Mat E 272 Lecture 21:
Precipitation hardening, metalworking, steel classification, non-ferrous metals

November 15, 2001

Introduction:

We previously learned about three approaches for strengthening metals; solid solution hardening, cold working (or strain hardening), and grain size refinement. Today, we will learn about a fourth technique, precipitation hardening. While not applicable to every alloy system (and that is an important point), it does offers a convenient and easily controlled mechanism to exploit the temperature dependence of solid solubility in a certain class of systems.

We will also review the most commonly-used methods for casting and forming metals, and discuss the AISI/SAE designation for steels. Finally, we will conclude the metals portion of the course by examining several non-ferrous alloy systems and their applications.

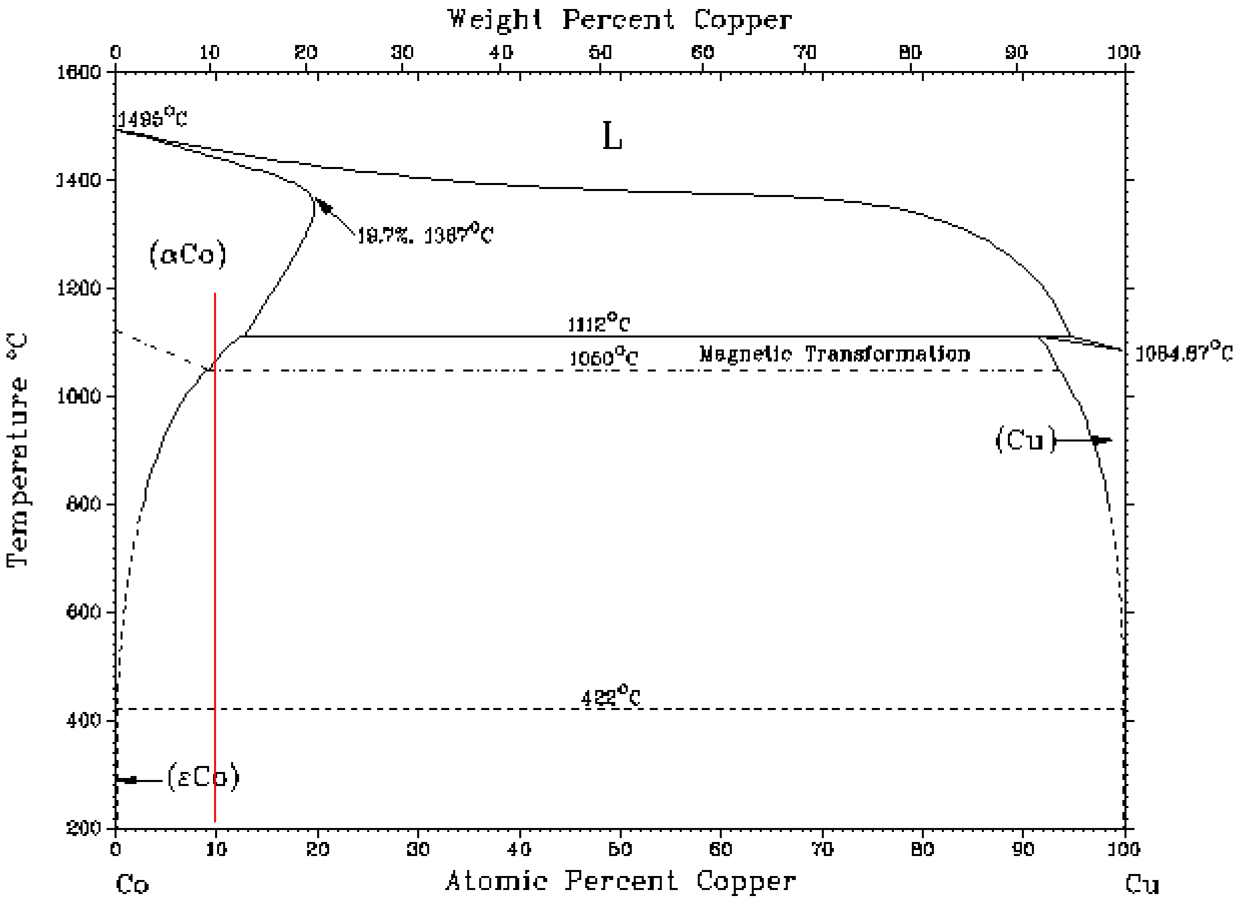
.

Precipitation hardening

Theory:

Consider the Co-Cu binary phase diagram, shown on the right. At equilibrium, (after what we call a solution heat treatment) a composition of 10 atomic % Cu in Co at 1200°C corresponds to a single phase alloy.

If the alloy is slowly cooled (under equilibrium conditions), Cu precipitates will nucleate and grow, mostly within the α-Co grain boundaries. Precipitation occurs because at this composition, the α-Co alloy below 1100°C becomes *supersaturated* with Cu atoms. The lattice strain caused by so many Cu atoms becomes too great, and the excess Cu is rejected "*out of solution*."

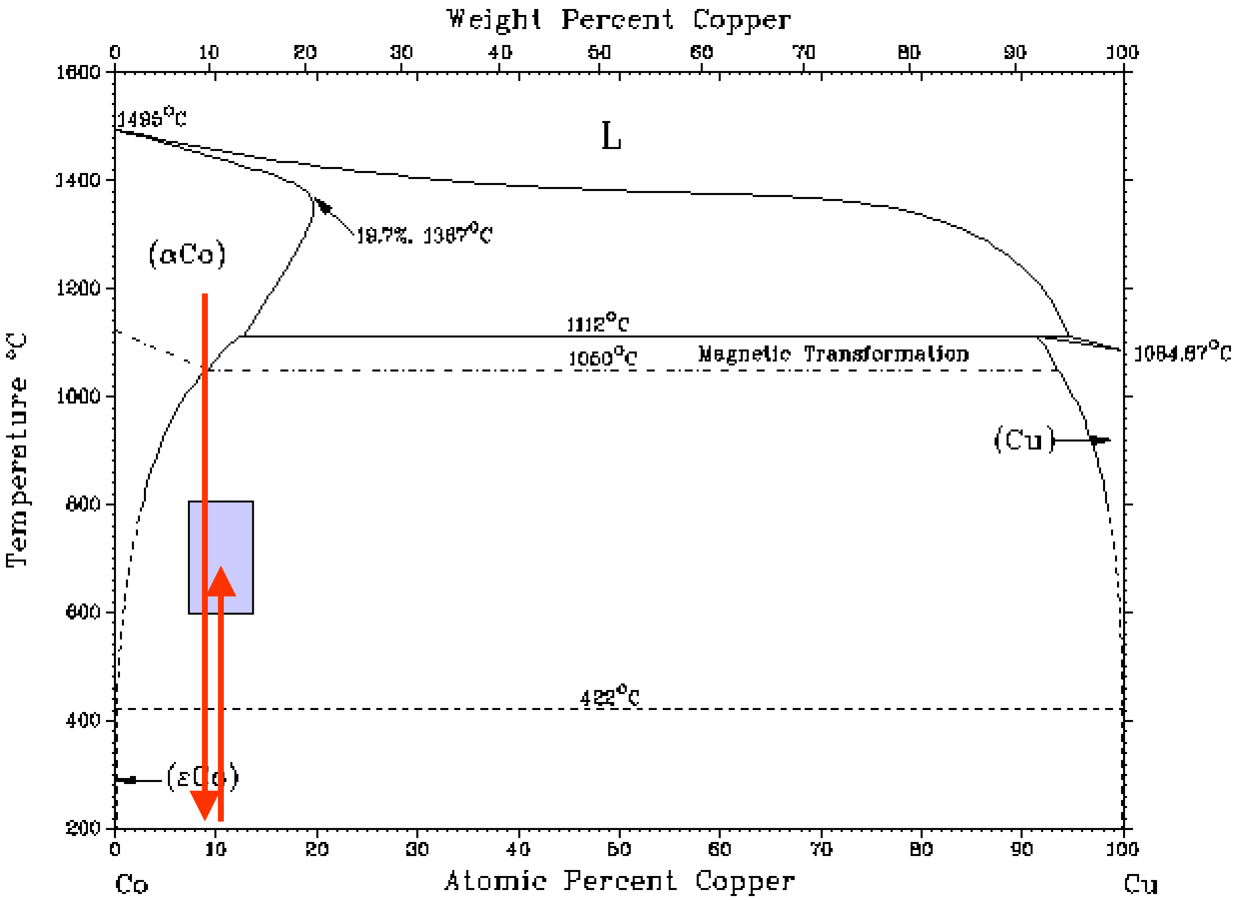


Precipitation hardening

Theory:

After equilibrium cooling, the Cu precipitates will be “large” (by microstructural standards), perhaps on the order of a few microns in size, and concentrated mostly in the grain boundaries. (Such artifacts are ineffective at strengthening metals; dislocations are pinned more readily as the precipitate radius decreases.)

Suppose the alloy shown at right is *quenched* from 1200°C. The Cu atoms remain in solution, although the lattice is now highly strained and unstable. If we then *re-heat* to a moderate temperature within the 2-phase region, say, 600 to 800°C, diffusion rates become appreciable and the Cu begins to precipitate out of solution, initially forming extremely small zones.



Precipitation hardening

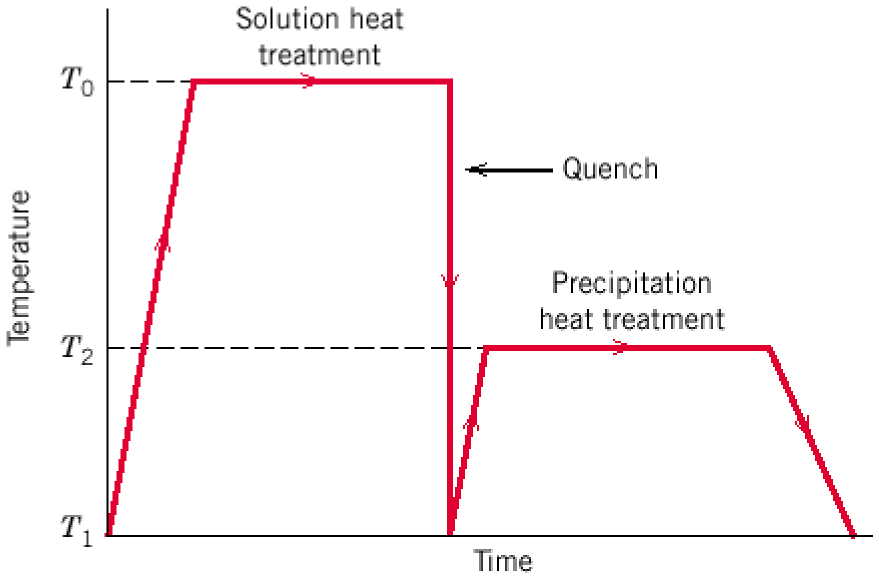
Theory:

During the precipitation heat treatment within the two phase region, the Cu precipitates grow, a process called *aging*.

(Some precipitates form even at room temperature, which is called natural aging. 2017 Al provides an example of natural aging - it precipitation-hardens at room temperature and must be refrigerated until use.)

Precipitates, of the appropriate size, can be very effective at pinning dislocations, and consequently, strengthening the metal.

The precipitation heat treatment is required in order to control the nucleation and growth of the precipitate phase.



Schematic drawing illustrating a solution heat treatment (which puts all of the atoms in a single phase solution), the rapid quench (which "locks in" the supersaturated solution), and a precipitation heat treatment (which causes a controlled nucleation and growth of tiny precipitates within the matrix grains).

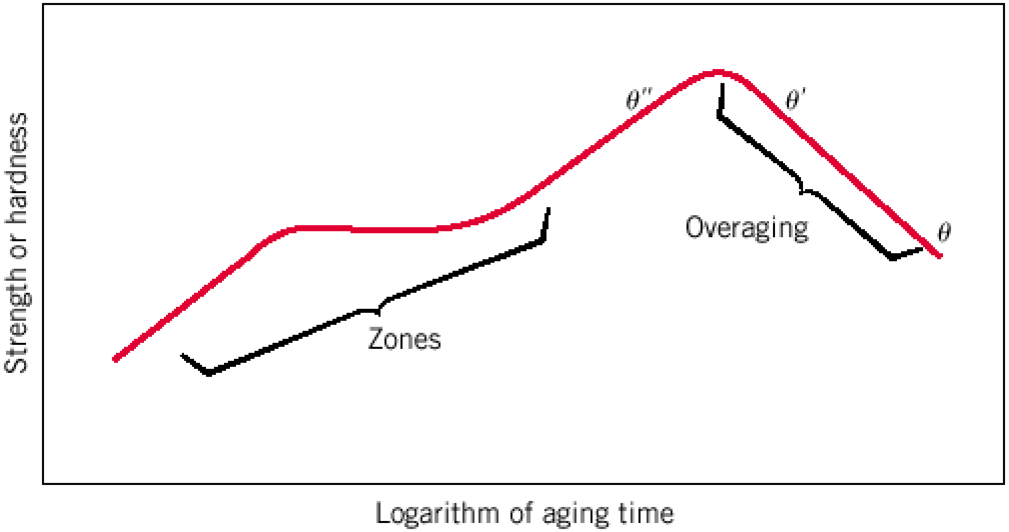
Precipitation hardening

Aging:

During the precipitation heat treatment, the size of the nuclei will continue to grow.

Initially, the precipitates start out as clusters of only a few atoms, then grow by diffusion to form 8 nm diameter by 0.5 nm thick zones. These zones were first discovered by Gunier and Preston in the 1930s, hence the name, G-P zones.

Upon continued heating, the G-P zones dissolve and a more well-defined precipitate phase forms, called θ". These are typically plates of thickness 2 nm and diameter 30 nm. The size of the θ" precipitate continues to increase, and eventually may develop a unique crystal structure.



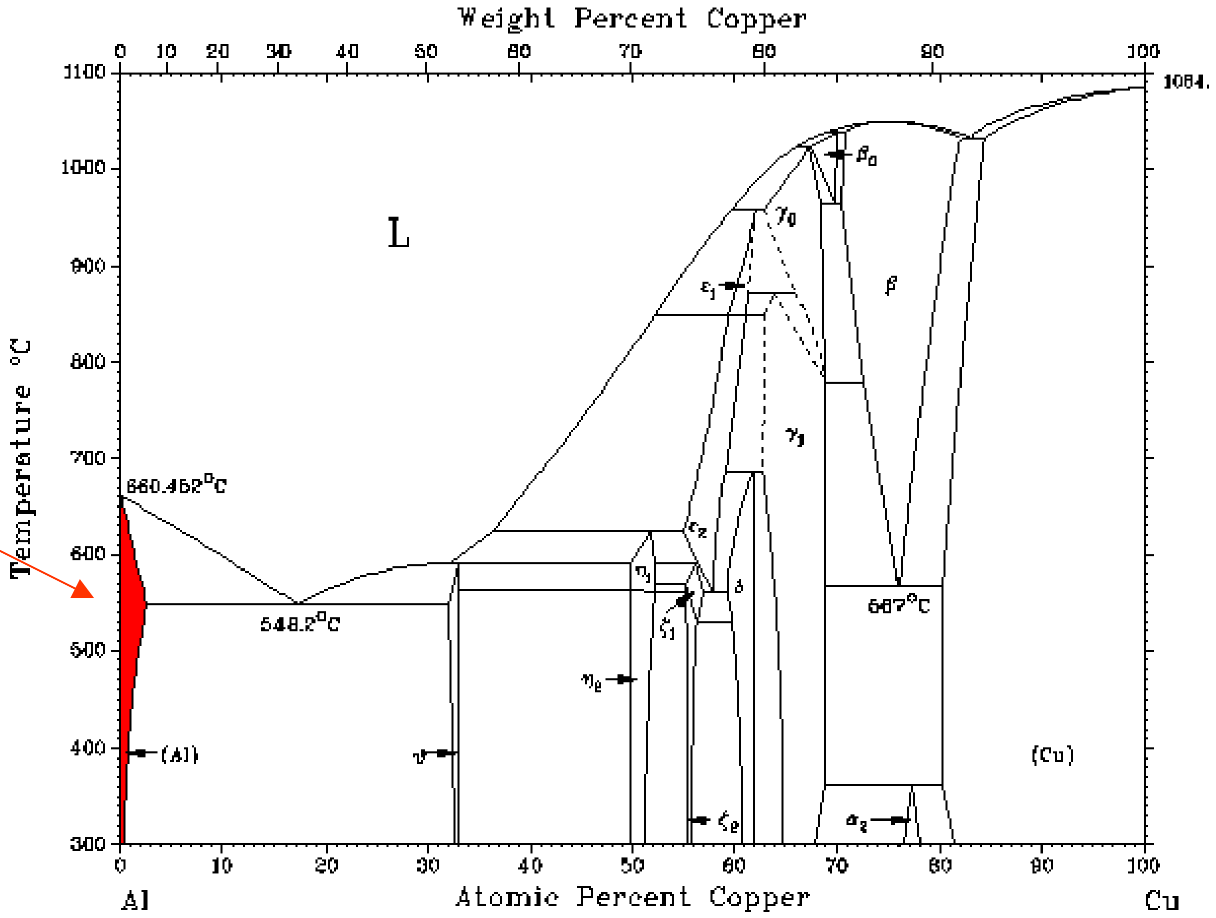
There is an optimum size for precipitates, in terms of interaction with dislocations. If the material is *precipitation heated* for too long a time, the precipitates become so large that they begin to loose their effectiveness at pinning dislocations, a phenomenon referred to as overaging.

Precipitation hardening

Example: Al-Cu

<u>Not all alloys are amenable to precipitation hardening</u>. There must exist a single phase terminal solid solution, in which the solubility limit (solvus) increases from room temperature up to some maximum. A good example is afforded by the Al-Cu system, shown at right.

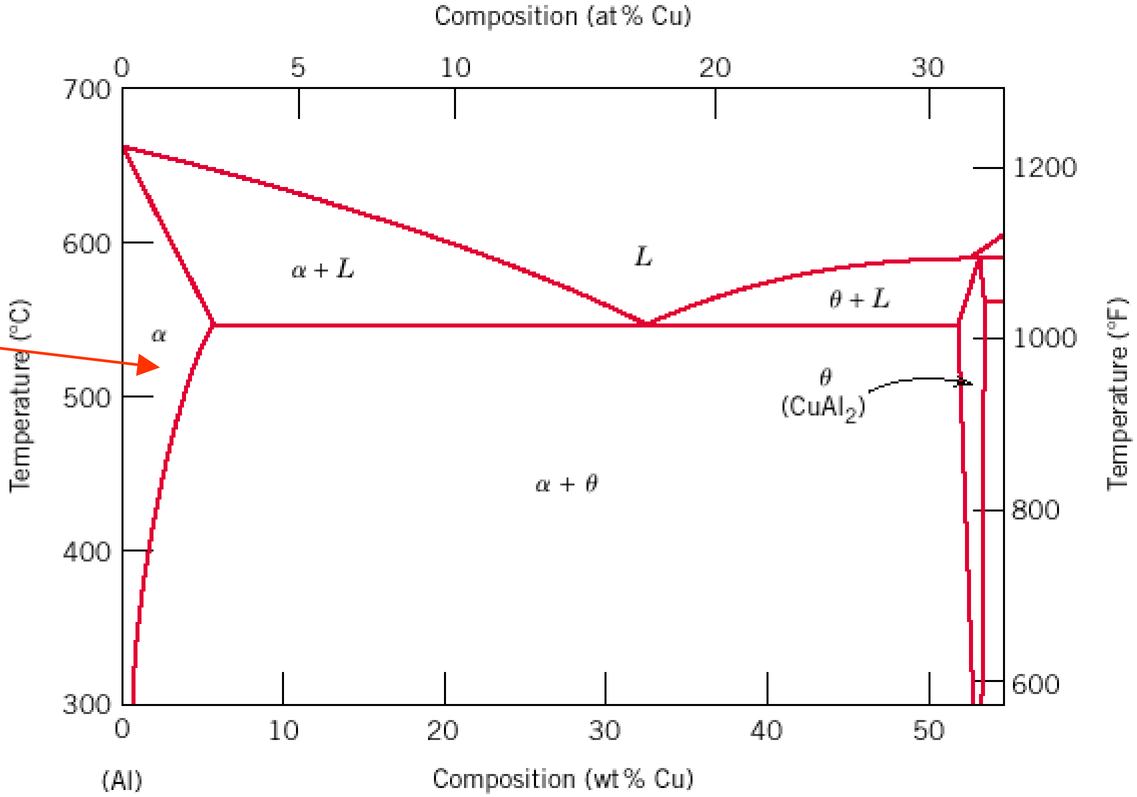
Note the single phase α region, highlighted in red. The phase diagram must exhibit this type of feature for precipitation hardening to work.



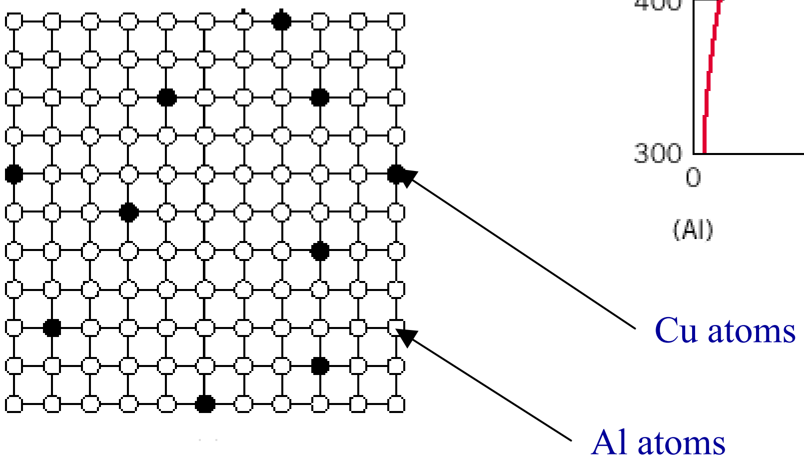
Precipitation hardening

Example: Al-Cu

Let’s take a closer look at the Al-rich portion of the Al-Cu phase diagram, where precipitation hardening is possible:



During the solution heat treatment, Cu atoms are randomly positioned on Al lattice sites (this is by definition of a single phase solid solution):

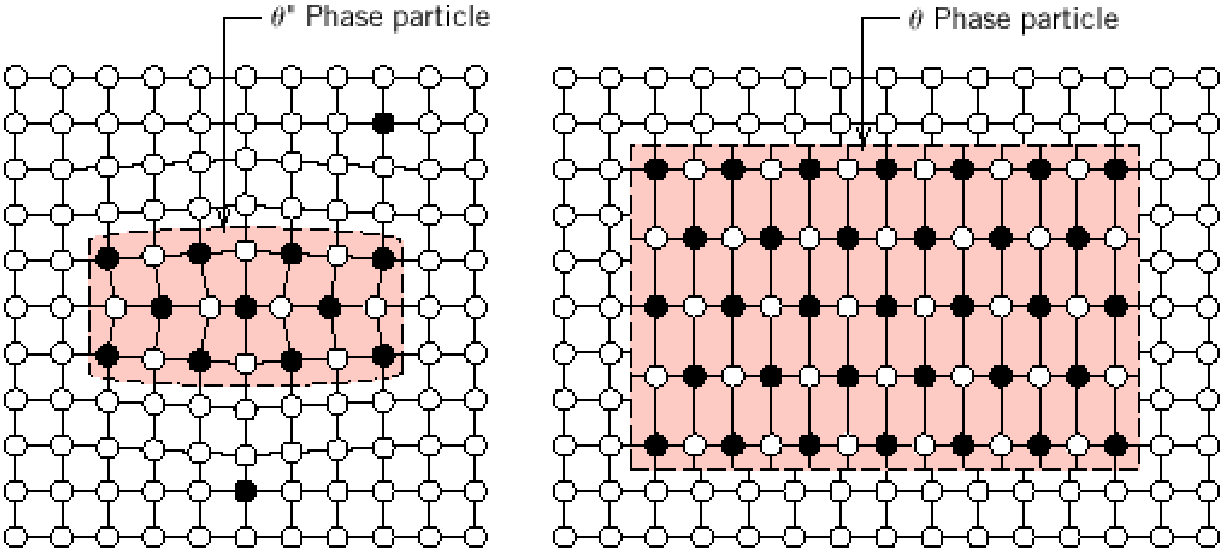


This arrangement of atoms is preserved upon quenching

Precipitation hardening

Upon aging, diffusion causes the Cu atoms to cluster, forming G-P zones. These zones eventually become θ" and finally the more stable θ precipitate.

Continued aging will cause the θ precipitates to grow, eventually becoming too large to effectively strengthen the metal.



Precipitation Hardening

Examples of alloy systems amenable to precipitation hardening:

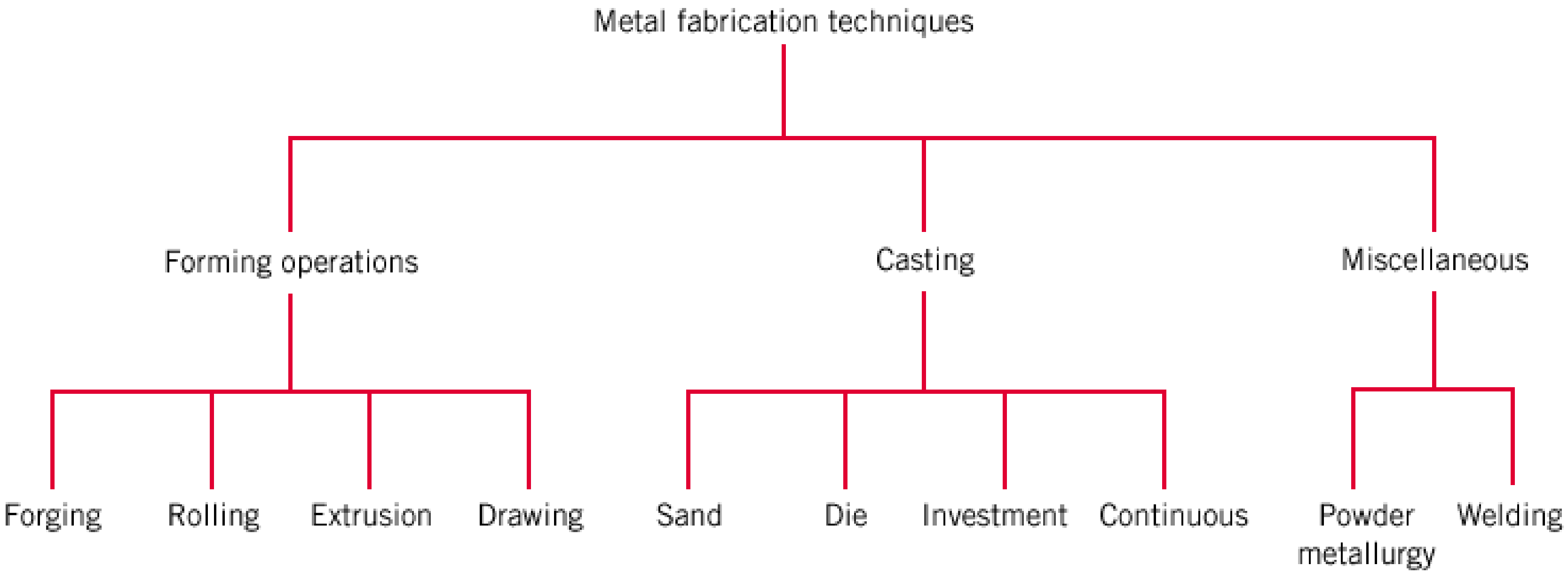
Aluminum:	Al-Ag
	Al-Cu
	Al-Zn-Mg
	Al-Mg-Si
	Al-Mg-Cu
Copper:	Cu-Be
	Cu-Co
Iron:	Fe-C
	Fe-N
Nickel:	Ni-Cr-Ti-Al

(after J. D. Verhoeven, Physical Metallurgy, copyright 1975, John Wiley & Sons)

Metal forming and casting

Introduction

Once an alloy is prepared, it must be formed or cast into a usable shape, and there are many different ways in which to accomplish this:



- Metal fabrication techniques
  - Forming operations
    - Forging
    - Rolling
    - Extrusion
    - Drawing
  - Casting
    - Sand
    - Die
    - Investment
    - Continuous
  - Miscellaneous
    - Powder metallurgy
    - Welding

Metal casting

Casting involves pouring liquid metal into a mold having the desired shape. Recall the simple example performed in class where molten solder was “cast” into an alumina mold. Casting is usually the preferred processing route when the end product is either large or brittle (or both). Casting is almost always the most economical solidification route.

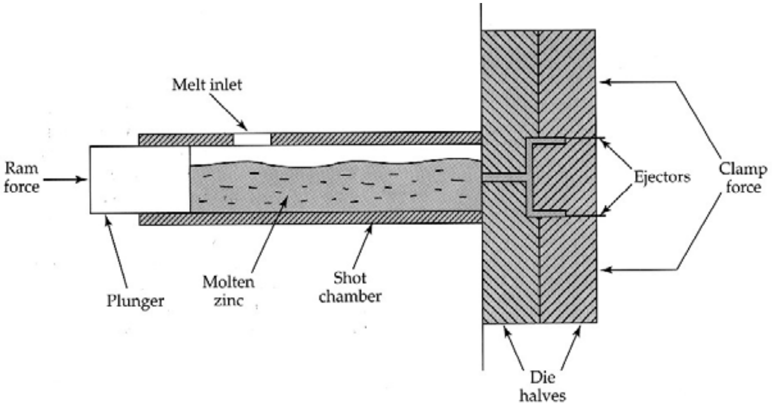
Sand casting:

Packed sand is used as the mold material. Large products such as fire hydrants and cylinder blocks are commonly fabricated using this approach. ‘Also used for particularly complex shapes and for cases in which a fine grain size is not critical. (sand is not a good thermal conductor; therefore, the rate of heat extraction from the ignot is low.)

Die casting:

Liquid metal (usually of a low melting temperature species) is forced into a *metal* mold under high pressure and solidifies while pressure is maintained. The mold consists of two pieces which clamp together; after solidification, the clamps are release and the part removed. Rapid casting rates are possible making this ideal for high throughput demands.

A typical “die-cast” set-up



Since metal molds are used, the cost of die casting is higher than that of sand casting. Consequently, this becomes economical when large numbers of parts, in the thousands, are required.

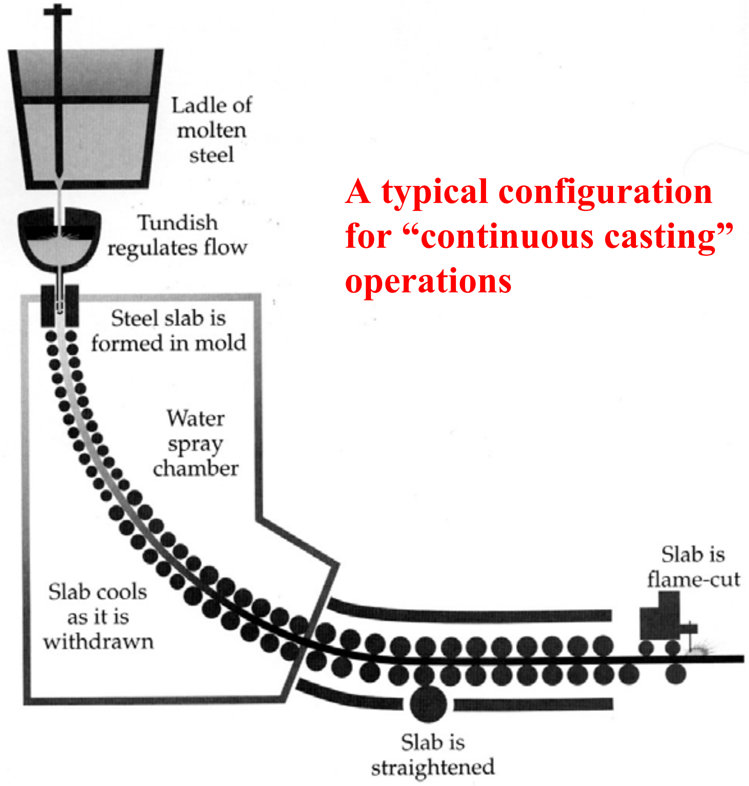
Metal casting (cont'd)

Investment casting:

Originated in antiquity; molds were produced by pressing clay around a pattern carved from beeswax. When the clay was "fired," the wax became liquid and ran out a small hole in the bottom of the clay. The result was a cavity ready to receive a molten metal charge. This method allows for a high degree of precision in dimension and is useful for fabricating components from very hard materials which cannot be shaped by forging or machining.

Continuous casting:

Used extensively in the fabrication of large-scale steel plates and slabs. Casting and rolling (a forming process) are combined into one continuous operation wherein the molten metal is cast into a continuous *strand*. The strand is subsequently cooled and shaped by passing through a series of rolling mills. The bulk of ordinary steel today is produced by continuous casting methods. A diagram of one type of continuous casting procedure, the curved mold method, is shown on the right.



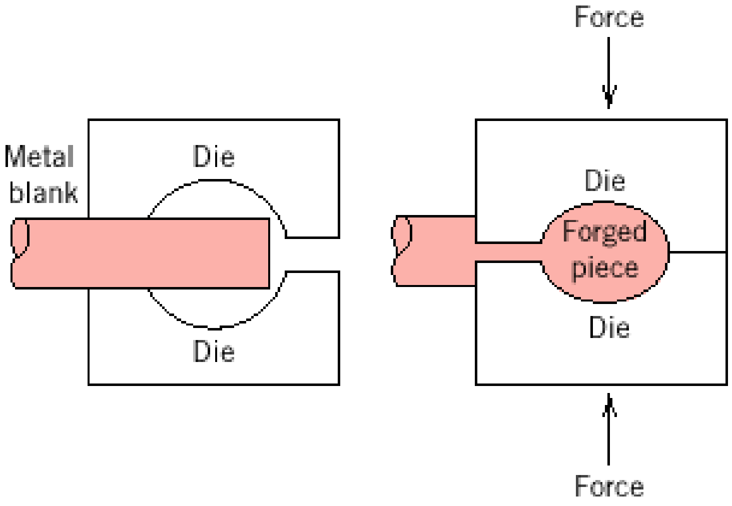
A typical configuration for "continuous casting" operations

Metal forming

Forging:

Mechanically working or deforming hot metal either by successive blows or by continuous squeezing.

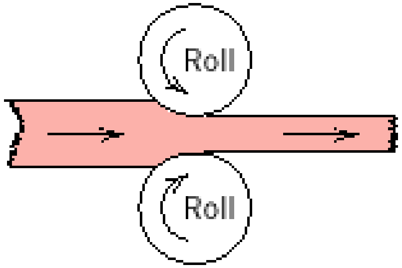
Forged parts usually have excellent mechanical properties (automotive crankshafts, piston connecting rods) (Hot pressing evolved out of forging.)



“Drop forging”

Hot rolling:

An ingot is fed between two rollers and is reduced in thickness to foil, sheet, plate, or strip form. Grooved rollers are used to make I-beams. Most metals are more malleable at high temperatures.

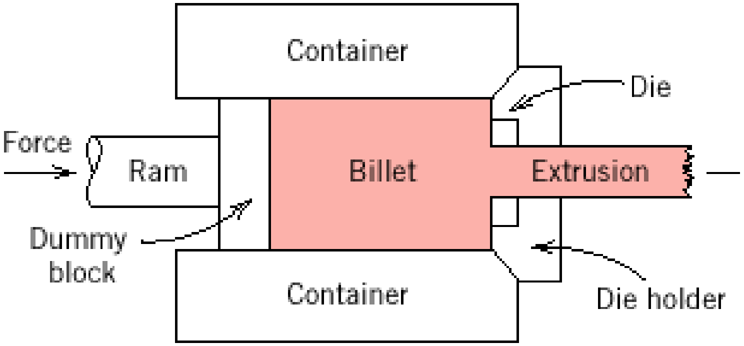


“Rolling”

Metal forming

Extrusion:

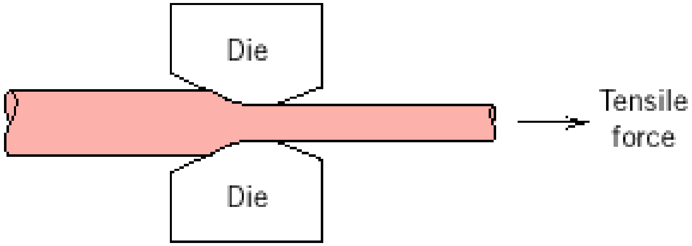
Solid metal bar is forced through a die orifice by a compressive force applied to a ram (not unlike the operation of a toothpaste tube). The cross sectional area of the die determines the final shape of the product. Both simple and complex shapes are possible. Tubes and rods are commonly formed in this manner.



"Extrusion"

Drawing:

Metal is pulled through a die (or series of dies), having a tapered bore which reduces the cross sectional area. Used in production of wire (also, rods and tubing).



"Drawing"

Classification system for steels

Background:

Because of the enormous variety of steels, an extensive alpha-numerical classification scheme was jointly devised by the American Iron and Steel Institute (AISI) and the Society of Automotive Engineers (SAE).

Starting with the 10XX series, the first digit ("1") indicates a plain carbon steel. The second digit indicates the presence or absence of a chemical additive to the alloy.

> 10XX indicates a plain carbon steel; the second digit (zero in this example) tells us that there is no chemical additive to this alloy. The last two digits specify the carbon content. For example SAE 1040 is a plain carbon steel where the "40" represent 0.40 % C.

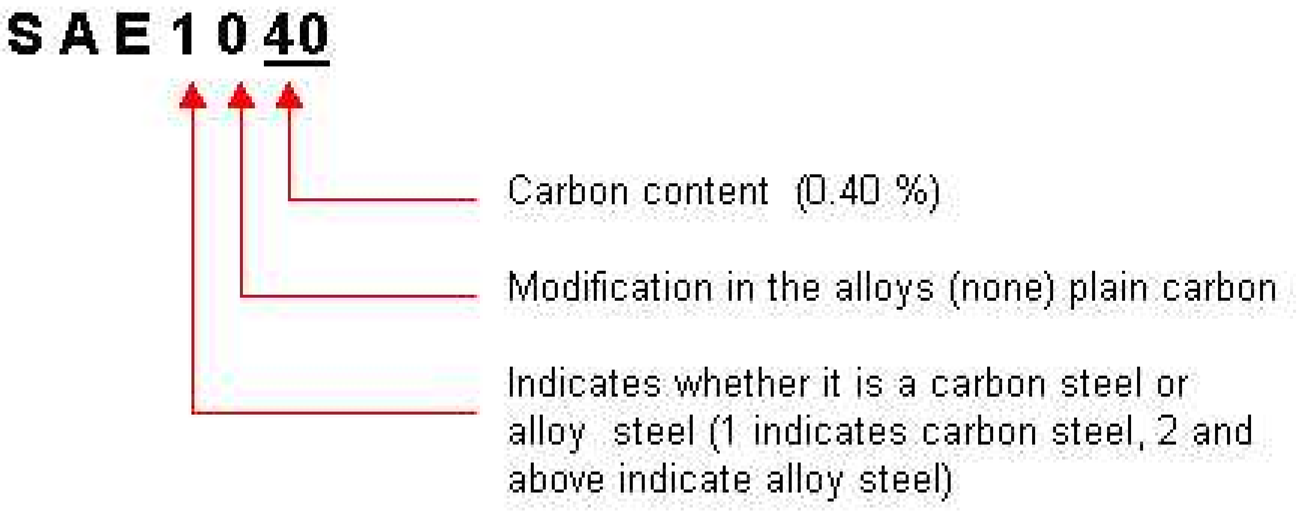
Alloy steels are denoted by 2XXX, 3XXX, 4XXX, etc. The AISI and SAE revised the percentages of the alloys to be used in the making of steel, retained the numbering system, and adding a letter prefix to indicate the *method* used in steel making. These prefixes are:

A = alloy, basic open hearth
B = carbon, acid Bessemer
C = carbon, basic open hearth
D = carbon, acid open hearth
E = electric furnace

(If the prefix is omitted, the steel is assumed to be open hearth.)
Example: AISI C1050 = plain carbon, basic-open hearth steel w/ 0.50 % C

Classification system for steels

Examples: (alloy steels)



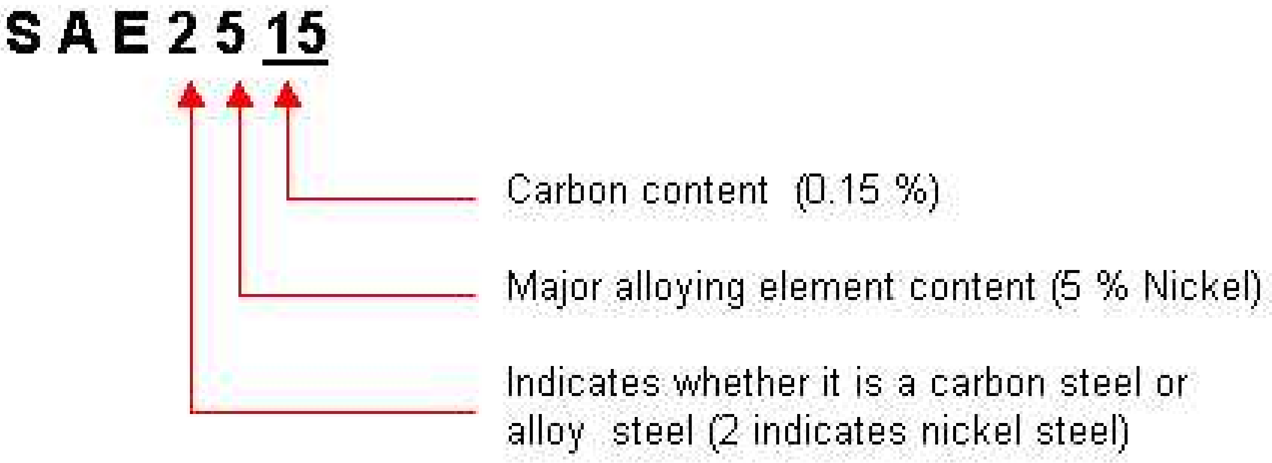
Carbon content (0.40 %)

Modification in the alloys (none) plain carbon

Indicates whether it is a carbon steel or alloy steel (1 indicates carbon steel, 2 and above indicate alloy steel)

Classification system for steels

Examples: (alloy steels)



SAE 2515

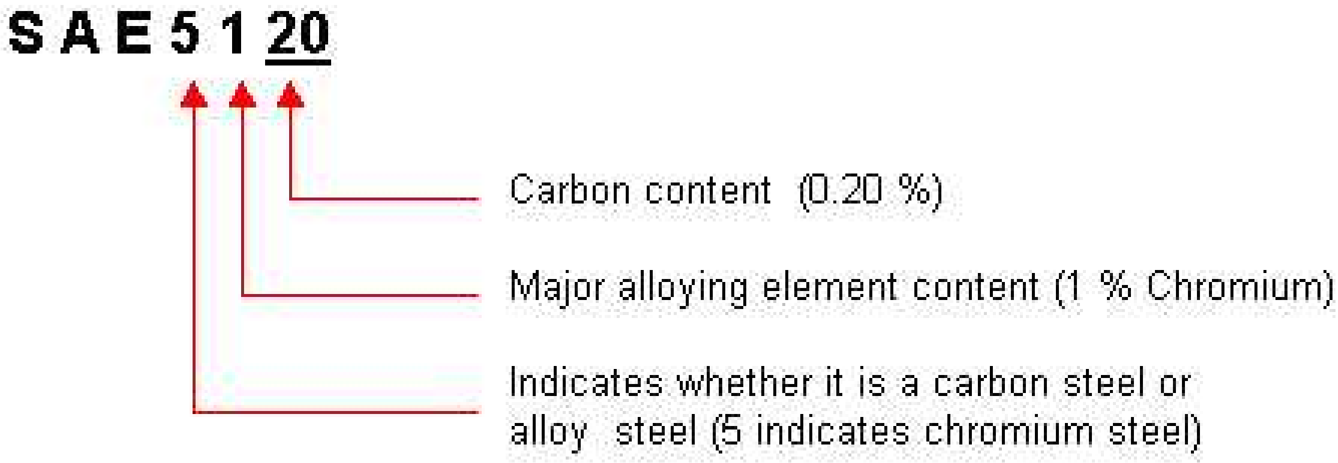
Carbon content (0.15 %)

Major alloying element content (5 % Nickel)

Indicates whether it is a carbon steel or alloy steel (2 indicates nickel steel)

Classification system for steels

Examples: (alloy steels)



S A E 5 1 20

Carbon content (0.20 %)

Major alloying element content (1 % Chromium)

Indicates whether it is a carbon steel or alloy steel (5 indicates chromium steel)

SAE - AISI Number	Classification
1XXX	**Carbon steels** Low carbon steels: 0 to 0.25 % C Medium carbon steels: 0.25 to 0.55 % C High carbon steels: Above 0.55 % Carbon
2XXX	**Nickel steels** 5 % Nickel increases the tensile strength without reducing ductility. 8 to 12 % Nickel increases the resistance to low temperature impact 15 to 25 % Nickel (along with Al, Cu and Co) develop high magnetic properties. (Alnicometals) 25 to 35 % Nickel offers resistance to corrosion at elevated temperatures.
3XXX	**Nickel-chromium steels** These steels are tough and ductile and exhibit high wear resistance , hardenability and resistance to corrosion.
4XXX	**Molybdenum steels** Molybdenum is a strong carbide former. It has a strong effect on hardenability and high temperature hardness. Molybdenum also increases the tensile strength of low carbon steels.
5XXX	**Chromium steels** Chromium is a ferrite strengthener in low carbon steels. It increases the core toughness and the wear resistnace of the case in carburized steels.
86XX 87XX 93XX 94XX 97XX 98XX	**Triple Alloy steels** which include Nickel (Ni), Chromium (Cr), and Molybdenum (Mo). These steels exhibit high strength and also high strength to weight ratio, good corrosion resistance.

What do the alloying additives do?

Aluminum	Ferrite hardener, Graphite former, Deoxidizer
Chromium	Mild ferrite hardener, Moderate effect on hardenability Graphite former, Resists corrosion, Resists abrasion
Cobalt	High effect on ferrite as a hardener, High hot hardness
Molybdenum	Strong effect on hardenability, Strong carbide former, High hot hardness, Increases abrasion resistance
Mangenese	Strong ferrite hardener, prevents hot shorts (see next slide)
Nickel	Ferrite strengthener, Increases toughness in hypoeutectoid steel With chromium, retains austenite, Graphite former
Copper	Austenite stabilizer, Improves resistance to corrosion
Silicon	Ferrite hardener, Increases magnetic properties in steel
Phosphorus	Ferrite hardener, Improves machinability, Increases hardenability

A word of caution -- “hot shorts”

Brittleness at high temperatures in steels is called hot-shortness, which is usually caused by sulfur.

When sulfur is present, iron and sulfur combine to form iron sulfide (FeS) that is usually concentrated at the grain boundaries and melts at temperatures below the melting point of steel. Due to the melting of iron sulfide, the cohesion between the grains is destroyed, allowing cracks to develop. This occurs when the steel is forged or rolled at elevated temperatures. In the presence of manganese, sulfur tends to form manganese sulfide (MnS) which prevents hot-shortness.

Stainless Steels

Stainless steel is a generic term for a family of corrosion resistant alloy steels containing at least 10.5% Cr. Corrosion resistance is attributable to a Cr-rich oxide film that forms on the surface of the steel. Although thin, this passivating oxide coating is highly tenacious and adheres to the metal, consequently, it offers excellent protection in a wide range of corrosive environments. The oxide is rapidly self healing in the presence of oxygen, and damage by abrasion, cutting or machining is quickly repaired.

In addition to Cr, Ni, Mo, Ti, Nb and other elements may be added to stainless steels in order to obtain a range of physical properties. All stainless steels fall into five basic categories:

- Austenitic
- Ferritic
- Martensitic
- Duplex
- Precipitation-hardened

Addition of Ni (on the order of 8%), stabilizes the FCC crystal structure against transformation to the low temperature BCC polymorph. Consequently, an *austenitic* crystal structure can be obtained (and stabilized) at ambient temperatures.

The most common composition of austenitic stainless steels is 18% Cr and 8% Ni. Of all stainless steels, the austenitic grades are the most widely used, accounting for more than 70% of production # 304 is the most common grade.

Ferritic stainless steels contain only Cr (12 - 18 %) (no Ni)

Fun Fact: Austenitic and Ferritic account for ~ 95% of all applications of stainless steel

Some Important non-Ferrous alloys

Nickel:

- corrosion resistance
- corrosion AND oxidation resistance when alloyed with Cr.
- high temperature oxidation and corrosion behavior when alloyed with Mn.
- resistance to heat when alloyed with Co.

Cobalt:

- used in many high value, “high performance” applications.
- Amenable to solid solution strengthening and precipitation hardening.
- Typically alloyed with Cr, Mo, or W, which all possess high melting temperatures
- frequently difficult to machine because of the ease with which alloys based on Co harden

Titanium:

- Combination of lightweight (low density), high melting temperature (1670°C), and high modulus (15.5×10^6 psi). Therefore, Ti-based alloys tend to be light and strong.
- High-Ti content alloys can be difficult to machine
- Excellent corrosion resistance at (and near) ambient temperature
- Ti-alloys find extensive use in the aerospace, petroleum, and chemical industries.

Some Important non-Ferrous alloys

Aluminum:

- low density
- high electrical conductivity
- high thermal conductivity
- good corrosion resistance
- high ductility (even to low temperatures)
- low melting temperature (660°C) precludes many high temperature applications
- can be strengthened by cold work and solid solution alloying
  (both of which DECREASE conductivity and corrosion resistance)

Al alloys are described by a four-digit classification scheme that indicates the major impurities. The numbering system designates the series as shown below:

Primary Alloying Element	Designation
99% Aluminum	1xxx
Cu	2xxx
Mn	3xxx
Si	4xxx
Mg	5xxx
Mg + Si	6xxx
Zn	7xxx

Some Important non-Ferrous alloys

Copper:

- Outstanding electrical and thermal conductor
- malleable and easy to cast and shape
- Copper and its alloys may assume a number of different names; two of the most common include:

Brasses (copper, zinc, lead)
Bronze (copper, tin, silicon, aluminum)