MECH 423 Casting, Welding, Heat Treating and NDT

Time_ _ W _ F 14:45 - 16:00

Credits: 3.5 Session: Fall

Phase Diagrams

Lecture 5

Casting Alloy Systems

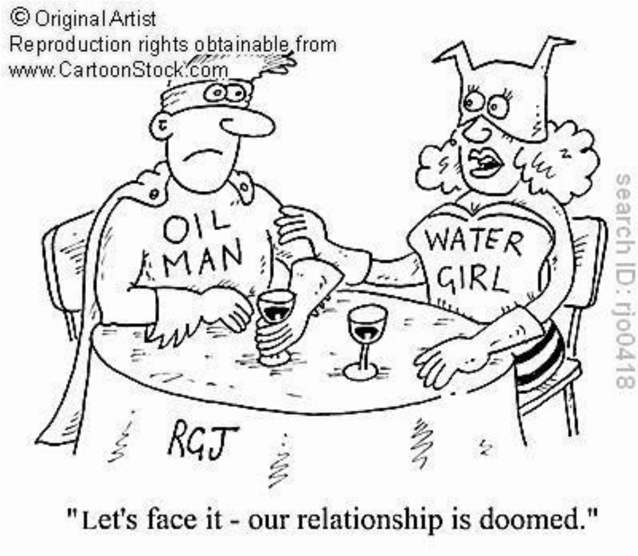
- Most metals originally cast from liquid to form ingots. Many go through subsequent hot/cold working;
  - homogenization of composition
  - healing of defects, pores/cracks
  - recrystallisation, annealing.
- For Final castings (i.e. to finished or semi-finished shape) the alloy selection is more specific:
  - high fluidity
  - lower melting points (eutectic compositions)
  - short freezing ranges
  - low shrinkage
  - strength that doesn’t rely on cold working
    - eutectic
    - solid solution strengthening
    - precipitation hardening
    - fine grain size

What is a Phase?

- Sand and Salt
- Coffee and Sugar
- Water and Alcohol

How many phases in each?

- A phase is a homogenous, physically distinct and mechanically separable portion of the material with a given chemical composition and structure.
- For solids: Chemically and structurally distinct
- For liquids: Miscibility
- For gases: Always 1 phase

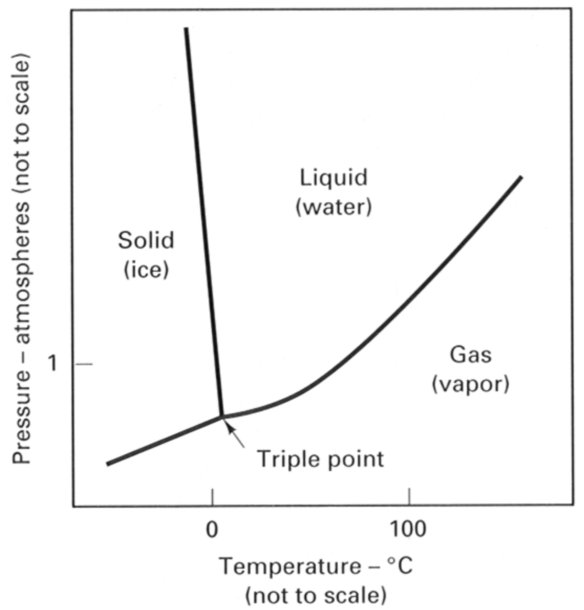


Lecture 5

Equilibrium Phase Diagram

- Graphic mapping of material under different conditions assuming equilibrium has been attained
- Simplest P-T diagram for fixed composition mat'l
- 4.1 gives the P-T diagram of water
- @1 atm: water is solid < 0° and gas > 100°
- At normal pressure find a temperature at which water is liquid
- Reduce the temperature until it becomes solid
- At that temperature reduce pressure and at one point, the solid directly goes to gas, without going to liquid phase – sublimation (process is called as freeze drying)
- If we have phase diagram, we can calculate the conditions required

FIGURE 4.1 Pressure–temperature diagram for water.



Here's how freeze drying works.

1. Fresh or cooked foods are flash frozen, then placed in a vacuum chamber.

2. About 98% of the food's moisture is drawn off by evaporating the ice, at temperatures as low as -50° F.

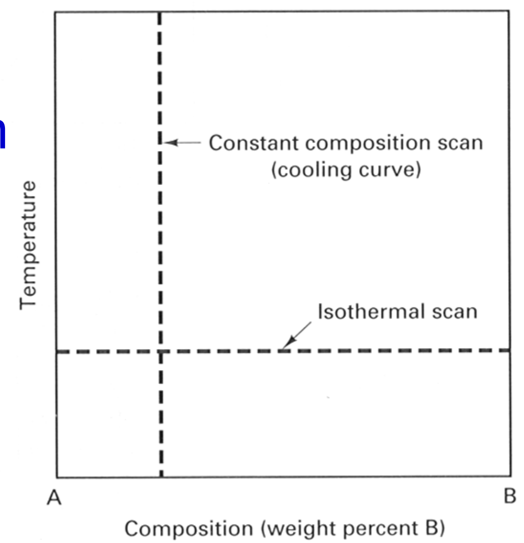
3. The freeze-dried food is sealed in moisture-and-oxygen proof packaging, to ensure freshness until opened.

4. When the water is replaced, the food regains its original fresh flavor, aroma, texture, and appearance.

Temperature Composition Diagram

- Generally engineering processes are done at constant pressure (mostly atmospheric)
- Variations will be in temperature and composition
- 4.2 gives the temperature composition diagram
- A and B at the ends are pure metals
- In between is the composition percentage of B in A

FIGURE 4.2 Mapping for a temperature–composition equilibrium phase diagram.



- Constant composition at various temperatures give the cooling curve
- Constant temperature at various compositions give isothermal scan
- Cooling curves are the ones that we will be interested in for various alloy compositions
- Example, salt added to water, reduces the freezing point, and used commonly in winter

Solubility

- If we move away from pure metals, we have one metal dispersed over the other
- If it is partially soluble Tin and Lead shown in 4-5
- Three single phase regions (α - solid solution of Tin in Lead matrix, β = solid solution of Pb in Sn marix, L - liquid)
- Three two-phase regions (α + L, β +L, α +β)
- Solvus line separates one solid solution from a mixture of solid solutions.
- The Solvus line shows limit of solubility
- 4-6 shows copper nickel diagram, which is completely soluble

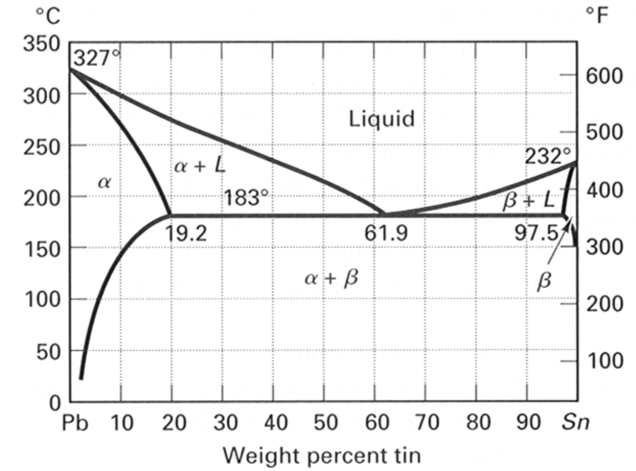


FIGURE 4.5 Lead–tin equilibrium diagram.

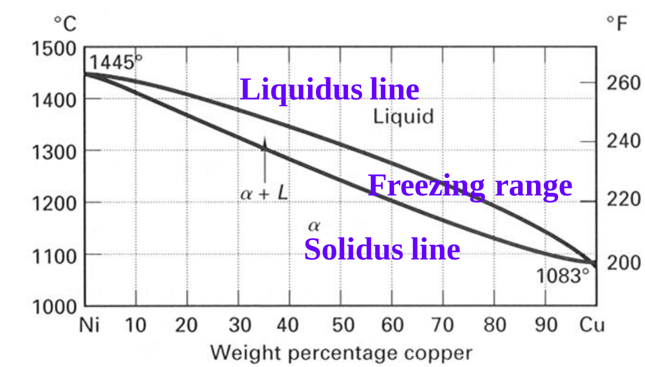
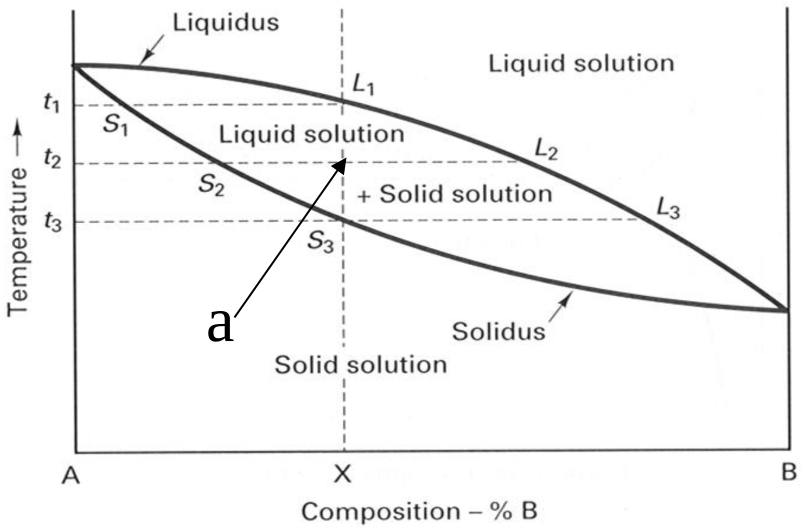


FIGURE 4.6 Copper–nickel equilibrium diagram, showing complete solubility in both liquid and solid states.

Solidification

FIGURE 4.8 Equilibrium diagram showing the changes that occur during the cooling of alloy X.



- Each temperature and composition gives 3 different pieces of info
- For composition X we have above L_1, below S_3 and in between
- For temperature t_2, we have below S_2 above L_2 and in between
- At point a, the tie line runs from S_2 to L_2 and the solid at this 2 phase mixture will have composition of S_2 and the liquid will have that of L_2
- For alloy X, t_1 is the temperature at which first amount solid starts forming with chemistry of S_1
- As t reduces, more solid forms and chemistries follow the tie line point
- At t_3, the alloy is completely solidified to give a single phase alloy X

Intermetallic Compounds

- Suffix *ic* tells one of the phase is liquid and *oid* tells all phases are solid
- Eutectic reaction – transition between liquid and two solid phases mixture at eutectic concentration – e.g. $L \leftrightarrow \alpha + \beta$
- A peritectic reaction - solid and liquid phase will form a second solid phase at particular t & c - e.g. $L + \alpha \leftrightarrow \beta$
- A Monotectic reaction - liquid phase will form a second liquid and solid phase at particular t & c - e.g. $L_1 \leftrightarrow L_2 + \alpha$

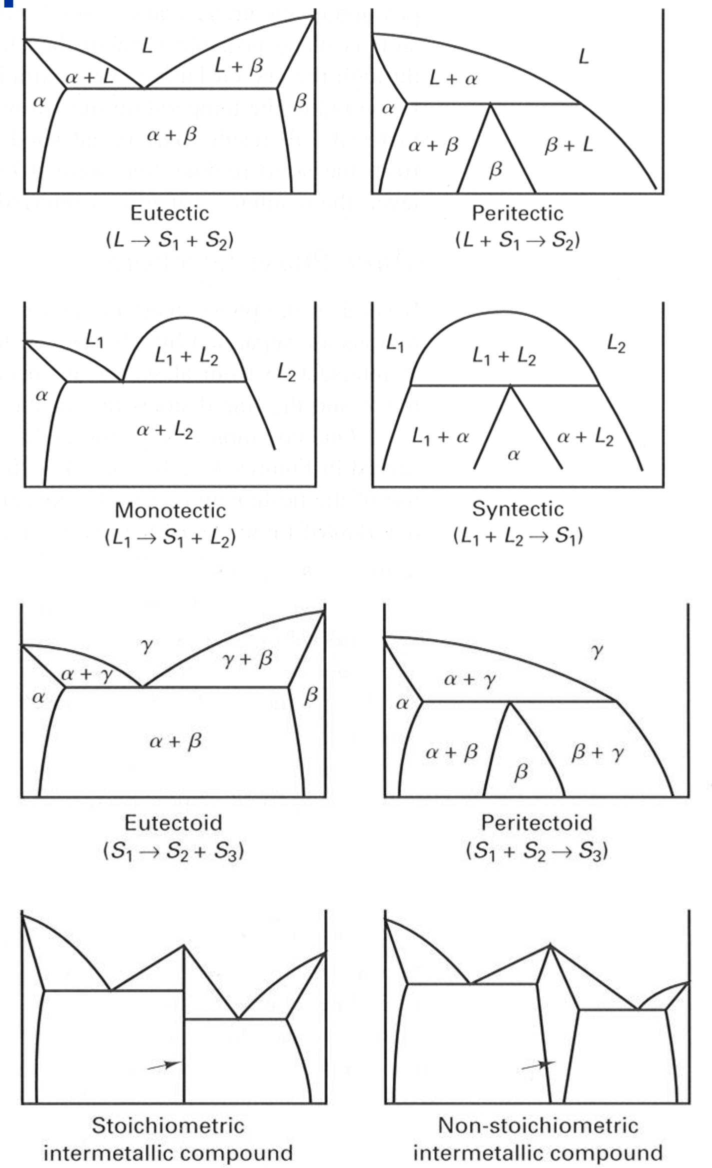
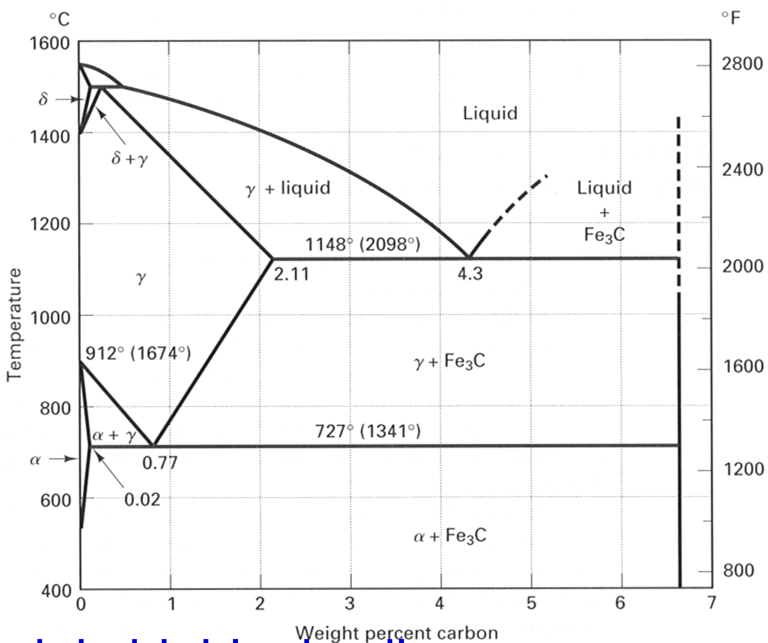


FIGURE 4.9 Schematic summary of three-phase reactions and intermetallic compounds.

Iron-Carbon Diagrams

FIGURE 4.10 The iron–carbon equilibrium diagram: α, ferrite; γ, austenite; δ, δ–ferrite; Fe_3C, cementite.

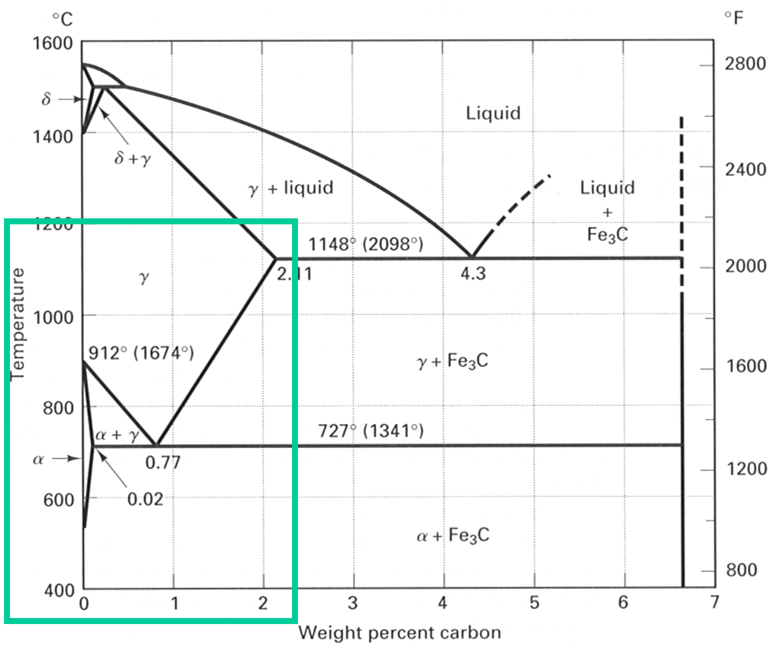


- Steel is an iron carbon compound and of great engineering importance
- Fe_3C is used which caps C at 6.67 %
- Pure iron forms delta ferrite at 1394° upon cooling which has BCC structure – not much engineering importance
- 1394-912° FCC structure, austenite - good formability & good solubility of C
- Austenite is used for hot forming because it is highly ductile
- Below 912° ferrite or alpha-ferrite is formed (more stable BCC). But cannot take more than .02% of C without forming 2 phase structure
- Below 770° (curie point) changes from non-magnetic to magnetic. No phase change, so not seen

Iron-Carbon Diagrams

- 4^{th} single phase is Fe_3C iron carbide
- Also called as cementite - quite hard and brittle
- Exact mp of Fe_3C is unknown and hence the liquidus line is not clear at high c %
- 3 distinct phase reactions @ 1495° peritectic reaction for low C alloys
- High temperature and single phase austenite below it, no significance

FIGURE 4.10 The iron–carbon equilibrium diagram: α, ferrite; γ, austenite; δ, δ–ferrite; Fe_3C, cementite.



- @ 1148° Eutectic reaction with 4.3% carbon. All alloys having more than 2.11% C go thro eutectic reaction and are called Cast Iron
- @ 727° we have the eutectoid reaction of 0.77%C. all alloys with less than 2.11%C go though 2 phase mixture upon cooling (AKA steels)

Cast Iron

- Iron with more than 2.11% C is cast Iron, excellent fluidity, inexpensive and easy to cast. Lot of applications
- Generally contain significant silicon%
- Typical values are 2-4% C, 0.5 – 3% Si less than 1% mn, less than 0.2% S
- Adding Si promotes graphite formation and 2 distinct stages of eutectics
- Ferrite + Austenite & Ferrite + Graphite
- Different cast irons (various composition)
  - Gray Cast Iron
  - White Cast Iron
  - Ductile Iron
  - Malleable Iron

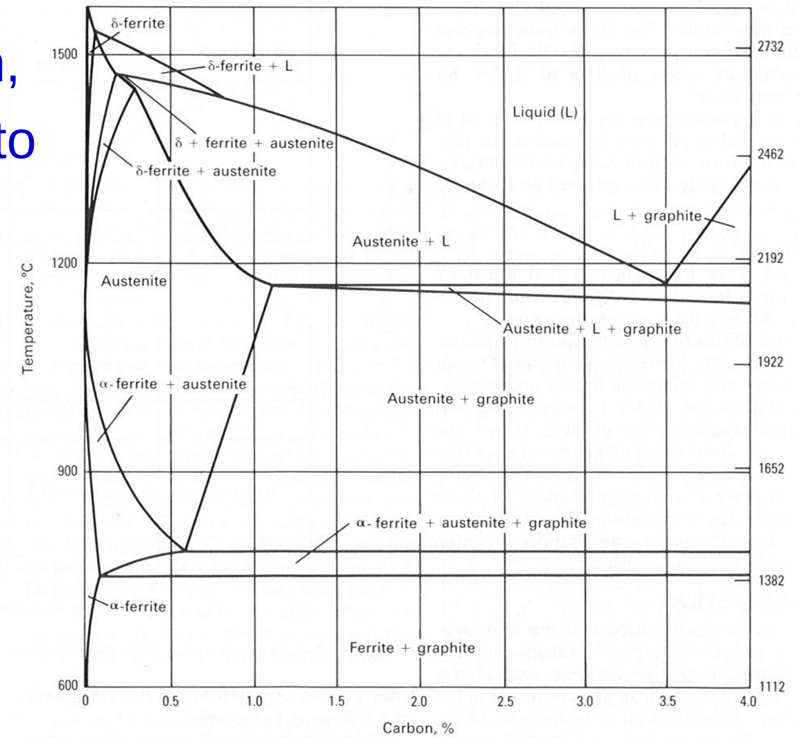
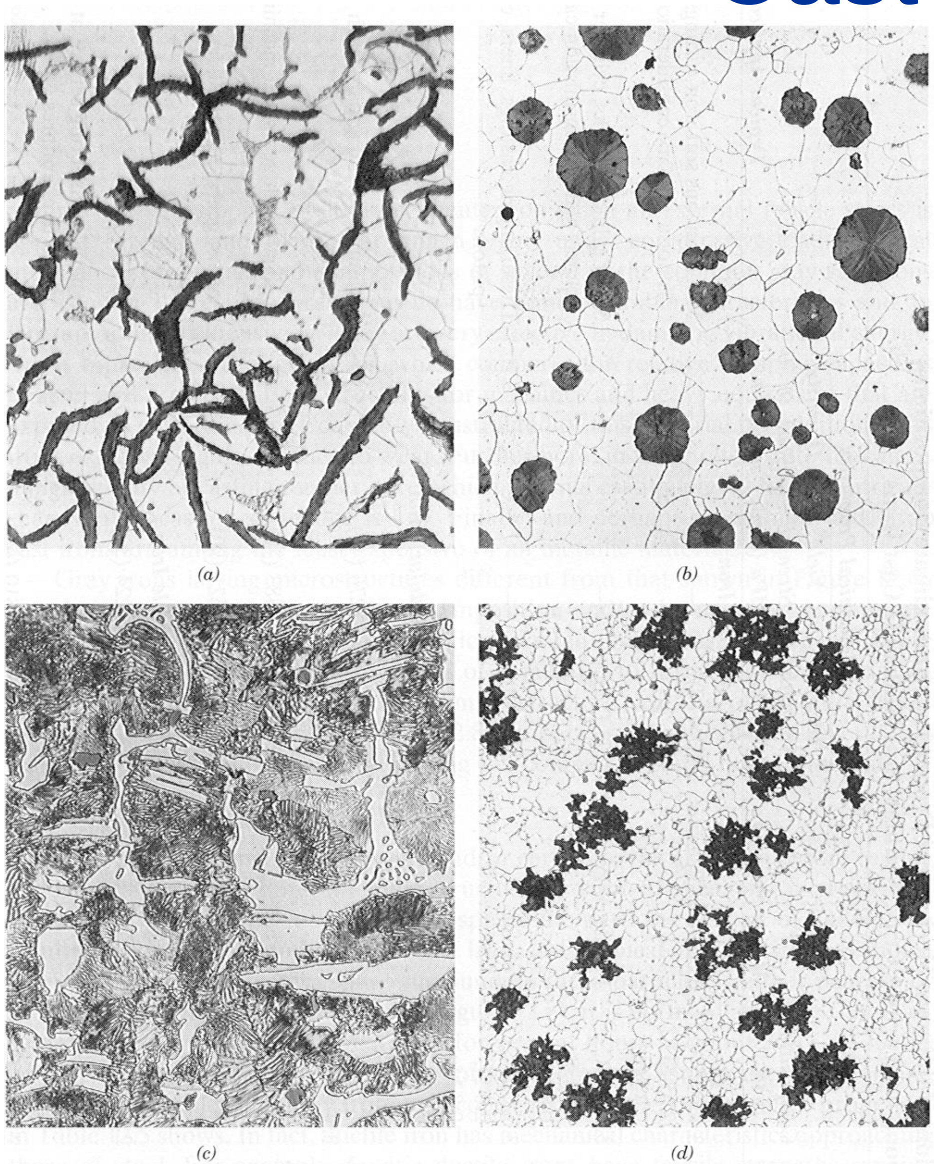


Fig. 1 Iron-carbon phase diagram at 2.5% Si. Source: Ref 1

Type of iron	Total carbon, %	Silicon, %
Class 20	3.40–3.60	2.30–2.50
Class 30	3.10–3.30	2.10–2.30
Class 40	2.95–3.15	1.70–2.00
Class 50	2.70–3.00	1.70–2.00
Class 60	2.50–2.85	1.90–2.10

Cast Iron



- Optical micrographs of various cast irons.

(a) Gray iron: the dark graphite flakes are embedded in an α-ferrite matrix. 500x.

(b) Nodular (ductile) iron: the dark graphite nodules are surrounded by an α-ferrite matrix. 200x.

(c) White iron: the light cementite regions are surrounded by pearlite, which has the ferrite-cementite layered structure. 400x.

(d) Malleable iron: dark graphite rosettes (temper carbon) in an α -ferrite matrix. l50x.

Grey Cast Iron

- 2.5 - 4% C; 1 – 3% Si; 0.4 – 1% mn; Least expensive and promote graphite formation. Large 3d graphite flakes
- Common in high carbon equivalent irons and heavy-section castings
- Desirable properties such as damping capacity, dimensional stability, resistance to thermal shock, and ease of machining.
- Higher tensile strength and modulus of elasticity values
- Smooth machined surfaces are obtainable with irons having small flakes which are promoted by low carbon equivalents and faster cooling rates
- Sold in class (increasing strength)

	Tensile strength		Torsional shear strength		Compressive strength		Reversed bending fatigue limit		Transverse load on test bar		Hardness,
Class	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	kgf	lbf	HB
20	152	22	179	26	572	83	69	10	839	1850	156
25	179	26	220	32	669	97	79	11.5	987	2175	174
30	214	31	276	40	752	109	97	14	1145	2525	210
35	252	36.5	334	48.5	855	124	110	16	1293	2850	212
40	293	42.5	393	57	965	140	128	18.5	1440	3175	235
50	362	52.5	503	73	1130	164	148	21.5	1633	3600	262
60	431	62.5	610	88.5	1293	187.5	169	24.5	1678	3700	302

Grey Cast Iron

Table 6 Typical pouring temperatures for some classes of gray iron

Class	Approximate liquidus temperature		Pouring temperature: Small castings, Thin sections		Small castings, Thick sections		Large castings, Thin sections		Large castings, Thick sections	
	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F
30	1150	2100	1400	2550	1370	2500	1345	2450	1315	2400
35	1175	2150	1425	2600	1400	2550	1370	2500	1345	2450
40	1200	2190	1450	2640	1420	2590	1395	2540	1365	2490
45	1220	2230	1470	2680	1445	2630	1415	2580	1390	2530

- Refinement and stabilization of structures result in an increase in hardness, tensile strength, and wear resistance.
- In addition to composition (particularly carbon equivalent) and section size, factors such as alloy additions, heat treatment, thermal properties of the mold, and casting geometry affect the microstructure and therefore the properties of the iron.

Grey Cast Iron

Table 9 Typical applications for gray iron castings

Specification	Grade or class	Typical applications
ASTM A 48	20, 25	Small or thin-sectioned castings requiring good appearance, good machinability, and close dimensional tolerances
	30, 35	General machinery, municipal and waterworks, light compressors, automotive applications
	40, 45	Machine tools, medium-duty gear blanks, heavy compressors, heavy motor blocks
	50, 55, 60	Dies, crankshafts, high-pressure cylinders, heavy-duty machine tool parts, large gears, press frames
ASTM A 159, SAE J431	G1800	Miscellaneous soft iron castings in which strength is the primary consideration; exhaust manifolds
	G2500	Small cylinder blocks and heads, air-cooled cylinders, pistons, clutch plates, oil pump bodies, transmission cases, gear boxes, light-duty brake drums
	G2500a	Brake drums and clutch plates for moderate service where high carbon is desirable to minimize heat checking
	G3000	Cylinder blocks, heads, liners, flywheels, pistons, clutch plates
	G3500	Truck cylinder blocks and heads, heavy flywheels, differential carriers
	G3500b	Brake drums and clutch plates for heavy-duty service that require heat resistance and high strength
	G4000	Truck and tractor cylinder blocks and heads, heavy flywheels, tractor transmission cases, differential carriers, heavy gear boxes
	G3500c	Extraheavy-duty brake drums
	G4000d	Alloyed automotive engine camshafts
	G4500	Diesel engine castings, liners, cylinders, and pistons; heavy-duty parts for general industry
ASTM A 278	40, 50, 60, 70, 80	Valve bodies, paper mill dryer rollers, chemical process equipment, pressure vessel castings
ASTM A 319	I, II, III	Stoker and firebox parts, grate bars, process furnace parts, ingot molds, glass molds, caustic pots, metal melting pots
ASTM A 823	. . .	Automobile, truck, appliance, and machinery castings in quantity
ASTM A 436	1	Valve guides, insecticide pumps, flood gates, piston ring bands
	1b	Seawater valve and pump bodies, pump section belts
	2	Fertilizer applicator parts, pump impellers, pump casings, plug valves
	2b	Caustic pump casings, valves, pump impellers
	3	Turbocharger housings, pumps and liners, stove tops, steam piston valve rings, caustic pumps and valves
	4	Range tops
	5	Glass rolls and molds, machine tools, gages, optical parts requiring minimal expansion and good damping qualities, solder rails and pots
	6	Valves

White Cast Iron

- 1.8 – 3.6% C; 0.5 – 1.9% Si; 0.25 – 0.8% mn; Carbon content is from Fe_3C. Promotes cementite instead of graphite and rapid cooling
- Hard and brittle, used in application where abrasion resistance is needed

Table 1 Composition and mechanical requirements of abrasion-resistant cast irons per ASTM A 532

Class	Type	Designation	Composition C	Mn	Si	Ni	Cr	Mo
I	A	Ni-Cr-HC	3.0–3.6	1.3 max	0.8 max	3.3–5.0	1.4–4.0	1.0 max(a)
I	B	Ni-Cr-LC	2.5–3.0	1.3 max	0.8 max	3.3–5.0	1.4–4.0	1.0 max(a)
I	C	Ni-Cr-GB	2.9–3.7	1.3 max	0.8 max	2.7–4.0	1.1–1.5	1.0 max(a)
I	D	Ni-Hi Cr	2.5–3.6	1.3 max	1.0–2.2	5.0–7.0	7.0–11.0	1.0 max(b)
II	A	12% Cr	2.4–2.8	0.5–1.5	1.0 max	0.5 max	11.0–14.0	0.5–1.0(c)
II	B	15% Cr-Mo-LC	2.4–2.8	0.5–1.5	1.0 max	0.5 max	14.0–18.0	1.0–3.0(c)
II	C	15% Cr-Mo-HC	2.8–3.6	0.5–1.5	1.0 max	0.5 max	14.0–18.0	2.3–3.5(c)
II	D	20% Cr-Mo-LC	2.0–2.6	0.5–1.5	1.0 max	1.5 max	18.0–23.0	1.5 max(c)
II	E	20% Cr-Mo-HC	2.6–3.2	0.5–1.5	1.0 max	1.5 max	18.0–23.0	1.0–2.0(c)
III	A	25% Cr	2.3–3.0	0.5–1.5	1.0 max	1.5 max	23.0–28.0	1.5 max(c)

Class	Type	Designation	Mechanical requirements: Hardness, HB: Sand cast, min	Chill cast, min	Hardened, min	Softened, max	Typical section thickness, max: in.	mm
I	A	Ni-Cr-HC	550	600	. . .	. . .	8	200
I	B	Ni-Cr-LC	550	600	. . .	. . .	8	200
I	C	Ni-Cr-GB	550	600	. . .	. . .	3 diam ball	75 diam ball
I	D	Ni-Hi Cr	550	500	600	400	12	300
II	A	12% Cr	550	. . .	600	400	1 diam ball	25 diam ball
II	B	15% Cr-Mo-LC	450	. . .	600	400	4	100
II	C	15% Cr-Mo-HC	550	. . .	600	400	3	75
II	D	20% Cr-Mo-LC	450	. . .	600	400	8	200
II	E	20% Cr-Mo-HC	450	. . .	600	400	12	300
III	A	25% Cr	450	. . .	600	400	8	200

(a) Maximum: 0.30% P, 0.15% S. (b) Maximum: 0.10% P, 0.15% S. (c) Maximum: 0.10% P, 0.06% S, 1.2% Cu

Ni-Cr White Cast Iron

- Low cost, Ni-Cr white irons are consumed in large tonnages in mining operations as grinding balls.
- Class I type A castings are used in applications requiring maximum abrasion resistance, such as ash pipes, slurry pumps, roll heads, muller tires, augers, coke-crusher segments, classifier shoes, brick molds, pipe elbows carrying abrasive slurries.
- Type B is recommended for applications requiring more strength and exerting moderate impact, such as crusher plates, crusher concaves, and pulverizer pegs.

Fig. 1 Typical microstructure of class I type A nickel-chromium white cast iron. 340×

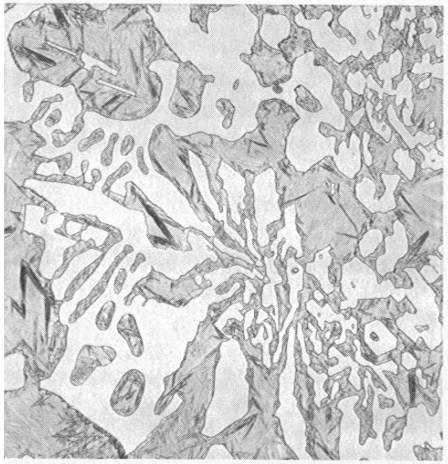


Fig. 2 Typical microstructure of class I type D nickel-chromium white cast iron. 340×

Ni-Cr White Cast Iron

- Class I type D, (Ni-Hard type 4), has a higher level of strength and toughness and is therefore used for the more severe applications that justify its added alloy costs. It is commonly used for pump volutes handling abrasive slurries and coal pulverizer table segments and tires.
- The class I type C alloy (Ni-Hard 3) is specifically designed for the production of grinding balls. This grade is both sand cast and chill cast. Chill casting has the advantage of lower alloy cost, and, more important, provides a 15 to 30% improvement in life. All grinding balls require tempering for 8 h at 260 to 315°C (500 to 600°F) to develop adequate impact toughness.

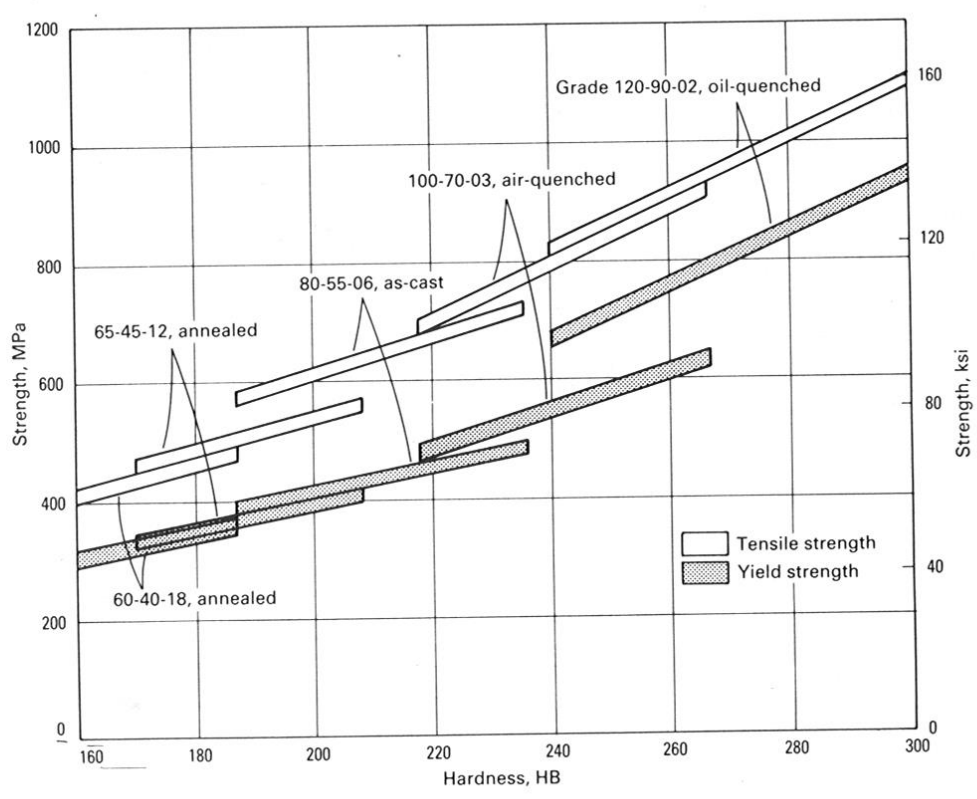
High Cr White Cast Iron

- Applications of High Cr White Cast Irons
- The high-chromium white irons are superior in abrasion resistance and are used effectively in impellers and volutes in slurry pumps, classifier wear shoes, brick molds, impeller blades and liners for shot blasting equipment, and refiner disks in pulp refiners.
- In many applications they withstand heavy impact loading, such as from impact hammers, roller segments and ring segments in coal-grinding mills, feed-end lifter bars and mill liners in ball mills for hard- rock mining, pulverizer rolls, and rolling mill rolls.

Ductile Iron

- Ductile iron replace gray iron because of its superior properties
- Examples - crankshafts, piston rings, exhaust manifolds, and cylinder liners.
- ductile iron provides increased strength and reduces weight
- In agricultural and earth-moving applications, brackets, couplings, rollers, hydraulic valves, sprocket wheels, and track components of improved strength and toughness are made of ductile iron.

Grade	Composition C	Si	Mn	P	S
3.1	3.5–4.6	<3.0	<0.1	<0.08	0.03 max
3.2	3.5–4.6	<4.0	<0.1–0.4	<0.08	0.03 max



Ductile Iron

- General engineering applications include hydraulic cylinders, mandrels, machine frames, switch gear , rolling mill rolls, tunnel segments, low-cost rolls, bar stock, rubber molds, street furniture such as covers and frames, and railway rail- clip supports. For these applications, ductile iron has provided increased performance or weight savings.
- Ductile iron gears have performed well in noncritical engineering and agricultural applications, but austempered (heat treatment) ductile iron offers a combination of strength, fatigue properties, and wear resistance that makes it of great interest for heavy engineering and automotive gears-applications
- However, many new engineering components are likely to be amenable to design with ductile iron

Ductile Iron

Table 5 Some mechanical properties expected in ductile iron grades covered by UK standard B52789

Grade	Tensile strength		Yield strength		Elongation, %	Yield strength in compres-sion		Shear strength		Torsional strength		Modulus of elasticity (E)		Modulus of rigidity (G)		Poisson's ratio, ν	Hardness, HB	Fatigue limit(a) Notched		Unnotched	
	MPa	ksi	MPa	ksi		MPa	ksi	MPa	ksi	MPa	ksi	GPa	10^6 psi	GPa	10^6 psi			MPa	ksi	MPa	ksi
Ferritic grades																					
350/22; 350/22L40	350	51	215	31	22	229	33	315	46	315	46	169	24.5	65.9	9.6	0.275	107–130	114	17	180	26
400/18; 400/18L20	400	58	259	38	18	273	40	360	52	360	52	169	24.5	65.9	9.6	0.275	120–140	122	18	195	28
420/12..................	420	61	278	40	12	292	42	378	55	378	55	169	24.5	65.9	9.6	0.275	140–155	124	18	201	29
Intermediate grades																					
450/10..................	450	65	305	44	10	319	46	405	59	405	59	169	24.5	65.9	9.6	0.275	150–172	128	19	210	30
500/7..................	500	73	339	49	7	351	57	450	65	450	65	169	24.5	65.9	9.6	0.275	172–216	134	20	224	32
600/3..................	600	87	372	54	3	382	55	540	78	540	78	174	25.2	67.9	9.8	0.275	216–247	149	22	248	36
Pearlitic as-cast and normalized																					
700/2..................	700	102	416	60	2	425	62	630	91	630	91	176	25.5	68.6	9.9	0.275	247–265	168	41	280	41
800/2..................	800	116	471	68	2	480	70	720	104	720	104	176	25.5	68.6	9.9	0.275	>265	182	44	304	44
900/2..................	900	131	526	76	2	535	78	810	117	810	117	176	25.5	68.6	9.9	0.275	>265	190	46	317	46
Hardened-and-tempered grades																					
700/2..................	700	102	550	80	2	559	81	630	91	630	91	172	24.9	67.1	9.7	0.275	232–259	168	41	280	41
800/2..................	800	116	630	91	2	639	93	720	104	720	104	172	24.9	67.1	9.7	0.275	>259	182	44	304	44
900/2..................	900	131	710	103	2	719	104	810	117	810	117	172	24.9	67.1	9.7	0.275	>259	190	46	317	46

(a) Wöhler specimen 10.6 mm (0.42 in.) in diameter unnotched; 10.6 mm (0.042 in.) in diameter at root of notch in notched tests. Circumferential 45° V-notch with 25 mm (1 in.) root radius and notch depth of 3.6 mm (0.14 in.). Source: Ref 9

Malleable Iron

- Malleable Iron is a cast metal produced as white cast iron and heat treated to convert the carbon-containing phase from Fe_3C to a nodular form of graphite called temper carbon.

Table 1 Chemical composition of malleable iron

Element	Composition, %
Carbon	2.16–2.90
Silicon	0.90–1.90
Manganese	0.15–1.25
Sulfur	0.02–0.20
Phosphorus	0.02–0.15

- There are two types of ferritic malleable iron: blackheart and whiteheart. Only the blackheart type is produced in the United States. This material has a matrix of ferrite with interspersed nodules of temper carbon.
- Malleable iron, like ductile iron, possesses considerable ductility and toughness because of its combination of nodular graphite and low-carbon metallic matrix. Because of the way in which graphite is formed in malleable iron, however, the nodules are not truly spherical as they are in ductile iron but are irregularly shaped aggregates.

Malleable Iron

- Malleable iron and ductile iron are used for some of the same applications in which ductility and toughness are important. In many cases, the choice between malleable and ductile iron is based on economy or availability rather than on properties. In certain applications, however, malleable iron has a distinct advantage. It is preferred for thin-section castings; for parts that are to be pierced, coined, or cold formed; for parts requiring maximum machinability; for parts that must retain good impact resistance at low temperatures; and for some parts requiring wear resistance (martensitic malleable iron only).
- Ductile iron has a clear advantage where low solidification shrinkage is needed to avoid hot tears or where the section is too thick to permit solidification as white iron. (Solidification as white iron throughout a section is essential to the production of malleable iron.) Malleable iron castings are produced in section thicknesses ranging from about 1.5 to 100 mm and in weights from less than 0.03 to 180 kg or more.

Malleable Iron

Table 3 Properties of malleable iron castings

Microstructures and typical applications are given in Table 2.

Specification No.	Class or grade	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Hardness, HB	Elongation(a), %
Ferritic							
ASTM A47 and A338, ANSI G48.1, FED QQ-I-666c	32510	345	50	224	32	156 max	10
	35018	365	53	241	35	156 max	18
ASTM A197	...	276	40	207	30	156 max	5
Pearlitic and martensitic							
ASTM A220, ANSI G48.2, MIL-I-11444B	40010	414	60	276	40	149–197	10
	45008	448	65	310	45	156–197	8
	45006	448	65	310	45	156–207	6
	50005	483	70	345	50	179–229	5
	60004	552	80	414	60	197–241	4
	70003	586	85	483	70	217–269	3
	80002	655	95	552	80	241–285	2
	90001	724	105	621	90	269–321	1
Automotive							
ASTM A602, SAE J158	M3210(b)	345	50	224	32	156 max	10
	M4504(c)	448	65	310	45	163–217	4
	M5003(c)	517	75	345	50	187–241	3
	M5503(d)	517	75	379	55	187–241	3
	M7002(d)	621	90	483	70	229–269	2
	M8501(d)	724	105	586	85	269–302	1

(a) Minimum in 50 mm (2 in.). (b) Annealed. (c) Air quenched and tempered. (d) Liquid quenched and tempered

Malleable Iron

- The requirement that any iron produced for conversion to malleable iron must solidify white places definite section thickness limitations on the malleable iron industry .
- High-production foundries are usually reluctant to produce castings more than about 40 mm thick. Some foundries, however, routinely produce castings as thick as 100 mm (4 in.).
- Automotive and associated applications of ferritic and pearlitic malleable irons include many essential parts in vehicle power trains, frames, suspensions, and wheels.
- Ferritic and pearlitic malleable irons are also used in the railroad industry and in agricultural equipment.

Malleable Iron

- Malleable iron castings are often selected because the material has excellent machinability in addition to significant ductility.
- In other applications, malleable iron is chosen because it combines castability with good toughness and machinability.
- Malleable iron is often chosen because of shock resistance alone.

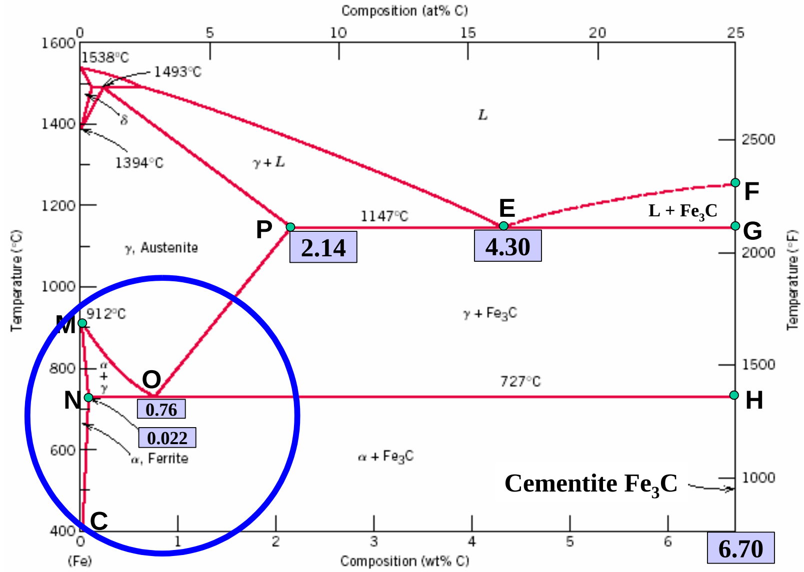
Table 2 Applications of malleable iron castings

Mechanical properties are given in Table 3.

Specification No.	Class or grade	Microstructure	Typical applications
Ferritic			
ASTM A47, ANSI G48.1, FED QQ-1-666c	32510 35018	Temper carbon and ferrite	General engineering service at normal and elevated temperatures for good machinability and excellent shock resistance
ASTM A338	32510 35018	Temper carbon and ferrite	Flanges, pipe fittings, and valve parts for railroad, marine, and other heavy-duty service to 345 °C (650 °F)
ASTM A197, ANSI G49.1	. . .	Free of primary graphite	Pipe fittings and valve parts for pressure service
Pearlitic and martensitic			
ASTM A220, ANSI G48.2, MIL-I-11444B	40010 45008 45006 50005 60004 70003 80002 90001	Temper carbon in necessary matrix without primary cementite or graphite	General engineering service at normal and elevated temperatures. Dimensional tolerance range for castings is stipulated
Automotive			
ASTM A602, SAE J158	M3210	Ferritic	For low-stress parts requiring good machinability: steering-gear housings, carriers, and mounting brackets
	M4504	Ferrite and tempered pearlite(a)	Compressor crankshafts and hubs
	M5003	Ferrite and tempered pearlite(a)	For selective hardening: planet carriers, transmission gears, and differential cases
	M5503	Tempered martensite	For machinability and improved response to induction hardening
	M7002	Tempered martensite	For high-strength parts: connecting rods and universal-joint yokes
	M8501	Tempered martensite	For high strength plus good wear resistance: certain gears

(a) May be all tempered martensite for some applications

Steel Castings



Plain Carbon Steels Low carbon (≤ 0.20%C)

(≤ 1%Mn) Medium Carbon (0.2 – 0.5%C)

High Carbon (≥ 0.5%C)

- Two methods of identifying grades of cast steels are extensively used in the United States. AISI designations for wrought steels are examples of the first method -first two digits indicate the alloy type, and the second two digits represent the carbon content. For example, a 1010 steel represents a carbon steel with 0.10% C, while a 1320 steel represents a manganese steel with 0.20% C. This system does not include mechanical properties or heat treatment. Accordingly, a cast 1040 steel (0.40% C) can exhibit a yield strength of 330 MPa (48 ksi) or of 496 MPa (72 ksi), depending on the choice of heat treatment.

Steel Castings

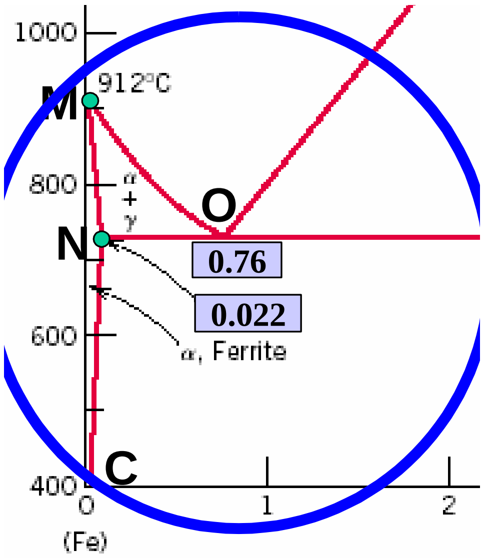
Plain Carbon Steels	Low carbon (≤ 0.20%C)
(≤ 1%Mn)	Medium Carbon (0.2 – 0.5%C)
	High Carbon (≥ 0.5%C)

- In the second method, letters and numbers are arbitrarily assigned to steels with well-defined compositions, which index the heat treatment as well as the mechanical properties. There are usually many steel grade designations that represent a single type of steel. For example, there are four ASTM specifications that together include 16 grades of chromium-molybdenum steels. These 16 grades, however, are made up of only three different steels. Although such a system may appear confusing because of the redundancy of designations, the system does offer the advantage of characterizing the cast steel end product as thoroughly as is needed for its end use.

Steel Castings

- Low-carbon cast steels (less than 0.20% C) are mainly produced for electrical and magnetic equipment and are normally given a full anneal heat treatment.
- Some castings for the railroad industry are produced from low-carbon cast steel. Castings for the automotive industry are also produced from this class of steel, as are annealing boxes and hot metal ladles.
- Steel castings in this class are also produced for case carburizing, by which process the castings are given a hard wear-resistant exterior and a tough, ductile core.
- The magnetic properties of cast low-carbon steels make them useful in the manufacture of electrical equipment.

Steel Castings



- The medium-carbon cast steels (0.20 to 0.50%C) represents bulk of steel casting production. Mostly heat treated by normalizing, which consists of cooling the castings in air from approximately 50°C above the upper critical temperature. A stress-relief treatment can be used to relieve stresses set up in the casting by cooling conditions or welding operations and to soften the HAZ resulting from welding.

- used in a wide variety of ways, including applications in the railroad and other transportation industries, machinery and tools, equipment for rolling mills, mining and construction equipment, and many other miscellaneous applications.

Steel Castings

- High-Carbon Cast Steels. (more than 0.50% C) Because of their high carbon contents, these grades are the most hardenable of the plain carbon cast steels. They are therefore used in applications that require relatively high strength levels.
- In addition to Plain carbon steels, there are steels with alloying elements
- Low Alloy Steels (< 8% alloying elements)

Cast steel designation	Nearest wrought equivalent	Alloying elements
1300	1300	Manganese
8000, 8400....	8000, 8400	Manganese, molybdenum
80B00	80B00	Manganese, molybdenum, boron
2300.........	2300	Nickel
8600, 4300....	8600, 4300	Nickel, chromium, molybdenum
9500.........	9500	Manganese, nickel, chromium, molybdenum
4100.........	4100	Chromium, molybdenum

- High–Alloy Steel Castings (including stainless steel castings)
- Widely used for corrosion resistance, and for high temperature service in hot gases, liquids.

Steel Castings

Table 1 Properties of various classes of cast carbon and low-alloy steels

Class(a)	Heat treatment(b)	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Reduction in area, %	Elongation, %	Hardness, HB	Fatigue endurance limit MPa	Fatigue endurance limit ksi	Ratio of endurance limit to tensile strength
Carbon steels											
60	A	434	63	241	35	54	30	131	207	30	0.48
65	N	469	68	262	38	48	28	131	207	30	0.44
70	N	517	75	290	42	45	27	143	241	35	0.47
80	NT	565	82	331	48	40	23	163	255	37	0.45
85	NT	621	90	379	55	38	20	179	269	39	0.43
100	QT	724	205	517	75	41	19	212	310	45	0.47
Low-alloy steels(c)											
65	NT	469	68	262	38	55	32	137	221	32	0.47
70	NT	510	74	303	44	50	28	143	241	35	0.47
80	NT	593	86	372	54	46	24	170	269	39	0.45
90	NT	655	95	441	64	44	20	192	290	42	0.44
105	NT	758	110	627	91	48	21	217	365	53	0.48
120	QT	883	128	772	112	38	16	262	427	62	0.48
150	QT	1089	158	979	142	30	13	311	510	74	0.47
175	QT	1234	179	1103	160	25	11	352	579	84	0.47
200	QT	1413	205	1172	170	21	8	401	607	88	0.43

(a) Class of steel based on tensile strength (ksi). (b) A, annealed; N, normalized; NT, normalized and tempered; QT, quenched and tempered. (c) Below 8% total alloy content

Steel Castings

Table 1 Compositions and microstructures of corrosion-resistant high-alloy cast steels

Alloy	Wrought alloy type(a)	Most common end-use microstructure	Composition, %(b) Cr	Ni	Mo	Si	Mn	P	S	C	Others
Chromium steels											
CA-15	410	Martensite	11.5–14.0	1.00	0.50	1.50	1.00	0.04	0.04	0.15	. . .
CA-15M	. . .	Martensite	11.5–14.0	1.00	0.15–1.0	0.65	1.00	0.04	0.04	0.15	. . .
CA-40	420	Martensite	11.5–14.0	1.00	0.5	1.50	1.00	0.04	0.04	0.20 –0.40	. . .
CB-30	431,442	Ferrite + carbides	18.0–21.0	2.00	. . .	1.50	1.00	0.04	0.04	0.30	. . .
CC-50	446	Ferrite + carbides	26.0–30.0	4.00	. . .	1.50	1.00	0.04	0.04	0.50	. . .
Chromium-nickel steels											
CA-6NM	. . .	Martensite	11.5–14.0	3.5–4.5	0.40–1.0	1.00	1.00	0.04	0.03	0.06	. . .
CB-7Cu	17-4PH	Martensite-age hardenable	15.5–17.0	3.6–4.6	. . .	1.50	1.00	0.04	0.04	0.07	2.3–3.3 Cu
CD-4MCu	. . .	Austenite in ferrite-age hardenable	25.0–26.5	4.75–6.0	1.75–2.25	1.00	1.00	0.04	0.04	0.04	2.75–3.25 Cu
CE-30	. . .	Ferrite in austenite	26.0–30.0	8.0–11.0	. . .	2.00	1.50	0.04	0.04	0.30	. . .
CF-3	304L	Ferrite in austenite	17.0–21.0	8.0–12.0	. . .	2.00	1.50	0.04	0.04	0.03	. . .
CF-8	304	Ferrite in austenite	18.0–21.0	8.0–11.0	. . .	2.00	1.50	0.04	0.04	0.08	. . .
CF-20	302	Austenite	18.0–21.0	8.0–11.0	. . .	2.00	1.50	0.04	0.04	0.20	. . .
CF-3M	316L	Ferrite in austenite	17.0–21.0	9.0–13.0	2.0–3.0	1.50	1.50	0.04	0.04	0.03	. . .
CF-8M	316	Ferrite in austenite	18.0–21.0	9.0–12.0	2.0–3.0	1.50	1.50	0.04	0.04	0.08	. . .
CF-12M	. . .	Ferrite in austenite or austenite	18.0–21.0	9.0–12.0	2.0–3.0	2.00	1.50	0.04	0.04	0.12	. . .
CF-8C	347	Ferrite in austenite	18.0–21.0	9.0–12.0	. . .	2.00	1.50	0.04	0.04	0.08	Nb = 8 × C, 1.0 max
CF-16F	303	Austenite	18.0–21.0	9.0–12.0	1.50	2.00	1.50	0.17	0.04	0.16	0.20–0.35 Se
CG-8M	317	Ferrite in austenite	18.0–21.0	9.0–13.0	3.0–4.0	1.50	1.50	0.04	0.04	0.08	. . .
CH-20	309	Austenite	22.0–26.0	12.0–15.0	. . .	2.00	1.50	0.04	0.04	0.20	. . .
CK-20	310	Austenite	23.0–27.0	19.0–22.0	. . .	1.75	1.50	0.04	0.04	0.20	. . .
Nickel-chromium steel											
CN-7M	320	Austenite	19.0–22.0	27.5–30.5	2.0–3.0	1.50	1.50	0.04	0.04	0.07	3.0–4.0 Cu

(a) Wrought alloy type numbers are AISI designations for grades most closely corresponding to casting alloys. Wrought alloy type numbers are given only as a guide for determining corresponding cast and wrought grades. Buyers should use cast alloy designations when specifying castings. (b) Maximum unless range is given. All compositions contain balance of iron.

Aluminum and Aluminum Alloys

- 1xx.x: Controlled unalloyed compositions
- 2xx.x: Al alloys containing copper as the major alloying element
- 3xx.x: Al-Si alloys also containing magnesium and/or copper
- 4xx.x: Binary Al-Si alloys .
- 5xx.x: Al alloys containing magnesium as major alloying element
- 6xx.x: Currently unused
- 7xx.x: Al alloys containing zinc as the major alloying element, usually also containing additions of either copper, magnesium, chromium, manganese, or combinations of these elements
- 8xx.x: Al alloys containing tin as the major alloying element
- 9xx.x: Currently unused

Aluminum and Aluminum Alloys

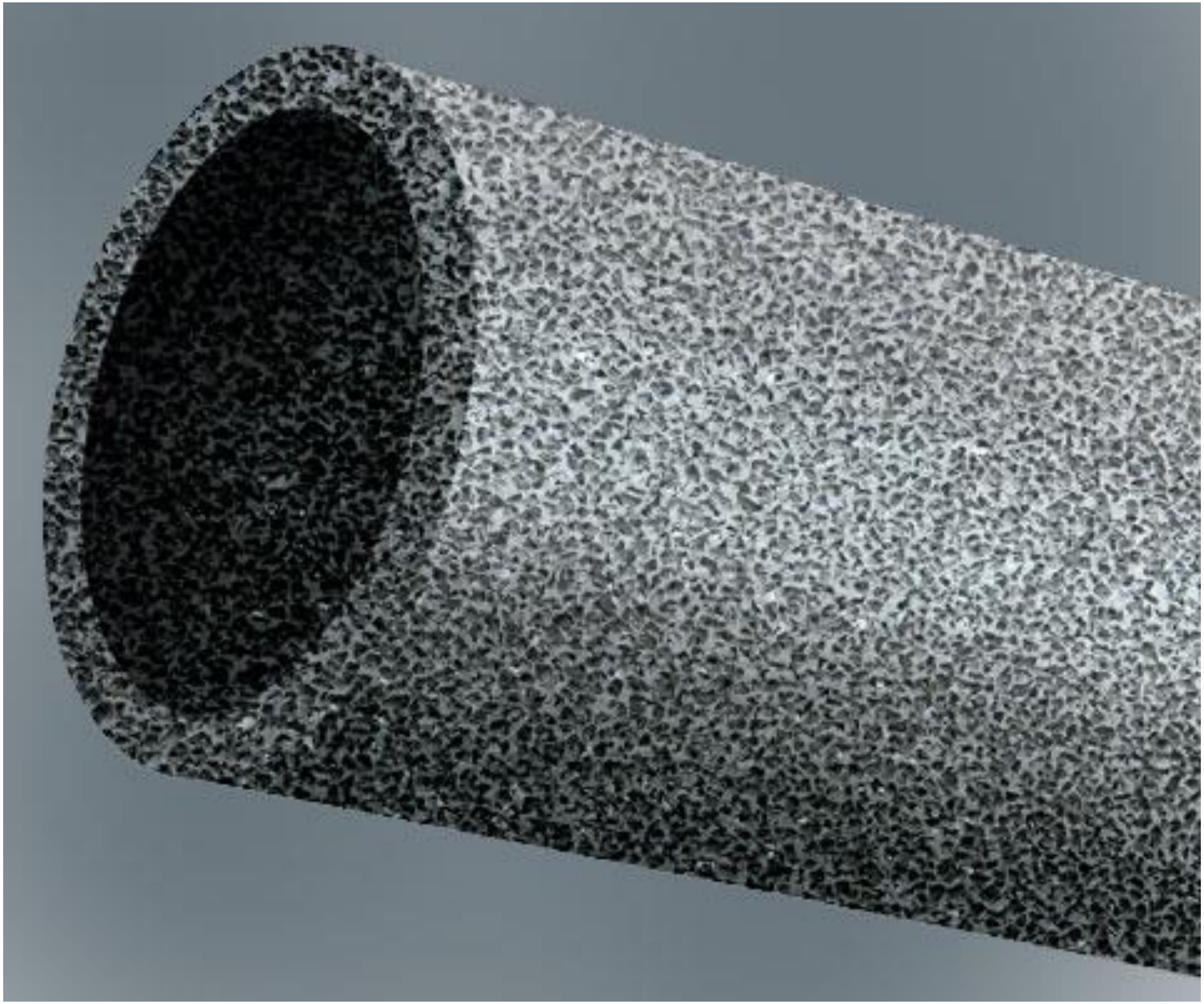
Table 1 Compositions of registered aluminum casting alloys used to cast shapes

Compositions of alloys used to cast primary ingots are not shown.

Alloy	Products(a)	Composition, %(b)										Others	
		Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Sn	Ti	Each	Total
201.1	S	0.10	0.15	4.0–5.2	0.20–0.50	0.15–0.55	...	...	...	...	0.15–0.35	0.05(c)	0.10
A201.0	S	0.05	0.10	4.0–5.0	0.20–0.40	0.15–0.35	...	...	...	...	0.15–0.35	0.03(c)	0.10
B201.0	S	0.05	0.05	4.5–5.0	0.20–0.50	0.25–0.35	...	...	...	...	0.15–0.35	0.05(d)	0.15
202.0	S	0.10	0.15	4.0–5.2	0.20–0.8	0.15–0.55	0.20–0.6	...	...	...	0.15–0.35	0.05(c)	0.10
203.0	S	0.30	0.50	4.5–5.5	0.20–0.30	0.10	...	1.3–1.7	0.10	...	0.15–0.25(e)	0.05(f)	0.20
204.0	S, P	0.20	0.35	4.2–5.0	0.10	0.15–0.35	...	0.05	0.10	0.05	0.15–0.30	0.05	0.15
206.0	S, P	0.10	0.15	4.2–5.0	0.20–0.50	0.15–0.35	...	0.05	0.10	0.05	0.15–0.30	0.05	0.15
A206.0	S, P	0.05	0.10	4.2–5.0	0.20–0.50	0.15–0.35	...	0.05	0.10	0.05	0.15–0.30	0.05	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
213.0	S, P	1.0–3.0	1.2	6.0–8.0	0.6	0.10	...	0.35	2.5	...	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
224.0	S, P	0.06	0.10	4.5–5.5	0.20–0.50	...	...	...	...	...	0.35	0.03(g)	0.10
238.0	P	3.5–4.5	1.5	9.0–11.0	0.6	0.15–0.35	...	1.0	1.5	...	0.25	...	0.50
240.0	S	0.50	0.50	7.0–9.0	0.30–0.7	5.5–6.5	...	0.30–0.7	0.10	...	0.20	0.05	0.15
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
A242.0	S	0.6	0.8	3.7–4.5	0.10	1.2–1.7	0.15–0.25	1.8–2.3	0.10	...	0.07–0.20	0.05	0.15
243.0	S	0.35	0.40	3.5–4.5	0.15–0.45	1.8–2.3	0.20–0.40	1.9–2.3	0.05	...	0.06–0.20	0.05(h)	0.15
249.0	P	0.05	0.10	3.8–4.6	0.25–0.50	0.25–0.50	...	...	2.5–3.5	...	0.02–0.35	0.03	0.10
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
296.0	P	2.0–3.0	1.2	4.0–5.0	0.35	0.05	...	0.35	0.50	...	0.25	...	0.35
305.0	S, P	4.5–5.5	0.6	1.0–1.5	0.50	0.10	0.25	...	0.35	...	0.25	0.05	0.15
A305.0	S, P	4.5–5.5	0.20	1.0–1.5	0.10	0.10	...	...	0.10	...	0.20	0.05	0.15
308.0	S, 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
A319.0	S, P	5.5–6.5	1.0	3.0–4.0	0.50	0.10	...	0.35	3.0	...	0.25	...	0.50
B319.0	S, P	5.5–6.5	1.2	3.0–4.0	0.8	0.10–0.50	...	0.50	1.0	...	0.25	...	0.50
320.0	S, P	5.0–8.0	1.2	2.0–4.0	0.8	0.05–0.6	...	0.35	3.0	...	0.25	...	0.50
324.0	P	7.0–8.0	1.2	0.40–0.6	0.50	0.40–0.7	...	0.30	1.0	...	0.20	0.15	0.20
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
A333.0	P	8.0–10.0	1.0	3.0–4.0	0.50	0.05–0.50	...	0.50	3.0	...	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	...
339.0	P	11.0–13.0	1.2	1.5–3.0	0.50	0.50–1.5	...	0.50–1.5	1.0	...	0.25	...	0.50
343.0	D	6.7–7.7	1.2	0.50–0.9	0.50	0.10	0.10	...	1.2–2.0	0.50	...	0.10	0.35
354.0	P	8.6–9.4	0.20	1.6–2.0	0.10	0.40–0.6	...	...	0.10	...	0.20	0.05	0.15
355.0	S, P	4.5–5.5	0.6(i)	1.0–1.5	0.50(i)	0.40–0.6	0.25	...	0.35	...	0.25	0.05	0.15
A355.0	S, P	4.5–5.5	0.09	1.0–1.5	0.05	0.45–0.6	...	...	0.05	...	0.04–0.20	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(i)	0.25	0.35(i)	0.20–0.45	...	...	0.35	...	0.25	0.05	0.15
A356.0	S, P	6.5–7.5	0.20	0.20	0.10	0.25–0.45	...	...	0.10	...	0.20	0.05	0.15
B356.0	S, P	6.5–7.5	0.09	0.05	0.05	0.25–0.45	...	...	0.05	...	0.04–0.20	0.05	0.15
C356.0	S, P	6.5–7.5	0.07	0.05	0.05	0.25–0.45	...	...	0.05	...	0.04–0.20	0.05	0.15
F356.0	S, P	6.5–7.5	0.20	0.20	0.10	0.17–0.25	...	...	0.10	...	0.04–0.20	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(j)	0.15
B357.0	S, P	6.5–7.5	0.09	0.05	0.05	0.40–0.6	...	...	0.05	...	0.04–0.20	0.05	0.15
C357.0	S, P	6.5–7.5	0.09	0.05	0.05	0.45–0.7	...	...	0.05	...	0.04–0.20	0.05(j)	0.15
D357.0	S	6.5–7.5	0.20	...	0.10	0.55–0.6	...	...	...	...	0.10–0.20	0.05(j)	0.15
358.0	S, P	7.6–8.6	0.30	0.20	0.20	0.40–0.6	0.20	...	0.20	...	0.10–0.20	0.05(k)	0.15
359.0	S, P	8.5–9.5	0.20	0.20	0.10	0.50–0.7	...	...	0.10	...	0.20	0.05	0.15
360.0	D	9.0–10.0	2.0	0.6	0.35	0.40–0.6	...	0.50	0.50	0.15	...	...	0.25

(continued)

(a) D, die casting; P, permanent mold; S, sand. Other products may pertain to the composition but are not listed. (b) Weight percent; maximum unless range is given or otherwise indicated. All compositions contain balance of aluminum. (c) 0.40–1.0 Ag. (d) 0.50–1.0 Ag. (e) 0.50 max Ti + Zr. (f) 0.20–0.30 Sb, 0.20–0.30 Co, 0.10–0.30 Zr. (g) 0.05–0.15 V, 0.10–0.25 Zr. (h) 0.06–0.20 V. (i) If iron exceeds 0.45%, manganese content shall not be less than one-half of iron content. (j) 0.04–0.07 Be. (k) 0.10–0.30 Be. (l) 0.8 max Mn + Cr. (m) 0.25 max Pb. (n) 0.02–0.04 Be. (o) 0.08–0.15 V. (p) 0.10 max Pb. (q) 0.003–0.007 Be, 0.005 max B. Source: Ref 1



Aluminum and Aluminum Alloys

Table 1 (continued)

Alloy	Products(a)	Composition, %(b) Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Sn	Ti	Others Each	Others Total
A360.0	D	9.0–10.0	1.3	0.6	0.35	0.40–0.6	. . .	0.50	0.50	0.15	. . .	. . .	0.25
361.0	D	9.5–10.5	1.1	0.50	0.25	0.40–0.6	0.20–0.30	0.20–0.30	0.50	0.10	0.20	0.05	0.15
363.0	S, P	4.5–6.0	1.1	2.5–3.5	(l)	0.15–0.40	(l)	0.25	3.0–4.5	0.25	0.20	(m)	0.30
364.0	D	7.5–9.5	1.5	0.20	0.10	0.20–0.40	0.25–0.50	0.15	0.15	0.15	. . .	0.05(n)	0.15
369.0	D	11.0–12.0	1.3	0.50	0.35	0.25–0.45	0.30–0.40	0.05	1.0	0.10	. . .	0.05	0.15
380.0	D	7.5–9.5	2.0	3.0–4.0	0.50	0.10	. . .	0.50	3.0	0.35	. . .	. . .	0.50
A380.0	D	7.5–9.5	1.3	3.0–4.0	0.50	0.10	. . .	0.50	3.0	0.35	. . .	. . .	0.50
B380.0	D	7.5–9.5	1.3	3.0–4.0	0.50	0.10	. . .	0.50	1.0	0.35	. . .	. . .	0.50
383.0	D	9.5–11.5	1.3	2.0–3.0	0.50	0.10	. . .	0.30	3.0	0.15	. . .	. . .	0.50
384.0	D	10.5–12.0	1.3	3.0–4.5	0.50	0.10	. . .	0.50	3.0	0.35	. . .	. . .	0.50
A384.0	D	10.5–12.0	1.3	3.0–4.5	0.50	0.10	. . .	0.50	1.0	0.35	. . .	. . .	0.50
385.0	D	11.0–13.0	2.0	2.0–4.0	0.50	0.30	. . .	0.50	3.0	0.30	. . .	. . .	0.50
390.0	D	16.0–18.0	1.3	4.0–5.0	0.10	0.45–0.65	. . .	. . .	0.10	. . .	0.20	0.10	0.20
A390.0	S, P	16.0–18.0	0.50	4.0–5.0	0.10	0.45–0.65	. . .	. . .	0.10	. . .	0.20	0.10	0.20
B390.0	D	16.0–18.0	1.3	4.0–5.0	0.50	0.45–0.65	. . .	0.10	1.5	. . .	0.20	0.10	0.20
392.0	D	18.0–20.0	1.5	0.40–0.8	0.20–0.6	0.8–1.2	. . .	0.50	0.50	0.30	0.20	0.15	0.50
393.0	S, P, D	21.0–23.0	1.3	0.7–1.1	0.10	0.7–1.3	. . .	2.0–2.5	0.10	. . .	0.10–0.20	0.05(o)	0.15
413.0	D	11.0–13.0	2.0	1.0	0.35	0.10	. . .	0.50	0.50	0.15	. . .	. . .	0.25
A413.0	D	11.0–13.0	1.3	1.0	0.35	0.10	. . .	0.50	0.50	0.15	. . .	. . .	0.25
B413.0	S, P	11.0–13.0	0.50	0.10	0.35	0.05	. . .	0.05	0.10	. . .	0.25	0.05	0.20
443.0	S, P	4.5–6.0	0.8	0.6	0.50	0.05	0.25	. . .	0.50	. . .	0.25	. . .	0.35
A443.0	S	4.5–6.0	0.8	0.30	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
C443.0	D	4.5–6.0	2.0	0.6	0.35	0.10	. . .	0.50	0.50	0.15	. . .	. . .	0.25
444.0	S, P	6.5–7.5	0.6	0.25	0.35	0.10	. . .	. . .	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
511.0	S	0.30–0.7	0.50	0.15	0.35	3.5–4.5	. . .	. . .	0.15	. . .	0.25	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
515.0	D	0.50–1.0	1.3	0.20	0.40–0.6	2.5–4.0	. . .	. . .	0.10	. . .	. . .	0.05	0.15
516.0	D	0.30–1.5	0.35–1.0	0.30	0.15–0.40	2.5–4.5	. . .	0.25–0.04	0.20	0.10	0.10–0.20	0.05(p)	. . .
518.0	D	0.35	1.8	0.25	0.35	7.5–8.5	. . .	0.15	0.15	0.15	. . .	. . .	0.25
520.0	S	0.25	0.30	0.25	0.15	9.5–10.6	. . .	. . .	0.15	. . .	0.25	0.05	0.15
535.0	S	0.15	0.15	0.05	0.10–0.25	6.2–7.5	. . .	. . .	. . .	. . .	0.10–0.25	0.05(q)	0.15
A535.0	S	0.20	0.20	0.10	0.10–0.25	6.5–7.5	. . .	. . .	. . .	. . .	0.25	0.05	0.15
B535.0	S	0.15	0.15	0.10	0.05	6.5–7.5	. . .	. . .	. . .	. . .	0.10–0.25	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
713.0	S, P	0.25	1.1	0.40–1.0	0.6	0.20–0.50	0.35	0.15	7.0–8.0	. . .	0.25	0.10	0.25
771.0	S	0.15	0.15	0.10	0.10	0.8–1.0	0.06–0.20	. . .	6.5–7.5	. . .	0.10–0.20	0.05	0.15
772.0	S	0.15	0.15	0.10	0.10	0.6–0.8	0.06–0.20	. . .	6.0–7.0	. . .	0.10–0.20	0.05	0.15
850.0	S, P	0.7	0.7	0.7–1.3	0.10	0.10	. . .	0.7–1.3	. . .	5.5–7.0	0.20	. . .	0.30
851.0	S, P	2.0–3.0	0.7	0.7–1.3	0.10	0.10	. . .	0.30–0.7	. . .	5.5–7.0	0.20	. . .	0.30
852.0	S, P	0.40	0.7	1.7–2.3	0.10	0.6–0.9	. . .	0.9–1.5	. . .	5.5–7.0	0.20	. . .	0.30
853.0	S, P	5.5–6.5	0.7	3.0–4.0	0.50	. . .	. . .	. . .	. . .	5.5–7.0	0.20	. . .	0.30

(a) D, die casting; P, permanent mold; S, sand. Other products may pertain to the composition but are not listed. (b) Weight percent; maximum unless range is given or otherwise indicated. All compositions contain balance of aluminum. (c) 0.40–1.0 Ag. (d) 0.50–1.0 Ag. (e) 0.50 max Ti + Zr. (f) 0.20–0.30 Sb, 0.20–0.30 Co, 0.10–0.30 Zr. (g) 0.05–0.15 V, 0.10–0.25 Zr. (h) 0.06–0.20 V. (i) If iron exceeds 0.45%, manganese content shall not be less than one-half of iron content. (j) 0.04–0.07 Be. (k) 0.10–0.30 Be. (l) 0.8 max Mn + Cr. (m) 0.25 max Pb. (n) 0.02–0.04 Be. (o) 0.08–0.15 V. (p) 0.10 max Pb. (q) 0.003–0.007 Be, 0.005 max B. Source: Ref 1

Aluminum and Aluminum Alloys

Table 8 Representative applications for aluminum casting alloys

Alloy	Representative applications
100.0	Electrical rotors larger than 152 mm (6 in.) in diameter
201.0	Structural members; cylinder heads and pistons; gear, pump, and aerospace housings
208.0	General-purpose castings; valve bodies, manifolds, and other pressure-tight parts
222.0	Bushings; meter parts; bearings; bearing caps; automotive pistons; cylinder heads
238.0	Sole plates for electric hand irons
242.0	Heavy-duty pistons; air-cooled cylinder heads; aircraft generator housings
A242.0	Diesel and aircraft pistons; air-cooled cylinder heads; aircraft generator housings
B295.0	Gear housings; aircraft fittings; compressor connecting rods; railway car seat frames
308.0	General-purpose permanent mold castings; ornamental grilles and reflectors
319.0	Engine crankcases; gasoline and oil tanks; oil pans; typewriter frames; engine parts
332.0	Automotive and heavy-duty pistons; pulleys, sheaves
333.0	Gas meter and regulator parts; gear blocks; pistons; general automotive castings
354.0	Premium-strength castings for the aerospace industry
355.0	Sand: air compressor pistons; printing press bedplates; water jackets; crankcases. Permanent: impellers; aircraft fittings; timing gears; jet engine compressor cases
356.0	Sand: flywheel castings; automotive transmission cases; oil pans; pump bodies. Permanent: machine tool parts; aircraft wheels; airframe castings; bridge railings
A356.0	Structural parts requiring high strength; machine parts; truck chassis parts
357.0	Corrosion-resistant and pressure-tight applications
359.0	High-strength castings for the aerospace industry
360.0	Outboard motor parts; instrument cases; cover plates; marine and aircraft castings
A360.0	Cover plates; instrument cases; irrigation system parts; outboard motor parts; hinges
380.0	Housings for lawn mowers and radio transmitters; air brake castings; gear cases
A380.0	Applications requiring strength at elevated temperature
384.0	Pistons and other severe service applications; automatic transmissions
390.0	Internal combustion engine pistons, blocks, manifolds, and cylinder heads
413.0	Architectural, ornamental, marine, and food and dairy equipment applications
A413.0	Outboard motor pistons; dental equipment; typewriter frames; street lamp housings
443.0	Cookware; pipe fittings; marine fittings; tire molds; carburetor bodies
514.0	Fittings for chemical and sewage use; dairy and food handling equipment; tire molds
A514.0	Permanent mold casting of architectural fittings and ornamental hardware
518.0	Architectural and ornamental castings; conveyor parts; aircraft and marine castings
520.0	Aircraft fittings; railway passenger car frames; truck and bus frame sections
535.0	Instrument parts and other applications where dimensional stability is important
A712.0	General-purpose castings that require subsequent brazing
713.0	Automotive parts; pumps; trailer parts; mining equipment
850.0	Bushings and journal bearings for railroads
A850.0	Rolling mill bearings and similar applications

Source: Compiled from *Aluminum Casting Technology*, American Foundrymen's Society, 1986

Aluminum and Aluminum Alloys

Table 7 Typical mechanical properties of aluminum casting alloys

Alloy	Temper	Ultimate tensile strength MPa	Ultimate tensile strength ksi	0.2% offset yield strength MPa	0.2% offset yield strength ksi	Elongation in 50 mm (2 in.), %	Hardness, HB(a)
Sand casting alloys							
201.0	T43	414	60	255	37	17.0	. . .
	T6	448	65	379	55	8.0	130
	T7	467	68	414	60	5.5	. . .
A206.0	T4	354	51	250	36	7.0	. . .
208.0	F	145	21	97	14	2.5	55
213.0	F	165	24	103	15	1.5	70
222.0	O	186	27	138	20	1.0	80
	T61	283	41	276	40	<0.5	115
	T62	421	61	331	48	4.0	. . .
224.0	T72	380	55	276	40	10.0	123
240.0	F	235	34	200	28	1.0	90
242.0	F	214	31	217	30	0.5	. . .
	O	186	27	124	18	1.0	70
	T571	221	32	207	30	0.5	85
	T77	207	30	159	23	2.0	75
A242.0	T75	214	31	. . .	. . .	2.0	. . .
295.0	T4	221	32	110	16	8.5	60
	T6	250	36	165	24	5.0	75
	T62	283	41	221	32	2.0	90
319.0	F	186	27	124	18	2.0	70
	T5	207	30	179	26	1.5	80
	T6	250	36	164	24	2.0	80
355.0	F	159	23	83	12	3.0	. . .
	T51	193	28	159	23	1.5	65
	T6	241	35	172	25	3.0	80
	T61	269	39	241	35	1.0	90
	T7	264	38	250	26	0.5	85
	T71	241	35	200	29	1.5	75
C355.0	T6	269	39	200	29	5.0	85
356.0	F	164	24	124	18	6.0	. . .
	T51	172	25	138	20	2.0	60
	T6	228	33	164	24	3.5	70
	T7	234	34	207	30	2.0	75
	T71	193	28	145	21	3.5	60
A356.0	F	159	23	83	12	6.0	. . .
	T51	179	26	124	18	3.0	. . .
	T6	278	40	207	30	6.0	75
	T71	207	30	138	20	3.0	. . .
357.0	F	172	25	90	13	5.0	. . .
	T51	179	26	117	17	3.0	. . .
	T6	345	50	296	43	2.0	90
	T7	278	40	234	34	3.0	60
A357.0	T6	317	46	248	36	3.0	85
A390.0	F	179	26	179	26	<1.0	100
	T5	179	26	179	26	<1.0	100
	T6	278	40	278	40	<1.0	140
	T7	250	36	250	36	<1.0	115
443.0	F	131	19	55	8	8.0	40
A444.0	F	145	21	62	9	9.0	. . .
	T4	159	23	62	9	12.0	. . .
511.0	F	145	21	83	12	3.0	50
512.0	F	138	20	90	13	2.0	50
514.0	F	172	25	83	12	9.0	50
520.0	T4	331	48	179	26	16.0	75
A535.0	F	250	36	124	18	9.0	65
710.0	F	241	35	172	25	5.0	75
712.0(h)	F	241	35	172	25	5.0	75
713.0(h)	F	241	35	172	25	5.0	74
850.0	T5	138	20	76	11	8.0	45
851.0	T5	138	20	76	11	5.0	45
852.0	T5	186	27	152	22	2.0	65
Permanent mold casting alloys							
201.0	T43	414	60	255	37	17.0	. . .
	T6	448	65	379	55	8.0	130
	T7	469	68	414	60	5.0	. . .
A206.0	T4	431	62	264	38	17.0	. . .
	T7	436	63	347	50	11.7	. . .
213.0	F	207	30	165	24	1.5	85
222.0	T52	241	35	214	31	1.0	100
	T551	255	37	241	35	<0.5	115
	T65	331	48	248	36	<0.5	140
238.0	F	207	30	165	24	1.5	100
242.0	T571	276	40	234	34	1.0	105
	T61	324	47	290	42	0.5	110
249.0	T63	476	69	414	60	6.0	. . .
	T7	278	62	359	52	9.0	. . .
296.0	T4	255	37	131	19	9.0	75
	T6	276	40	179	26	5.0	90
	T7	270	39	138	20	4.5	80
308.0	F	193	28	110	16	2.0	70
319.0	F	234	34	131	19	2.5	85
	T6	276	40	186	27	3.0	95
324.0	F	207	30	110	16	4.0	70
	T5	248	36	179	26	3.0	90
	T62	310	45	269	39	3.0	105
332.0	T5	248	36	193	28	1.0	105
333.0	F	234	34	131	19	2.0	90
	T5	234	34	172	25	1.0	100
	T6	290	42	207	30	1.5	105
	T7	255	37	193	28	2.0	90
336.0	T551	248	36	193	28	0.5	105
	T65	324	47	296	43	0.5	125
356.0	F	179	26	124	18	5.0	. . .
	T51	186	27	138	20	2.0	. . .
	T6	262	38	186	27	5.0	80
	T7	221	32	165	24	6.0	70
A356.0	T61	283	41	207	30	10.0	90
357.0	F	193	28	103	15	6.0	. . .
	T51	200	29	145	21	4.0	. . .
	T6	359	52	296	43	5.0	100
A357.0	T6	359	52	290	42	5.0	100
359.0	T62	345	50	290	42	5.5	. . .
A390.0	F	200	29	200	29	<1.0	110
	T5	200	29	200	29	<1.0	110
	T6	310	45	310	45	<1.0	145
	T7	262	38	262	38	<1.0	120
443.0	F	159	23	62	9	10.0	45
A444.0	F	165	24	76	11	13.0	44
	T4	159	23	69	10	21.0	45
513.0	F	186	27	110	16	7.0	60
711.0	F	241	35	124	18	8.0	70
850.0	T5	159	23	76	11	12.0	45
851.0	T5	138	20	76	11	5.0	45
852.0	T5	221	32	159	23	5.0	70
Die casting alloys							
360.0	F	324	47	172	25	3.0	75
A360.0	F	317	46	165	24	5.0	75
364.0	F	296	43	159	23	7.5	. . .
380.0	F	331	48	165	24	3.0	80
A380.0	F	324	47	159	23	4.0	75
384.0	F	324	47	172	25	1.0	. . .
390.0	F	279	40.5	241	35	1.0	120
	T5	296	43	265	38.5	1.0	. . .
392.0	F	290	42	262	38	<0.5	. . .
413.0	F	296	43	145	21	2.5	80
A413.0	F	241	35	110	16	3.5	80
443.0	F	228	33	110	16	9.0	50
513.0	F	276	40	152	22	10.0	. . .
515.0	F	283	41	. . .	. . .	10.0	. . .
518.0	F	310	45	186	27	8.0	80

Aluminum and Aluminum Alloys

Table 6 Ratings of castability, corrosion resistance, machinability, and weldability for aluminum casting alloys

1, best; 5, worst. Individual alloys may have different ratings for other casting processes.

Alloy	Resistance to hot cracking(a)	Pressure tightness	Fluidity(b)	Shrinkage tendency	Corrosion resistance(c)	Machin-ability(d)	Weld-ability(e)
Sand casting alloys							
201.0	4	3	3	4	4	1	2
208.0	2	2	2	2	4	3	3
213.0	3	3	2	3	4	2	2
222.0	4	4	3	4	4	1	3
240.0	4	4	3	4	4	3	4
242.0	4	3	4	4	4	2	3
A242.0	4	4	3	4	4	2	3
295.0	4	4	4	3	3	2	2
319.0	2	2	2	2	3	3	2
354.0	1	1	1	1	3	3	2
355.0	1	1	1	1	3	3	2
A356.0	1	1	1	1	2	3	2
357.0	1	1	1	1	2	3	2
359.0	1	1	1	1	2	3	1
A390.0	3	3	3	3	2	4	2
A443.0	1	1	1	1	2	4	4
444.0	1	1	1	1	2	4	1
511.0	4	5	4	5	1	1	4
512.0	3	4	4	4	1	2	4
514.0	4	5	4	5	1	1	4
520.0	2	5	4	5	1	1	5
535.0	4	5	4	5	1	1	3
A535.0	4	5	4	4	1	1	4
B535.0	4	5	4	4	1	1	4
705.0	5	4	4	4	2	1	4
707.0	5	4	4	4	2	1	4
710.0	5	3	4	4	2	1	4
711.0	5	4	5	4	3	1	3
712.0	4	4	3	3	3	1	4
713.0	4	4	3	4	2	1	3
771.0	4	4	3	3	2	1	...
772.0	4	4	3	3	2	1	...
850.0	4	4	4	4	3	1	4
851.0	4	4	4	4	3	1	4
852.0	4	4	4	4	3	1	4
Permanent mold casting alloys							
201.0	4	3	3	4	4	1	2
213.0	3	3	2	3	4	2	2
222.0	4	4	3	4	4	1	3
238.0	2	3	2	2	4	2	3
240.0	4	4	3	4	4	3	4
296.0	4	3	4	3	4	3	4
308.0	2	2	2	2	4	3	3
319.0	2	2	2	2	3	3	2
332.0	1	2	1	2	3	4	2
333.0	1	1	2	2	3	3	3
336.0	1	2	2	3	3	4	2
354.0	1	1	1	1	3	3	2
355.0	1	1	1	2	3	3	2
C355.0	1	1	1	2	3	3	2
356.0	1	1	1	1	2	3	2
A356.0	1	1	1	1	2	3	2
357.0	1	1	1	1	2	3	2
A357.0	1	1	1	1	2	3	2
359.0	1	1	1	1	2	3	1
A390.0	2	2	2	3	2	4	2
443.0	1	1	2	1	2	5	1
A444.0	1	1	1	1	2	3	1
512.0	3	4	4	4	1	2	4
513.0	4	5	4	4	1	1	5
711.0	5	4	5	4	3	1	3
771.0	4	4	3	3	2	1	...
772.0	4	4	3	3	2	1	...
850.0	4	4	4	4	3	1	4
851.0	4	4	4	4	3	1	4
852.0	4	4	4	4	3	1	4
Die casting alloys							
360.0	1	1	2	2	3	4	
A360.0	1	1	2	2	3	4	
364.0	2	2	1	3	4	3	
380.0	2	1	2	5	3	4	
A380.0	2	2	2	4	3	4	
384.0	2	2	1	3	3	4	
390.0	2	2	2	2	4	2	
413.0	1	2	1	2	4	4	
C443.0	2	3	3	2	5	4	
515.0	4	5	5	1	2	4	
518.0	5	5	5	1	1	4	

Copper and Copper Alloys

- Group I alloys – that have a narrow freezing range of 50°C
- Group II alloys – that have intermediate freezing range of 50 – 110°C between the liquidus and the solidus.
- Group III alloys –that have wide freezing range over 110°C up to 170°C.

Table 1 Nominal chemical composition and typical mechanical properties for group I alloys

Alloy type	UNS No.	Composition, % Cu	Sn	Pb	Zn	Ni	Fe	Al	Mn	Si	Other	Yield strength(a), 0.5% MPa	ksi	Tensile strength(a) MPa	ksi	Elongation(a), %
Copper	C81100	100	...	...	...	...	...	...	...	...	...	28	4	124	18	40
Chrome copper	C81500	99	...	...	...	...	...	...	...	...	1.0 Cr	276	40 (HT)	34	5 (HT)	17 (HT)
Yellow brass.........	C85200	72	1	3	24	...	...	...	...	...	...	90	13	262	38	35
	C85400	67	1	3	29	...	...	...	...	...	...	83	12	234	34	35
	C85700	61	1	1	37	...	...	...	...	...	...	124	18	345	50	40
	C85800	62	1	1	36	...	...	...	...	...	...	207	30	379	55	15
	C87900	65	...	...	34	...	...	...	...	1	...	241	35	483	70	25
Manganese bronze....	C86200	63	...	...	27		3	4	3	...	...	331	48	654	95	20
	C86300	61	...	...	27	...	3	6	3	...	...	476	69	793	115	15
	C86400	58	1	1	38	...	1	5	5	...	...	172	25	448	65	20
	C86500	58	...	...	39	...	1	1	1	...	...	207	30	489	71	30
	C86700	58	1	1	34	...	2	2	2	...	...	290	42	586	85	20
	C86800	55	...	...	36	3	2	1	3	...	...	262	38	565	82	22
Aluminum bronze	C95200	88	...	...	...	...	3	9	...	...	...	186	27	552	80	35
	C95300	89	...	...	...	...	1	10	...	...	...	186–290	27–42 (HT)	517–586	75–85 (HT)	25–18 (HT)
	C95400	86	...	...	...	...	4	10	...	...	...	241–317	35–46 (HT)	586–758	85–110 (HT)	20–12 (HT)
	C95410	84	...	...	...	2	4	10	...	...	...	248–400	36–58 (HT)	662–800	96–116 (HT)	15–10 (HT)
	C95500	81	...	...	...	4	4	11	...	...	...	303–496	44–72 (HT)	717–827	104–120 (HT)	12–6 (HT)
	C95600	91	...	...	...	...	...	7	...	2	...	234	34	517	75	18
	C95700	75	...	...	...	2	3	8	12	...	...	310	45	655	95	26
	C95800	81	...	...	...	4.5	4	9	1.5	...	...	262	38	655	95	25
Nickel bronze........	C97300	57	2	9	20	12	...	...	...	...	...	117	17	241	35	30
	C97600	64	4	4	8	20	...	...	...	...	...	165	24	310	45	20
	C97800	66	5	2	2	25	...	...	...	...	...	207	30	379	55	15
White brass..........	C99700	58	...	2	22	5	...	1	12	...	...	172	25	379	55	25
	C99750	58	...	1	20	...	...	1	20	...	...	221	32	448	65	30

(a) HT, heat treated

Copper and Copper Alloys

Table 2 Nominal chemical composition and typical mechanical properties for group II alloys

Alloy type	UNS No.	Composition, % Cu	Zn	Ni	Fe	Mn	Si	Nb	Other	Yield strength(b)(c), 0.5% MPa	ksi	Tensile strength(b) MPa	ksi	Elongation(b), %
Beryllium copper	C81400	99.1	. . .	. . .	. . .	. . .	. . .	. . .	0.6 Be	248	36 (HT)	365	53 (HT)	11 (HT)
									0.8 Cr	. . .		. . .		. . .
	C82000	97	. . .	. . .	. . .	. . .	. . .	. . .	0.5 Be	121	17.6	243	35.2	20
									2.5 Co	517	75 (HT)	689	100 (HT)	3 (HT)
	C82200	98	. . .	1.5	. . .	. . .	. . .	. . .	0.5 Be	145	21.1	276	40.1	20
									. . .	517	75 (HT)	654	95 (HT)	8 (HT)
	C82400	97.8	. . .	. . .	. . .	. . .	. . .	. . .	1.7 Be	179	26.0	349	50.6	20
									0.5 Co	965	140 (HT)	1035	150 (HT)	1 (HT)
	C82500	97.2	. . .	. . .	. . .	. . .	0.3	. . .	2.0 Be	218	31.6	387	56.2	20
									0.5 Co	. . .		1105	160 (HT)	1 (HT)
	C82600	96.8	. . .	. . .	. . .	. . .	0.3	. . .	2.4 Be	228	33.0	397	57.6	20
									0.5 Co	1070	155 (HT)	1140	165 (HT)	1 (HT)
	C82800	96.6	. . .	. . .	. . .	. . .	0.3	. . .	2.6 Be	267	38.7	470	68.2	20
									0.5 Co	1000	145 (HT)	1140	165 (HT)	1 (HT)
Silicon brass	C87500	82	14	. . .	. . .	. . .	4	. . .	30	462	67	145	21	. . .
Silicon bronze	C87300	9.5	. . .	. . .	. . .	1	4	. . .	25	400	58	241	35	. . .
	C87600	91	5	. . .	. . .	. . .	4	. . .	32	455	66	138	20	. . .
	C87610	92	4	. . .	. . .	. . .	4	. . .	25	400	58	207	30	. . .
	C87800(a)	82	14	. . .	. . .	. . .	4	. . .	50	586	85	172	25	. . .
Copper-nickel	C96200	87	. . .	10	1.5	1	. . .	1	27	345	50	152	22	. . .
	C96400	66	. . .	30.5	0.5	1	. . .	1	37	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 3 Nominal chemical composition and typical mechanical properties for group III alloys

Alloy type	UNS No.	Composition, % Cu	Sn	Pb	Zn	Ni	Yield strength, 0.5% MPa	ksi	Tensile strength, 0.5% MPa	ksi	Elongation, %
Leaded red brass...............	C83450	88	2.5	2	6.5	1	103	15	255	37	34
	C83600	85	5	5	5	. . .	110	16	248	36	32
	C83800	83	4	6	7	. . .	110	16	241	35	28
Leaded semired brass.........	C84400	81	3	7	9	. . .	96	14	234	34	28
	C84800	76	2.5	6.5	15	. . .	103	15	255	37	29
Tin bronze	C90300	88	8	. . .	4	. . .	138	20	310	45	30
	C90500	88	10	. . .	2	. . .	152	22	317	46	30
	C90700	89	11	. . .	. . .	. . .	152	22	303	44	20
	C91100	84	16	. . .	. . .	. . .	172	25	241	35	2
	C91300	81	19	. . .	. . .	. . .	241	35	207	30	0.5
Leaded tin bronze............	C92200	86	6	1.5	4.5	. . .	110	16	283	41	45
	C92300	87	8	1	4	. . .	138	20	290	42	32
	C92600	87	10	1	2	. . .	138	20	303	44	30
	C92700	88	10	2	. . .	. . .	142	21	300	42	20
High-leaded tin bronze........	C92900	84	10	2.5	. . .	3.5	179	26	324	47	20
	C93200	83	7	7	3	. . .	117	17	262	38	30
	C93400	84	8	8	. . .	. . .	110	16	248	36	25
	C93500	85	5	9	1	. . .	110	16	221	32	20
	C93700	80	10	10	. . .	. . .	124	18	276	40	30
	C93800	78	7	15	. . .	. . .	110	16	221	32	20
	C94300	70	5	25	. . .	. . .	110	16	207	30	18

Copper and Copper Alloys

- Plumbing hardware, pump parts, and valves and fittings – usually red and semi-red brasses. C83300 to C84800.
- Bearings and bushings – Usually phosphor bronzes, Copper-tin-lead, Manganese, silicon, and aluminum bronzes.
- Gears – Tin bronzes, nickel-tin bronzes. C90700, C90800, C91600, C91700, C92900.
- Marine castings – Copper-nickels (high strength) C96200, C96400; Bronzes.
- Electrical components - Pure copper, beryllium-copper, leaded red brasses, bronzes.
- Architectural and ornamental parts - Bronze C87200, Yellow, and leaded yellow brasses.

Copper and Copper Alloys

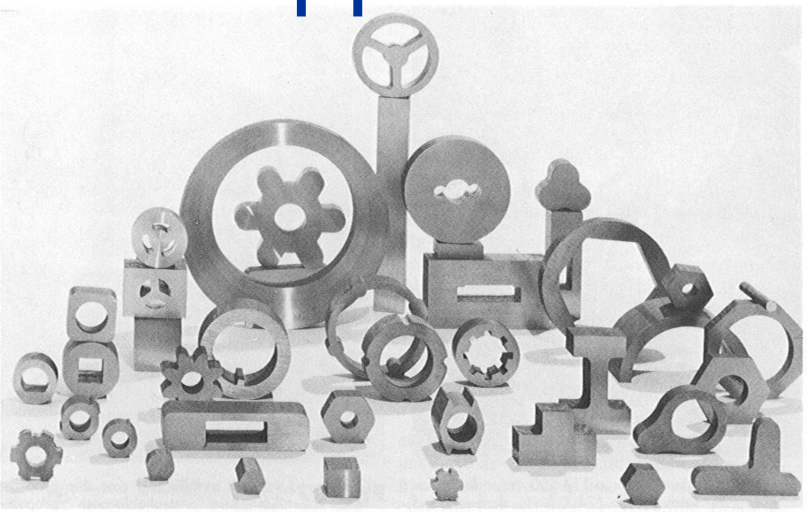


Fig. 22 Variety of intricate shapes and sizes obtained by using continuous casting methods to produce brass and bronze alloy parts. Courtesy of ASARCO, Inc.

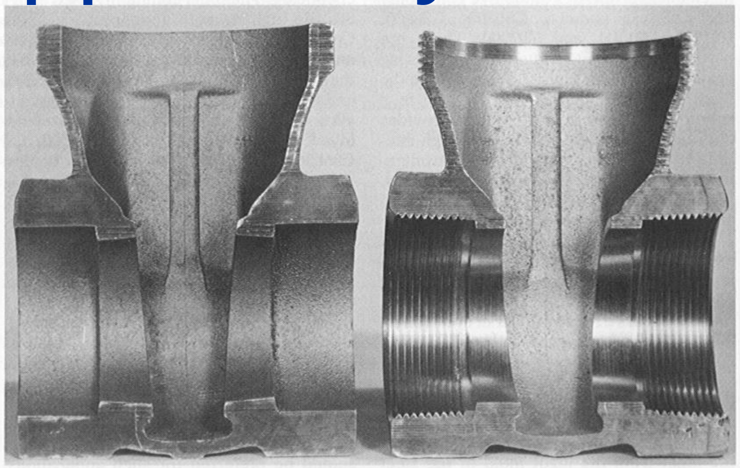


Fig. 23 Cutaway views of an as-cast and finish machined/threaded body of a 50 mm (2 in.) gate valve-union bonnet assembly rated at 1.0 MPa (150 psi). The body section was sand cast of C83600 alloy (Cu-5Sn-5Pb-5Zn composition) and weighs 2.4 kg (5.2 lb). Courtesy of Crane Company

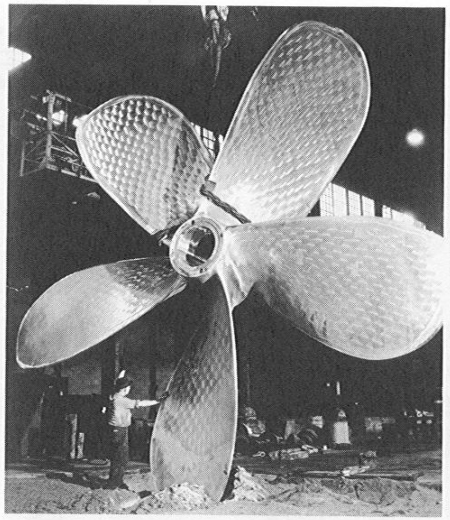


Fig. 26 Propeller for a 114 000 ton tanker measures 7.5 m (24.7 ft) in diameter and weighs 37.52 Mg (82 725 lb). Part was machined and polished from a single 53.75 Mg (118 500 lb) nickel-aluminum bronze casting. Courtesy of Baldwin-Lima-Hamilton Corporation

Fig. 27 Vertical centrifugally cast ship propeller hub for controllable-pitch propeller blades is made of nickel-aluminum bronze, weighs 8.44 Mg (18 600 lb), and measures 1575 mm (62 in.) in diameter and 1270 mm (50 in.) in length. Courtesy of Wisconsin Centrifugal, Inc.

Zinc and Zinc Alloys

Table 1 Compositions of zinc casting alloys

Alloy	Applicable standards	Composition, %(a) Al	Cu	Mg	Fe	Pb	Cd	Sn	Ni	Zn
No. 3 (UNS Z33521)	ASTM B 86	3.5–4.3	0.25	0.02–0.05	0.100 0.100	0.005	0.004	0.003	. . .	rem
No. 5 (UNS Z35531)	ASTM B 86	3.5–4.3	0.75–1.25	0.03–0.08	0.075	0.005	0.004	0.003	. . .	rem
No. 7 (UNS Z33522)	ASTM B 86	3.5–4.3	0.25	0.005–0.02	0.10	0.003	0.002	0.001	0.005–0.02	rem
ZA-8 (UNS Z25630)	ASTM B 669	8.0–8.8	0.8–1.3	0.015–0.03	0.075	0.004	0.003	0.002	. . .	rem
ZA-12 (UNS Z35630)	ASTM B 669	10.5–11.5	0.5–1.25	0.015–0.03	0.10	0.004	0.003	0.002	. . .	rem
ZA-27 (UNS Z35840)	ASTM B 669	25.0–28.0	2.0–2.5	0.01–0.02	. . .	0.004	0.003	0.002	. . .	rem

(a) Maximum unless range is given or otherwise indicated.

Table 2 Comparison of typical mechanical properties of casting alloys

Alloy and product form(a)	Ultimate tensile strength MPa	ksi	0.2% offset yield strength MPa	ksi	Elongation, % in 50 mm (2 in.)	Hardness, HB	Impact strength J	ft · lbf	Fatigue strength MPa	ksi	Young's modulus GPa	ksi × 10^3
Zinc alloys												
No. 3 (D)	283	41	. . .	. . .	10	82	58(c)	43	47.6	6.9	. . .	. . .
No. 5 (D)	331	48	. . .	. . .	7	91	65(c)	48	56.5	8.2	. . .	. . .
No. 7 (D)	283	41	. . .	. . .	13	80	58(c)	43	. . .	. . .	. . .	. . .
ZA-8 (S)	248–276	36–40	200	29	1–2	80–90	20(c)	15	. . .	. . .	85.5	12.4
ZA-8 (P)	221–255	32–37	207	30	1–2	85–90	. . .	. . .	51.8	7.5	85.5	12.4
ZA-8 (D)	372	54	290	42	6–10	95–110	42(c)	31	. . .	. . .	. . .	. . .
ZA-12 (S)	276–317	40–46	207	30	1–3	90–105	25(c)	19	103.5	15	83.0	12.0
ZA-12 (P)	310–345	45–50	207	30	1–3	90–105	. . .	. . .	. . .	. . .	83.0	12.0
ZA-12 (D)	400	58	317	46	4–7	95–115	28(c)	21	. . .	. . .	. . .	. . .
ZA-27 (S)(b)	400–440	58–64	365	53	3–6	110–120	47(c)	35	172.5	25	75.2	10.9
ZA-27 (P)	421–427	61–62	365	53	1	110–120	. . .	. . .	. . .	. . .	75.2	10.9
ZA-27 (D)	421	61	365	53	1–3	105–125	. . .	. . .	. . .	. . .	. . .	. . .
Aluminum alloys												
319 (S)	185	27	124	18	2	70	5(c)	4	69	10	74.0	10.7
356-T6 (P)	262	38	185	27	5	80	11(c)	8	90	13	72.4	10.5
380 (D)	325	47	159	23	3.5	80–85	4(c)	3	138	20	71.0	10.3
Copper alloys												

[redacted]

Zinc and Zinc Alloys

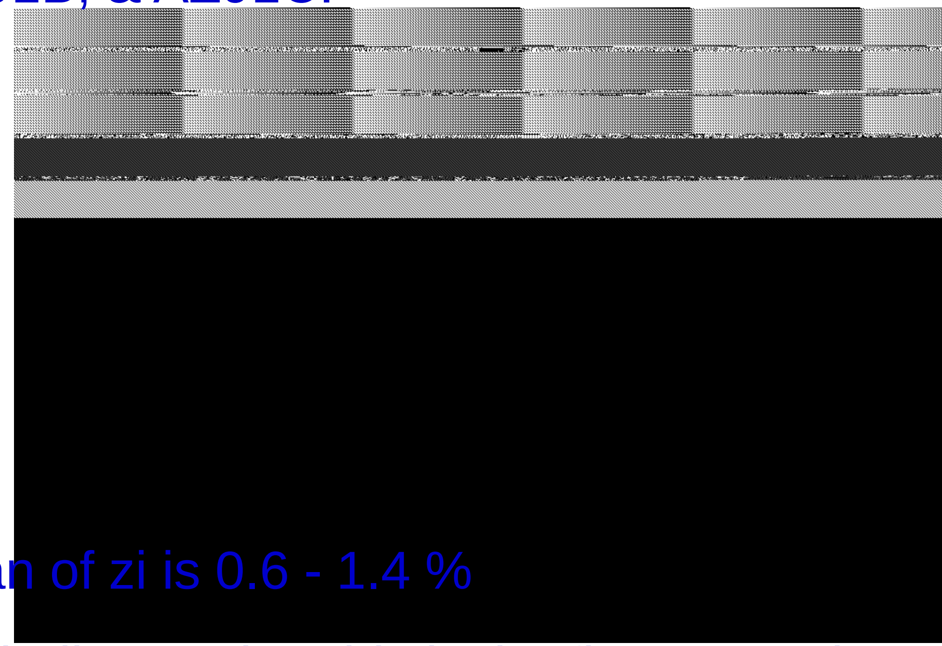
- Applications for Zinc Die Castings
- The automotive industry is the largest user of zinc die castings: carburetor bodies, bodies for fuel pumps, windshield wiper parts, control panels, grilles, horns, and parts for hydraulic brakes. Structural and decorative zinc alloy castings include grilles for radios and radiators, lamp and instrument bezels, steering wheel hubs, interior and exterior hardware, instrument panels, and body moldings.
- Also: electrical, electronic, and appliance industries, business machines and other light machines of all types (including beverage vending machines, and tools. Building hardware, padlocks, and toys and novelties are major areas of application for zinc die castings.

Zinc and Zinc Alloys

- Other Casting Processes for Zinc Alloys
- Sand Casting. The ZA alloys, especially ZA-12 and ZA-27, are being increasingly used in gravity sand casting operations. The use of chills or patterns that promote directional solidification is recommended.
- Permanent mold casting is done using both metallic and machined graphite molds. Cast iron or steel is most commonly used for metallic permanent molds. The use of graphite molds permits as-cast tolerances similar to those obtained in die casting. Machining time is reduced or eliminated, making the graphite process attractive for intermediate production volumes (500 to 20 000 parts per year).
- Squeeze casting - employed to cast MMCs with ZA alloy matrices and SiC or alumina fibres.

Magnesium and Magnesium Alloys

- Consider the 3 alloys AZ91A, AZ91B, & AZ91C.
- A represents Al, the greatest alloying element present
- Z represents Zi, second greatest alloying element
- 9 indicates that the rounded mean of al is 8.6 - 9.4 %



- 1 indicates that the rounded mean of zi is 0.6 - 1.4 %
- Final letter A in the first example indicates that this is the first alloy whose composition qualified assignment of the designation AZ91
- B and C in other examples signify alloys subsequently developed whose specified compositions differ slightly from the first and from one another but do not differ sufficiently to effect a change in the basic designation.

Magnesium and Magnesium Alloys

Table 2 Nominal compositions of magnesium casting alloys for sand, investment, and permanent mold castings

Alloy	Composition, % Al	Zn	Mn	Rare earths	Th	Y	Zr
AM100A	10.0	...	0.1 min	...	...	...	...
AZ63A	6.0	3.0	0.15	...	...	...	...
AZ81A	8.0	0.7	0.13	...	...	...	...
AZ91C	9.0	0.7	0.13	...	...	...	...
AZ91E	9.0	2.0	0.10	...	...	...	...
AZ92A	9.0	2.0	0.10	...	...	...	...
EZ33A	...	2.7	...	3.3	...	...	0.60
HK31A	...	...	...	...	3.3	...	0.70
HZ32A	...	2.1	...	...	3.3	...	0.70
QE22A(a)	...	...	...	2.0	...	...	0.60
EQ21A(a,b)	...	...	...	2.0	...	...	0.60
ZE41A	...	4.2	...	1.2	...	...	0.70
ZE63A	...	5.7	...	2.5	...	...	0.70
ZH62A	...	5.7	...	...	1.8	...	0.70
ZK51A	...	4.6	...	...	...	...	0.70
ZK61A	...	6.0	...	...	...	...	0.70
WE54A	...	...	...	3.50(c)	...	5.25	0.50

(a) These alloys also contain silver, that is, 2.5% in QE22A and 1.5% in EQ21A. (b) EQ21A also contains 0.10% Cu. (c) Comprising 1.75% other heavy rare earths in addition to the 1.75% Nd present

Table 3 Nominal compositions of magnesium casting alloys for die castings

Alloy	Alloying element Mg	Al	Mn	Si	Zn
AM60A	rem	6.0	0.13 min	...	...
AS41A	rem	4.25	0.35	1.0	...
AZ91A	rem	9.0	0.13 min	...	0.7
AZ91B	rem	9.0	0.13 min	...	0.7
AZ91D (HP)(b)	rem	9.0	(a)	...	0.7

(a) Manganese content to be dependent upon iron content. (b) The proposed alloy to have very low limits for iron, nickel, and copper. HP, high purity

Magnesium and Magnesium Alloys

- General Applications
- The most important feature of magnesium castings is their light weight.
- Magnesium castings have found considerable use since World War II in aircraft and aerospace applications
- Due to general requirement for lighter weight automobiles to conserve energy, there has been a growing use of magnesium as die castings
- Magnesium has other important casting advantages over other metals:
  - It is an abundantly available metal
  - It is easier to machine than aluminum.
  - It can be machined much faster than aluminum, preferably dry

Magnesium and Magnesium Alloys

- In die casting, MG can be cast up to four times faster than aluminum. Die lives are considerably longer
- Modern casting methods and the application of protective coatings currently available ensure long life for well-designed components.
- Able to produce complex parts having thin-wall sections. The end product has a high degree of stability as well as being light in weight.
- Mg castings of all types have found use in many applications, where their lightness and rigidity are required, such as for chain saw bodies, computer components, camera bodies, and certain portable tools. Magnesium alloy sand castings are used extensively for aerospace components.

Titanium and Titanium Alloys

- The term castings considered inferior to wrought products.
- This is not true with titanium cast parts.
- They are comparable to wrought products in all respects and superior
- crack propagation and creep resistance can be superior
- So, titanium castings can reliably replace forged/machined parts
  - Allotropic phase transformation at 705 to 1040°C, which is well below the solidification temperature of the alloys.
  - As a result, the cast dendritic structure is wiped out during the solid state cooling stage

Table 2 Comparison of cast titanium alloys

Alloy	Estimated relative usage of castings	Nominal composition, wt %										Special properties(a)
		O	N	H	Al	Fe	V	Cr	Sn	Mo	Zr	
Ti-6Al-4V	90%	0.18	0.015	0.006	6	0.13	4	...	...	...	...	General purpose
Ti-6Al-4V ELI	2%	0.11	0.010	0.006	6	0.10	4	...	...	...	...	Cryogenic toughness
Commercially pure titanium Gr2	5%	0.25	0.015	0.006	...	0.15	...	...	...	...	...	Corrosion resistance
Ti-6Al-2Sn-4Zr-2Mo	2%	0.10	0.010	0.006	6	0.15	...	...	2	2	4	Elevated-temperature creep
Ti-6Al-2Sn-4Zr-6Mo	<1%	0.10	0.010	0.006	6	0.15	...	...	2	6	4	Elevated-temperature strength
Ti-5Al-2.5Sn	<1%	0.16	0.015	0.006	5	0.2	...	...	2.5	...	...	Cryogenic toughness
Ti-3Al-8V-6Cr-4Zr-4Mo	<1%	0.10	0.015	0.006	3.5	0.2	8.5	6	...	4	4	Strength
Ti-15V-3Al-3Cr-3Sn	<1%	0.11	0.015	0.006	3	0.2	15	3	3	...	...	Strength
Total	**100%**											

(a) Superior, relative to Ti-6Al-4V

Titanium and Titanium Alloys

Table 3 Typical room-temperature tensile properties of titanium alloy castings (bars machined from castings)

Specification minimums are less than these typical properties.

Alloy(a)	Yield strength MPa	Yield strength ksi	Ultimate strength MPa	Ultimate strength ksi	Elongation, %	Reduction of area, %
Commercially pure (Grade 2)	448	65	552	80	18	32
Ti-6Al-4V, annealed	855	124	930	135	12	20
Ti-6Al-4V-ELI	758	110	827	120	13	22
Ti-6Al-2Sn-4Zr-2Mo, annealed	910	132	1006	146	10	21
Ti-6Al-2Sn-4Zr-6Mo, STA	1269	184	1345	195	1	1
Ti-3Al-8V-6Cr-4Zr-4Mo, STA	1241	180	1330	193	7	12
Ti-15V-3Al-3Cr-3Sn, STA	1200	174	1275	185	6	12

(a) Solution-treated and aged (STA) heat treatments may be varied to produce alternate properties.

- Product Applications
- since 1960s, used in corrosion-resistant service in pump and valve parts
- Aerospace use of castings in the early 1970s for aircraft brake torque tubes, missile wings, and hot gas nozzles.
- As the more precise investment casting technology developed and the commercial use of HIP became a reality in the mid-1970s, titanium casting applications quickly expanded into critical airframe and gas turbine engine components.

Titanium and Titanium Alloys

- Today, titanium cast parts are routinely produced for critical structural applications such as space shuttle attachment fittings, complex airframe structures, engine mounts, compressor cases and frames of many types, missile bodies and wings, and hydraulic housings.
- Titanium castings are used for framework for very sensitive optical equipment due to their stiffness and the compatibility of the coefficient of thermal expansion of titanium with that of glass.
- Applications evolving for engine airfoil shapes include individual vanes and integral vane rings for stators, as well as a few rotating parts that would otherwise be made from wrought product.
- Growth will continue as users seek to take advantage of the flexibility of design inherent in the investment casting process and the improvement in economics of net and near-net shapes.