	0.0002–0.005
Nylon 6⁄6	3.1–8.3	0.006–0.190	Polyphenylene sulfide	2.9–4.5	0.001–0.002
Polycarbonate	2.9–3.8	0.0006–0.026	Polyarylate	2.6–3.1	0.001–0.022
TP Polyester	3.0–4.5	0.0012–0.022	Liquid crystal	3.7–10	0.010–0.060

Comparative tracking index (CTI) is another UL test that is similar to the arc resistance test except that the surface to be tested is precoated with an ammonium chloride electrolyte. The test measures the voltage required to cause a conductive path to form between the electrodes, and indicates the arc resistance of a contaminated surface, often found in electrical and electronic equipment.

End-Use Environmental Considerations.—The environment that will be encountered by the product is a prime consideration at the design stage. Problems with cracking, crazing, discoloration, loss of properties, melting, or dissolving can be encountered in the presence of high or low temperatures, chemical substances, energy sources, and radiation. Plastics components also are often subjected to processing, assembly, finishing, and cleaning operations before reaching their ultimate environment.

The stress level in the plastics product greatly affects performance. Generally, increased stress levels resulting from injection molding, forming, assembly work, and end-use forces reduce resistance to environmental factors. Although many plastics are hygroscopic and absorption of water results in dimensional and property changes, plastics are widely accepted because of their relative compatibility with the environment compared with metals. Some chemicals attack the polymer chain directly by reaction, resulting in a progressive lowering of the molecular weight of the polymer and changes in the short-term mechanical properties. Others dissolve the material, although high-molecular-weight plastics dissolve very slowly. Swelling, changes in weight and dimensions, and loss of properties are evidence of solvation.

Plasticization may result if the chemical is miscible with the polymer, resulting in loss of strength, stiffness, and creep resistance, and increased impact resistance. The material may swell and warp due to relaxation of molded-in stresses. Environmental stress cracking may cause catastrophic failure when plastics are stressed, even when the product appears to be unaffected by exposure to a chemical.

Chemical compatibility data are obtained from standard test bars exposed to or placed in the chemical of study and tested as previously described for such properties as tensile strength, flexural modulus, dimensional change, weight, and discoloration. Chemical resistance from some commonly used thermoplastics materials are shown in Table 3, but are only general guidelines and cannot substitute for tests on the end product. More extensive tests expose samples to a chemical in the presence of fixed stress or fixed strain distribution along its length, followed by examination for the stress or strain location at which damage begins.

The preceding tests may provide data about chemical compatibility but do not generate reliable information on performance properties for design purposes. The only test that provides such information is the creep rupture test, conducted at appropriate temperatures in the environment that will be encountered by the product, preferably on prototype parts. Plastics are degraded to varying degrees by ultraviolet light, which causes fading, chalking, and embrittlement. Plastics that will resist the action of ultraviolet rays are available on the market.

Table 3. Chemical Resistance of Various Materials by Chemical Classes

	Acetal Copolymer	Acetal Homopolymer	Nylon 6/6	Thermoplastic Polyester (PBT)	Thermoplastic Polyester (PET)	Polyester Elastomer	Liquid Crystal Polymer*	Polyphenylene Sulfide*	Polyarylate	Polycarbonate	Polysulfone*	Modified Polyphenylene Oxide	Polypropylene	ABS	316 Stainless Steel	Carbon Steel	Aluminum	
ACIDS AND BASES																		
Acids, weak	A	B	C	A	A	A	A	A	A	A	B	A	A	A	A	A	C	Dilute mineral acids
Acids, strong	C	C	C	B	—	C	B	A	—	C	C	—	A	A	B	C	C	Concentrated mineral acids
Bases, weak	A	C	A	B	B	A	B	A	—	C	A	A	A	A	A	B	C	Dilute sodium hydroxide
Bases, strong	A	C	C	—	—	B	C	A	—	C	A	—	A	A	B	B	C	Concentrated sodium hydroxide
Acids, organic, weak	A	B	C	A	A	A	A	A	A	A	B	A	A	A	A	C	C	Acetic acid, vinegar
Acids, organic, strong	C	C	C	B	—	C	B	A	—	C	C	A	A	A	B	C	C	Trichloroacetic acid
AUTOMOTIVE																		
Automotive, fuel	A	A	A	A	A	A	A	A	C	C	A	C	C	A	A	A	A	
Automotive, lubricants	A	A	A	A	A	A	A	A	C	C	A	A	A	A	A	B	A	
Automotive, hydraulic	A	A	—	A	A	—	A	A	C	C	C	A	A	A	—	—	—	
SOLVENTS																		
Aliphatic hydrocarbons	A	A	A	A	A	A	A	A	A	A	A	B	C	A	A	A	A	Heptane, hexane
Aliphatic hydrocarbons, halogenated	A	B	C	B	B	A	A	A	C	C	C	—	—	—	B	B	B	Ethylene chloride, chloroform
Alcohols	A	A	B	A	A	A	A	A	A	A	A	A	A	A	A	A	B	Ethanol, cyclohexanol
Aldehydes	A	A	A	A	B	B	A	A	—	C	B	—	A	—	A	B	A	Acetaldehyde, formaldehyde
Amines	—	—	—	—	—	—	C	B	—	C	C	—	A	—	A	B	B	Aniline, triethanolamine
Aromatic hydrocarbons	A	B	A	A	B	B	A	A	C	C	C	C	C	C	A	A	A	Toluene, xylene, naphtha
Aromatic hydrocarbons, halogenated	—	—	—	—	—	C	—	A	C	C	C	—	—	—	A	A	A	Chlorobenzene
Aromatic, hydroxy	C	C	C	C	—	C	A	A	—	C	C	—	A	—	B	C	A	Phenol
Esters	B	B	A	B	B	B	A	A	C	C	C	—	C	—	B	B	B	Ethyl acetate, dioctyl phthalate
Ethers	B	—	A	A	—	—	—	A	—	A	B	—	C	—	A	A	A	Butyl ether, diethyl ether
Ketones	B	B	A	B	B	B	A	A	C	C	C	—	B	C	A	A	A	Methyl ethyl ketone, acetone
MISCELLANEOUS																		
Detergents	A	—	A	—	B	—	—	A	A	A	—	B	A	—	A	A	B	Laundry and dishwashing detergents, soaps
Inorganic salts	B	B	B	—	A	—	—	A	—	A	—	—	A	A	B	B	B	Zinc chloride, cupric sulfate
Oxidizing agents, strong	C	C	C	—	C	—	B	B	—	C	—	—	A	—	C	C	C	30% hydrogen peroxide, bromine (wet)
Oxidizing agents, weak	C	C	C	A	—	A	A	A	—	A	—	A	A	A	B	C	A	Sodium hypochlorite solution
Water, ambient	A	A	B	A	A	A	A	A	A	A	A	A	A	—	A	C	B	
Water, hot	B	C	B	C	C	B	A	A	—	C	—	A	C	—	A	C	B	
Water, steam	C	C	C	C	C	C	B	A	—	C	—	—	C	—	A	C	—	

This information is presented for instructional purposes and is not intended for design. The data were extracted from numerous sources making consistent rating assignments difficult. Furthermore, the response of any given material to specific chemicals in any one class can vary significantly. Indeed, during the preparation of the table, the effect on one plastics of various chemicals in the same category ranged from essentially no effect to total dissolution. Therefore, an "A" rating for a particular plastics exposed to a particular class of chemicals should not be interpreted as applying to all chemicals in that class. The rating simply means that for the chemicals in that class found in the literature reviewed, the rating was generally an "A." There may be other chemicals in the same class for which the rating would be "C." Finally, the typical chemicals listed do not necessarily correspond to the ones on which the individual ratings are based.

A—minimal effect; B—some effect; C—generally not recommended.

Room temperature except for hot water, steam, and materials marked with a * ≡ 200°. Generally, extended exposure (more than a week) data were used.

DESIGN ANALYSIS

Structural Analysis.—Even the simplest plastics parts may be subjected to stresses caused by assembly, handling, temperature variations, and other environmental effects. Simple analysis using information in *Calculating Moment of Inertia* starting on page 217 and *Beam Calculations* on page 236 can be used to make sure that newly designed parts can withstand these stresses. These methods may also be used for product improvement, cost reduction, and failure analysis of existing parts.

Safety Factors: In setting safety factors for plastics parts there are no hard and fast rules. The most important consideration is the consequence of failure. For example, a little extra deflection in an outside wall or a crack in one of six internal screw bosses may not cause much concern, but the failure of a pressure vessel or water valve might have serious safety or product liability implications. Tests should be run on actual parts at the most extreme operating conditions that could possibly be encountered before any product is marketed. For example, maximum working load should be applied at the maximum temperature and in the presence of any chemicals that might be encountered in service. Loads, temperatures, and chemicals to which a product may be exposed prior to its end use also should be investigated. Impact loading tests should be performed at the lowest temperature expected, including during assembly and shipping. Effects of variations in resin lots and molding conditions must also be considered.

Failures in testing of preproduction lots often can be corrected by increasing the wall thickness, using ribs or gussets, and eliminating stress concentrations. Changing the material to another grade of the same resin or to a different plastics with more suitable mechanical properties is another possible solution. Reviews of product data and discussions with experienced engineers suggest the design stresses shown in Table 4 are suitable for use with the structural analysis information indicated above and the equations presented here, for preliminary design analysis and evaluating general product dimensions. Products designed under these guidelines must be thoroughly tested before being marketed.

Table 4. Design Stresses for Preliminary Part Designs Expressed as a Percentage of Manufacturers' Data Sheet Strength Values

	Failure Not Critical	Failure Critical
Intermittent (Nonfatigue) loading	25–50	10–25
Continuous loading	10–25	5–10

Failure Criteria: Setting of failure criteria is beyond the scope of this section, which is intended to give only basic general information on plastics. Designers who wish to rationalize complex stress states and analyses might investigate the maximum shear theory of failure (otherwise known as Coulomb or Tresca theory). It is further suggested that the shear strength be taken as the manufacturer's published shear strength, or half the tensile strength, whichever is lower. Better still, use half the stress at the elastic limit, if known.

Pressure Vessels: The most common plastics pressure vessel takes the form of a tube with internal pressure. In selecting a wall thickness for the tube, it is convenient to use the thin-wall hoop stress equation:

$$\text{hoop stress } \sigma = \frac{Pd}{2t} \tag{14}$$

where P = the uniform internal pressure in the tube, d = inside diameter of the tube, and t = the tube wall thickness. This equation is reasonably accurate for tubes where the wall thickness is less than 0.1 of the inside diameter of the tube. As the wall thickness increases, the error becomes quite large.

For thick-walled tubes the maximum hoop stress on the wall surface inside the tube can be calculated from

$$\text{hoop stress } \sigma = P\frac{1+R}{1-R} \tag{15}$$

where $R = (d_i / d_o)^2$, and d_i and d_o are the inside and outside diameters of the tube, respectively.

Press Fits: Press fits are used widely in assembly work for speed and convenience, although they sometimes are unsatisfactory with thermoplastics parts. Common applications are to a plastics hub or boss accepting a plastics or metal shaft or pin. Forcing the pin into the hole expands the hub, creating a tensile or hoop stress.

If the interference is too great, very high strain and stress develop and the plastics part will J) fail immediately by developing a crack parallel to the hub axis to relieve the stress, a typical hoop stress failure; K) survive assembly but fail prematurely due to creep rupture caused by the high induced-stress levels; and L) undergo stress relaxation sufficient to reduce the stress to a level that can be sustained.

For a typical press fit, the allowable design stress depends on the particular plastics material, temperature, and other environmental considerations. Hoop stress equations for such a design make use of a geometry factor γ:

$$\gamma = \frac{1 + (d_s / d_o)^2}{1 - (d_s / d_o)^2} \tag{16}$$

where d_s = diameter of the pin to be inserted and d_o = outside diameter of the boss.

When both the shaft and the hub are of the same, or essentially the same, materials, the hoop stress σ, given the diametral interference, $i = d_s - d_i$, is

$$\sigma = \frac{i}{d_s} E_p \frac{\gamma}{\gamma + 1} \tag{17}$$

and the allowable interference i_a, given the permissible design stress σ_a, is

$$i_a = d_s \frac{\sigma_a}{E_p} \frac{\gamma + 1}{\gamma} \tag{18}$$

When the shaft is metal and the hub is plastics, the hoop stress, given i, is obtained from

$$\sigma = \frac{i}{d_s} E_p \frac{\gamma}{\gamma + v_p} \tag{19}$$

and the allowable interference i_a, given the permissible design stress for plastics σ_a, is

$$i_a = d_s \frac{\sigma_a}{E_p} \frac{\gamma + v_p}{\gamma} \tag{20}$$

where E_p = modulus of elasticity of plastics and v_p = Poisson's ratio for plastics.

Pipe Threads: Pipe threads on plastics pipes and other parts used in plastics plumbing and pneumatic assemblies require only hand tight assembly to effect a good seat, especially if a compatible sealant tape or compound is used. Assembling a tapered male pipe thread into a mating female thread in a plastics part is analogous to driving a cone into a round hole and may result in a split boss. Sometimes straight threads and an O-ring seal can avoid the need for pipe threads. When pipe threads must be used, torque control is essential.

When mating metal to plastics pipe threads, the threaded plastics component should be the male member, so that the plastics are in compression. If torque can be controlled during assembly, use fluoroplastics tape on female plastics pipe threads. If torque cannot be controlled, consider using an external hoop ring, either pressed on or molded in. Do not design flats into plastics parts for assembly purposes, because they will encourage overtightening. If some provision for improved gripping must be made, use wings or a textured surface. An approximate formula for the hoop stress σ produced in a plastics boss with internal pipe threads is

$$\sigma = \frac{3T}{tdL} \tag{21}$$

where T = torque in in.-lb, t = wall thickness of the plastics boss in in., d = pipe outside diameter in in., and L = length of thread engagement in in.

This equation assumes certain geometric relationships and a coefficient of friction of 0.15. If compatible thread lubricants are used during assembly, the torque must be reduced. To ensure safety and reliability, all threaded assemblies must be subjected to long-term testing under operating pressures, temperatures, and stresses caused by installation procedures exceeding those likely to be encountered in service.

Thermal Stresses.—When materials with different coefficients of thermal expansion are bolted, riveted, bonded, crimped, pressed, welded, or fastened by any method that prevents relative movement between the parts, there is potential for thermal stress to exist. Typical examples are joining of nonreinforced thermoplastics parts with materials such as metals, glass, or ceramics that usually have much lower coefficients of thermal expansion. The basic relationship for thermal expansion is

$$\Delta L = \alpha L \Delta T \tag{22}$$

where ΔL = change in length, α = coefficient of thermal expansion (see Table 4), L = linear dimension under consideration (including hole diameters), and ΔT = temperature change.

If the plastics component is constrained so that it cannot expand or contract, the strain $\in_T$, induced by a temperature change, is calculated by

$$\in_T = \frac{\Delta L}{L} = \alpha \Delta T \tag{23}$$

The stress can then be calculated by multiplying the strain $\in_T$ by the tensile modulus of the material at the temperature involved. A typical example is of a plastics part to be mounted to a metal part, such as a window in a housing. Both components expand with changes in temperature. The plastics imposes insignificant load to the metal but considerable stress is generated in the plastics. For such an example, the approximate thermal stress σ_T in the plastics is given by

$$\sigma_T = (\alpha_m - \alpha_p) E_p \Delta T \tag{24}$$

where α_m = coefficient of thermal expansion of the metal, α_p = coefficient of thermal expansion of the plastics, and E_p = tensile modulus of the plastics at the temperature involved.

Other equations for thermal expansion in various situations are shown in Fig. 7.

Most plastics expand more than metals with temperature increases and their modulus drops. The result is a compressive load in the plastics that often results in buckling. Conversely, as the temperature drops, the plastics shrinks more than the metal and develops an increased tensile modulus. These conditions can cause tensile rupture of the plastics part. Clearances around fasteners, warpage, creep, or failure, or yield of adhesives tend to relieve the thermal stress. Allowances must be made for temperature changes, especially with large parts subjected to wide variations. Provision is often made for relative motion ΔL_{rel}, between two materials, as illustrated in Fig. 7:

$$\Delta L_{rel} = (\alpha_p - \alpha_m) L \Delta T \tag{25}$$

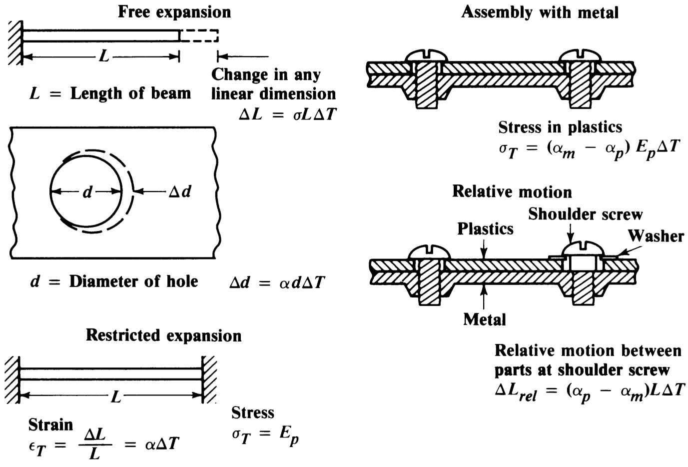


Fig. 7. Thermal Expansion Equations for Various Combinations of Materials and Situations

Design for Injection Moldings.—Injection molding uses equipment similar to that for die casting, in that a precision steel mold is clamped shut, and melted material (here, plasticized plastics) is forced into the cavity between the mold components. The pelletized plastics material is fed into a heated chamber, or barrel, by a large, slowly rotating screw, and is melted. When a sufficient quantity to fill the cavity has been prepared, the screw is moved axially under high pressure to force the material into the cavity. The mold has channels through which coolant is circulated to remove heat and to chill the plastics. When the plastics has cooled sufficiently, the mold is unclamped and opened, and the molding is forced out by strategically located ejectors. During cooling and removal, material for the next part is plasticized within the barrel, ready for the cycle to be repeated.

Product analysis provides a good approach to design for plastics molding. A basic principle of plastics molding design, when moldings are being substituted for parts made by other means, is to incorporate as many functions into the molding as possible, especially those requiring nuts, bolts, and washers, for instance. Material should be selected that fulfills the maximum requirements, such as the functions mentioned, as well as insulation from the passage of heat or electricity, and allows use of the minimum amount of material.

Important material selection criteria include ability to withstand the heat of assembly, finishing, shipping, operating, and heat from internal sources. Effects of chemicals in the environment and approvals of government and other agencies also should be checked. Many such approvals specify wall thicknesses, color additives, fillers, and operating temperatures. Plans for assembly by bonding may dictate use of certain materials, and the question of painting, plating, or other surface coatings must be considered. Cost of candidate materials compared with the alternatives must be weighed, using the formula for cost per in.^{3} = 0.0361 × specific gravity × material cost per lb. Material cost required for a part is obtained by multiplying the cost per in.^{3} by the part volume. A rough estimate of likely part cost is double the cost of material for the part.

Wall Thicknesses: The thickness of material used in a plastics molding is of the greatest importance, and should be settled before the mold is made, since modifications are costly. In general, wall thicknesses should be kept as thin as practical and as uniform as possible.

Ideally, the flow of molding material should be so arranged that it moves through thicker sections into thinner ones rather than the reverse. Geometric, structural, or functional needs may prevent ideal design, but examination of alternatives can often prevent problems from arising. Most injection-molded plastics parts range in thickness from $\frac{1}{32}$ to $\frac{3}{16}$ in. (0.8 to 4.8 mm) with the dimensions within that range related to the total size of the part.

Impact Resistance: The impact resistance of a plastics part is directly related to its ability to absorb mechanical energy without fracture or deformation, and this ability depends on the material properties and the part geometry. Increasing wall thickness may improve the impact resistance but may also hurt impact resistance by making the part too stiff so that it is unable to deflect and distribute the force.

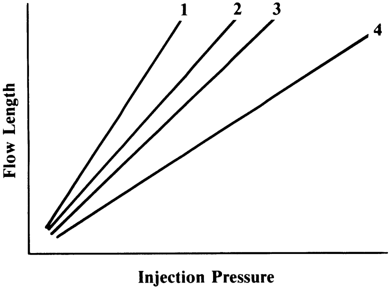


Fig. 8. Typical Spiral-Flow Curves for (1) Nylon 6/6, (2) Polyester Thermoplastics PBT, Liquid-Crystal-Glass-Reinforced, and Polyphenylene-Sulfide-Glass-Reinforced, (3) Acetal Copolymer, and (4) PBT-Glass-Reinforced Plastics Materials

Design engineers must also have some knowledge of mold design and, in determining wall thickness, should consider the ability of plastics to flow into the narrow mold channels. This flowability depends on temperature and pressure to some extent, but varies for different materials, as shown in Fig. 8.

Table 5 shows some typical nominal wall thicknesses for various types of thermoplastics.

Table 5. Typical Nominal Wall Thicknesses for Various Classes of Thermoplastics

Thermoplastics Group	Typical Working Range (in.)
Acrylonitrile-butadiene-styrene (ABS)	0.045–0.140
Acetal	0.030–0.120
Acrylic	0.025–0.150
Liquid-crystal polymer	0.008–0.120
Long-fiber-reinforced plastics	0.075–1.000
Modified polyphenylene ether	0.045–0.140
Nylon	0.010–0.115
Polyarylate	0.045–0.150
Polycarbonate	0.040–0.150
Polyester	0.025–0.125
Polyester elastomer	0.025–0.125
Polyethylene	0.030–0.200
Polyphenylene sulfide	0.020–0.180
Polypropylene	0.025–0.150
Polystyrene	0.035–0.150
Polysulfone	0.050–0.150
Polyurethane	0.080–0.750
Polyvinyl chloride (PVC)	0.040–0.150
Styrene-acrylonitrile (SAN)	0.035–0.150

If the plastics part is to carry loads, load-bearing areas should be analyzed for stress and deflection. When stress or deflection is too high, solutions are to use ribs or contours to increase section modulus; to use a higher-strength, higher-modulus (fiber-reinforced) material; or to increase the wall thickness if it is not already too thick. Where space allows, adding or thickening ribs can increase structural integrity without thickening walls.

Equations (11), (12), and (13) can be related to formulas using the section modulus and moment of inertia on page 237, where Case 2, for (i), stress at the beam center is given by $\sigma = -Wl/4Z$.

On page 236, note that $Z = I \div$ distance from neutral axis to extreme fiber ($h \div 2$ in the plastics example). The rectangular beam section diagrammed on page 219 gives the equivalent of $I = bh^3/12$ for the rectangular section in the plastics example. Therefore,

$$Z = \frac{I}{h/2} = \frac{bh^3}{12} \times \frac{2}{h} = \frac{bh^2}{6}$$

In $\sigma = -Wl/4Z$, the ($-$) sign indicates that the beam is supported at the ends, so that the upper fibers are in compression and the lower fibers are in tension. Also, $W = F$ and $l = L$ in the respective equations, so that stress, $\sigma = FL/4(bh^2)/6$, and $\sigma = 3FL/2bh^2$.

To calculate (ii) maximum deflection Y at load, use $Y = Wl^3/48EI$ from page 237, where $W = F$, $l = L$, $E = E$, from Equation (12) and $I = bh^3/12$. Therefore,

$$Y = \frac{FL^3}{48E(bh^2/12)} = \frac{FL^3}{4Ebh^3}$$

As an example, assume that a beam as described in connection with Equations (11), (12), and (13) is 0.75 in. wide, with a constant wall thickness of 0.080 in., so that the cross-sectional area is 0.060 in.^{2}, and there is a central load W of 5 lb. Based on a bending or flexural modulus of 300,000 lb/in.^{2}, the maximum stress is calculated at 6250 lb/in.^{2} and the maximum deflection at 0.694 in. Both the stress and the deflection are too high, so a decision is made to add a rib measuring 0.040 in. thick by 0.400 in. deep, with a small draft of ½ degree per side, to reinforce the structure.

The equations on page 237, the drawing page representing the ribbed section (neglecting radii), and the accompanying formulas, permit calculation of the maximum stress and deflection for the ribbed section.

With the new cross-sectional area only slightly larger at 0.0746 in.^{2}, the calculated stress is reduced to 2270 lb/in.^{2}, and the deflection goes down to 0.026 in., which is acceptable for both the material and the application. To achieve the same result from a heavier beam would require a thickness of 0.239 in., tripling the weight of the beam and increasing molding difficulties. The rib adds only 25 percent to the total section weight.

Use of ribs allows the structural characteristics of a part to be tailored to suit its function, but ribs can cause warping and appearance problems, so are best avoided if they are not structurally necessary. If the first parts produced require strengthening, ribs can be added or thickened without high cost after the tool is finished because the work consists only of removing steel from the mold. In general, ribs should have a base thickness of about half the thickness of the adjacent wall, and be kept as thin as possible where they are positioned near faces that need to have a good appearance.

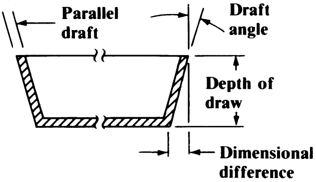
Where structural strength is more important than appearance, or when using materials that have low shrinkage, ribs can be made 75 or 100 per cent of the wall thickness. However, where the rib base joins the main molding there is an increase in thickness forming a heavy mass of material. Shrinkage of this mass can produce a cavity or void, a hollow area or sink, or can distort the molding. If the mass is very large, cooling time may be prolonged, leading to low output from the machine. Large masses of material in other parts of a molding are also best avoided. These problems can usually be addressed by good mold design.

Ribs need not be of constant height or width, and are often varied in proportions to suit the stress distribution in the part. All ribs should have a minimum of ½ degree of draft per side for ease of removal from the mold, and a minimum radius of 0.005 in. at the base to avoid stress-raising corners. Draft and thickness requirements will usually limit the height of the rib, which can be from 1.5 to 5 times the base thickness, and several evenly spaced ribs are generally preferred to a single large one. Smooth transitions should be made to other structural features such as bosses, walls, and pads.

Other ways to improve section properties include use of top-hat and corrugated sections, crowning or doming of some areas, and reinforcement with metal or other inserts that are placed in the mold before it is closed. To keep molded parts uniform in wall thickness, cores or projections may be provided in the mold to prevent a space being filled with molding material. Blind holes can be cored by pins that are supported on only one side of the mold and through holes by pins that pass through both sides. The length to width ratio should be kept as low as possible to prevent bending or breakage under the high pressures used in the injection molding process.

Agency approvals for resistance to flammability or heat, electrical properties, or other characteristics are usually based on specific wall thicknesses. These restrictions sometimes necessitate thicker walls than are required for structural strength purposes.

Table 6. Dimensional Changes for Various Combinations of Draft Angles and Draw Depths (Values to Nearest 0.001 in.)



Draw Depth (in)	Draft Angle (degrees)							
	⅛	¼	½	1	2	3	4	5
1	0.002	0.004	0.009	0.017	0.035	0.052	0.070	0.080
2	0.004	0.009	0.017	0.035	0.070	0.105	0.140	0.175
3	0.007	0.013	0.026	0.053	0.105	0.157	0.210	0.263
4	0.009	0.018	0.035	0.070	0.140	0.210	0.280	0.350
5	0.011	0.022	0.044	0.088	0.175	0.262	0.350	0.437
6	0.013	0.026	0.052	0.105	0.209	0.314	0.420	0.525
7	0.015	0.031	0.061	0.123	0.244	0.367	0.490	0.612
8	0.018	0.035	0.070	0.140	0.279	0.419	0.559	0.700
9	0.020	0.040	0.078	0.158	0.314	0.472	0.629	0.787
10	0.022	0.044	0.087	0.175	0.349	0.524	0.699	0.875

Draft: Most molded parts have features that must be cut into the mold perpendicular to the parting line. Removal of these parts from the mold is easier if they are tapered in the direction of mold opening. This taper is called draft in the line of draw or mold movement, and it allows the part to break free of the mold by creating a clearance as soon as the mold starts to open. Plastics materials shrink as they cool, so they grip mold projections very tightly and ejection can be difficult without sufficient draft. A draft of ½ degree on each side of a projection on the part is generally considered as a minimum, although up to 3 degrees per side is often used. Draft angles in degrees for various draw depths, and the resulting dimensional changes per side in inches (rounded to three decimal places), between the dimensions at the base and at the top of a projection are shown in Table 6. A rule of thumb is that 1 degree of draft yields 0.017 in. of difference in dimension per inch of draw length. Where a minimum of variation in wall thickness is needed to produce walls that are perpendicular to the direction of draw, the mold sometimes can be designed to produce parallel draft, as seen at the left in Table 6. The amount of draft required also depends on the surface finish of the mold walls. Any surface texture will increase the draft requirement by at least 1 degree per side for every 0.001 in. of texture depth.

Fillets, Radii, and Undercuts: Sharp corners are always to be avoided in injection-molded part designs because they represent points of stress concentration. Sharp corners in metal parts often are less important because the stresses are low compared with the strength of the material or because local yielding redistributes the loads. Sharp inside corners are particularly to be avoided in moldings because severe molded-in stresses are generated as the material shrinks onto the mold corner. Sharp corners also cause poor material flow patterns, reduced mechanical properties, and increased tool wear. Therefore, inside corner radii should be made equal to half the nominal wall thickness, with a minimum of 0.020 in. for parts subject to stress and 0.005 in. radius for stress-free parts. Outside corners should have a radius equal to the inside corner radius plus the wall thickness.

With an inside radius of half the wall thickness, a stress concentration of 1.5 is a reasonable assumption, and for radii down to 0.1 times the wall thickness, a stress concentration of 3 is likely. More information on stress concentrations is found in *Working Stress* on page 200, *Stress Concentration Factors* on page 200, and in the charts pages 201 through 204. A suitable value for q in Equation (8) on page 200, for plastics materials, is 1. Most plastics parts are so designed that they can be ejected parallel with the direction of mold parting. Complex parts with undercuts may require mold designs with cavity-forming projections that must move at an angle to the direction of opening. Between these two extremes lie such items as “windows,” or simple openings in the side of a molding, which can be produced by the normal interaction of the two main parts of the mold.

Design for Assembly.—An advantage of the flexibility of plastics parts is that they can often be designed for assembly by means of molded-in snap-fit, press-fit, pop-on, and thread fasteners, so that no additional fasteners, adhesives, solvents, or special equipment is required. Improper assembly can be minimized, but tooling is often made more complex and disassembly may be difficult with these methods.

Chemical bonding involves fixtures, substances, and safety equipment, is suited to applications that must be leak-tight, and does not create stresses. However, adhesives and solvents can be dangerous and preparation and cure times can be prolonged.

Thermal welding methods include ultrasonic, hot-plate, spin, induction, and radio-frequency energy and require special equipment. Thermal methods are also used for staking, swaging, and other heat deformation procedures. Materials must be compatible and have similar melting temperatures.

Mechanical fasteners designed for metals are generally usable with plastics, and there are many other fasteners designed specifically for plastics. Typical are bolts, self-tapping and thread-forming screws, rivets, threaded inserts, and spring clips. Care must be taken to avoid overstressing the parts. Creep can result in loss of preload in poorly designed systems.

Snap-fit designs are widely used, a typical application being to battery compartment covers. All snap-fit designs have a molded part that must flex like a spring, usually past a designed-in interference, then return to its unflexed position to hold the parts together. There must be sufficient holding power without exceeding the elastic or fatigue limits of the material. With the typical snap-fit designs in Fig. 9, beam equations can be used to calculate the maximum strain during assembly. If the stress is kept below the yield point of the material, the flexing finger returns to its original position.

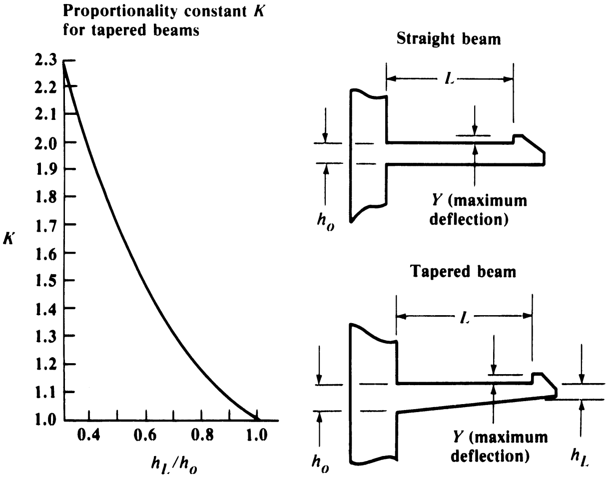


Fig. 9. Snap-fit Designs for Cantilever Beams with Rectangular Cross Sections

With some materials the calculated bending stress can exceed the yield point stress considerably if the movement is done rapidly. In other words, the flexing finger passes through its maximum deflection or strain and the material does not respond as it should if the yield stress has been greatly exceeded. It is common to evaluate snap-ins by calculating strain instead of stress.

Dynamic strain $\in$, for the straight beam, is calculated from

$$\in \; = \frac{3Yh_o}{2L^2} \tag{26}$$

and for the tapered beam, from

$$\in \; = \frac{3Yh_o}{2L^2K} \tag{27}$$

The derived values should be compared with the permissible dynamic strain limits for the material in question, if known. A tapered finger provides more-uniform stress distribution and is recommended where possible. Sharp corners or structural discontinuities that will cause stress concentrations on fingers such as those shown must be avoided.

Snap-in arrangements usually require undercuts produced by a sliding core in the mold as shown in Fig. 10a. Sometimes the snap finger can be simply popped off when the mold is opened. An alternative to the sliding core is shown in Fig. 10b, which requires an opening in the molding at the base of the flexing finger. Other snap-in assembly techniques that take advantage of the flexibility of plastics are shown in Fig. 11.

Molded-in threads in holes usually are formed by cores that require some type of unscrewing or collapsing mechanism leading to tooling complications. External threads can often be molded by positioning them across the parting plane of the mold. Molding of threads finer than 28 to the inch is generally not practical.

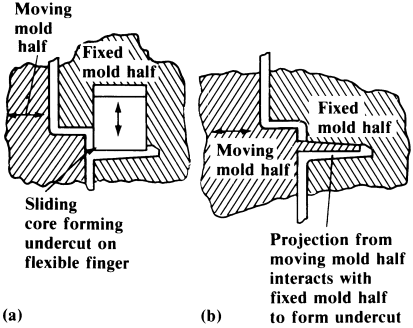


Fig. 10. (left) (a) Arrangement for Molding an Undercut on the End of a Flexible Finger Using a Sliding Core; (b) With the Undercut Formed by a Mold Projection, the Sliding Core is Eliminated.

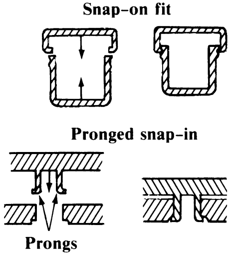


Fig. 11. (right) Examples of Snap-In and Snap-On Arrangements

Chemical bonding may use solvents or adhesives. Use of solvents is limited to compatible materials that can be dissolved by the same solvent. Chemical resistance of many plastics, especially crystalline materials, limits the use of this method. Safety precautions must also be considered in handling the solvents to protect workers and for solvent recovery. With adhesive bonding, a third adhesive substance is introduced at the interface between the parts to be joined. Adhesives can join plastics, metals, ceramics, glass, wood, or other bondable substances.

Typical adhesives used for thermoplastics are epoxies, acrylics, polyurethanes, phenolics, rubbers, polyesters, and vinyls. Cyanoacrylates are often used because of their rapid adhesion to many materials. Manufacturers' recommendations should be sought because many adhesives contain solvents that partially dissolve the plastics surfaces, giving improved adhesion. However, some adhesives can attack certain plastics, leading to deterioration and failure. The main disadvantages of adhesives are that they are slow, use long clamp times, require fixtures, and may involve special ovens or curing conditions. Surface preparation also may be difficult because the presence of grease, oil, mold-release material, or even a fingerprint can spoil a bond. Some materials may need surface preparation such as chemical etching or mechanical roughening to improve joint strength.

Ultrasonic welding is frequently used for joining parts of similar material, of small and medium size, is rapid, and can be automated. High-frequency (20–40 kHz) vibrational energy is directed to the interfaces to be joined, creating localized molecular excitation that causes the plastics to melt. With proper joint designs, welds can be made in only 2 seconds that are as strong as the base materials. When the energy is switched off, the plastics solidifies immediately. Parts to be welded ultrasonically must be so designed that the energy is concentrated in an initially small contact area, creating rapid melting and melt flow that progresses along the joint as the parts are pressed together. The lower part of the assembly is supported in a rigid nest fixture and the upper part is aligned, usually by the joint design. This upper part has freedom to couple acoustically when it is in contact with the horn through which the ultrasonic energy is transmitted.

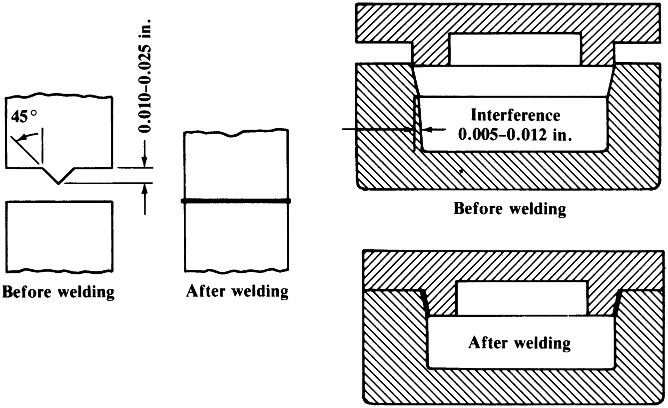


Fig. 12. (left) Energy Director Types of Ultrasonic Weld Joint Designs for Assembly of Plastics Moldings, and (right) Typical Shear Interference

Typical joint designs are shown in Fig. 12, where the example at the left is of a simple butt-type energy director design that works well with amorphous materials. The inverted V-projection, known as an energy director, concentrates the energy in a small area on both sides of the joint. This area melts quickly and the material flows as the parts are pressed together. A basic shear interference joint is seen at the right in Fig. 12. Melting of both components starts at the small initial contact area and flow continues along the near-vertical wall as the parts are pressed together, creating a continuous, leakproof joint with a strength that often exceeds that of the parts joined.

This design is preferred with liquid crystal polymers and crystalline materials such as nylon, acetal, and thermoplastics polyester, and for any application of these materials where high strength and a hermetic seal are required. Many variations of these basic designs are possible and manufacturers of materials and ultrasonic equipment offer literature and design assistance. Ultrasonic vibrations may also be used for staking, swaging, and spot-welding in assembly of plastics parts.

With hygroscopic materials, welding should be completed as soon as possible after molding because moisture can cause weaker bonds. Drying may be advisable immediately before welding. Drawbacks with ultrasonic welding are that design, quality control, equipment maintenance, and settings are of critical importance for consistent, high-strength welds; the equipment is costly; the process uses large amounts of electric power especially with large parts; and parts to be joined must be of the same or similar materials. Filled and reinforced materials also present difficulties with compatibility.

Operating frequencies used in ultrasonic welding are in the range of 20–40 kHz, above the range detectable by the ear. However, discomforting sounds may be generated when plastics parts vibrate at lower frequencies, and may make sound-proofing necessary.

Vibration welding resembles ultrasonic welding except that the parts to be joined are rubbed together to produce heat to melt the joint faces by friction. The energy is transferred in the form of high-amplitude, low-frequency, reciprocating motion. When the vibration stops, the weld area cools and the parts remain joined in the alignment provided by the welding fixture. Typical frequencies used are 120–240 Hz and amplitudes range between 0.10 and 0. 20 in. of linear displacement. When the geometry or assembly design prevents linear movement, vibration-welding equipment can be designed to produce angular displacement of parts.

Like ultrasonic welding, vibration welding produces high-strength joints and is better suited to large parts and irregular joint faces. Moisture in hygroscopic materials such as nylon has less effect on the joint strength than it does with ultrasonic methods.

Spin welding is a rapid and economical method of joining parts that have circular joint interfaces. The process usually is completed in about 3 seconds and can be automated easily. Frictional heat for welding is generated by rotating one part against the other (usually fixed) with a controlled pressure. When the rotation is stopped, pressure is maintained during cooling and solidification of the melted material. Simple equipment such as a drill press is often sufficient for this process.

Radio-frequency welding, often called heat sealing, is widely used with flexible thermoplastics films and sheets of materials such as vinyl (plasticized PVC) and polyurethane, and for joining injection-molded parts, usually to film. Heat for welding is generated by a strong radio-frequency field to the joint region through a metal die formed to suit the joint shape. The die also applies the pressure required to complete the weld. Some plastics are transparent to radio frequency, so cannot be welded by this method.

Electromagnetic or induction welding uses inductive heating to generate fusion temperatures in thermoplastics materials as shown at the top in Fig. 13. Fine, magnetizable particles embedded in a gasket, preform, filament, ribbon, adhesive, coextruded film, or molded part are excited by the radio frequency and are thus heated to welding temperatures. The heated parts are pressed together, and as the temperature rises, the material of the particle carrier flows under pressure through the joint interface, filling voids and cavities and becoming an integral part of the weld. Ideally, the melted material should be contained and subjected to an internal pressure by the surrounding component surfaces. Proper joint design is essential to successful welding and some basic designs are also shown in Fig. 13.

Requirements of the preform often add cost to this welding method but the cost is offset by low reject rates resulting from good reliability of the welds. Structural, hermetic welds can be produced in most thermoplastics materials and automation can be used for large-volume production. The process also offers great latitude in joint size, configuration, tolerance requirements, and ability to bond some dissimilar materials. A disadvantage is that no metal can be near the joint line during energization of the inductor coil. All components of an assembly to be induction-welded must therefore be nonmetallic, or metallic components must be placed where they will not be subjected to the radio-frequency field from the inductor.

Assembly with Fasteners.—Metal fasteners of high strength can overstress plastics parts, so torque-controlled tightening or special design provisions are needed. Examples of poor and preferred designs are shown in Fig. 14. Where torque cannot be controlled, even with a shoulder screw, various types of washers can be used to spread the compression force over wider areas.

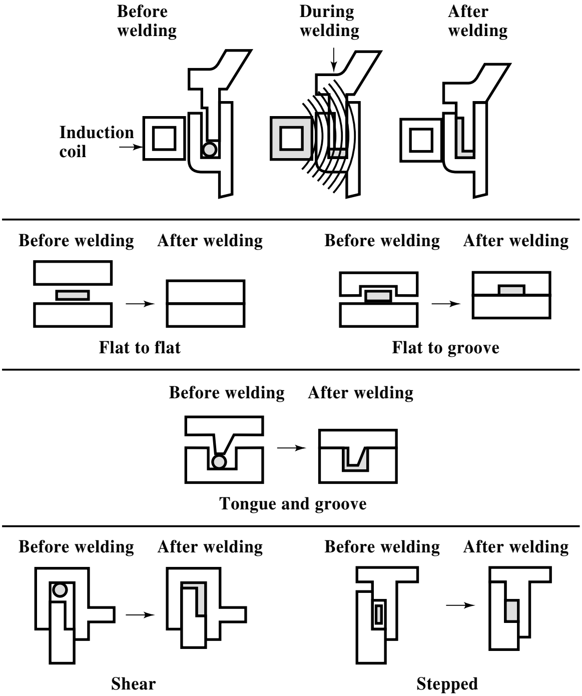


Fig. 13. Typical Joint Designs Used in Induction Welding of Plastics Materials

Metal inserts are available in a wide range of shapes and sizes for permanent installation of metal threads or bushings in plastics parts. Inserts are typically installed in molded bosses, designed with holes to suit the insert to be used. Some inserts are pressed into place and others are installed by methods designed to limit stress and increase strength. Generally, the outside of the insert is provided with projections of various configurations that penetrate the plastics and prevent movement under normal forces exerted during assembly. Inserts can also be installed with equipment similar to that used for ultrasonic welding, the plastics being melted to enhance contact with the metal and reduce insertion stresses.

Thread-cutting and -forming screws are widely used with plastics parts. Information on standard self-threading screws is found in *SELF-THREADING SCREWS* starting on page 1620. Thread-forming screws must be used carefully with high-modulus, low-creep materials, as high hoop stresses can be generated during insertion. Screws with multiple lobes and screws with alternating low and high threads have excellent holding power in plastics. Molded holes must have sufficient depth to prevent bottoming, and boss walls must be thick enough to resist stresses. A rule of thumb is that the outside diameter of the boss should be double the major diameter of the screw.

Hollow aluminum or other metal rivets are often used in plastics assembly, as arestamped sheet metal components, especially push-on or -in designs. Molded plastics fasteners also are frequently used.

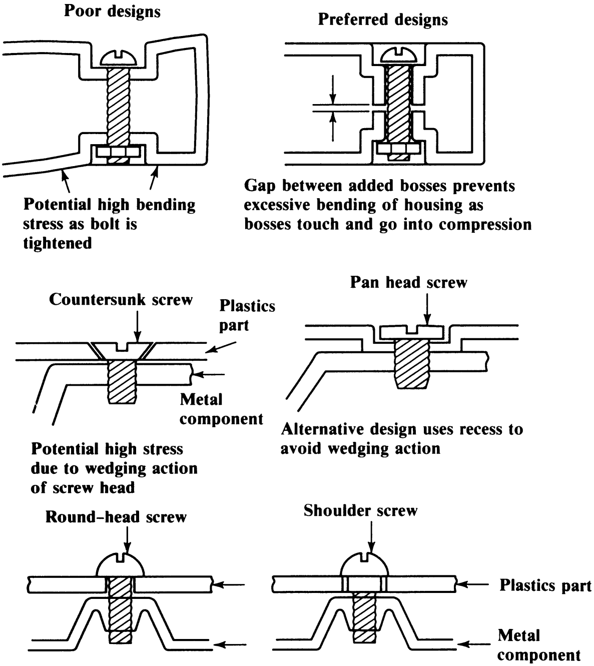


Fig. 14. Examples of Poor and Good Designs Used for Assembly of Plastics Parts with Metal Fasteners

Machining Plastics.—Plastics can be molded into complex shapes so do not usually need to be machined. However, machining is sometimes more cost-effective than making a complex tool, especially when requirements are for prototype development, low-volume production, undercuts, angular holes, or other openings that are difficult to produce in a mold. Specialized methods for development of prototypes are discussed later. All machining of plastics requires dust control, adequate ventilation, safety guards, and eye protection.

Like some metals, plastics may need to be annealed before machining to avoid warpage. Specific annealing instructions can be obtained from plastics suppliers. The modulus of elasticity of plastics is 10–60 times smaller than for metals, and this resilience permits much greater deflection of the work material during cutting. Thermoplastics materials must be held and supported firmly to prevent distortion, and sharp tools are essential to keep cutting forces to a minimum.

Plastics recover elastically during and after machining so that drilled or tapped holes often end up tapered or of smaller diameter than the tool. Turned diameters also can end up larger than the dimensions measured immediately after the finishing cut. The low thermal conductivity of plastics causes most of the heat generated in cutting to be absorbed by the tool. Heat in the plastics tends to stay at the surface. The heat must be removed by an air blast or a liquid coolant for good results in machining.

Plastics have thermal expansion coefficients some 10 times higher than those of metals, so that more heat is generated during machining than with metals. Adequate tool clearances must be provided to minimize heating. Compared with metals, temperatures at which plastics soften, deform and degrade are quite low. Allowing frictional heat to build up causes gumming, discoloration, poor tolerance control, and rough finishes. These effects are more pronounced with plastics such as polystyrene and polyvinyl chloride, having low melting points, than with plastics having higher melting points such as nylon, fluoroplastics, and polyphenylene sulfide. Sufficient clearances must be provided on cutting tools to prevent rubbing contact between the tool and the work. Tool surfaces that will come into contact with plastics during machining must be polished to reduce frictional drag and resulting temperature increases. Proper rake angles depend on depth of cut, cutting speed, and type of plastics being cut. Large rake angles should be used to produce continuous-type cuttings, but they should not be so large as to cause brittle fracture of the work, and resulting discontinuous chips. A discussion of machining techniques follows.

Turning and Cutting Off: High speed steel and carbide tools are commonly used with cutting speeds of 200–500 and 500–800 ft/min, respectively. Water-soluble coolants can be used to keep down temperatures at the shear zone and improve the finish, except when they react with the work material. Chatter may result from the low modulus of elasticity and can be reduced by close chucking and follow rests. Box tools are good for long, thin parts. Tools for cutting off plastics require greater front and side clearances than are needed for metal. Cutting speeds should be about half those used for turning operations.

Drilling: Chip flow in drilling is poor, the rake angles are insufficient and cutting speeds vary from the center to the periphery of the drill, so that drilling imposes severe loading on the workpiece. Drills of high speed steel or premium high speed steel (T15, M33, or M41–M47) are recommended, with low helix angles, point angles of 70–120 deg, and wide, highly polished flutes to ease chip exit. Normal feed rates are in the range of 0.001–0.012 in./rev for holes of $\frac{1}{16}$ to 2 in. diameter, with speeds of 100–250 ft/min, using lower speeds for deep and blind holes. Point angles of 60–90 deg (included) are used for many plastics, but an angle of 120 deg should be used for rigid polyvinyl chloride and acrylic (polymethyl methacrylate).

Clearance angles of 9–15 deg are usually sufficient to prevent the drill flanks from rubbing in the bottom of the hole, but acrylic materials require angles of 12–20 deg. Tests may be needed to determine the drill diameter for accurately sized holes, taking thermal expansion and elastic recovery into account. Reaming may be used to size holes accurately, but diameters produced may also be affected by thermal expansion of the plastics. Close-fitting bushings in drill jigs may increase friction on the drill and cause chips to plug up the drill flutes. For positioning accuracy, removable templates may be used to spot the hole position, then removed for the drilling to be completed. Pilot holes are not necessary, except when the hole is to be reamed or counterbored. Peck feeds to remove chips and compressed air cooling may be needed, especially for deep holes.

Drilling and reaming speed and feed recommendations for various materials are shown in Table 7.

These speeds and feeds can be increased where there is no melting, burning, discoloration, or poor surface finish. Drilling is best done with commercially available drills designed for plastics, usually having large helix angles, narrow lands, and highly polished or chromium-plated flutes to expel chips rapidly and minimize frictional heating. Circle cutters are often preferred for holes in thin materials. Deep holes may require peck feeds. Drills must be kept sharp and cool, and carbide tools may be needed in high production, especially with glass-reinforced materials. Cool with clean compressed air to avoid contamination. Use aqueous solutions for deep drilling because metalcutting fluids and oils may degrade or attack the plastics and may cause a cleaning problem. Hold plastics parts firmly during drilling to counter the tendency for the tooling to grab and spin the work.

Table 7. Speeds and Feeds for Drilling Holes of 0.25 to 0.375 in. Diameter in Various Thermoplastics

Material	Speed (rpm)	Feed[a]	Comments
Polyethylene	1,000–2,000	H	Easy to machine
Polyvinyl chloride	1,000–2,000	M	Tends to become gummy
Acrylic	500–1,500	M–H	Easy to drill with lubricant
Polystyrene	500–1,500	H	Must have coolant
ABS	500–1,000	M–H	
Polytetrafluoroethylene	1,000	L–M	Easy to drill
Nylon 6⁄6	1,000	H	Easy to drill
Polycarbonate	500–1,500	M–H	Easy to drill, some gumming
Acetal	1,000–2,000	H	Easy to drill
Polypropylene	1,000–2,000	H	Easy to drill
Polyester	1,000–1,500	H	Easy to drill

[a] H = high; M = medium; L = low.

Tapping and Threading of Plastics: Many different threaded fasteners can be used with plastics, including thread-tapping and -forming screws, threaded metal inserts, and molded-in threads, but threads must sometimes be machined after molding. For tapping of through-holes in thin cast, molded, or extruded thermoplastics and thermosets, a speed of 50 ft/min is appropriate. Tapping of filled materials is done at 25 ft/min. These speeds should be reduced for deep or blind holes, and when the percentage of thread is greater than 65–75 per cent. Taps should be of M10, M7, or M1, molybdenum high-speed steel, with finish-ground and -polished flutes. Two-flute taps are recommended for holes up to 0.125 in. diameter. Oversize taps may be required to make up for elastic recovery of the plastics. The danger of retapping on the return stroke can be reduced by blunting the withdrawal edges of the tool.

Sawing Thermoset Cast or Molded Plastics: Circular or band saws may be used for sawing. Circular saws provide smoother cut faces than band saws, but band saws run cooler so are often preferred even for straight cuts. Projection of the circular saw above the table should be minimized. Saws should have skip teeth or buttress teeth with zero front rake and a raker set. Precision-tooth saw blades should be used for thicknesses up to 1 in., and saws with buttress teeth are recommended for thicknesses above 1 in. Dull edges to the teeth cause chipping of the plastics and may cause breakage of the saw. Sawing speeds and other recommendations for using blades of high-carbon steel are shown in the accompanying table.

Speeds and Numbers of Teeth for Sawing Plastics Materials with High-Carbon Steel Saw Blades

Material Thickness (in.)	Number of Teeth on Blade	Peripheral Speed (ft/min)	
		Thermoset Cast or Molded Plastics	Thermoplastics (and Epoxy, Melamine, Phenolic and Allyl Thermosets)
0–0.5	8–14	2000–3000	4000–5000
0.5–1	6–8	1800–2200	3500–4300
1–3	3	1500–2200	3000–3500
>3	>3	1200–1800	2500–3000

Milling of Plastics: Peripheral cutting with end mills is used for edge preparation, slotting and similar milling operations, and end cutting can also be used for facing operations. Speeds for milling range from 800 to 1400 ft/min for peripheral end milling of many thermoplastics and from 400 to 800 ft/min for many thermosets. However, slower speeds are generally used for other milling operations, with some thermoplastics being machined at 300–500 ft/min, and some thermosets at 150–300 ft/min. Adequate support and suitable feed rates are very important. A table feed that is too low will generate excessive heat and cause surface cracks, loss of dimensional accuracy, and poor surface finish. Too high a feed rate will produce a rough surface. High-speed steel tools (M2, M3, M7, or T15) are generally used, but for glass-reinforced nylon, silicone, polyimide, and allyl, carbide (C2) is recommended.

New Techniques: Lasers can be used for machining plastics, especially sheet laminates, although their use may generate internal stresses. Ultrasonic machining has no thermal, chemical, or electrical reaction with the workpiece and can produce holes down to 0.003 in. diameter, tight tolerances (0.0005 in.), and very smooth finishes (0.15 μin. with No. 600 boron carbide abrasive powder). Water-jet cutting using pressures up to 60,000 lb/in.^{2} is widely used for plastics and does not introduce stresses into the material. Tolerances of ± 0.004 in. can be held, depending on the equipment available. Process variables, pressures, feed rates, and the nozzle diameter depend on the material being cut. This method does not work with hollow parts unless they can be filled with a solid core.

Development of Prototypes.—Prototypes are made for testing of properties such as stress and fatigue resistance, to find ways to improve quality and reliability, to improve tooling, and to reduce time to market. Prototyping may answer questions about finish, sink marks that result from contraction, witness lines from mold joints, ejector pin marks, knit or weld lines, texturing, moldability, shrinkage, mechanical strength, pull-out resistance of inserts, electrical properties, and problems of mating with other parts.

Prototypes of moldings are made in five major steps including design; refining the design; making a model (physical or computer); making a mold; and producing parts. The model may be made from wood, plaster, plastics (by machining), or a metal. Some 90 per cent of prototypes are made by modern CAD/CAM methods that allow holding of dimensional tolerances of 2–3 per cent of drawing specifications.

Prototypes can also be made by a process called stereo lithography that uses a tank of photosensitive liquid polymer, an x-y scanning, ultraviolet laser with a beam diameter of 0.010 in., a z-axis elevator platform, and a controlling computer. The platform height is adjusted so that a suitable thickness of liquid polymer covers its surface. The laser beam is focused on the liquid surface and hardens the polymer at this point by heating.

The CAD representation of the prototype is described by a model in which thin (0.005–0.020 in.) cross sections can be isolated. Data representing the lowest level of the prototype are used to move the platform so that a layer of the polymer corresponding to the lowest "slice" is hardened. The platform is then lowered, the liquid polymer flows over the hardened layer, and the platform is again raised, less an amount equal to the next "slice." The process is repeated for successive "slices" of the prototype, which is thus built up gradually to form a hollow, three-dimensional shape corresponding to the model in the CAD program. The part thus produced is fairly brittle but can be used for visual examination, design verification, and marketing evaluation, and can be replicated from other materials such as plastics or metals by casting or other methods.

Finishing and decorating methods used for plastics parts include spray painting, vacuum metallizing, hot stamping, silk screening, and plating. Conductive coatings may be applied to inside surfaces, usually by flame- or arc-spraying, to dissipate static electricity and provide electromagnetic shielding. Thorough cleaning is essential. Materials such as polyethylene, polypropylene, and acetal have waxlike surfaces that may not be painted easily or may need pretreatment or special primers. Many amorphous plastics are easy to paint.

Suitable coatings include polyurethane-, epoxy-, acrylic-, alkyd-, and vinyl-based paints. Oven curing may distort parts made from non-heat-resistant materials.

Vacuum metallizing and sputter-plating require application of a special base coat and a protective clear top coat before and after treatment. Resistance heating or an electron beam can be used to melt the metallizing materials such as aluminum, silver, copper, and gold, which usually are pure elements. Sputter plating uses a plasma to produce the metallic vapor and can use brass as well as the metals mentioned. Chromium plating requires etched surfaces to ensure good adhesion.

Plastics may be polished by buffing methods similar to those used on metals, but experiments to determine the effect of frictional heat are recommended. Surfaces can be heated to 300–400 deg. F by buffing, and some plastics soften and melt at these temperatures. Heating sometimes causes plastics to give off toxic gases, so masks should be worn to filter out such gases and dust. Parting lines, imperfections, scratches, saw lines, imperfections and scars resulting from fabrication can be treated with abrasives prior to buffing. Wet or dry abrasives such as silicon carbide or aluminum oxide are generally used, in grain sizes of 60 to as fine as 320. Some buffing compounds are ineffective on plastics. Scratch lines should be presented at a slight angle to the buff surface for best results. Light, tallow-free grease will help keep the abrasive surface free from buildup, and speeds of 5,000 to 6,000 surface feet per minute are recommended.

For low-melting point plastics, soft cotton buffs are best, with surface speeds of 4,000 to 5,000 feet per minute, using a wet or greasy tripoli or silica compound. For finishing, only rouge may be needed for a satisfactory finish. If a cleaning solvent is used it should be checked to see that it does not dissolve the plastics, and it should be used only in a well-ventilated area. Acrylics such as Acrylite or Plexiglass may also be ‘flame polished,’ under advice from the materials supplier.

Plastics Gearing.—Plastics gears may be cut from blanks, as with metal gears, or molded to shape in an injection-molding machine, for lower production costs, though tooling may cost more. Cut plastics gears may be of similar design to their metal counterparts, but molded gears are usually of modified form to suit the material characteristics. Plastics materials also may be preferred for gears because of superior sliding properties with reduced noise and need for lubrication, chemical or electrical properties, or resistance to wear. However, plastics gear teeth slide more smoothly and easily against metal teeth than do plastics against plastics, and wear is less. For power transmission, plastics gear teeth are usually of involute form. See also *Non-metallic Gearing* on page 2119.

Most plastics gears are made from nylons and acetals, although acrylonitrile-butadiene-styrenes (ABS), polycarbonates, polysulfones, phenylene oxides, poly-urethanes, and thermoplastic polyesters can also be used. Additives used in plastics gears include glass fiber for added strength, and fibers, beads, and powders for reduced thermal expansion and improved dimensional stability. Other materials, such as molybdenum disulfide, tetrafluoroethylene (TFE), and silicones, may be added as lubricants to improve wear resistance.

Choice of plastics gear material depends on requirements for size and nature of loads to be transmitted, speeds, required life, working environment, type of cooling, lubrication, and operating precision. Because of cost, plastics gears are sometimes not enclosed in sealed housings, so are often given only a single coating of lubricant grease. Overloading of lubricated plastics gear teeth will usually cause tooth fracture, and unlubricated teeth often suffer excessive wear. Thermoplastics strength varies with temperature, with higher temperatures reducing root stress and permitting tooth deformation. In calculating power to be transmitted by spur, helical, and straight bevel gearing, the following formulas should be used with the factors given in Tables 2, 3 and 1.

For internal and external spur gears,

$$HP = \frac{S_s FYV}{55(600 + V)PC_s}$$

For internal and external helical gears,

$$HP = \frac{S_s FYV}{423(78 + \sqrt{V})P_n C_s}$$

For straight bevel gears,

$$HP = \frac{S_s FYV(C - F)}{55(600 + V)PCC_s}$$

where S_s = safe stress in bending (from Table 2); F = face width in inches; Y = tooth form factor (from Table 1); C = pitch cone distance in inches; C_s = service factor (from Table 3); P = diametral pitch; P_n = normal diametral pitch; and V = velocity at pitch circle diameter in ft/min.

Table 1. Tooth Form Factors *Y* for Plastics Gears

Number of Teeth	14½-deg Involute or Cycloidal	20-deg Full Depth Involute	20-deg Stub Tooth Involute	20-deg Internal Full Depth	
				Pinion	Gear
12	0.210	0.245	0.311	0.327	…
13	0.220	0.261	0.324	0.327	…
14	0.226	0.276	0.339	0.330	…
15	0.236	0.289	0.348	0.330	…
16	0.242	0.259	0.361	0.333	…
17	0.251	0.302	0.367	0.342	…
18	0.261	0.308	0.377	0.349	…
19	0.273	0.314	0.386	0.358	…
20	0.283	0.320	0.393	0.364	…
21	0.289	0.327	0.399	0.371	…
22	0.292	0.330	0.405	0.374	…
24	0.298	0.336	0.415	0.383	…
26	0.307	0.346	0.424	0.393	…
28	0.314	0.352	0.430	0.399	0.691
30	0.320	0.358	0.437	0.405	0.679
34	0.327	0.371	0.446	0.415	0.660
38	0.336	0.383	0.456	0.424	0.644
43	0.346	0.396	0.462	0.430	0.628
50	0.352	0.480	0.474	0.437	0.613
60	0.358	0.421	0.484	0.446	0.597
75	0.364	0.434	0.496	0.452	0.581
100	0.371	0.446	0.506	0.462	0.565
150	0.377	0.459	0.518	0.468	0.550
300	0.383	0.471	0.534	0.478	0.534
Rack	0.390	0.484	0.550	…	…

These values assume a moderate temperature increase and some initial lubrication. With bevel gearing, divide the number of teeth by the cosine of the pitch angle and use the data in the table. For example, if a 20-deg PA bevel gear has 40 teeth and a pitch angle of 58 deg, 40 divided by the cosine of 58 deg = 40 ÷ 0.529919 ~ 75, and $Y = 0.434$.

Table 2. Safe Bending Stress (lb/in^2) Values for Plastics Gears

Plastics Type	Safe Stress	
	Unfilled	Glass-filled
ABS	3,000	6,000
Acetal	5,000	7,000
Nylon	6,000	12,000
Polycarbonate	6,000	9,000
Polyester	3,500	8,000
Polyurethane	2,500	…

Table 3. Service Factors for Plastics Gears

Type of Load	8–10 Hr/Day	24 Hr/Day	Intermittent, 3 Hr/Day	Occasional, ½ Hr/Day
Steady	1.00	1.25	0.80	0.50
Light shock	1.25	1.5	1.00	0.80
Medium shock	1.5	1.75	1.25	1.00
Heavy shock	1.75	2.00	1.5	1.25

As an example, assume that a material is to be selected for a spur gear that must transmit ⅛ hp at 350 rpm, for 8 hrs/day under a steady load. The gear is to have 75 teeth, 32 diametral pitch, 20 deg pressure angle, 0.375 in. face width, and a pitch diameter of 2.3438 in. Using the first formula above,

$$HP = \frac{S_s FYV}{55(600+V)PC_s} \quad \text{or} \quad S_s = \frac{55(600+V)PC_s HP}{FYV}$$

$$\text{hp} = 0.125, \quad Y = 0.434 \quad \text{and}$$

$$V = \frac{rpm \times \pi \times D}{12} = \frac{350 \times 3.1416 \times 2.3438}{12} = 215 \text{ ft/min}$$

therefore,

$$S_s = \frac{55(600+215)32 \times 1.00 \times 0.125}{0.375 \times 0.434 \times 215} = 5{,}124 \text{ lb/in.}^2$$

From Table 2 it is apparent that the gear could be molded from several materials. Available physical and chemical characteristics must now be considered in relation to the operating environment for the gear. Strengths of plastics materials decrease with increasing temperatures and not all plastics resist the effects of some liquids, including some lubricants. Some plastics deteriorate when in sunlight for long periods; some are more dimensionally stable than others; and wear resistance varies from one to another. Manufacturers' data sheets will answer some of these questions.

Backlash: Plastics gears should be so dimensioned that they will provide sufficient backlash at the highest temperatures likely to be encountered in service. Dimensional allowances must also be made for gears made of hygroscopic plastics that may be exposed to damp service conditions. Teeth of heavily loaded gears usually have tip relief to reduce effects of deflection, and have full fillet radii to reduce stress concentrations. Such modifications to tooth form are also desirable in plastics gears. If the pinion in a pair of gears has a small number of teeth, undercutting may result. Undercutting weakens teeth, causes undue wear, and may affect continuity of action. The undercutting can be reduced by using the long-short addendum system, which involves increasing the addendum of the pinion teeth and reducing that of the gear teeth. The modified addendum method will also reduce the amount of initial wear that takes place during the initial stages of contact between the teeth.

Accuracy: The Gear Handbook, AGMA 390-03a-1980, Part 2, Gear Classification, provides a system whereby results of gear accuracy measurements are expressed in terms of maximum tooth-to-tooth and composite tolerances. This system uses AGMA quality numbers related to maximum tolerances, by pitch and diameter, and is equally applicable to plastics gears as to metal gears. AGMA quality numbers must be chosen for a pair of mating gears early in the design process, and the finished gears must be inspected by being run in close mesh with a master gear in a center-distance measuring instrument to make sure that the errors do not exceed the specified tolerances.

To prevent failure from fatigue and wear caused by excessive flexing of the teeth, plastics gears must be made to the same standards of acccuracy as metal gears. Solidification shrinkage of plastics requires that dimensions of molds for gears be larger than the dimensions of the parts to be produced from them. The amount of the shrinkage is usually added to the mold dimension (with the mold at operating temperature). However, this procedure cannot be followed for the tooth profile as it would introduce large errors in the pressure angle. Increases in pressure angle cause gear teeth to become wider at the root and more pointed. Sliding conditions are improved and the teeth are stronger, so that higher loading values can be used.

Shrinkage allowances have the greatest effect on the accuracy of the molded gears, so tooth profiles must be calculated extremely carefully in terms of mold profile. If a tooth is merely made larger by using a standard hobbing cutter to cut the tool whereby the teeth in the mold are electroeroded, differential shrinkage caused by the molded tooth being thicker at the root than at the tip will distort the shape of the molded tooth, making it thinner at the tip and thicker at the root. With two mating gears, these faulty shapes will affect the pressure angle resulting in binding, wear, and general malfunction. If the tooth thickness limits for a molded gear are to be held to +0.000 in., –0.001 in., the outside diameter must be permitted to vary up to 0.0027 in. for 20-deg, and 0.0039 in. for 14½-deg pressure angle gears. All high-accuracy gears should be specified with AGMA quality numbers and inspected with center-distance measuring machines if the required accuracy is to be achieved.