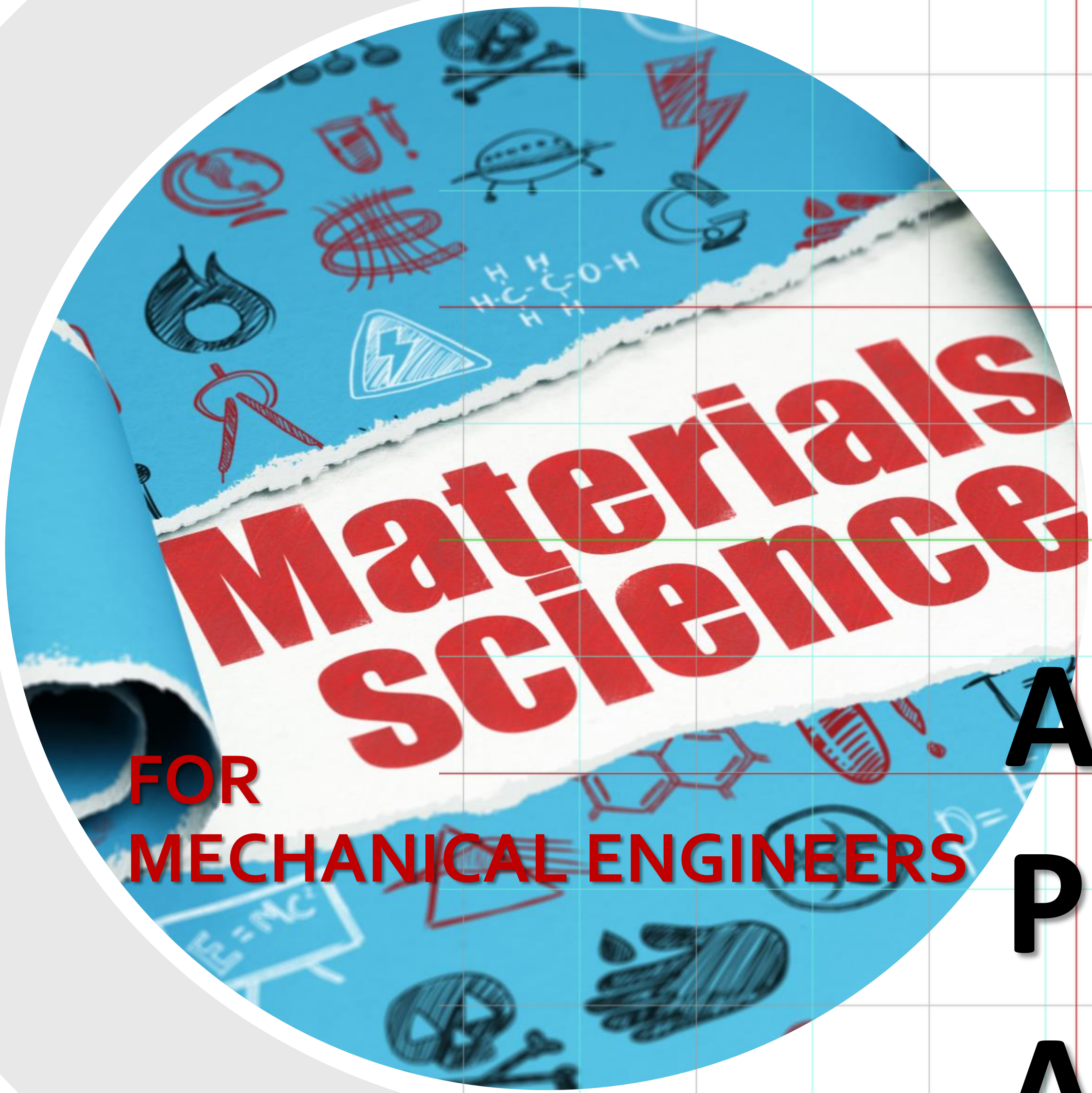


FOR
MECHANICAL ENGINEERS

Applications and Processing of Metal Alloys

SPRING 2022-2023

INTRODUCTION

Often a materials problem is really one of selecting the material that has the right combination of characteristics for a specific application.

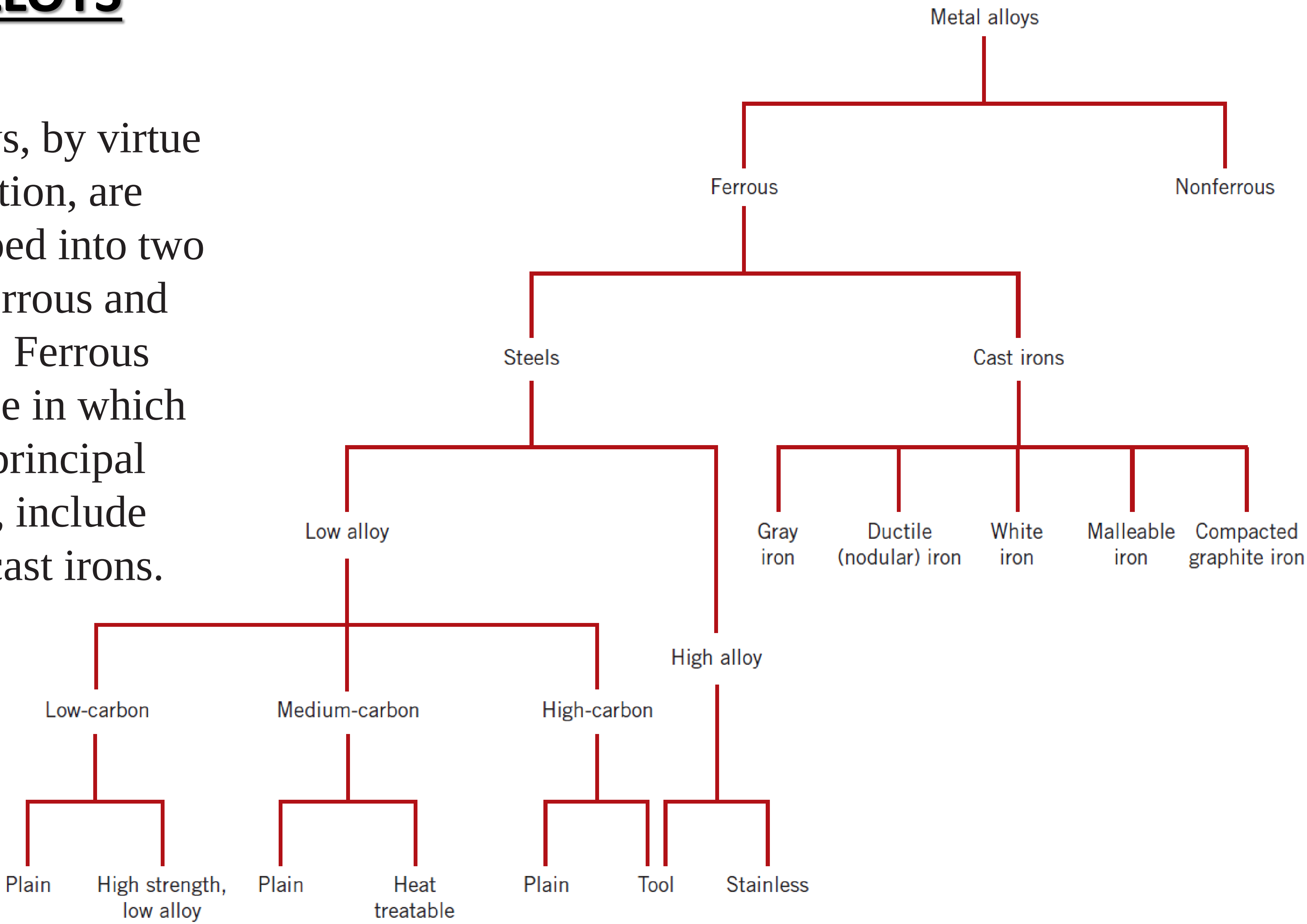
Therefore, the people who are involved in the decision making should have some knowledge of the available options.

Materials selection decisions may also be influenced by the ease with which metal alloys may be formed or manufactured into useful components.

Alloy properties are altered by fabrication processes, and, in addition, further property alterations may be induced by the employment of appropriate heat treatments.

METAL ALLOYS

Metal alloys, by virtue of composition, are often grouped into two classes—ferrous and nonferrous. Ferrous alloys, those in which iron is the principal constituent, include steels and cast irons.

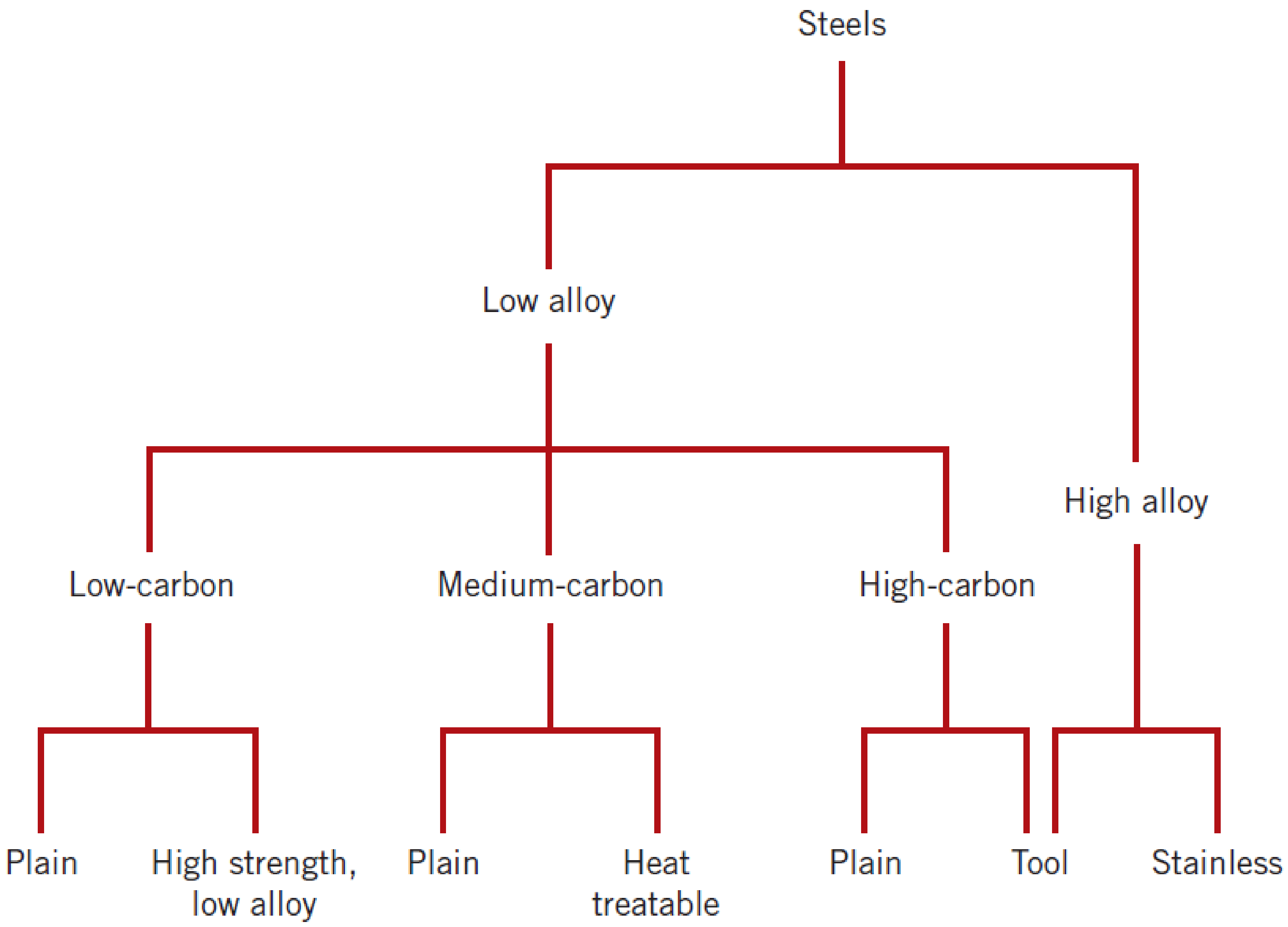


STEELS

Steels are iron–carbon alloys that may contain appreciable concentrations of other alloying elements; there are thousands of alloys that have different compositions and/or heat treatments.

The mechanical properties are sensitive to the content of carbon, which is normally less than 1.0 wt%.

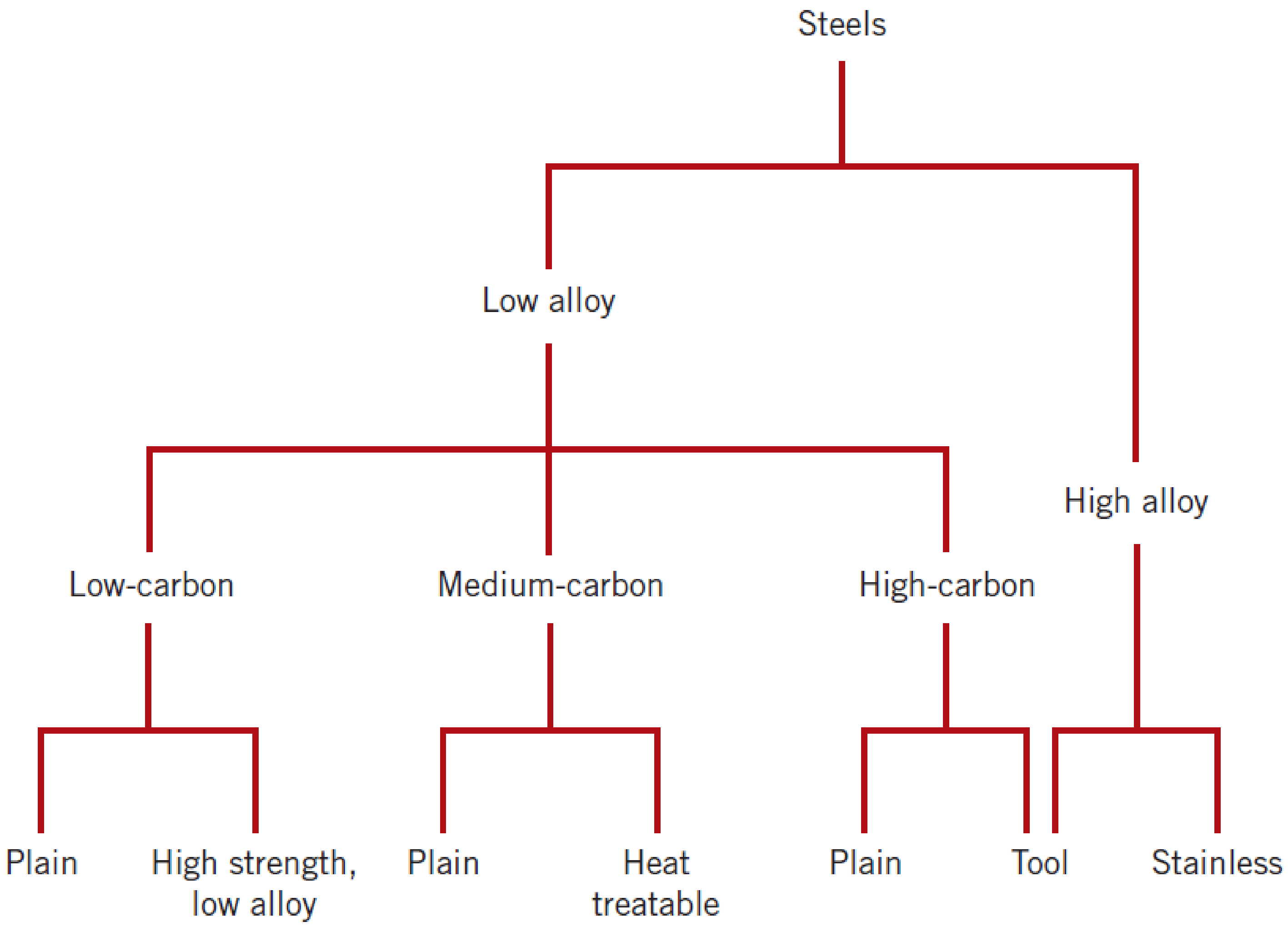
Some of the more common steels are classified according to carbon concentration into low-, medium-, and high-carbon types.



STEELS

Subclasses also exist within each group according to the concentration of other alloying elements.

Plain carbon steels contain only residual concentrations of impurities other than carbon and a little manganese. For **alloy steels,** more alloying elements are intentionally added in specific concentrations.



STEELS

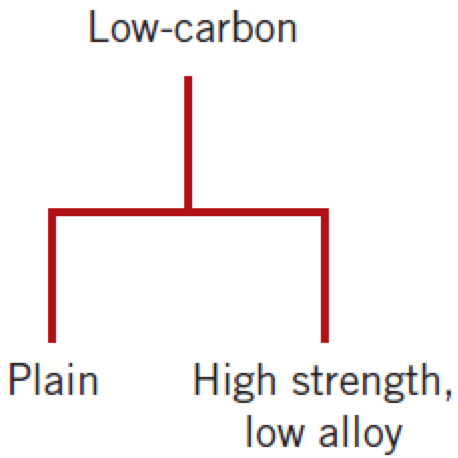
Low-Carbon Steels

Of the different steels, those produced in the greatest quantities fall within the low- carbon classification.

These generally contain less than about 0.25 wt% C and are unresponsive to heat treatments intended to form martensite; strengthening is accomplished by cold work.

Microstructures consist of ferrite and pearlite constituents. As a consequence, these alloys are relatively soft and weak but have outstanding ductility and toughness; in addition, they are machinable, weldable, and, of all steels, are the least expensive to produce.

Typical applications include automobile body components, structural shapes (e.g., I-beams, channel and angle iron), and sheets that are used in pipelines, buildings, bridges, and tin cans.



STEELS

They typically have a yield strength of 275 MPa (40,000 psi), tensile strengths between 415 and 550 MPa (60,000 and 80,000 psi), and a ductility of 25%EL.

Another group of low-carbon alloys are the **high-strength, low-alloy (HSLA) steels.**

They contain other alloying elements such as copper, vanadium, nickel, and molybdenum in combined concentrations as high as 10 wt%, and they possess higher strengths than the plain low-carbon steels.

Most may be strengthened by heat treatment, giving tensile strengths in excess of 480 MPa (70,000 psi); in addition, they are ductile, formable, and machinable.

HSLA steels are more resistant to corrosion than the plain carbon steels, which they have replaced in many applications where structural strength is critical (e.g., bridges, towers, support columns in high-rise buildings, pressure vessels).

STEELS

Designation[a]		*Composition (wt%)*[b]		
AISI/SAE or ASTM Number	*UNS Number*	*C*	*Mn*	*Other*
		Plain Low-Carbon Steels		
1010	G10100	0.10	0.45	
1020	G10200	0.20	0.45	
A36	K02600	0.29	1.00	0.20 Cu (min)
A516 Grade 70	K02700	0.31	1.00	0.25 Si
		High-Strength, Low-Alloy Steels		
A572 Grade 42	—	0.21	1.35	0.30 Si, 0.20 Cu (min)
A633 Grade E	K12002	0.22	1.35	0.30 Si, 0.08 V, 0.02 N, 0.03 Nb
A656 Type 3	—	0.18	1.65	0.60 Si, 0.08 V, 0.02 N, 0.10 Nb

[a]The codes used by the American Iron and Steel Institute (AISI), the Society of Automotive Engineers (SAE), and the American Society for Testing and Materials (ASTM), and in the Uniform Numbering System (UNS) are explained in the text.
[b]Also a maximum of 0.04 wt% P, 0.05 wt% S, and 0.30 wt% Si (unless indicated otherwise).

Source: Adapted from *Metals Handbook: Properties and Selection: Irons and Steels,* Vol. 1, 9th edition, B. Bardes (Editor), 1978. Reproduced by permission of ASM International, Materials Park, OH.

STEELS

AISI/SAE or ASTM Number	*Tensile Strength [MPa (ksi)]*	*Yield Strength [MPa (ksi)]*	*Ductility [%EL in 50 mm (2 in.)]*	*Typical Applications*
		Plain Low-Carbon Steels		
1010	325 (47)	180 (26)	28	Automobile panels, nails, and wire
1020	380 (55)	210 (30)	25	Pipe; structural and sheet steel
A36	400 (58)	220 (32)	23	Structural (bridges and buildings)
A516 Grade 70	485 (70)	260 (38)	21	Low-temperature pressure vessels
		High-Strength, Low-Alloy Steels		
A572 Grade 42	415 (60)	290 (42)	24	Bolted/rivet bridges & buildings
A633 Grade E	515 (75)	380 (55)	23	Structures used at low ambient temperatures
A656 Type 3	655 (95)	552 (80)	15	Truck frames & railway cars

STEELS

Medium-Carbon Steels

The medium-carbon steels have carbon concentrations between about 0.25 and 0.60 wt%.

These alloys may be heat-treated by austenitizing, quenching, and then tempering to improve their mechanical properties. They are most often utilized in the tempered condition, having microstructures of tempered martensite.

The plain medium-carbon steels have low hardenabilities and can be successfully heat-treated only in very thin sections and with very rapid quenching rates. Additions of chromium, nickel, and molybdenum improve the capacity of these alloys to be heat-treated, giving rise to a variety of strength–ductility combinations.

These heat-treated alloys are stronger than the low-carbon steels, but at a sacrifice of ductility and toughness. Applications include railway wheels and tracks, gears, crankshafts, and other machine parts and high-strength structural components calling for a combination of high strength, wear resistance, and toughness.

STEELS

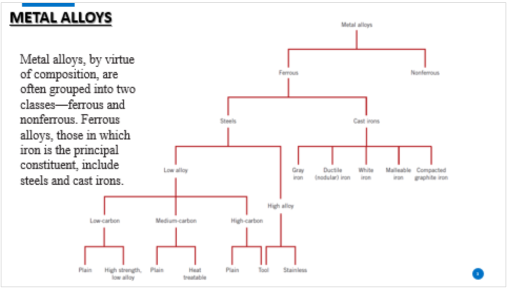
High-Carbon Steels

The high-carbon steels, normally having carbon contents between 0.60 and 1.4 wt%, are the hardest, strongest, and yet least ductile of the carbon steels.

They are almost always used in a hardened and tempered condition and, as such, are especially wear resistant and capable of holding a sharp cutting edge.

The tool and die steels are high-carbon alloys, usually containing chromium, vanadium, tungsten, and molybdenum.

These alloying elements combine with carbon to form very hard and wear-resistant carbide compounds (e.g., Cr23C6, V4C3, and WC).



STEELS

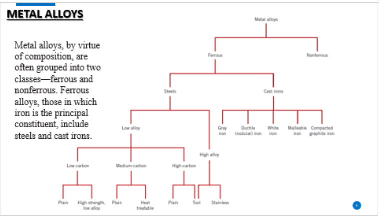
Stainless Steels

The **stainless steels** are highly resistant to corrosion (rusting) in a variety of environments, especially the ambient atmosphere.

Their predominant alloying element is chromium; a concentration of at least 11 wt% Cr is required.

Corrosion resistance may also be enhanced by nickel and molybdenum additions.
Stainless steels are divided into three classes on the basis of the predominant phase constituent of the microstructure—martensitic, ferritic, or austenitic.

A wide range of mechanical properties combined with excellent resistance to corrosion make stainless steels very versatile in their applicability.



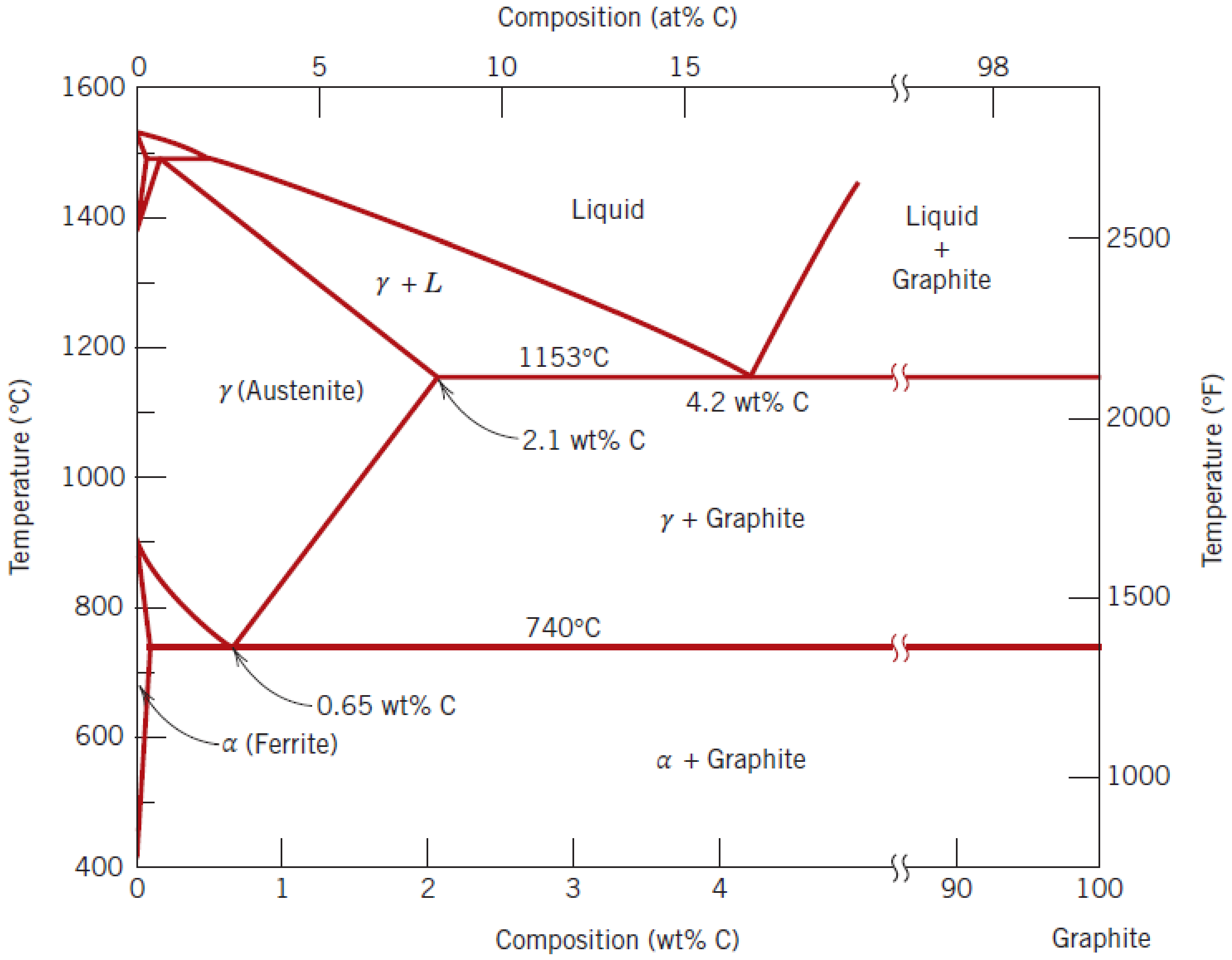
STEELS

AISI Number	UNS Number	Composition (wt%)[a]	Condition[b]	Mechanical Properties: Tensile Strength [MPa (ksi)]	Mechanical Properties: Yield Strength [MPa (ksi)]	Mechanical Properties: Ductility [%EL in 50 mm (2 in.)]	Typical Applications
			Ferritic				
409	S40900	0.08 C, 11.0 Cr, 1.0 Mn, 0.50 Ni, 0.75 Ti	Annealed	380 (55)	205 (30)	20	Automotive exhaust components, tanks for agricultural sprays
446	S44600	0.20 C, 25 Cr, 1.5 Mn	Annealed	515 (75)	275 (40)	20	Valves (high temperature), glass molds, combustion chambers
			Austenitic				
304	S30400	0.08 C, 19 Cr, 9 Ni, 2.0 Mn	Annealed	515 (75)	205 (30)	40	Chemical and food processing equipment, cryogenic vessels
316L	S31603	0.03 C, 17 Cr, 12 Ni, 2.5 Mo, 2.0 Mn	Annealed	485 (70)	170 (25)	40	Welding construction, temporary biomedical orthopedic devices
			Martensitic				
410	S41000	0.15 C, 12.5 Cr, 1.0 Mn	Annealed Q & T	485 (70) 825 (120)	275 (40) 620 (90)	20 12	Rifle barrels, cutlery, jet engine parts
440A	S44002	0.70 C, 17 Cr, 0.75 Mo, 1.0 Mn	Annealed Q & T	725 (105) 1790 (260)	415 (60) 1650 (240)	20 5	Cutlery, bearings, surgical tools
			Precipitation Hardenable				
17-4PH	S17400	0.07 C, 16.25 Cr, 4 Ni, 4 Cu, 0.3 (Nb + Ta), 1.0 Mn, 1.0 Si	Precipitation hardened	1310 (190)	1172 (170)	10	Chemical, petrochemical, and food-processing equipment, aerospace parts

CAST IRON

Generically, **cast irons** are a class of ferrous alloys with carbon contents above 2.14 wt%; in practice, however, most cast irons contain between 3.0 and 4.5 wt% C and, in addition, other alloying elements.

Alloys within this composition range become completely liquid at temperatures between approximately 1150°C and 1300°C (2100°F and 2350°F), which is considerably lower than for steels. Thus, they are easily melted and amenable to casting.



CAST IRON

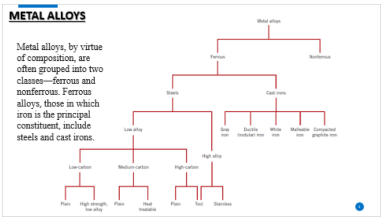
Gray Iron

The carbon and silicon contents of **gray cast irons** vary between 2.5 and 4.0 wt% and 1.0 and 3.0 wt%, respectively.

For most of these cast irons, the graphite exists in the form of flakes (similar to corn flakes), which are normally surrounded by an α-ferrite or pearlite matrix. Because of these graphite flakes, a fractured surface takes on a gray appearance—hence its name.

Mechanically, gray iron is comparatively weak and brittle in tension as a consequence
of its microstructure; the tips of the graphite flakes are sharp and pointed and may serve as points of stress concentration when an external tensile stress is applied.

Strength and ductility are much higher under compressive loads.



CAST IRON

Grade	UNS Number	Composition (wt%)[a]	Matrix Structure	Mechanical Properties: Tensile Strength [MPa (ksi)]	Mechanical Properties: Yield Strength [MPa (ksi)]	Mechanical Properties: Ductility [%EL in 50 mm (2 in.)]	Typical Applications
Gray Iron							
SAE G1800	F10004	3.40–3.7 C, 2.55 Si, 0.7 Mn	Ferrite + pearlite	124 (18)	—	—	Miscellaneous soft iron castings in which strength is not a primary consideration
SAE G2500	F10005	3.2–3.5 C, 2.20 Si, 0.8 Mn	Ferrite + pearlite	173 (25)	—	—	Small cylinder blocks, cylinder heads, pistons, clutch plates, transmission cases
SAE G4000	F10008	3.0–3.3 C, 2.0 Si, 0.8 Mn	Pearlite	276 (40)	—	—	Diesel engine castings, liners, cylinders, and pistons
Ductile (Nodular) Iron							
ASTM A536							
60–40–18	F32800	3.5–3.8 C, 2.0–2.8 Si, 0.05 Mg, <0.20 Ni, <0.10 Mo	Ferrite	414 (60)	276 (40)	18	Pressure-containing parts such as valve and pump bodies
100–70–03	F34800		Pearlite	689 (100)	483 (70)	3	High-strength gears and machine components
120–90–02	F36200		Tempered martensite	827 (120)	621 (90)	2	Pinions, gears, rollers, slides
Malleable Iron							
32510	F22200	2.3–2.7 C, 1.0–1.75 Si, <0.55 Mn	Ferrite	345 (50)	224 (32)	10	General engineering service at normal and elevated temperatures
45006	F23131	2.4–2.7 C, 1.25–1.55 Si, <0.55 Mn	Ferrite + pearlite	448 (65)	310 (45)	6	
Compacted Graphite Iron							
ASTM A842							
Grade 250	—	3.1–4.0 C, 1.7–3.0 Si, 0.015–0.035 Mg, 0.06–0.13 Ti	Ferrite	250 (36)	175 (25)	3	Diesel engine blocks, exhaust manifolds, brake discs for high-speed trains
Grade 450	—		Pearlite	450 (65)	315 (46)	1	

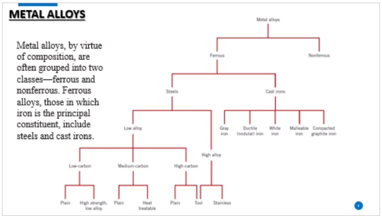
CAST IRON

Gray irons have some desirable characteristics and are used extensively.

They are very effective in damping vibrational energy. Base structures for machines and heavy equipment that are exposed to vibrations are frequently constructed of this material.

In addition, gray irons exhibit a high resistance to wear. Furthermore, in the molten state they have a high fluidity at casting temperature, which permits casting pieces that have intricate shapes; also, casting shrinkage is low.

Finally, and perhaps most important, gray cast irons are among the least expensive of all metallic materials.



CAST IRON

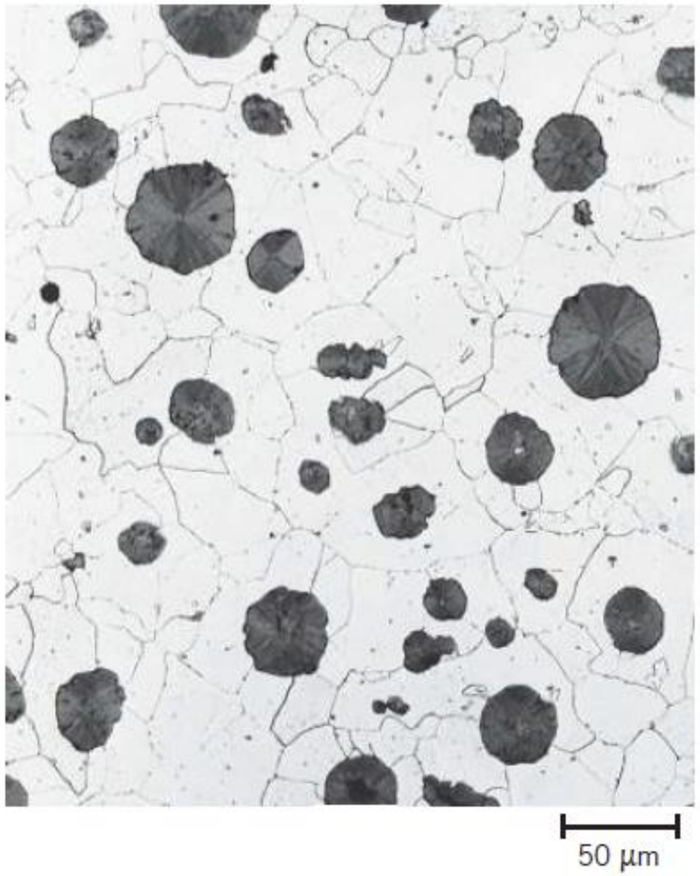
Ductile (or Nodular) Iron

Adding a small amount of magnesium and/or cerium to the gray iron before casting produces a distinctly different microstructure and set of mechanical properties.

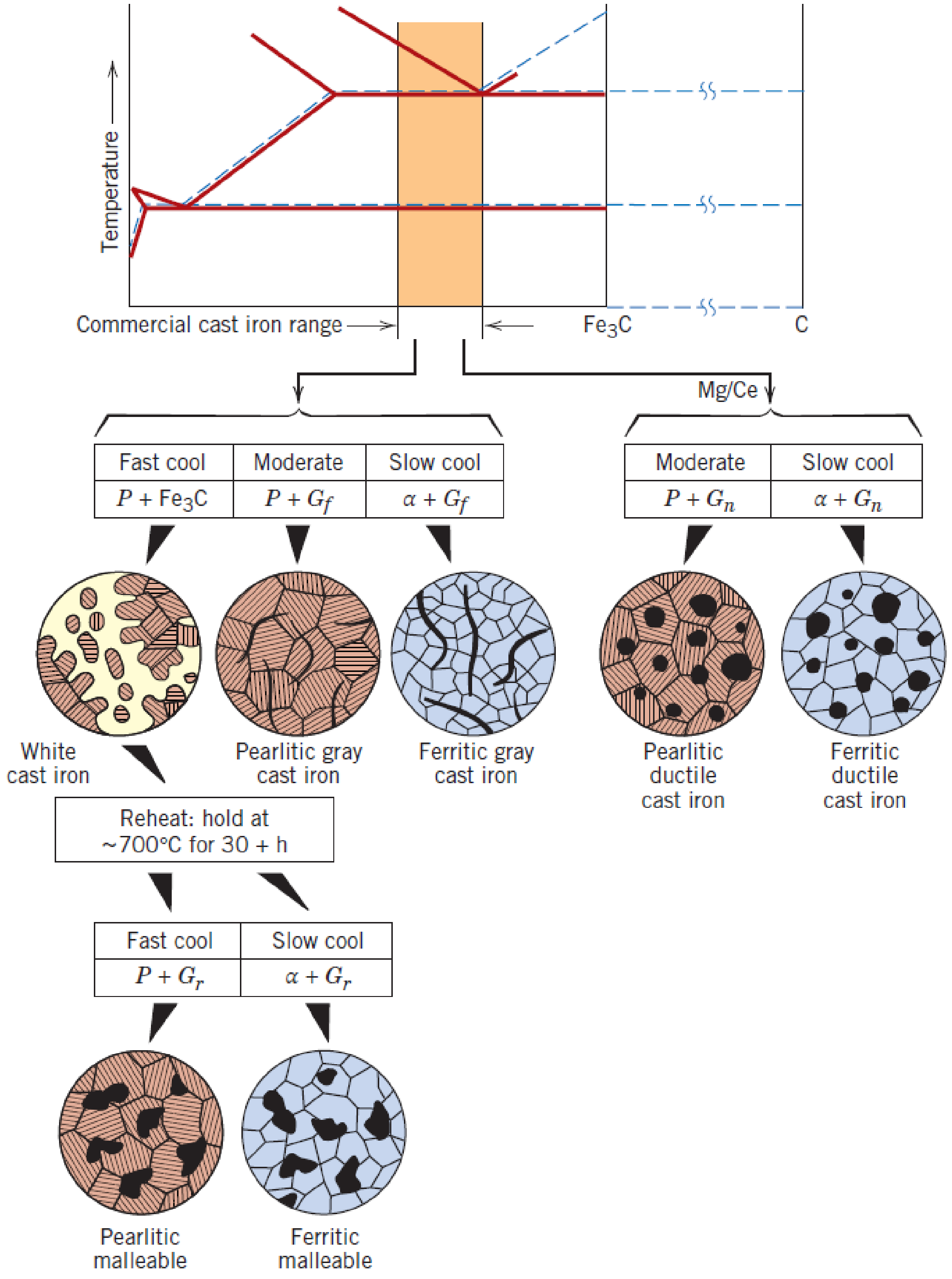
Graphite still forms, but as nodules or spherelike particles instead of flakes. The resulting alloy is called **ductile** or **nodular iron,** and a typical microstructure is shown.

The matrix phase surrounding these particles is either pearlite or ferrite, depending on heat treatment; it is normally pearlite for an as-cast piece.

However, a heat treatment for several hours at about 700°C (1300°F) yields a ferrite matrix.



CAST IRON



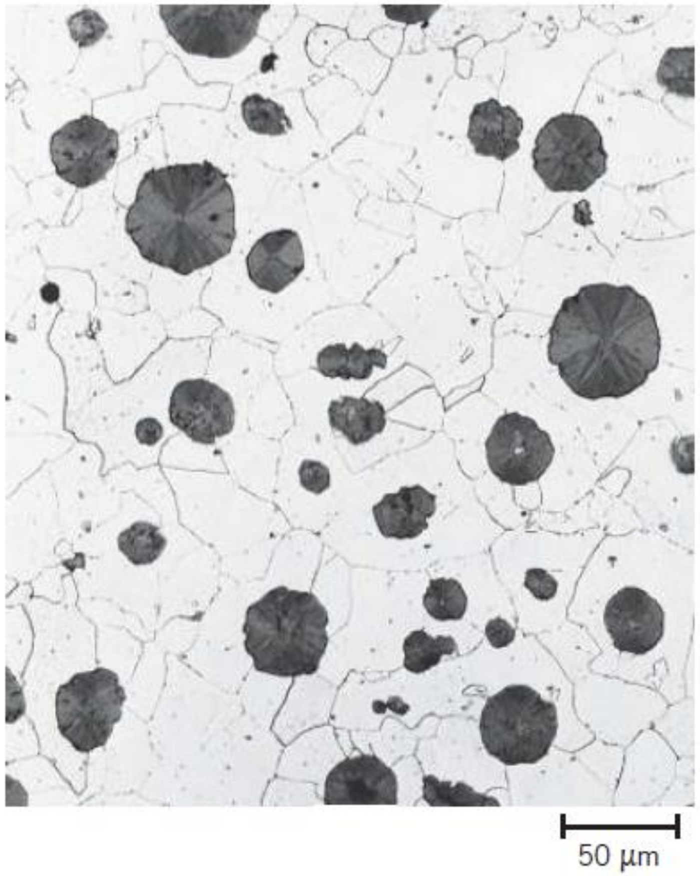
Temperature
Commercial cast iron range
Fe3C
C
Mg/Ce
Fast cool
Moderate
Slow cool
P + Fe3C
P + Gf
α + Gf
Moderate
Slow cool
P + Gn
α + Gn
White cast iron
Pearlitic gray cast iron
Ferritic gray cast iron
Pearlitic ductile cast iron
Ferritic ductile cast iron
Reheat: hold at ~700°C for 30 + h
Fast cool
Slow cool
P + Gr
α + Gr
Pearlitic malleable
Ferritic malleable

CAST IRON

Castings are stronger and much more ductile than gray iron. In fact, ductile iron has mechanical characteristics approaching those of steel.

For example, ferritic ductile irons have tensile strengths between 380 and 480 MPa (55,000 and 70,000 psi) and ductilities (as percent elongation) from 10% to 20%.

Typical applications for this material include valves, pump bodies, crankshafts, gears, and other automotive and machine components.



CAST IRON

As with the other types of cast irons, the mechanical properties of CGIs are related to microstructure: graphite particle shape, as well as the matrix phase/microconstituent.

An increase in degree of nodularity of the graphite particles leads to enhancements of both strength and ductility.

Furthermore, CGIs with ferritic matrices have lower strengths and higher ductilities than those with pearlitic matrices.

Tensile and yield strengths for compacted graphite irons are comparable to values for ductile and malleable irons, yet are greater than those observed for the higher-strength gray irons.

In addition, ductilities for CGIs are intermediate between values for gray and ductile irons; moduli of elasticity range between 140 and 165 GPa (20 × 106 and 24 × 106 psi).

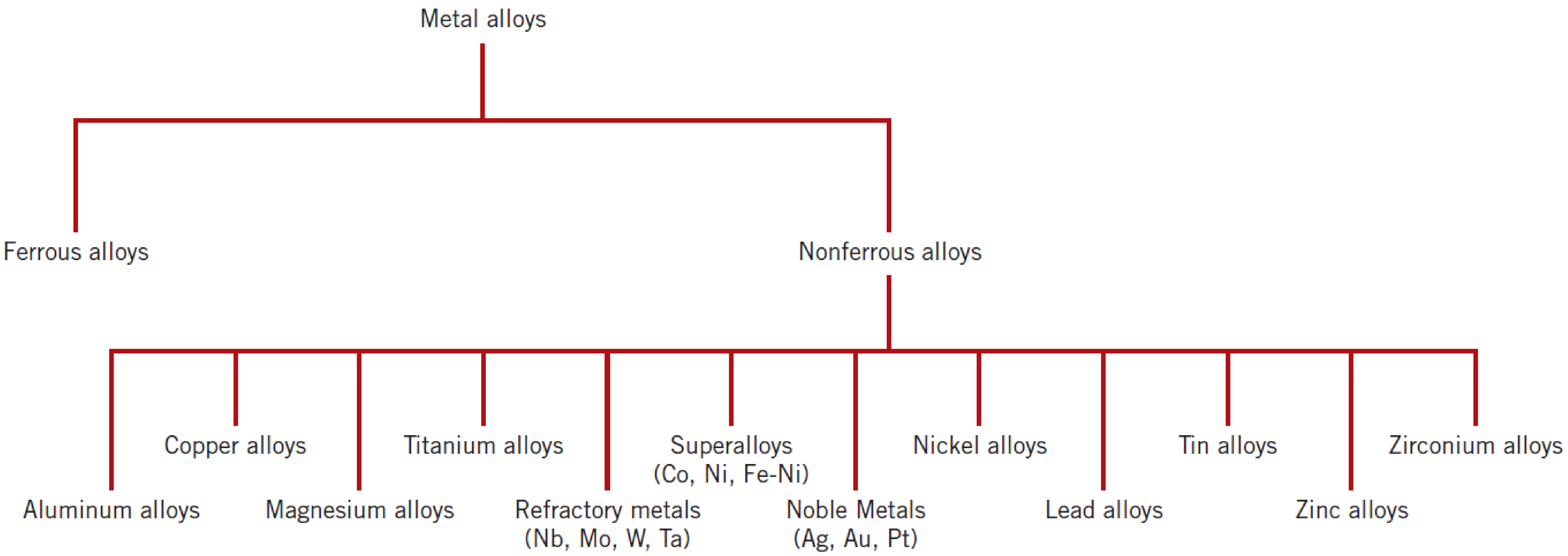
CAST IRON

Compared to the other cast iron types, desirable characteristics of CGIs include the following:

- Higher thermal conductivity
- Better resistance to thermal shock (i.e., fracture resulting from rapid temperature changes)
- Lower oxidation at elevated temperatures

Compacted graphite irons are now being used in a number of important applications, including diesel engine blocks, exhaust manifolds, gearbox housings, brake discs for high-speed trains, and flywheels.

NONFERROUS ALLOYS



NONFERROUS ALLOYS

Copper Alloys

Alloy Name	UNS Number	Composition (wt%)[a]	Condition	Mechanical Properties: Tensile Strength [MPa (ksi)]	Mechanical Properties: Yield Strength [MPa (ksi)]	Mechanical Properties: Ductility [%EL in 50 mm (2 in.)]	Typical Applications
Wrought Alloys							
Electrolytic tough pitch	C11000	0.04 O	Annealed	220 (32)	69 (10)	45	Electrical wire, rivets, screening, gaskets, pans, nails, roofing
Beryllium copper	C17200	1.9 Be, 0.20 Co	Precipitation hardened	1140–1310 (165–190)	965–1205 (140–175)	4–10	Springs, bellows, firing pins, bushings, valves, diaphragms
Cartridge brass	C26000	30 Zn	Annealed Cold-worked (H04 hard)	300 (44) 525 (76)	75 (11) 435 (63)	68 8	Automotive radiator cores, ammunition components, lamp fixtures, flashlight shells, kickplates
Phosphor bronze, 5% A	C51000	5 Sn, 0.2 P	Annealed Cold-worked (H04 hard)	325 (47) 560 (81)	130 (19) 515 (75)	64 10	Bellows, clutch disks, diaphragms, fuse clips, springs, welding rods
Copper–nickel, 30%	C71500	30 Ni	Annealed Cold-worked (H02 hard)	380 (55) 515 (75)	125 (18) 485 (70)	36 15	Condenser and heat-exchanger components, saltwater piping
Cast Alloys							
Leaded yellow brass	C85400	29 Zn, 3 Pb, 1 Sn	As cast	234 (34)	83 (12)	35	Furniture hardware, radiator fittings, light fixtures, battery clamps
Tin bronze	C90500	10 Sn, 2 Zn	As cast	310 (45)	152 (22)	25	Bearings, bushings, piston rings, steam fittings, gears
Aluminum bronze	C95400	4 Fe, 11 Al	As cast	586 (85)	241 (35)	18	Bearings, gears, worms, bushings, valve seats and guards, pickling hooks

NONFERROUS ALLOYS

Aluminum and Its Alloys

Aluminum and its alloys are characterized by a relatively low density (2.7 g/cm3 as compared to 7.9 g/cm3 for steel), high electrical and thermal conductivities, and a resistance to corrosion in some common environments, including the ambient atmosphere.

Many of these alloys are easily formed by virtue of high ductility; this is evidenced by the thin aluminum foil sheet into which the relatively pure material may be rolled.

Because aluminum has an FCC crystal structure, its ductility is retained even at very low temperatures. The chief limitation of aluminum is its low melting temperature [660°C (1220°F)], which restricts the maximum temperature at which it can be used.

NONFERROUS ALLOYS

Recent attention has been given to alloys of aluminum and other low-density metals (e.g., Mg and Ti) as engineering materials for transportation, to effect reductions in fuel consumption.

An important characteristic of these materials is **specific strength,** which is quantified by the tensile strength–specific gravity ratio.

Even though an alloy of one of these metals may have a tensile strength that is inferior to that of a denser material (such as steel), on a weight basis it will be able to sustain a larger load.

A generation of new aluminum–lithium alloys has been developed recently for use by the aircraft and aerospace industries.

These materials have relatively low densities (between about 2.5 and 2.6 g/cm3), high specific moduli (elastic modulus– specific gravity ratios), and excellent fatigue and low-temperature toughness properties.

NONFERROUS ALLOYS

Furthermore, some of them may be precipitation hardened.

However, these materials are more costly to manufacture than the conventional aluminum alloys because special processing techniques are required as a result of lithium's chemical reactivity.

Aluminum Association Number	UNS Number	Composition (wt%)[a]	Condition (Temper Designation)	Mechanical Properties: Tensile Strength [MPa (ksi)]	Mechanical Properties: Yield Strength [MPa (ksi)]	Mechanical Properties: Ductility [%EL in 50 mm (2 in.)]	Typical Applications/Characteristics
Wrought, Non-Heat-Treatable Alloys							
1100	A91100	0.12 Cu	Annealed (O)	90 (13)	35 (5)	35–45	Food/chemical handling and storage equipment, heat exchangers, light reflectors
3003	A93003	0.12 Cu, 1.2 Mn, 0.1 Zn	Annealed (O)	110 (16)	40 (6)	30–40	Cooking utensils, pressure vessels and piping
5052	A95052	2.5 Mg, 0.25 Cr	Strain hardened (H32)	230 (33)	195 (28)	12–18	Aircraft fuel and oil lines, fuel tanks, appliances, rivets, and wire
Wrought, Heat-Treatable Alloys							
2024	A92024	4.4 Cu, 1.5 Mg, 0.6 Mn	Heat-treated (T4)	470 (68)	325 (47)	20	Aircraft structures, rivets, truck wheels, screw machine products
6061	A96061	1.0 Mg, 0.6 Si, 0.30 Cu, 0.20 Cr	Heat-treated (T4)	240 (35)	145 (21)	22–25	Trucks, canoes, railroad cars, furniture, pipelines
7075	A97075	5.6 Zn, 2.5 Mg, 1.6 Cu, 0.23 Cr	Heat-treated (T6)	570 (83)	505 (73)	11	Aircraft structural parts and other highly stressed applications
Cast, Heat-Treatable Alloys							
295.0	A02950	4.5 Cu, 1.1 Si	Heat-treated (T4)	221 (32)	110 (16)	8.5	Flywheel and rear-axle housings, bus and aircraft wheels, crankcases
356.0	A03560	7.0 Si, 0.3 Mg	Heat-treated (T6)	228 (33)	164 (24)	3.5	Aircraft pump parts, automotive transmission cases, water-cooled cylinder blocks
Aluminum–Lithium Alloys							
2090	—	2.7 Cu, 0.25 Mg, 2.25 Li, 0.12 Zr	Heat-treated, cold-worked (T83)	455 (66)	455 (66)	5	Aircraft structures and cryogenic tankage structures
8090	—	1.3 Cu, 0.95 Mg, 2.0 Li, 0.1 Zr	Heat-treated, cold-worked (T651)	465 (67)	360 (52)	—	Aircraft structures that must be highly damage tolerant

NONFERROUS ALLOYS

Magnesium and Its Alloys

Perhaps the most outstanding characteristic of magnesium is its density, 1.7 g/cm3, which is the lowest of all the structural metals; therefore, its alloys are used where light weight is an important consideration (e.g., in aircraft components).

Magnesium has an HCP crystal structure, is relatively soft, and has a low elastic modulus: 45 GPa (6.5 × 106 psi).

At room temperature, magnesium and its alloys are difficult to deform; in fact, only small degrees of cold work may be imposed without annealing. Consequently, most fabrication is by casting or hot working at temperatures between 200°C and 350°C (400°F and 650°F).

Magnesium, like aluminum, has a moderately low melting temperature [651°C (1204°F)]. Chemically, magnesium alloys are relatively unstable and especially susceptible to corrosion in marine environments.

NONFERROUS ALLOYS

However, corrosion or oxidation resistance is reasonably good in the normal atmosphere; it is believed that this behavior is due to impurities rather than being an inherent characteristic of Mg alloys.

Fine magnesium powder ignites easily when heated in air; consequently, care should be exercised when handling it in this state.

ASTM Number	UNS Number	Composition (wt%)[a]	Condition	Mechanical Properties: Tensile Strength [MPa (ksi)]	Yield Strength [MPa (ksi)]	Ductility [%EL in 50 mm (2 in.)]	Typical Applications
Wrought Alloys							
AZ31B	M11311	3.0 Al, 1.0 Zn, 0.2 Mn	As extruded	262 (38)	200 (29)	15	Structures and tubing, cathodic protection
HK31A	M13310	3.0 Th, 0.6 Zr	Strain hardened, partially annealed	255 (37)	200 (29)	9	High strength to 315°C (600°F)
ZK60A	M16600	5.5 Zn, 0.45 Zr	Artificially aged	350 (51)	285 (41)	11	Forgings of maximum strength for aircraft
Cast Alloys							
AZ91D	M11916	9.0 Al, 0.15 Mn, 0.7 Zn	As cast	230 (33)	150 (22)	3	Die-cast parts for automobiles, luggage, and electronic devices
AM60A	M10600	6.0 Al, 0.13 Mn	As cast	220 (32)	130 (19)	6	Automotive wheels
AS41A	M10410	4.3 Al, 1.0 Si, 0.35 Mn	As cast	210 (31)	140 (20)	6	Die castings requiring good creep resistance

NONFERROUS ALLOYS

Titanium and Its Alloys

Titanium and its alloys are relatively new engineering materials that possess an extraordinary combination of properties.

The pure metal has a relatively low density (4.5 g/cm3), a high melting point [1668°C (3035°F)], and an elastic modulus of 107 GPa (15.5 × 106 psi).

Titanium alloys are extremely strong: Room-temperature tensile strengths as high as 1400 MPa (200,000 psi) are attainable, yielding remarkable specific strengths.

Furthermore, the alloys are highly ductile and easily forged and machined.

Unalloyed (i.e., commercially pure) titanium has a hexagonal close-packed crystal structure, sometimes denoted as the α phase at room temperature.

At 883°C (1621°F), the HCP material transforms into a body-centered cubic (or β) phase.

NONFERROUS ALLOYS

This transformation temperature is strongly influenced by the presence of alloying elements. For example, vanadium, niobium, and molybdenum decrease the α-to-β transformation temperature and promote the formation of the β phase (i.e., are β-phase stabilizers), which may exist at room temperature.

In addition, for some compositions, both α and β phases coexist. On the basis of which phase(s) is (are) present after processing, titanium alloys fall into four classifications: α, β, $\alpha + \beta$, and near α.

NONFERROUS ALLOYS

Alloy Type	Common Name (UNS Number)	Composition (wt%)	Condition	Average Mechanical Properties: Tensile Strength [MPa (ksi)]	Yield Strength [MPa (ksi)]	Ductility [%EL in 50 mm (2 in.)]	Typical Applications
Commercially pure	Unalloyed (R50250)	99.5 Ti	Annealed	240 (35)	170 (25)	24	Jet engine shrouds, cases and airframe skins, corrosion-resistant equipment for marine and chemical processing industries
α	Ti-5Al-2.5Sn (R54520)	5 Al, 2.5 Sn, balance Ti	Annealed	826 (120)	784 (114)	16	Gas turbine engine casings and rings; chemical processing equipment requiring strength to temperatures of 480°C (900°F)
Near α	Ti-8Al-1Mo-1V (R54810)	8 Al, 1 Mo, 1 V, balance Ti	Annealed (duplex)	950 (138)	890 (129)	15	Forgings for jet engine components (compressor disks, plates, and hubs)
$\alpha + \beta$	Ti-6Al-4V (R56400)	6 Al, 4 V, balance Ti	Annealed	947 (137)	877 (127)	14	High-strength prosthetic implants, chemical-processing equipment, airframe structural components
$\alpha + \beta$	Ti-6Al-6V-2Sn (R56620)	6 Al, 2 Sn, 6 V, 0.75 Cu, balance Ti	Annealed	1050 (153)	985 (143)	14	Rocket engine case airframe applications and high-strength airframe structures
β	Ti-10V-2Fe-3Al	10 V, 2 Fe, 3 Al, balance Ti	Solution + aging	1223 (178)	1150 (167)	10	Best combination of high strength and toughness of any commercial titanium alloy; used for applications requiring uniformity of tensile properties at surface and center locations; high-strength airframe components

NONFERROUS ALLOYS

The Superalloys

The superalloys have superlative combinations of properties. Most are used in aircraft turbine components, which must withstand exposure to severely oxidizing environments and high temperatures for reasonable time periods.

Mechanical integrity under these conditions is critical; in this regard, density is an important consideration because centrifugal stresses are diminished in rotating members when the density is reduced.

These materials are classified according to the predominant metal(s) in the alloy, of which there are three groups: iron–nickel, nickel, and cobalt.

Other alloying elements include the refractory metals (Nb, Mo, W, Ta), chromium, and titanium. Furthermore, these alloys are also categorized as wrought or cast. In addition to turbine applications, superalloys are used in nuclear reactors and petrochemical equipment.

NONFERROUS ALLOYS

	Composition (wt%)									
Alloy Name	***Ni***	***Fe***	***Co***	***Cr***	***Mo***	***W***	***Ti***	***Al***	***C***	***Other***
Iron–Nickel (Wrought)										
A-286	26	55.2	—	15	1.25	—	2.0	0.2	0.04	0.005 B, 0.3 V
Incoloy 925	44	29	—	20.5	2.8	—	2.1	0.2	0.01	1.8 Cu
Nickel (Wrought)										
Inconel-718	52.5	18.5	—	19	3.0	—	0.9	0.5	0.08	5.1 Nb, 0.15 max Cu
Waspaloy	57.0	2.0 max	13.5	19.5	4.3	—	3.0	1.4	0.07	0.006 B, 0.09 Zr
Nickel (Cast)										
Rene 80	60	—	9.5	14	4	4	5	3	0.17	0.015 B, 0.03 Zr
Mar-M-247	59	0.5	10	8.25	0.7	10	1	5.5	0.15	0.015 B, 3 Ta, 0.05 Zr, 1.5 Hf
Cobalt (Wrought)										
Haynes 25 (L-605)	10	1	54	20	—	15	—	—	0.1	
Cobalt (Cast)										
X-40	10	1.5	57.5	22	—	7.5	—	—	0.50	0.5 Mn, 0.5 Si

NONFERROUS ALLOYS

The Noble Metals

The noble or precious metals are a group of eight elements that have some physical characteristics in common.

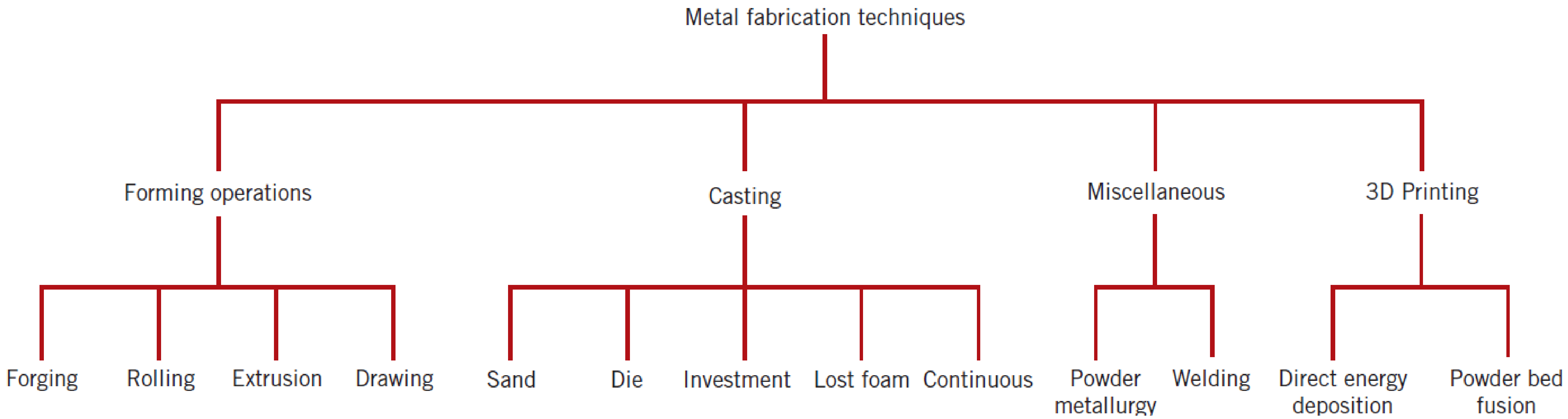
They are expensive (precious) and are superior or notable (noble) in properties—characteristically soft, ductile, and oxidation resistant.

The noble metals are silver, gold, platinum, palladium, rhodium, ruthenium, iridium, and osmium; the first three are most common and are used extensively in jewelry.

Silver and gold may be strengthened by solid-solution alloying with copper; sterling silver is a silver– copper alloy containing approximately 7.5 wt% Cu. Alloys of both silver and gold are employed as dental restoration materials.

Some integrated circuit electrical contacts are of gold. Platinum is used for chemical laboratory equipment, as a catalyst (especially in the manufacture of gasoline), and in thermocouples to measure elevated temperatures.

FABRICATION OF METALS



FABRICATION OF METALS

Forming operations are those in which the shape of a metal piece is changed by plastic deformation; for example, forging, rolling, extrusion, and drawing are common forming techniques.

The deformation must be induced by an external force or stress, the magnitude of which must exceed the yield strength of the material.

Most metallic materials are especially amenable to these procedures, being at least moderately ductile and capable of some permanent deformation without cracking or fracturing.

When deformation is achieved at a temperature above that at which recrystallization occurs, the process is termed **hot working**; otherwise, it is cold working.

With most of the forming techniques, both hot- and cold-working procedures are possible.

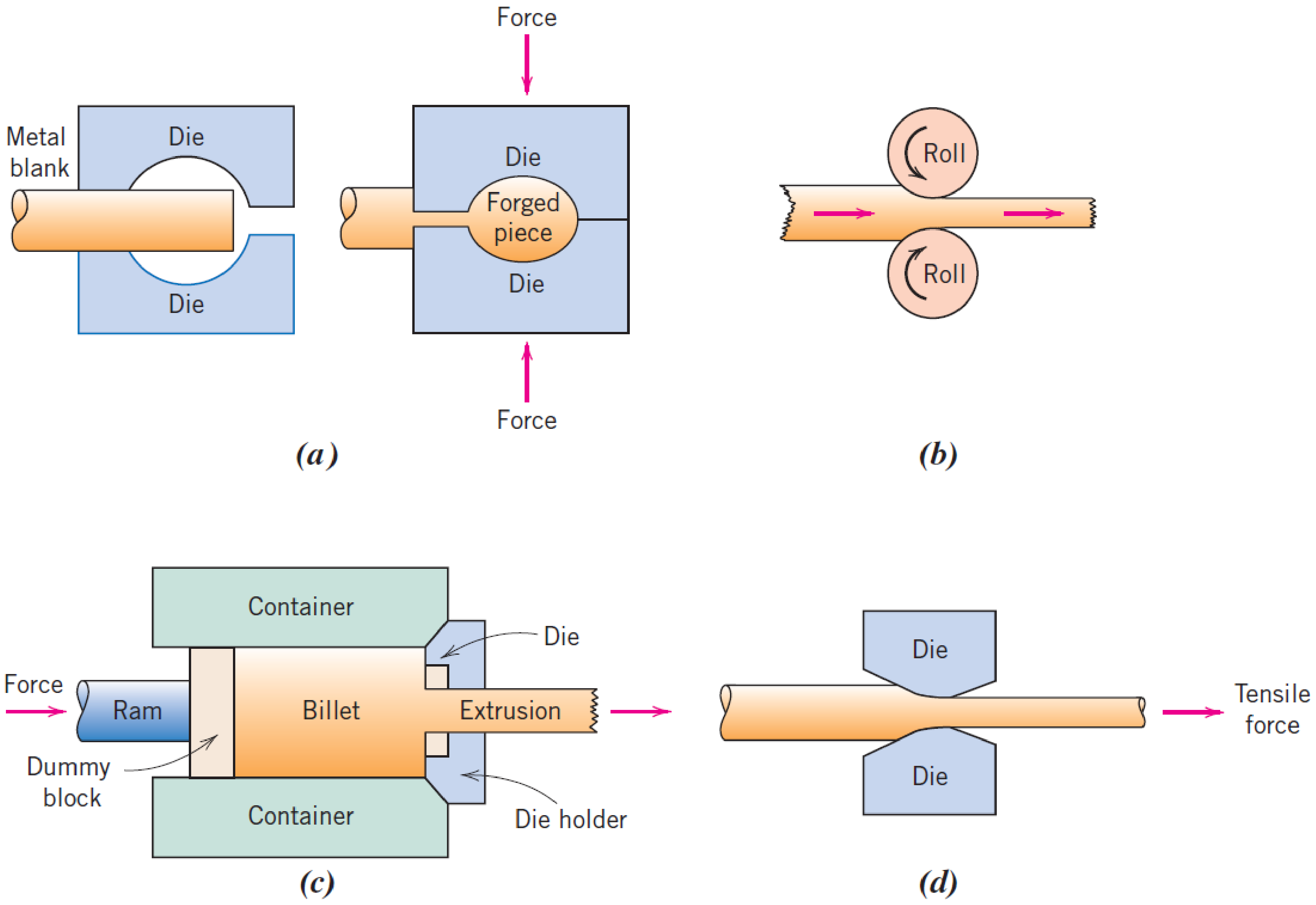
FABRICATION OF METALS

For hot-working operations, large deformations are possible, which may be successively repeated because the metal remains soft and ductile.

Also, deformation energy requirements are less than for cold working. However, most metals experience some surface oxidation, which results in material loss and a poor final surface finish.

Cold working produces an increase in strength with the attendant decrease in ductility because the metal strain hardens; advantages over hot working include a higher quality surface finish, better mechanical properties and a greater variety of them, and closer dimensional control of the finished piece.

FABRICATION OF METALS



Metal deformation during (*a*) forging, (*b*) rolling, (*c*) extrusion, and (*d*) drawing

THERMAL PROCESSING OF METALS

ANNEALING PROCESSES

The term **annealing** refers to a heat treatment in which a material is exposed to an elevated temperature for an extended time period and then slowly cooled.

Typically, annealing is carried out to (1) relieve stresses; (2) increase softness, ductility, and toughness; and/or (3) produce a specific microstructure.

A variety of annealing heat treatments are possible; they are characterized by the changes that are induced, which often are microstructural and are responsible for the alteration of the mechanical properties.

Any annealing process consists of three stages: (1) heating to the desired temperature, (2) holding or "soaking" at that temperature, and (3) cooling, usually to room temperature.

Time is an important parameter in these procedures.

THERMAL PROCESSING OF METALS

During heating and cooling, temperature gradients exist between the outside and interior portions of the piece; their magnitudes depend on the size and geometry of the piece.

If the rate of temperature change is too great, temperature gradients and internal stresses may be induced that may lead to warping or even cracking.

Also, the actual annealing time must be long enough to allow for any necessary transformation reactions. Annealing temperature is also an important consideration; annealing may be accelerated by increasing the temperature because diffusional processes are normally involved.

THERMAL PROCESSING OF METALS

Steel class	Type	Thermal processing	Microstructure	Properties
Plain carbon steels	Low-carbon	Full anneal, normalize, quench/temper	Pearlite/ferrite	$180 < \sigma_y < 350$ MPa, $15 < \%EL < 35$
Plain carbon steels	Medium-carbon	Full anneal, normalize, quench/temper, spheroidize	Pearlite, tempered martensite, spheroidite	$250 < \sigma_y < 650$ MPa, $10 < \%EL < 30$
Plain carbon steels	High-carbon	Quench/temper	Tempered martensite	$400 < \sigma_y < 980$ MPa, $10 < \%EL < 15$
Low-alloy steels	HSLA	Normalize, quench	Pearlite, bainite, martensite/ferrite	$300 < \sigma_y < 550$ MPa, $15 < \%EL < 25$
Low-alloy steels	Medium-carbon	Quench/temper	Tempered martensite	$600 < \sigma_y < 1800$ MPa, $5 < \%EL < 30$
Alloy steels — Stainless	Austenitic	Anneal	Austenite	$170 < \sigma_y < 965$ MPa, $4 < \%EL < 45$
Alloy steels — Stainless	Ferritic	Anneal	Ferrite	$170 < \sigma_y < 450$ MPa, $15 < \%EL < 30$
Alloy steels — Stainless	Martensitic	Quench/temper	Tempered martensite	$205 < \sigma_y < 1900$ MPa, $2 < \%EL < 22$
Alloy steels	Tool	Quench/temper	Metal carbide particles, tempered martensite	$380 < \sigma_y < 1930$ MPa, $4 < \%EL < 25$