Most engineering metallic materials are alloys. Metals are alloyed to enhance their properties, such as strength, hardness or corrosion resistance, and to create new properties, such as shape memory effect.

Engineering alloys can be broadly divided into Ferrous Alloys and Non-ferrous Alloys.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Global demand tonnes, x1000</th>
<th>Price $/tonne</th>
<th>Market $ billion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>730,000</td>
<td>400</td>
<td>292</td>
</tr>
<tr>
<td>Aluminium</td>
<td>20,000</td>
<td>1,500</td>
<td>30</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>13,000</td>
<td>2,000</td>
<td>26</td>
</tr>
<tr>
<td>Titanium</td>
<td>56</td>
<td>35,000</td>
<td>2</td>
</tr>
<tr>
<td>Nickel</td>
<td>1,000</td>
<td>12,000</td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>10,000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
1. Ferrous Alloys

Metal Alloys

Ferrous

Steels

Low Cast irons

Carbon

Low Alloy

High Alloy

Low-C

Medium-C

High-C

Tool

e.g., HSLA

Stainless

High-Mn

Tool

(Mo,V,W,Cr,Ni)

(<5% total alloying elements)

(>5% total alloying elements)

Grey iron

Nodular iron

White iron

Malleable iron

Alloy cast irons
Ferrous Alloys
- Alloys containing Fe as the main element.
- The most important ferrous alloy system (Fe-C system)
- Alloys of this system can be further divided into steels and cast irons.
- Steels contain less C (generally <1.4wt%C) than do cast irons (generally 2.4~4.3wt%C).
- Then, all steels solidify into a single $\gamma$-Fe structure first and then experience the complex eutectoid reaction. Therefore, heat treatment processes, which alter the eutectoid reaction, are vitally important for controlling microstructure and properties of steels.
- Cast irons experience complex eutectic reaction during solidification, due to the formation of graphite or cementite. Solidification control is the most important single factor for properties of cast irons.
Plain Carbon Steels

Low carbon steels (mild steels): 0.1-0.25% C
proeutectoid F + small amount of P
high formability, high ductility: elongation: \( \sim 30\% \)
relatively low strength: yield strength: 250~400MPa
excellent weldability
cannot be strengthened by heat treatment
usually strengthened by cold working
typical applications: pipes, panels, sheets, wires, I-beams etc.
Medium-carbon steels (structural steels)
0.25-0.55% C
Good combination of strength and ductility
Yield strength: 300~600MPa
Tensile strength: 400~800MPa
Elongation: ~25%
Strengthenable by heat treatment
Weldable; weldability deteriorates with increasing C%
Used for load-bearing applications, crankshaft, bolts, gears, heavy-duty machinery, mining equipment, cranes
High strength low alloy steels (HSLA)

Medium carbon steels have desired mechanical properties for structural applications, but suffer from welding-induced embrittlement due to the formation of martensite. To overcome this problem, C content in these steels is reduced (<0.3%) and the loss of strength is compensated by increasing Mn content (>1%) and by microalloying with Nb, V, Ti, Cr and Cu. This leads to the development of HSLA steels. These steels are widely used for manufacturing large welded structures, such as Sydney harbor bridge, ocean liners and cargo ships, oil drilling rigs and platforms, large mining and earth moving equipment, and pressure vessels and storage tanks.
High carbon steels

Spring steels: 0.6~0.8%C
predominately eutectoid pearlite at room temperature
often strengthened and hardened by heat treatment
high strength and moderate toughness

Tool steels: 0.8~1.2%C
proeutectoid cementite + pearlite
very high hardness, low toughness, very difficult to machine
used for chisels, hammers, knives, saw blades, drills, dies, punches,
cutlery, chine tools and wear resistant applications

High carbon steels have poor weldability and poor machinability

Extrusion dies  Cutting blades
**Alloy Designation** (carbon and low-alloy steels)

**AISI**: American Iron and Steel Institute  
**SAE**: Society of Automotive Engineers  
**ASTM**: American Society for Testing and Materials  
**UNS**: Uniform Numbering System

**AISI/SAE** | **UNS**  
--- | ---  
**carbon steels**  
1040 | G10400 plain carbon steel containing 0.4wt% C  
1xYY | G1xYY0 modified carbon steel (S, P, Mn)  
**low alloy steels**  
2xxx | G2xxx0 alloy steels

**Tool Steels**

High alloy tool steels are often alloyed with Mo, V, W, Cr and/or Ni.

**UNS**: Txxxxx

Normally specified by hardness and impact toughness.
Stainless Steels

Three basic classes, specified by microstructure:
Ferritics: Fe-Cr alloys (12~25%Cr), can be cheap
Martensitics: Fe-Cr alloys, low Cr, hard, cutting tools
Austenitics: Fe-Cr-Ni alloys (18Cr-8Ni), corrosion resistance
Precipitation hardened, high strength and hardness
Duplex (18Cr-5Ni)

Alloys designation

<table>
<thead>
<tr>
<th>Type</th>
<th>AISI</th>
<th>UNS</th>
</tr>
</thead>
<tbody>
<tr>
<td>2xx</td>
<td>S2xx00</td>
<td></td>
</tr>
<tr>
<td>3xx</td>
<td>S3xx00</td>
<td>304, 316, 316L (austenitics)</td>
</tr>
<tr>
<td>4xx</td>
<td>S4xx00</td>
<td>410 (martensitic), 446 (ferritic)</td>
</tr>
</tbody>
</table>

Typical Mechanical Properties

- Yield strength: 200MPa ~ 1600MPa
- Tensile strength: 300 MPa ~ 1800 MPa
- Ductility: EL% 40 ~ 2
- Young's modulus: ~ 170 GPa
Table 12.2a  AISI/SAE and UNS Designation Systems and Composition Ranges for Plain Carbon Steel and Various Low-Alloy Steels

<table>
<thead>
<tr>
<th>AISI/SAE Designation&lt;sup&gt;a&lt;/sup&gt;</th>
<th>UNS Designation</th>
<th>Composition Ranges (wt% of Alloying Elements in Addition to C)&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>10xx, Plain carbon</td>
<td>G10xx0</td>
<td>Ni 0.08–0.33S, Cr 0.04–0.12P, Mo 1.60–1.90Mn</td>
</tr>
<tr>
<td>11xx, Free machining</td>
<td>G11xx0</td>
<td></td>
</tr>
<tr>
<td>12xx, Free machining</td>
<td>G12xx0</td>
<td></td>
</tr>
<tr>
<td>13xx</td>
<td>G13xx0</td>
<td>Ni 0.20–0.30, Cr 0.80–1.10, Mo 0.15–0.25</td>
</tr>
<tr>
<td>40xx</td>
<td>G40xx0</td>
<td>Ni 0.70–2.00, Cr 1.65–2.00, Mo 0.15–0.30</td>
</tr>
<tr>
<td>41xx</td>
<td>G41xx0</td>
<td>Ni 3.25–3.75, Cr 0.70–1.10, Mo 0.20–0.30</td>
</tr>
<tr>
<td>43xx</td>
<td>G43xx0</td>
<td>Ni 0.50–1.10, Cr 0.40–0.90, Mo 0.20–0.30</td>
</tr>
<tr>
<td>46xx</td>
<td>G46xx0</td>
<td>Ni 0.40–0.70, Cr 0.40–0.60, Mo 0.15–0.25</td>
</tr>
<tr>
<td>48xx</td>
<td>G48xx0</td>
<td>Ni 1.80–2.20Si, Cr 0.70–1.10, Mo 0.20–0.30</td>
</tr>
<tr>
<td>51xx</td>
<td>G51xx0</td>
<td></td>
</tr>
<tr>
<td>61xx</td>
<td>G61xx0</td>
<td></td>
</tr>
<tr>
<td>86xx</td>
<td>G86xx0</td>
<td></td>
</tr>
<tr>
<td>92xx</td>
<td>G92xx0</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> The carbon concentration, in weight percent times 100, is inserted in the place of “xx” for each specific steel.

<sup>b</sup> Except for 13xx alloys, manganese concentration is less than 1.00 wt%.
Except for 12xx alloys, phosphorus concentration is less than 0.35 wt%.
Except for 11xx and 12xx alloys, sulfur concentration is less than 0.04 wt%.
Except for 92xx alloys, silicon concentration varies between 0.15 and 0.35 wt%.
| AISI Number | UNS Number | Tensile Strength [MPa (ksi)] | Yield Strength [MPa (ksi)] | Ductility [%EL in 50 mm (2 in.)] | Typical Applications  
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1040</td>
<td>G10400</td>
<td>605–780 (88–113)</td>
<td>430–585 (62–85)</td>
<td>33–19</td>
<td>Crankshafts, bolts</td>
</tr>
<tr>
<td>1080*</td>
<td>G10800</td>
<td>800–1310 (116–190)</td>
<td>480–980 (70–142)</td>
<td>24–13</td>
<td>Chisels, hammers</td>
</tr>
<tr>
<td>1095*</td>
<td>G10950</td>
<td>760–1280 (110–186)</td>
<td>510–830 (74–120)</td>
<td>26–10</td>
<td>Knives, hacksaw blades</td>
</tr>
</tbody>
</table>

**Plain Low-Carbon Steels**

**Alloy Steels**

| AISI Number | UNS Number | Tensile Strength [MPa (ksi)] | Yield Strength [MPa (ksi)] | Ductility [%EL in 50 mm (2 in.)] | Typical Applications  
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4063</td>
<td>G40630</td>
<td>786–2380 (114–345)</td>
<td>710–1770 (103–257)</td>
<td>24–4</td>
<td>Springs, hand tools</td>
</tr>
</tbody>
</table>

* Classified as high-carbon steels.
**Table 12.4** Designations, Compositions, Mechanical Properties, and Typical Applications for Austenitic, Ferritic, Martensitic, and Precipitation-Hardenable Stainless Steels

<table>
<thead>
<tr>
<th>AISI Number</th>
<th>UNS Number</th>
<th>Composition (wt%)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Condition&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Tensile Strength [MPa (ksi)]</th>
<th>Yield Strength [MPa (ksi)]</th>
<th>Ductility (%EL in 50 mm (2 in.))</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Ferritic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>409</td>
<td>S40900</td>
<td>0.08 C, 11.0 Cr, 1.0 Mn, 0.50 Ni, 0.75 Ti</td>
<td>Annealed</td>
<td>380 (55)</td>
<td>205 (30)</td>
<td>20</td>
<td>Automotive exhaust components, tanks for agricultural sprays</td>
</tr>
<tr>
<td>446</td>
<td>S44600</td>
<td>0.20 C, 25 Cr, 1.5 Mn</td>
<td>Annealed</td>
<td>515 (75)</td>
<td>275 (40)</td>
<td>20</td>
<td>Valves (high temperature), glass molds, combustion chambers</td>
</tr>
<tr>
<td><strong>Austenitic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>304</td>
<td>S30400</td>
<td>0.08 C, 19 Cr, 9 Ni, 2.0 Mn</td>
<td>Annealed</td>
<td>515 (75)</td>
<td>205 (30)</td>
<td>40</td>
<td>Chemical and food processing equipment, cryogenic vessels</td>
</tr>
<tr>
<td><strong>Martensitic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>410</td>
<td>S41000</td>
<td>0.15 C, 12.5 Cr, 1.0 Mn</td>
<td>Annealed Q &amp; T</td>
<td>485 (70)</td>
<td>275 (40)</td>
<td>20</td>
<td>Rifle barrels, cutlery, jet engine parts</td>
</tr>
<tr>
<td>440A</td>
<td>S44002</td>
<td>0.70 C, 17 Cr, 0.75 Mo, 1.0 Mn</td>
<td>Annealed Q &amp; T</td>
<td>725 (105)</td>
<td>415 (60)</td>
<td>20</td>
<td>Cutleries, bearings, surgical tools</td>
</tr>
<tr>
<td><strong>Precipitation Hardenable</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17-7PH</td>
<td>S17700</td>
<td>0.09 C, 17 Cr, 7 Ni, 1.0 Al, 1.0 Mn</td>
<td>Precipitation hardened</td>
<td>1450 (210)</td>
<td>1310 (190)</td>
<td>1–6</td>
<td>Springs, knives, pressure vessels</td>
</tr>
</tbody>
</table>
Cast Irons

\[ Fe_3C \rightarrow 3Fe(\alpha) + C(\text{graphite}) \]

\( >2.14 \text{ wt\% Carbon} \)

- On the Fe-C system, these are to the right of steels,
- with carbon between 2 & 5.3 \%
- but more usual 2.5 to 4\%.
- Really is tertiary alloy system,
- with the third element silicon.
- The microstructures present depend strongly on the chemical composition (\%Si) and the cooling rate of the cast.
BASIS

- Cast irons have carbon beyond the limit of solubility of C in $\gamma$,
- The different types of cast iron are merely the different forms the carbon takes.
- The carbon can be in the form of cementite, or “white” cast iron.
- If some silicon is added (1 to 2%, maybe 3 %) the carbon will tend to graphitize,
- and there are various forms the graphite can have.
- Then, the carbon can also be in the form of graphite (“gray”, “malleable” and “nodular” cast iron)
Meanwhile—

- the austenite is still there.
- What can austenite do?
- It changes to ferrite and graphite if cooled very slow (if enough silicon is added).
- It changes to pearlite if cooled slowly,
- and forms martensite if quenched, and
- bainite if cooled in between.
- In other words, we can do anything to the austenite we did with a steel,
- its just that with cast irons we’ll also have excess carbon in some form.
White Cast Iron

• It contains relatively less C and Si.

• If we cooled rapidly and we do not add enough Si, the cast iron solidifies as “White” in the Fe-Fe₃C System.

• We can have hypoeutectic and hypereutectic white cast irons.

• Cementite makes the alloy hard and brittle and it is practically useless as structural material.

• The high hardness renders them high resistant to abrasive wear.

• White irons are produced mainly for two purposes: (a) Intermediate product for producing malleable irons and (b) As abrasive wear resistant components, such as ball mill lining tiles, slurry pipe elbows, slurry pump bodies.
Gray Cast Iron

• If we put in 2 to 3 % Silicon,
• and cool the iron reasonably slowly (don’t quench it) the Si will cause the carbon to form as graphite flakes – Gray Cast Iron.

• If we put in more Silicon and cool slowly we can get virtually all the carbon out of the austenite
• and into the flakes, so the matrix is ferrite, or we have a ferritic gray CI.

• If we don’t cool as slowly, or we add less silicon,
• we’d have some carbon left in γ.
• When the austenite hits the eutectoid temperature it would form pearlite,
• just like it did when we talked about steels – pearlitic gray CI.
Grey Irons - Application

Grey irons are by far the most produced among all cast irons. Grey irons are used primarily for their low cost and excellent castability. Typical applications include:

engine cylinders, pistons, gear box casing, transmission casing, machine tool bases, balance weight of large cranes, large diameter underground pipework.

They are used always under compressive loading conditions. They are unsuitable for taking tensile loads or bending loads.

![Stress-strain curve of grey iron and mild steel](image)
Grey Irons

<table>
<thead>
<tr>
<th>SAE</th>
<th>UNS</th>
<th>Tensile Strength</th>
<th>yield</th>
<th>ductility</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1800</td>
<td>F10004</td>
<td>18 (ksi) (140MPa)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>G2500</td>
<td>F10005</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G3000</td>
<td>F10006</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>......</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G6000</td>
<td>F10012</td>
<td>60 (ksi) (400MPa)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cheap to produce, excellent castability, high damping capacity, good metal-metal wear resistance when lubricated, strength much higher in compression than in tension, brittle in tension.
Malleable Cast Iron

• If we heat white CI above its critical line, normally between 900 to 1000°C for 20 hours we’ll make the carbide convert to graphite,

• and it will produce a rough clump of graphite, kind of between a flake and a nodule (agglomerate), - malleable CI

• These cast irons are stronger, tougher and much more ductile than grey irons, compatible to nodular irons.

• They have certain capacity to take shock loading, bending and tension. They are suitable for castings of thin thickness.

• They are expensive to produce, largely due to the heat treatment.

• Typical applications include gear box casing, transmission casing, differential casing.

<table>
<thead>
<tr>
<th>ASTM</th>
<th>UNS</th>
<th>Yield strength</th>
<th>Ductility</th>
</tr>
</thead>
<tbody>
<tr>
<td>32510</td>
<td>F32510</td>
<td>32.5 (ksi)</td>
<td>10</td>
</tr>
<tr>
<td>......</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35018</td>
<td>F36200</td>
<td>35</td>
<td>18</td>
</tr>
</tbody>
</table>
Nodular or Ductile Cast Irons

• we add some magnesium or rare elements to the molten liquid just before casting (inoculation)
• and do things as we did with the gray CI
• we can produce nodular or ductile CI.
• We will produce nodules of graphite instead of flakes,
• but as before we can end up with a matrix of either ferrite or pearlite.
• These irons are much stronger and tougher than grey irons.
• They are produced and used for high specification applications.
• They are more expensive than grey irons. Typical applications include: gears, crankshafts, pump bodies, pressure valves, rollers.
• we had austenite, just like we had in steels,
• so if we quench it we get martensite, as long as we have enough hardenability.
• We can do the same thing with any of the CI types.
• In fact, austempered ductile iron (ADI) is very popular for many applications.
• That would have a bainitic microstructure.

**Nodular Irons** (ductile irons)

<table>
<thead>
<tr>
<th>ASTM</th>
<th>UNS</th>
<th>Tensile</th>
<th>Yield</th>
<th>Ductility</th>
</tr>
</thead>
<tbody>
<tr>
<td>60-40-18</td>
<td>F32800</td>
<td>60 (ksi)</td>
<td>40</td>
<td>18</td>
</tr>
<tr>
<td>.......</td>
<td>.......</td>
<td>.......</td>
<td>.......</td>
<td>.......</td>
</tr>
<tr>
<td>120-90-02</td>
<td>F36200</td>
<td>120</td>
<td>90</td>
<td>2</td>
</tr>
</tbody>
</table>
Hierro Fundido Maleable – Ferrítico y Perlítico

Hierro Fundido Nodular
Gray cast iron
Nodular (ductile)

White iron
Malleable

Graphite flakes in an $\alpha$-ferrite matrix

Graphite in an $\alpha$-ferrite matrix

Damping vibration energy

Pearlite

White cementite

Si (1–3%)
Table 12.5  Designations, Minimum Mechanical Properties, Approximate Compositions, and Typical Applications for Various Gray, Nodular, and Malleable Cast Irons

<table>
<thead>
<tr>
<th>Grade</th>
<th>UNS Number</th>
<th>Composition (wt%)</th>
<th>Matrix Structure</th>
<th>Mechanical Properties</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tensile Strength [MPa (ksi)]</td>
<td>Yield Strength [MPa (ksi)]</td>
</tr>
<tr>
<td>SAE G1800</td>
<td>F10004</td>
<td>3.40–3.7 C, 2.55 Si, 0.7 Mn</td>
<td>Ferrite + Pearlite</td>
<td>124 (18) --</td>
<td>--</td>
</tr>
<tr>
<td>SAE G2500</td>
<td>F10005</td>
<td>3.2–3.5 C, 2.20 Si, 0.8 Mn</td>
<td>Ferrite + Pearlite</td>
<td>173 (25) --</td>
<td>--</td>
</tr>
<tr>
<td>SAE G4000</td>
<td>F10008</td>
<td>3.0–3.3 C, 2.0 Si, 0.8 Mn</td>
<td>Pearlite</td>
<td>276 (40) --</td>
<td>--</td>
</tr>
</tbody>
</table>

**Ductile (Nodular) Iron**

<table>
<thead>
<tr>
<th>ASTM A536 60-40-18</th>
<th>UNS Number</th>
<th>Composition (wt%)</th>
<th>Matrix Structure</th>
<th>Mechanical Properties</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F32800</td>
<td>3.5–3.8 C, 2.0–2.8 Si, 0.05 Mg, &lt;0.20 Ni, &lt;0.10 Mo</td>
<td>Ferrite</td>
<td>414 (60) 276 (40)</td>
<td>18</td>
</tr>
<tr>
<td>100-70-03</td>
<td>F34800</td>
<td></td>
<td>Pearlite</td>
<td>689 (100) 483 (70)</td>
<td>3</td>
</tr>
<tr>
<td>120-90-02</td>
<td>F36200</td>
<td></td>
<td>Tempered martensite</td>
<td>827 (120) 621 (90)</td>
<td>2</td>
</tr>
</tbody>
</table>

**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              |           | 2.4–2.7 C, 1.25–1.55 Si, <0.55 Mn | Ferrite + Pearlite | 448 (65) 310 (45) | 6 |                                          |

* Note: The balance of the composition is iron.

Fabrication of Commercial Cast irons

Heat treatment to control the carbon morphology
Nonferrous Metals

- **NOT** iron (Fe) based
- Increasing importance in modern technology
- Typically more costly per pound than iron or steel
- Inferior strength to that of steel
- **Key properties: Examples**
  - Al and its alloys - lighter, thermal conductor
  - Mg and its alloys – the lightest metal
  - Cu and its alloys – electric conductor
  - Ni and its alloys – High temperature alloys
  - Ti and its alloys – light metal
  - Zn and its alloys – low melting point, easily injected
  - Lead and Tin – lower low melting points
  - Refractory metals
  - Precious metals
Copper

- Backbone of the electrical industry
- Major metal in a number of engineering alloys
- High conductivity and ductility
- Pure copper $\Rightarrow$ tensile strength 30 ksi
- Easily casted, machined and welded
- ETP and OFHC $\Rightarrow$ base for alloys & electrical applications

Classification of Copper

- Copper Development Association (CDA)
  - numbers 100 to 190 are copper with < 2% alloy addition
  - numbers 200 to 799 are wrought copper alloys
  - numbers 800 to 900 are copper casting alloys
- Hardness: as rolled, 1/4 hard, 1/2 hard, full hard, spring
Copper

Copper: tough pitch copper, deoxidized low-phosphorous copper, oxygen-free high-conductivity copper

Copper alloys: soft and ductile, easy cold work.

Brasses (Cu, Zn): $\alpha + \beta'$ (BCC)

CDA260 … Cartridge Brass, best combination of strength and ductility, deep drawing is a popular use
Poor cold working properties
Good hot working properties
Radiator, jewelry, musical instruments, etc..

Bronzes (Cu, Sn, Al, Si, Ni)

CDA521 … Phosphorus Bronze - Good strength, toughness and wear resistance.
Ex. pump parts, bearings and gears are a popular use

Solubility of Sn: 15.8% @ 520°C, ~ 0 at room temp.
Large atom, slow diffusion, easier ppt hardening
Monel (65%Ni), Corson (Cu-Si-Si)
Copper-Nickel
- High Thermal conductivity, high-temp strength
- Applications: heat exchangers, cookware, coins

Copper-Aluminum
- “Aluminum-Bronze” - high strength and corrosion resistance
- Application: marine hardware

Copper-Silicon
- “Silicon-Bronze”
- Good strength, formability, machinability, corrosion resistance
- Applications: boiler tank and stove application

Copper-Beryllium
- Highest strengths of Cu based alloys - Beryllium coppers: precipitation hardenable, Tensile strength: 1400MPa
- Applications: non-spark and plastic injection molds
- Toxic at elevated temperatures
Aluminum

- Aluminum 2\textsuperscript{nd} to steel in quantity and usage
- Most important of the non-ferrous metals
- Good thermal and electrical conductivity
- Lightweight and low stiffness
- Good corrosion resistance
- Pure aluminum
  - soft, ductile, and not strong
- Easily casted, machined and formed
- Not easily welded
Mechanical Applications of Al
  - alloying can increase strength by a factor of 30
  - increasing automotive applications

Corrosion Resistance of Al and Al Alloys
  - pure Al readily oxidizes forming an oxide coating resistant to many corrosive environments
  - alloying decreases corrosion resistance
  - corrosion resistance is a property of the surface oxide
  - special preparation prior to welding
Classification of Al

• 2 Major Groups
  – Wrought Alloys
  – Casting Alloys

• 4 digit designation system
  – 1\text{st} digit ⇒ major alloy element
  – 2\text{nd} digit ⇒ special control of impurities
  – 3\text{rd} & 4\text{th} digits
    • 1xxx series ⇒ nearest 1/100th % of aluminum
    • 2xxx to 8xxx series ⇒ alloy number
Aluminum alloys: soft and ductile, easy cold work.

1xxx…8xxx

Last two digits: purity

F: as fabricated
H: strain hardened
O: annealed
T: heat treated
T3: solution heat treated

Table 12.7 Compositions, Mechanical Properties, and Typical Applications for Several Common Aluminum Alloys

<table>
<thead>
<tr>
<th>Aluminum Association Number</th>
<th>UNS Number</th>
<th>Composition (wt%)</th>
<th>Condition (Temp Designation)</th>
<th>Tensile Strength [MPa (ksi)]</th>
<th>Yield Strength [MPa (ksi)]</th>
<th>Ductility [%EL in 50 mm (2 in.)]</th>
<th>Typical Applications/Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1100</td>
<td>A91100</td>
<td>0.12 Cu</td>
<td>Annealed (O)</td>
<td>90 (13)</td>
<td>35 (5)</td>
<td>35–45</td>
<td>Food/chemical handling &amp; storage equipment, heat exchangers, light reflectors</td>
</tr>
<tr>
<td>3003</td>
<td>A93003</td>
<td>0.12 Cu, 1.2 Mn, 0.1 Zn</td>
<td>Annealed (O)</td>
<td>110 (16)</td>
<td>40 (6)</td>
<td>30–40</td>
<td>Cooking utensils, pressure vessels and piping</td>
</tr>
<tr>
<td>5052</td>
<td>A95052</td>
<td>2.5 Mg, 0.25 Cr</td>
<td>Strain hardened (T62)</td>
<td>230 (33)</td>
<td>195 (28)</td>
<td>12–18</td>
<td>Aircraft fuel &amp; oil lines, fuel tanks, appliances, rivets, and wire</td>
</tr>
<tr>
<td>2024</td>
<td>A92024</td>
<td>4.4 Cu, 1.5 Mg, 0.6 Mn</td>
<td>Heat treated (T4)</td>
<td>470 (68)</td>
<td>325 (47)</td>
<td>20</td>
<td>Aircraft structures, rivets, truck wheels, screw machine products</td>
</tr>
<tr>
<td></td>
<td>A96061</td>
<td>1.0 Mg, 0.6 Si, 0.3 Cu, 0.20 Cr</td>
<td>Heat treated (T4)</td>
<td>240 (35)</td>
<td>145 (21)</td>
<td>22–25</td>
<td>Trucks, canoes, railroad cars, furniture, pipelines</td>
</tr>
<tr>
<td></td>
<td>A97075</td>
<td>5.6 Zn, 2.5 Mg, 1.6 Cu, 0.23 Cr</td>
<td>Heat treated (T6)</td>
<td>570 (83)</td>
<td>505 (73)</td>
<td>11</td>
<td>Aircraft structural parts and other highly stressed applications</td>
</tr>
<tr>
<td>295.0</td>
<td>A02950</td>
<td>4.5 Cu, 1.1 Si</td>
<td>Heat treated (T4)</td>
<td>221 (32)</td>
<td>110 (16)</td>
<td>8.5</td>
<td>Flywheel and rear-axle housings, bus and aircraft wheels, crankcases</td>
</tr>
<tr>
<td></td>
<td>A03560</td>
<td>7.0 Si, 0.3 Mg</td>
<td>Heat treated (T6)</td>
<td>228 (33)</td>
<td>164 (24)</td>
<td>3.5</td>
<td>Aircraft pump parts, automotive transmission cases, water-cooled cylinder blocks</td>
</tr>
<tr>
<td>2090</td>
<td>—</td>
<td>2.7 Cu, 0.25 Mg, 2.25 Li, 0.12 Zr</td>
<td>Heat treated, cold worked (T63)</td>
<td>455 (66)</td>
<td>455 (66)</td>
<td>5</td>
<td>Aircraft structures and cryogenic tankage structures</td>
</tr>
<tr>
<td>8090</td>
<td>—</td>
<td>1.3 Cu, 0.95 Mg, 2.0 Li, 0.1 Zr</td>
<td>Heat treated, cold worked (T651)</td>
<td>465 (67)</td>
<td>360 (52)</td>
<td>—</td>
<td>Aircraft structures that must be highly damage tolerant</td>
</tr>
</tbody>
</table>

*The balance of the composition is aluminum.

Wrought Alloys

- Temper Designations (p. 176)
- 2 Basic Types
  - Non-heat-treatable
  - Heat-treatable
- Cladding

Casting Alloys

- Low melting temp
- Aluminum Association designation system
  - 1st digit ⇒ alloy group
  - 2nd & 3rd digits ⇒ particular alloy or aluminum purity
  - decimal place ⇒ indicates product form (casting or ingot)
Aluminum-Lithium

• Emerging as an attractive Al alloy
• Attractive aerospace material
• Available in both wrought and cast forms
• Easily machined, formed, and welded
Magnesium (Mg)

- **Lightest** of the commercially important metals
- Weak in the pure state
- Density is .0628 lbs/in\(^3\) compared to steel .283 lbs/in\(^3\)
- Weak at temps above 200\(^\circ\) F
- Cost per unit volume is low
- high strength to weight ratio

**Classification system**

- 1 or 2 prefix letters
  - Largest alloying metals
- 2 or 3 numbers
  - Percentages of the two alloy elements in whole numbers
- Suffix letter denotes variations in base alloy
**Magnesium alloys:** $T_m = 651^\circ C$. Used at lower temperature only

sp. Weight = 1.7

HCP, soft, low modulus, stiff at room temp.

In atmosphere, good resistance to oxidation and corrosion! (Due to impurities)

**Good specific tensile strength**

**Case of laptop computers**

<table>
<thead>
<tr>
<th>ASTM Number</th>
<th>UNS Number</th>
<th>Composition (wt%)</th>
<th>Condition</th>
<th>Tensile Strength [MPa (ksi)]</th>
<th>Yield Strength [MPa (ksi)]</th>
<th>Ductility [% EL in 50 mm (2 in.)]</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wrought Alloys</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AZ31B</td>
<td>M11311</td>
<td>3.0 Al, 1.0 Zn, 0.2 Mn</td>
<td>As extruded</td>
<td>262 (38)</td>
<td>200 (29)</td>
<td>15</td>
<td>Structures and tubing, cathodic protection</td>
</tr>
<tr>
<td>HK31A</td>
<td>M13310</td>
<td>3.0 Th, 0.6 Zr</td>
<td>Strain hardened, partially annealed</td>
<td>255 (37)</td>
<td>200 (29)</td>
<td>9</td>
<td>High strength to 315$^\circ C$ (600$^\circ F$) Forgings of maximum strength for aircraft</td>
</tr>
<tr>
<td>ZK60A</td>
<td>M16600</td>
<td>5.5 Zn, 0.45 Zr</td>
<td>Artificially aged</td>
<td>350 (51)</td>
<td>285 (41)</td>
<td>11</td>
<td></td>
</tr>
</tbody>
</table>

| 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 Die castings requiring good creep resistance |
| AS41A | M10410 | 4.3 Al, 1.0 Si, 0.35 Mn | As cast | 210 (31) | 140 (20) | 6 | |

*The balance of the composition is magnesium.*

Titanium alloys: $T_m = 1668^\circ C$ (Expensive)

- Extreme strong, 1400Mpa, high specific tensile strength
- But, high chemical reactivity with other materials
- Very good corrosion resistance at r.t.
- Good ductility, easily forged and machined

### Table 12.9 Compositions, Mechanical Properties, and Typical Applications for Several Common Titanium Alloys

<table>
<thead>
<tr>
<th>Alloy Type</th>
<th>Common Name (UNS Number)</th>
<th>Composition (wt%)</th>
<th>Condition</th>
<th>Tensile Strength [MPa (ksi)]</th>
<th>Yield Strength [MPa (ksi)]</th>
<th>Ductility [%EL in 50 mm (2 in.)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commerically pure</td>
<td>Unalloyed (R50500)</td>
<td>99.1 Ti</td>
<td>Annealed</td>
<td>484 (70)</td>
<td>414 (60)</td>
<td>25</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Ti-5Al-2.5Sn (R54520)</td>
<td>5 Al, 2.5 Sn, balance Ti</td>
<td>Annealed</td>
<td>826 (120)</td>
<td>784 (114)</td>
<td>16</td>
</tr>
<tr>
<td>Near $\alpha$</td>
<td>Ti-8Al-1Mo-1V (R54810)</td>
<td>8 Al, 1 Mo, 1 V, balance Ti</td>
<td>Annealed (duplex)</td>
<td>950 (138)</td>
<td>890 (129)</td>
<td>15</td>
</tr>
<tr>
<td>$\alpha-\beta$</td>
<td>Ti-6Al-4V (R56400)</td>
<td>6 Al, 4 V, balance Ti</td>
<td>Annealed</td>
<td>947 (137)</td>
<td>877 (127)</td>
<td>14</td>
</tr>
<tr>
<td>$\alpha-\beta$</td>
<td>Ti-6Al-6V-2Sn (R56620)</td>
<td>6 Al, 2 Sn, 6 V, 0.75 Cu, balance Ti</td>
<td>Annealed</td>
<td>1050 (153)</td>
<td>985 (143)</td>
<td>14</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Ti-10V-2Fe-3Al</td>
<td>10 V, 2 Fe, 3 Al, balance Ti</td>
<td>Solution + aging</td>
<td>1223 (178)</td>
<td>1150 (167)</td>
<td>10</td>
</tr>
</tbody>
</table>

**Typical Applications**

- Jet engine shrouds, cases and airframe skins, corrosion-resistant equipment for marine and chemical processing industries
- Gas turbine engine casings and rings; chemical processing equipment requiring strength to temperatures of 480°C (900°F)
- Forgings for jet engine components (compressor disks, plates, and hubs)
- High-strength prosthetic implants, chemical-processing equipment, airframe structural components
- Rocket engine case airframe applications and high-strength airframe structures
- 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