MATERIALS ENGINEERING
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Offered by:

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Nonferrous metals and their alloys

Content of this course

- Classification of nonferrous alloys
- Copper and its alloys
- Aluminum and its alloys
- Magnesium and its alloys
- Titanium and its alloys
- Nickel and its alloys

Textbooks referred to:

- Introduction to Physical Metallurgy – S. H. Avner
- Materials Science and Engineering an Introduction – W. D. Callister

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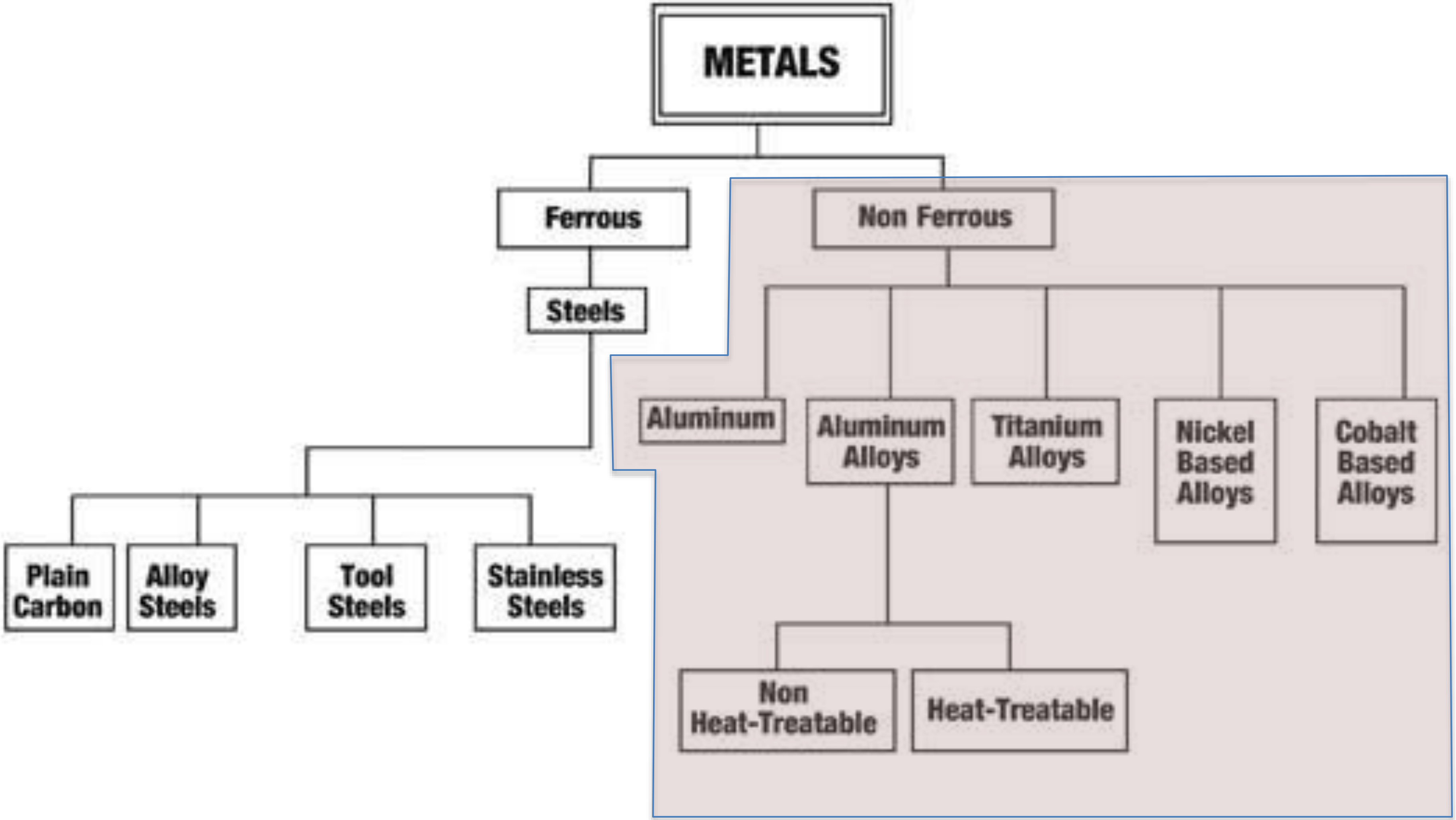
Classification of metallic materials



All metals other than iron are called non-ferrous metals

Nonferrous Alloys

- **Cu Alloys**

  Brass: Zn is subst. impurity (costume jewelry, coins, corrosion resistant)

  Bronze : Sn, Al, Si, Ni are subst. impurity (bushings, landing gear)

  Cu-Be: precip. hardened for strength

- **Al Alloys**

  -lower ρ: 2.7g/cm^3

  -Cu, Mg, Si, Mn, Zn additions

  -solid sol. or precip. strengthened (struct. aircraft parts & packaging)

- **Mg Alloys**

  -very low ρ: 1.7g/cm^3

  -ignites easily

  -aircraft, missiles

- **Ti Alloys**

  -lower ρ: 4.5g/cm^3 vs 7.9 for steel

  -reactive at high T

  -space applic.

- **Noble metals**

  -Ag, Au, Pt

  -oxid./corr. resistant

- **Refractory metals**

  -high melting T

  -Nb, Mo, W, Ta

NonFerrous Alloys

Some technologically important alloy systems will be discussed

Copper and its alloys

Important properties

Appearance: Red-metallic luster

Melting point: 1085 °C

Density: 8.96 g/cc

Crystal structure: FCC

CTE: 16.5×10^{-6} /°C

Thermal conductivity: 401 W/m.K

Young's modulus: 110 – 128 GPa

Shear modulus: 48 GPa

Copper and its alloys

- The most important properties of copper are high electrical and thermal conductivity, good corrosion resistance, machinability, strength and formability
- Moreover, copper is non-magnetic, has a pleasing colour and can be easily joined by welding/soldering/brazing
- Most copper used for electrical purposes contain > 99.9% copper and it is called Oxygen Free High Conductivity (OFHC) copper
- Some of the basic properties of copper can be improved by suitable alloying

Copper and its alloys

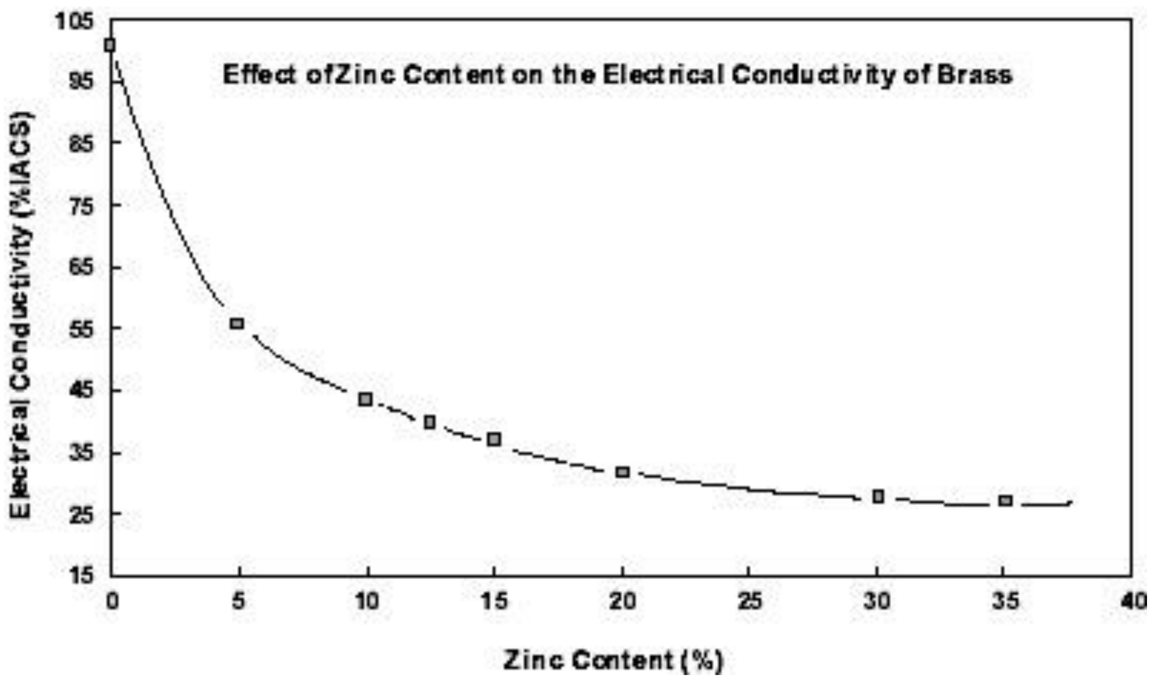
The important copper alloys can be classified as:

1. Brasses – alloys of copper and zinc
   a) Alpha brass – alloy containing upto 36 wt.% zinc
      i) Yellow alpha brass: 20-36 wt.% zinc
      ii) Red alpha brass: 5-20 wt.% zinc
   b) Alpha + beta brass – containing 54-62 wt.% copper
2. Bronzes – upto 12 wt.% of alloying element Tin/silicon/aluminum/beryllium
3. Cupronickel – alloys of copper and nickel

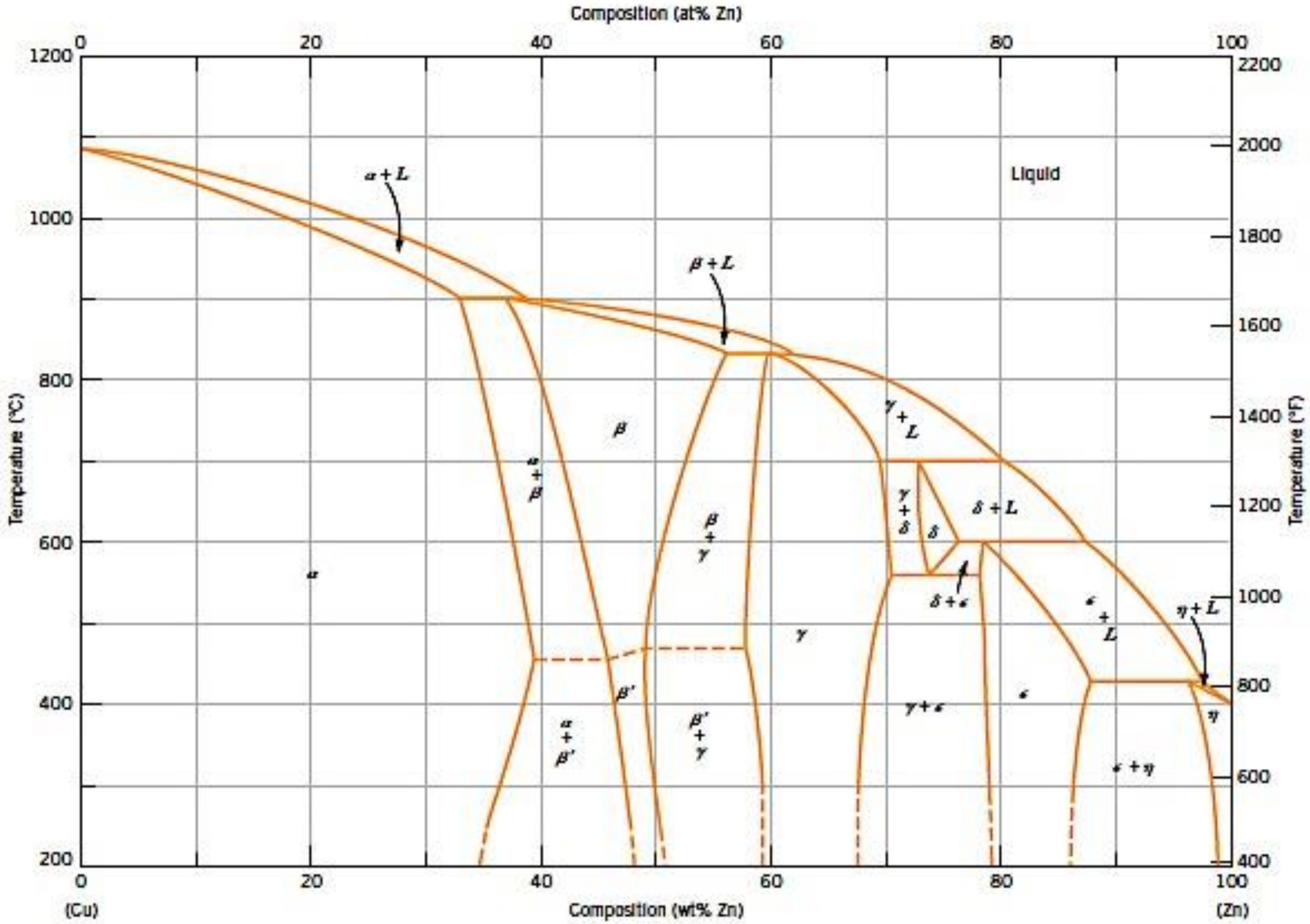
Brasses and tin bronzes will be briefly discussed in this course

Brasses: general

- Essentially alloy of copper with zinc with minor additions of Pb, Sn or Al to improve properties
- The addition of zinc in copper increases both its strength and ductility. The best combination of strength and ductility is obtained for 70Cu-30Zn brass
- Electrical conductivity of brass decreases with increasing zinc content



Brasses: Copper-zinc phase diagram



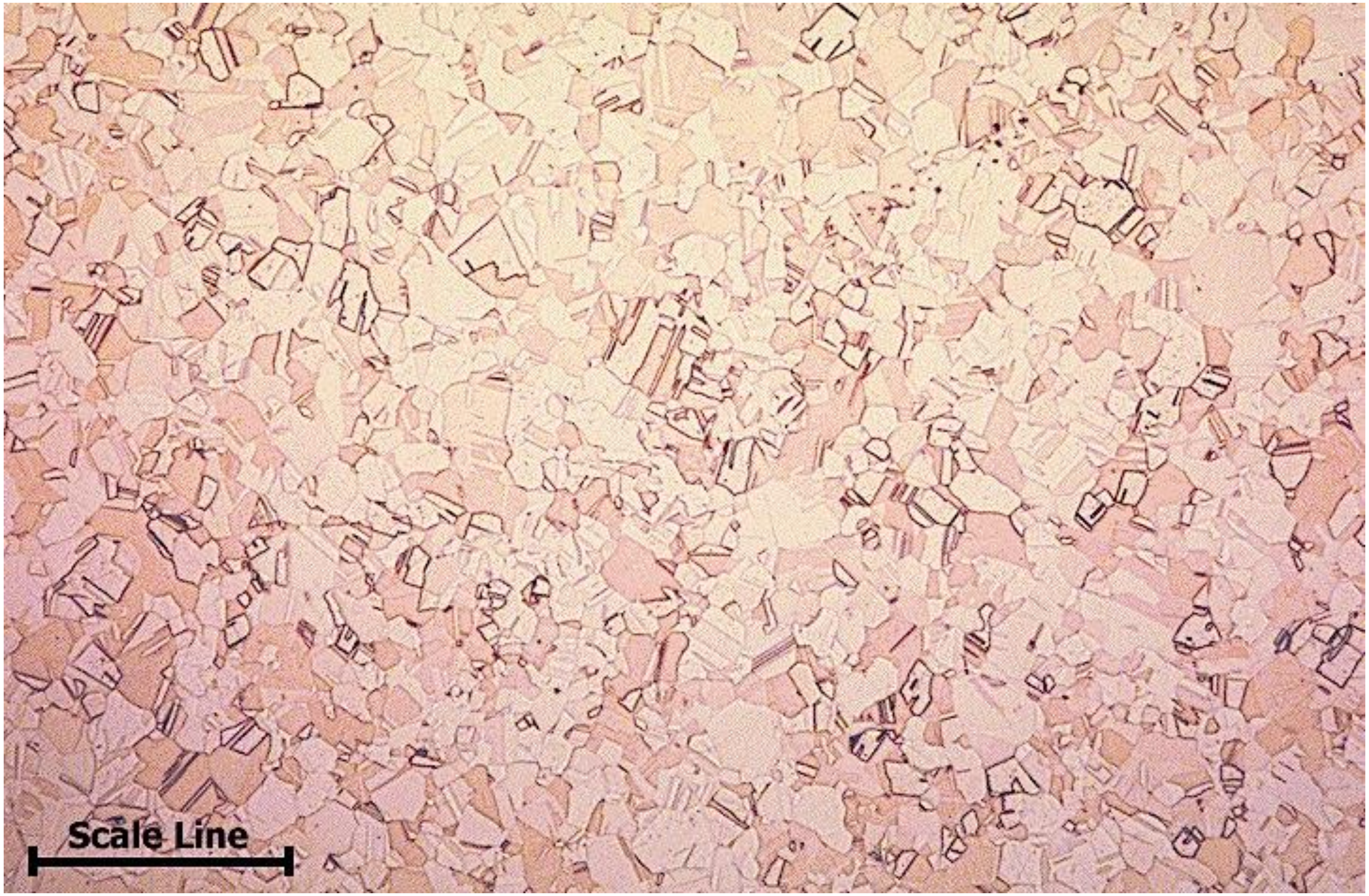
Brasses: Alpha brass

- Alpha brasses contain upto 36 wt.% zinc
- They possess relatively good corrosion resistance
- Colour of alpha brasses vary with zinc content – red at low zinc content to yellow at about 36 wt.% zinc
- Alpha brasses are classified into two groups – red alpha brasses and yellow alpha brasses

Brasses: Yellow alpha brass

- Yellow alpha brasses contain 20–36 wt.% zinc
- They combine good strength with high ductility and are therefore well suitable for cold rolling
- Residual stresses remaining after cold rolling make yellow brasses susceptible to stress corrosion cracking in ammonia atmosphere
- In contact with sea water, yellow alpha brasses are susceptible to pitting corrosion known as dezincification
- Typical applications include automotive radiator cores, rivets, springs, ammunition components etc.
- The addition of 0.5-3 wt.% lead improves the machinability significantly

Brasses: Yellow alpha brass

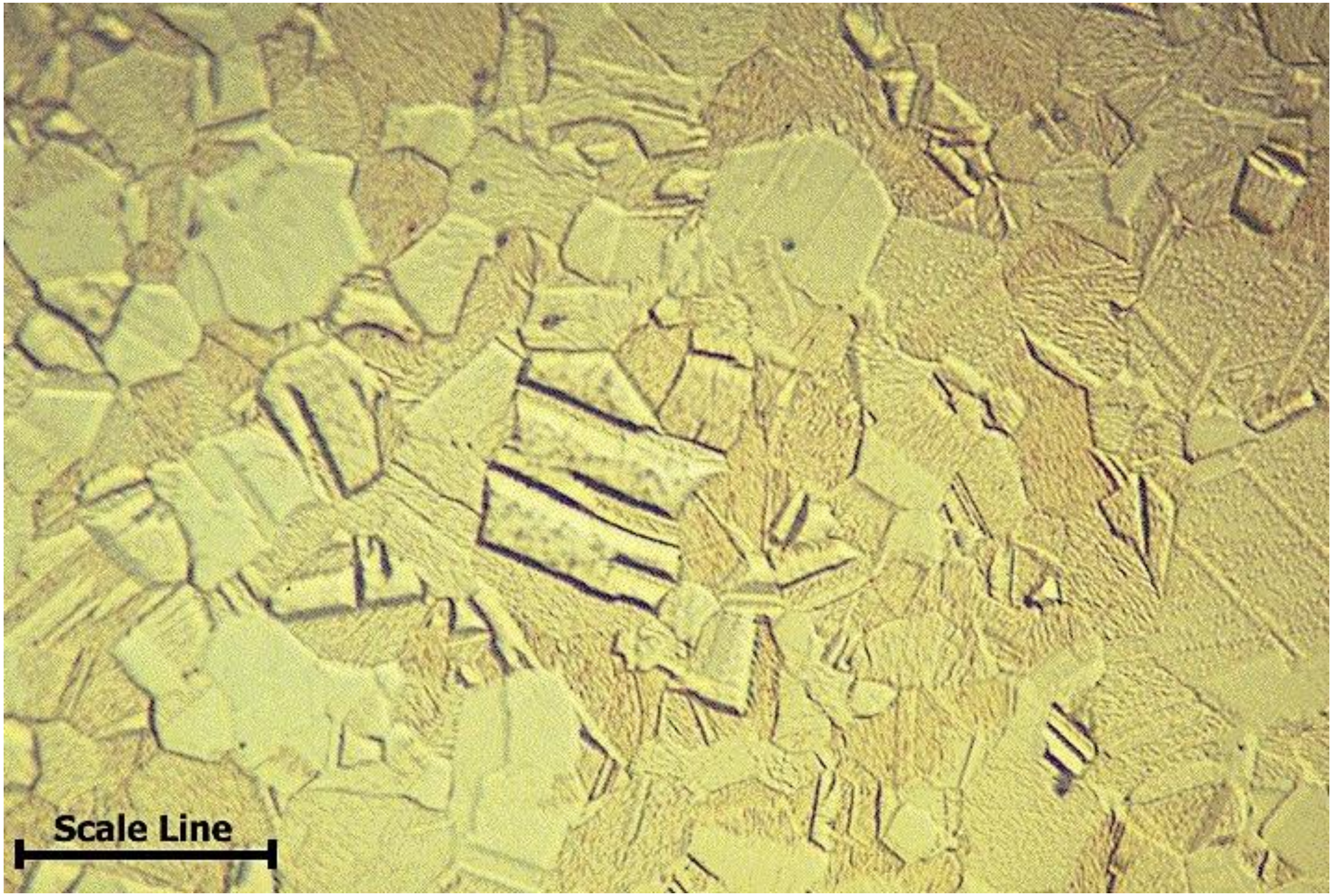


Microstructure of yellow alpha brass with nominal composition 70Cu-30Zn

Brasses: Red alpha brass

- Red brasses contain 5-20 wt.% zinc
- Red brasses have better corrosion resistance than yellow brasses and are not susceptible to stress corrosion cracking or dezincification
- Red brasses also possess excellent cold and hot working properties
- Typical applications include coins, medals, emblems, rivets and screws, sockets, heat exchanger tubes, musical instruments etc.

Brasses: Red alpha brass

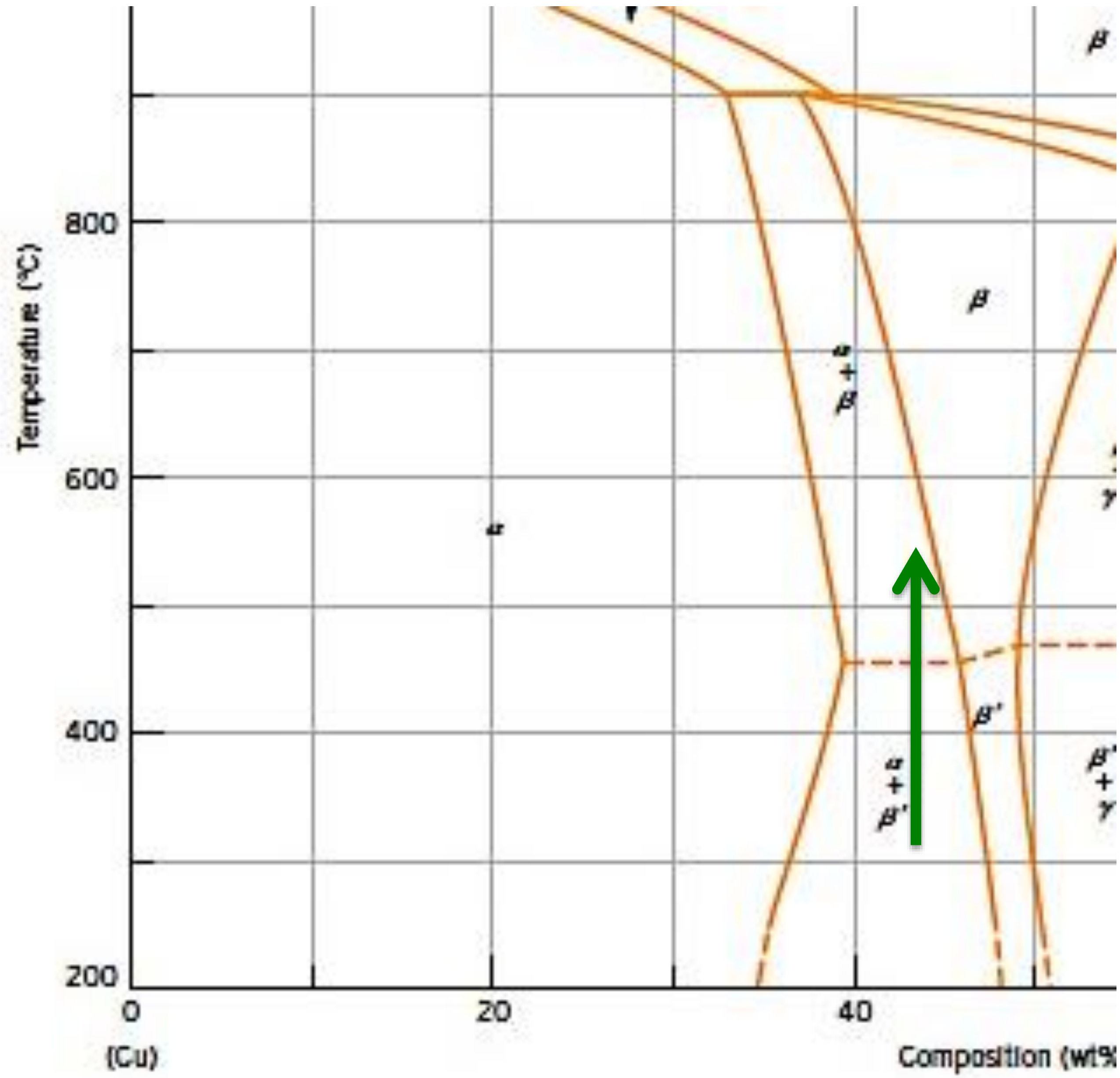


Microstructure of yellow alpha brass with nominal composition 85Cu-15Zn

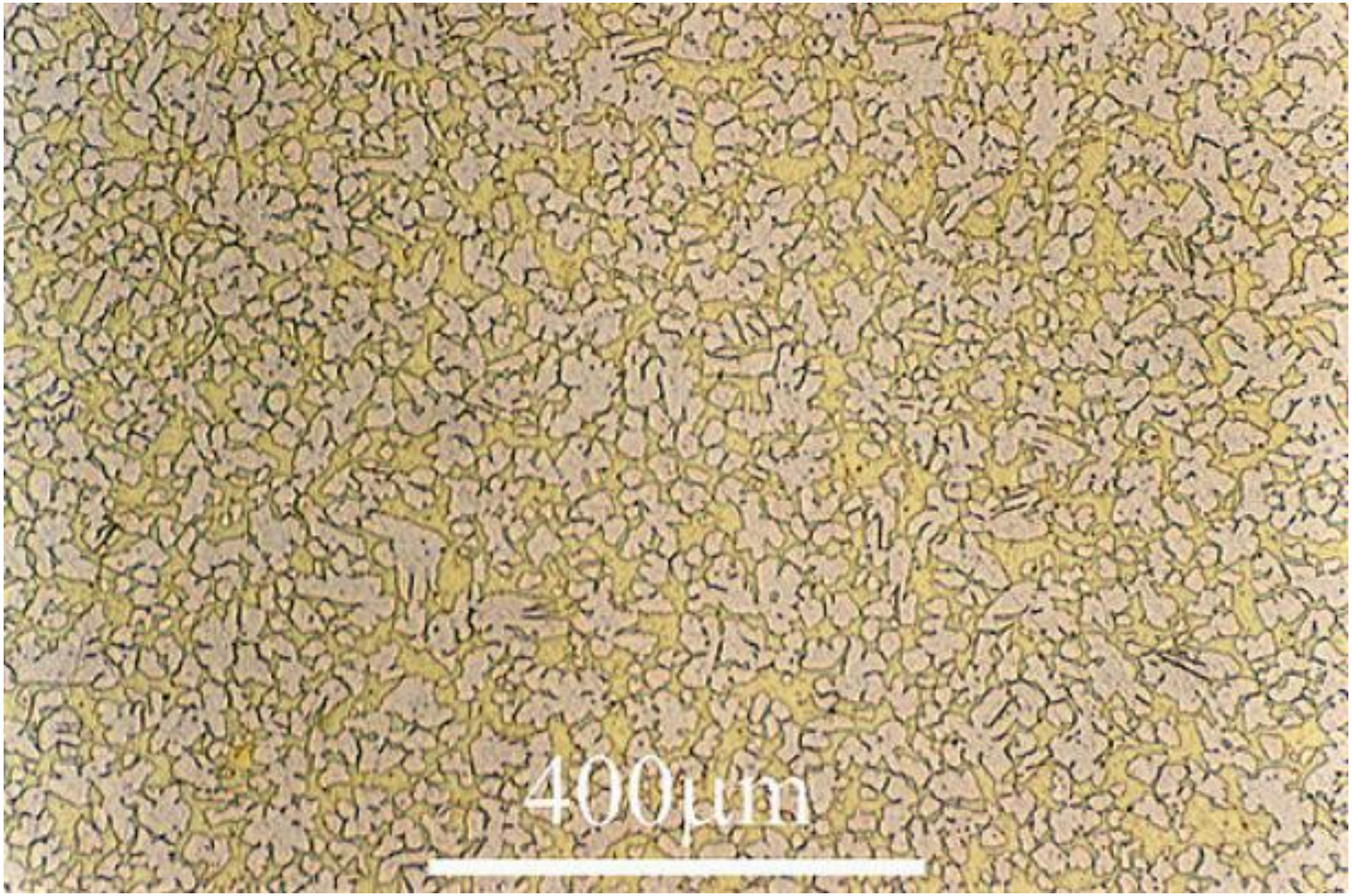
Brasses: Alpha beta brass

- Alpha beta brasses contain between 54 – 62 wt.% copper
- These alloys consist of two phases – alpha (α) and ordered beta prime (β‘)
- The β‘ phase is harder and more brittle at room temperature than the α phase ➔alpha beta brasses are therefore more difficult to cold work than tha alpha brasses
- At elevated temperatures the unordered β phase becomes very plastic
- As hot working of the alpha beta brasses is performed in the single phase β region, they have excellent hot working properties

Brasses: Copper-zinc phase diagram



Brasses: Alpha beta brass



Cast and annealed microstructure of 60-40 brass

Aluminum and its alloys

Important properties

Appearance: Silvery gray metallic

Melting point: 660 °C

Density: 2.70 g/cc

Crystal structure: FCC

CTE: 23.1×10^{-6} /°C

Thermal conductivity: 237 W/m.K

Young's modulus: 70 GPa

Shear modulus: 26 GPa

Aluminum and its alloys

- The most well known property of aluminum is its light weight, the density is only one third of steel or copper
- Due to their low weight, certain aluminum alloys have a higher strength to weight ratio than high speed steels
- Aluminum has good malleability and formability, high corrosion resistance and high electrical and thermal conductivity
- Its nontarnishing characteristic and high light reflectivity are attractive in photographic reflectors
- Aluminum is nontoxic and nonmagnetic.
- Its nonmagnetic characteristic makes it suitable for electrical shielding purposes

Aluminum and its alloys

- The electrical conductivity of aluminum is only 62% of that of copper. However, because of its light weight, aluminum is the preferred option in many applications
- The tensile strength of aluminum is rather low; this can however be significantly improved by alloying or cold work
- Aluminum has excellent workability and machinability ➔ can be cast by any known method, rolled to any desired thickness, stamped, drawn, spun, hammered, forged and extruded to almost any shape

Aluminum – alloy designation system

- Standardized designation system is used for wrought aluminum and wrought aluminum alloys
- It follows a four digit numbering system
- The first digit indicates the alloy group
- The second digit indicates modification of the original alloy or impurity limits ➔ zero is used for original alloy and integers 1 to 9 indicate alloy modifications
- In 1XXX series, the last two digits are the same as the two digits to the right of the decimal point in the minimum aluminum % when expressed to the nearest 0.01%. 1060 ➔ an alloy with 99.60 % aluminum purity
- In 2XXX – 8XXX series the last 2 digits serve to identify the different alloys

Aluminum – alloy designation system

Wrought Alloys	Designation	Casting Alloys	Designation
99.00% (minimum) aluminium	1XXX	99.00% (minimum) aluminium	1XX.X
Copper	2XXX	Copper	2XX.X
Manganese	3XXX	Silicon with added copper and/or magnesium	3XX.X
Silicon	4XXX	Silicon	4XX.X
Magnesium	5XXX	Magnesium	5XX.X
Magnesium and silicon	6XXX	Zinc	6XX.X
Zinc	7XXX	Tin	7XX.X
Others	8XXX	Others	8XX.X

For cast alloys

- The first digit identifies the group
- The second two digits identify the alloy
- The last digit preceded by the decimal point, indicates the product form (0 for casting and 1 for ingot)

Aluminum – alloy designation system

The cast or wrought alloy designation is typically followed by temper designation ➔ a letter followed by a number indicating the mechanical and/or heat treatment to which the alloy has been subjected.

Important temper designations

F: as fabricated

O: annealed, recrystallized

H1: strain hardened only

H2: strain hardened and partially annealed

T3: solution heat treated and cold worked

T4: solution heat treated and naturally aged

T6: solution heat treated and artifically aged

Heat treatment of aluminum alloys

In terms of the influence of heat treatment on the mechanical properties, aluminum alloys are claffied in two groups:

Heat treatable: These are the alloy systems whose strength and hardness can be improved by heat treatment

Non-heat treatable: In these alloy systems no significant strengthening can be achieved by heating and cooling. These alloy systems depend primarily on cold work to enhance strength

The heat treatment process employed to aluminum alloys is known as precipitation hardening

Heat treatment of aluminum alloys

To be able to get strengthened by precipitation hardening, the alloy ststem need to have certain characteristics:

- A temperature dependent equilibrium solid solubility
  - An appreciable maximum solubility of one component in the other
  - A solubility limit that rapidly decreases in concentration of the major component with temperature reduction
- Composition of the precipitation hardenable alloy must be less than the maximum solubility
- Formation of finely dispersed precipitates during the aging heat treatment which is coherent or semi-coherent with the matrix

Heat treatment of aluminum alloys

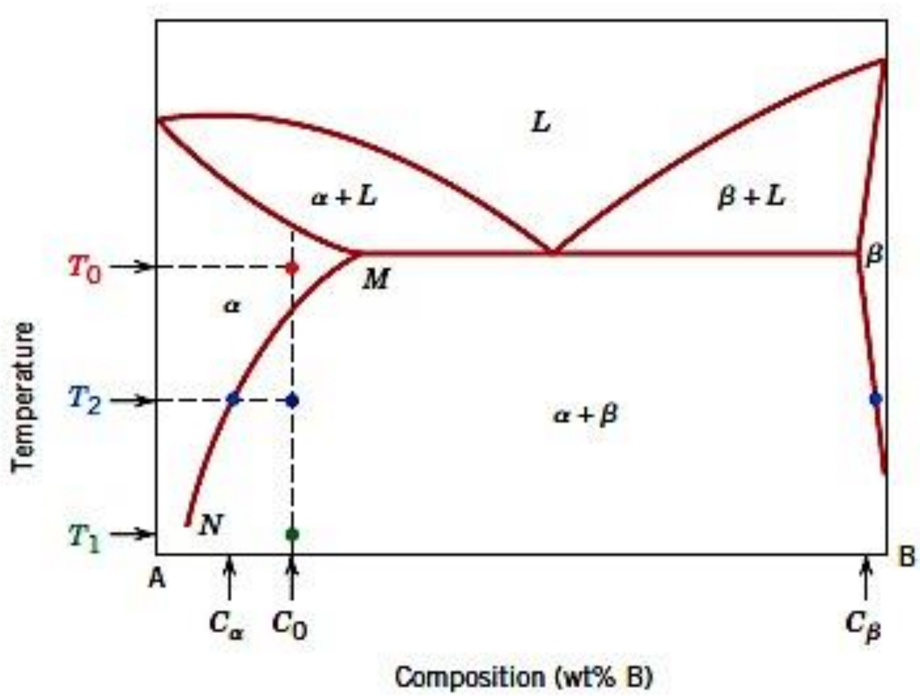
The major Al-alloy systems where precipitation hardening is prevalent are:

- Al-Cu systems
- Al-Cu-Mg systems
- Al-Mg-Si systems
- Al-Zn-Mg systems
- Al-Zn-Mg-Cu systems

The first Al-alloy to be strengthened by precipitation hardening is the Al-Cu-Mg-Mn alloy duralumin (Al alloy 2014)

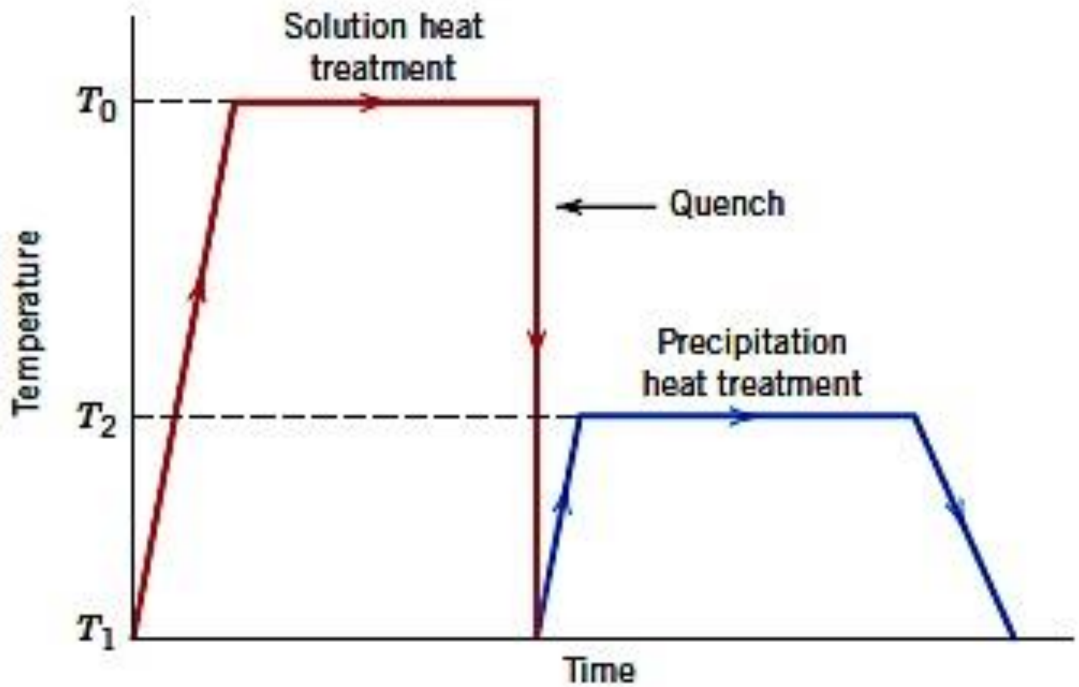
Precipitation hardening of Al-alloys

Enhancement of strength and hardness of an alloy by formation of extremely small uniformly distributed particles of a second phase within the original phase matrix by phase transformations induced by appropriate heat treatment is known as precipitation hardening.



Hypothetical binary phase diagram of an alloy strengthened by precipitation hardening

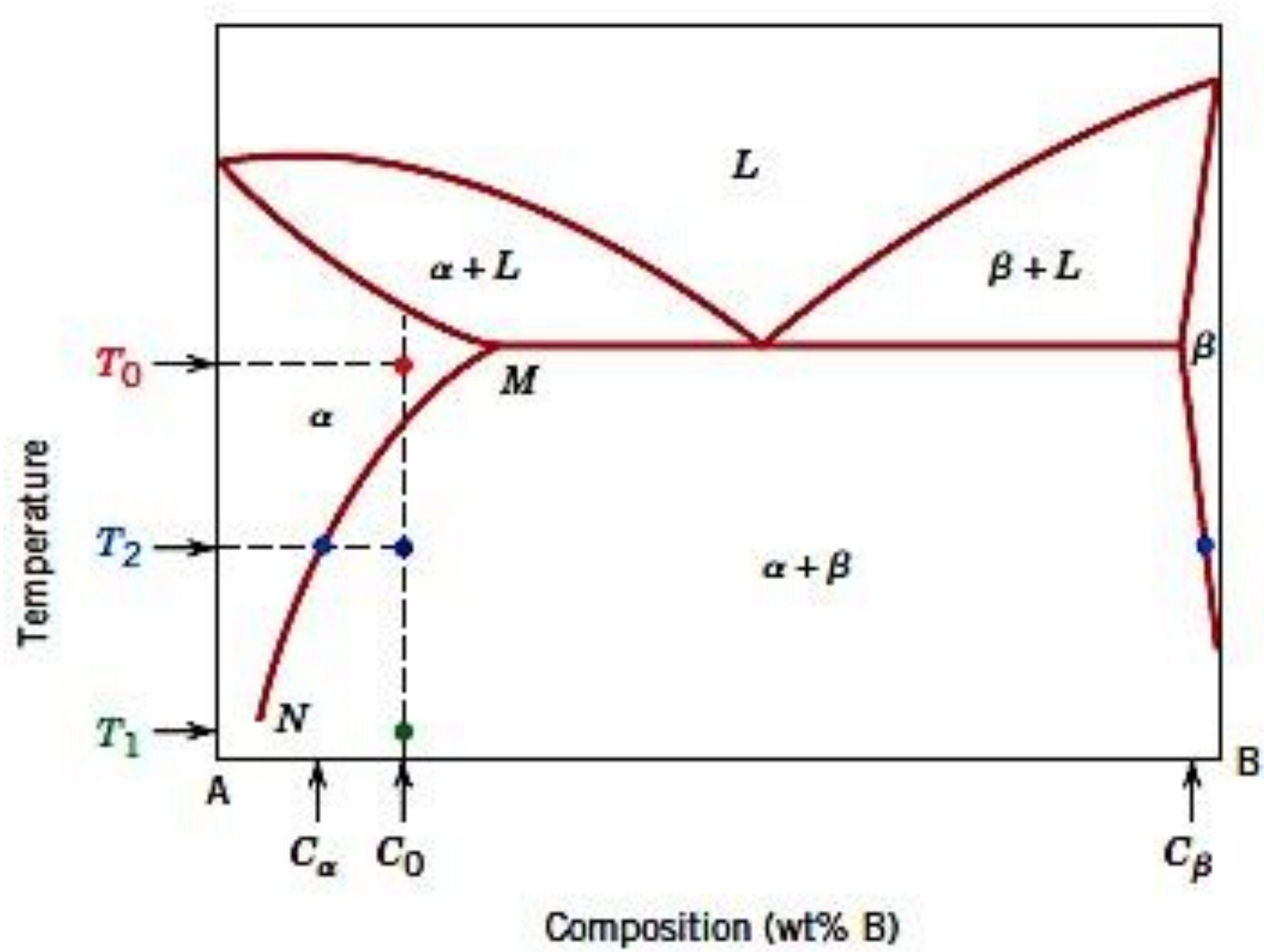
Precipitation hardening of Al-alloys



Precipitation hardening is accomplished by two different heat treatment processes:

1) Solution heat treatment
2) Precipitation heat treatment

Solution heat treatment



Step 1: Solution heat treatment

- The maximum solubility of B in A corresponds to the point M at the eutectic temperature
- Consider an alloy of composition C_0
- The first step of solution heat treatment consists of heating the alloy to a temperature in the α-single phase region ➔ this temperature is denoted as T_0
- After sufficient holding time at T_0, all β phase has dissolved and the alloy consists of single phase α phase of composition C_0
- The alloy is then rapidly quenched to a temperature T_1, which for many alloys is room temperature

Step 1: Solution heat treatment

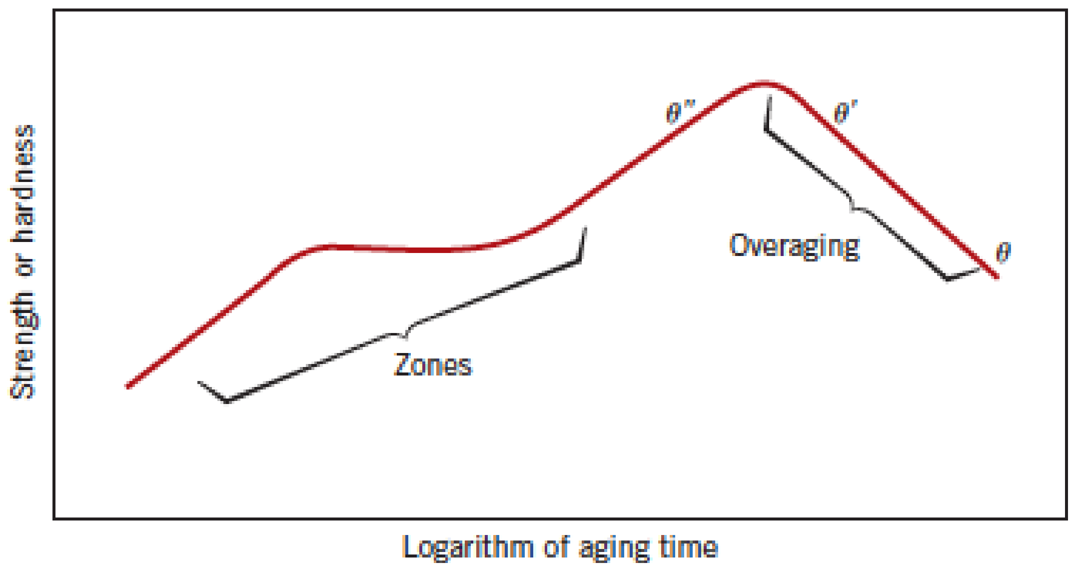
- Rapid quenching prevents any diffusion and hence no β phase is formed during cooling
- As a result, a non-equilibrium structure results where the α-phase is supersaturated with B atoms ➔ α-phase still has the composition C_0, whereas at temperature T1, the equilibrium solubility of B in A is denoted by point N.
- At the low temperature level of T_1, the diffusion rates are extremely small and hence the single α-phase is retained for relatively long periods.

Step 2: Precipitation heat treatment

- For the precipitation heat treatment, the supersaturated α-solid solution is heated to an intermediate temperature T_2, where the diffusion rate is appreciable
- At this temperature, β precipitates with a composition of C_β begin to form
- After appropriate holding time at the temperature T_2, the alloy is cooled down to room temperature. The cooling rate at this stage is not an important parameter
- The character of the β-particles as well as the final strength and hardness are dependent upon both the temperature T_2 and holding time at T_2 ➔ aging time

Precipitation hardening of Al-alloys

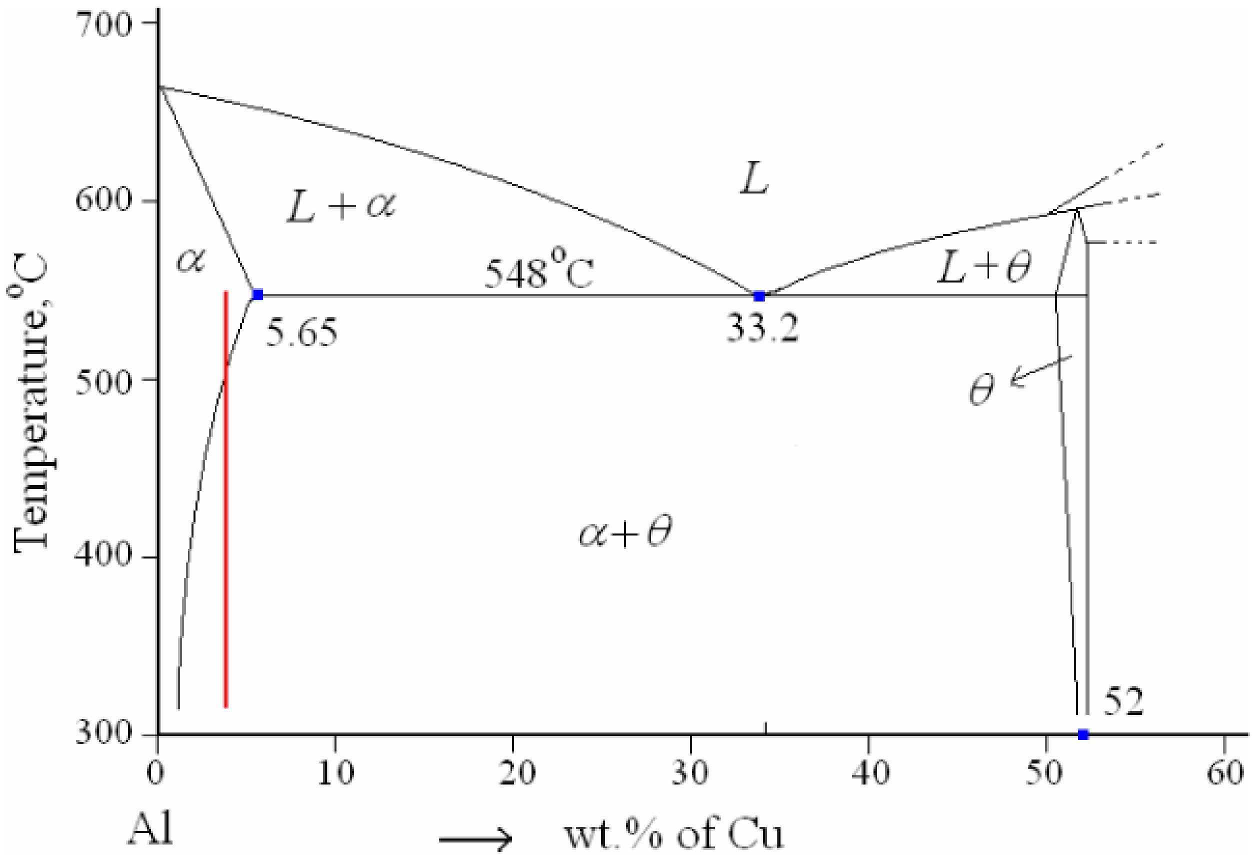
- The dependence of the growth of the β precipitate particles on time and temperature is conveniently presented as strength/hardness vs. logarithm of the aging time at the temperature T_2.



- With increasing time, the strength/hardness increases, reaches a maximum and finally diminishes ➔ The reduction at long times is called overaging

Mechanism of precipitation hardening

The mechanism of precipitation hardening has been studied most extensively for the Al-Cu alloys



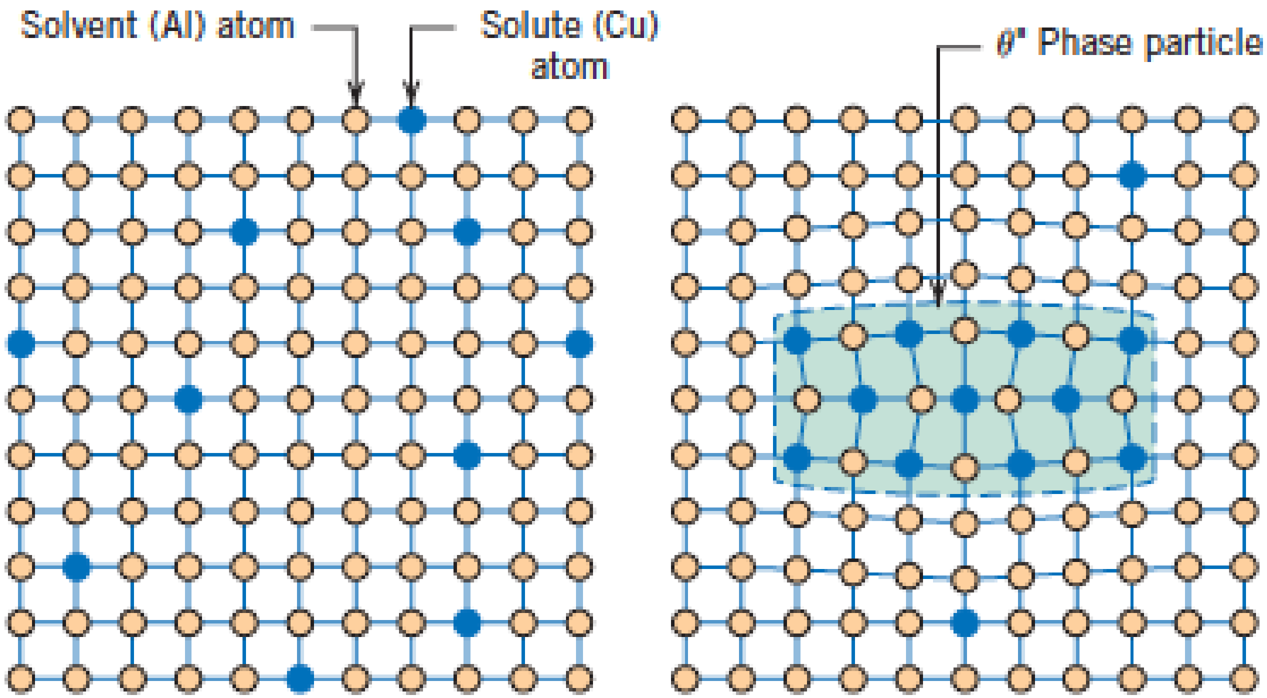
Aluminum rich portion of the Al-Cu phase diagram

Mechanism of precipitation hardening

- The α-phase is a substitutional solid solution of Cu in Al
- The intermetallic compound $CuAl_2$ is known as the θ-phase
- The maximum solubility of Cu in Al is 5.65 wt.% at 548 °C
- Consider an alloy of composition 96 wt.% Al – 4 wt.% Cu (denoted by the red vertical line)
- During the initial hardening stage at short times, copper atoms cluster together in very small discs, which form at countless positions within the α-phase.
- These clusters, called zones, are so small that they are really not regarded as distinct precipitate particles
- These zones are coherent with the matrix

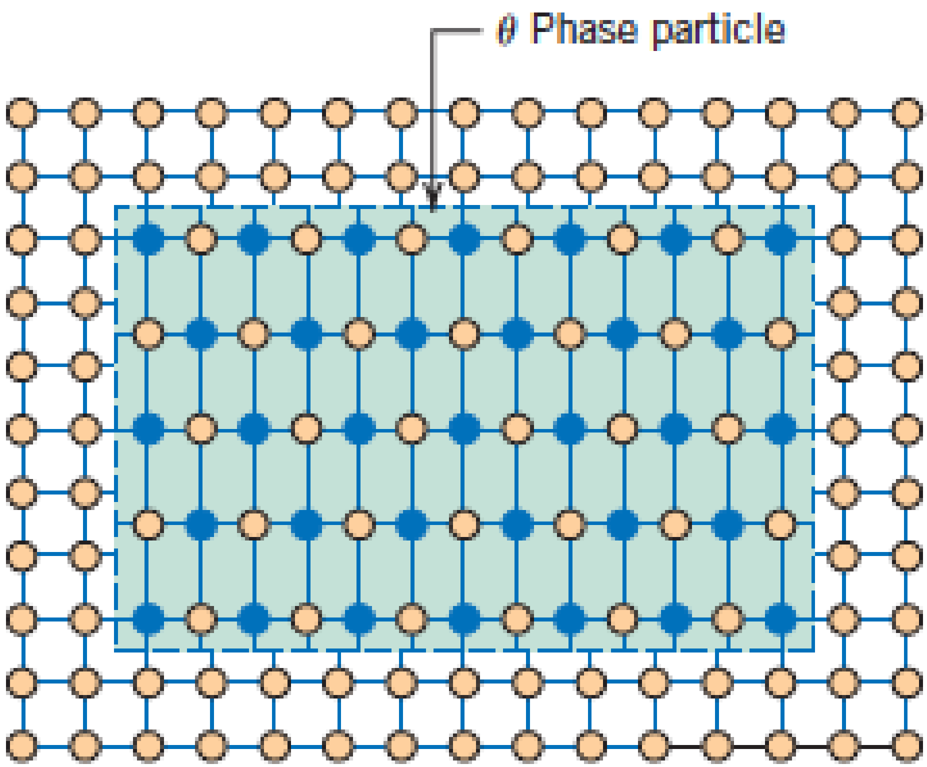
Mechanism of precipitation hardening

- With additional time and subsequent diffusion of copper atoms, the zones become particles as they increase in size.
- The precipitate particles pass through two transition phases denoted as θ" and θ'



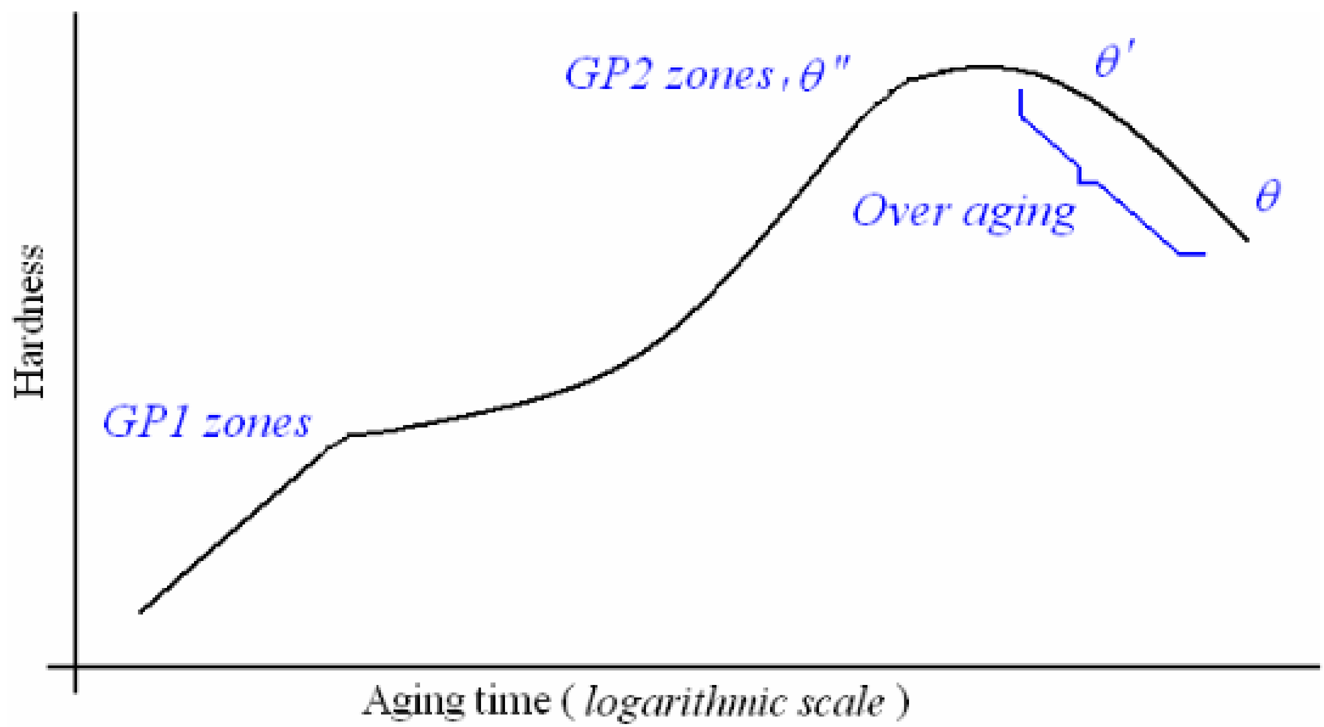
Mechanism of precipitation hardening

- With still additional aging the equilibrium phase $CuAl_2$ or θ is formed from the transition θ' phase
- The θ phase is incoherent with the matrix. The hardness is therefore lower than at the stage when coherency was present.



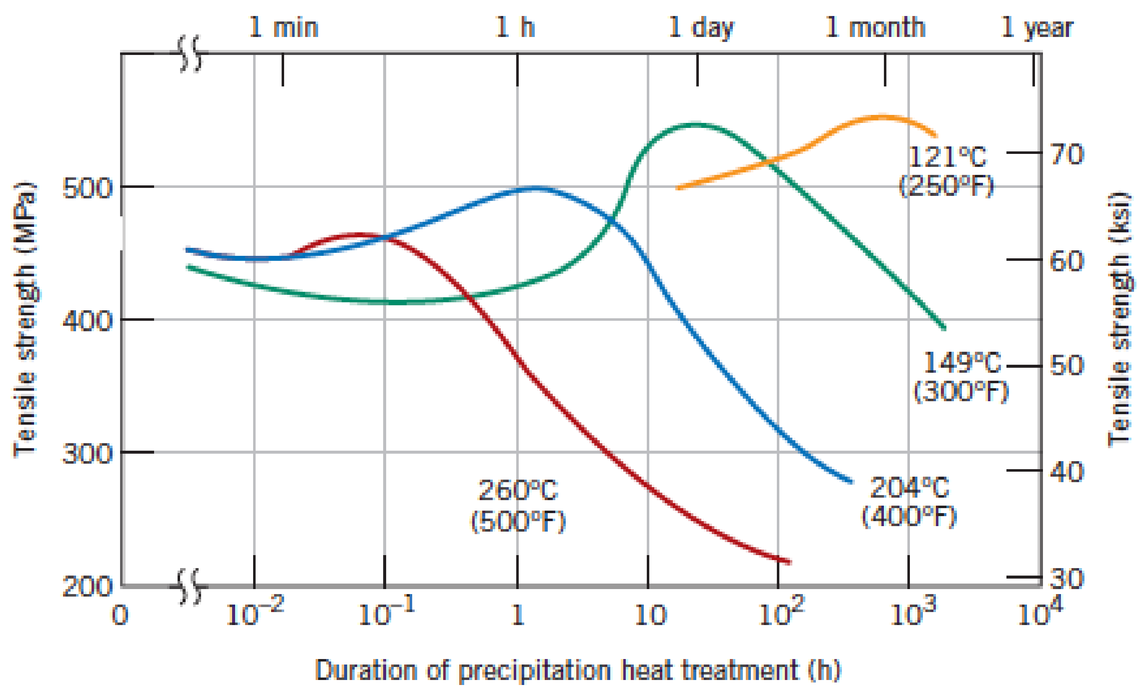
Mechanism of precipitation hardening

- The peak hardness is usually attained in the later stages of coherency or at the onset of incoherency ➔ with the formation of the θ“ phase
- With the continued particle growth and development, overaging occurs coinciding with the formation of θ‘ and θ phases.



Mechanism of precipitation hardening

- As the temperature is increased, the strengthening process is accelerated.
- Ideally, temperature and time for the precipitation heat treatment should be designed to produce a hardness and strength at the vicinity of the maximum.



Corrosion resistance of aluminum

- The high corrosion resistance of aluminum is due to the self protecting, thin, invisible oxide film that forms immediately on exposing the surface to atmosphere
- If the film is removed, in many atmospheres the film will form spontaneously, maintaining the resistance
- In ceratin strongly alkaline or acidic solutions, the protective film does not form rapidly ➔ further protection of aluminum is needed in these conditions
- Anodozing is a process whereby a relatively thick, clear and transparent oxide coating is formed on aluminum by dipping it in an aqueous solution containing 15 – 25% sulphuric acid.

Lecture 2

Magnesium and its alloys

Important properties

Appearance: Shiny gray

Melting point: 650 °C

Density: 1.738 g/cc

Crystal structure: HCP

CTE: 24.8×10^{-6} /°C

Thermal conductivity: 156 W/m.K

Young's modulus: 45 GPa

Shear modulus: 17 GPa

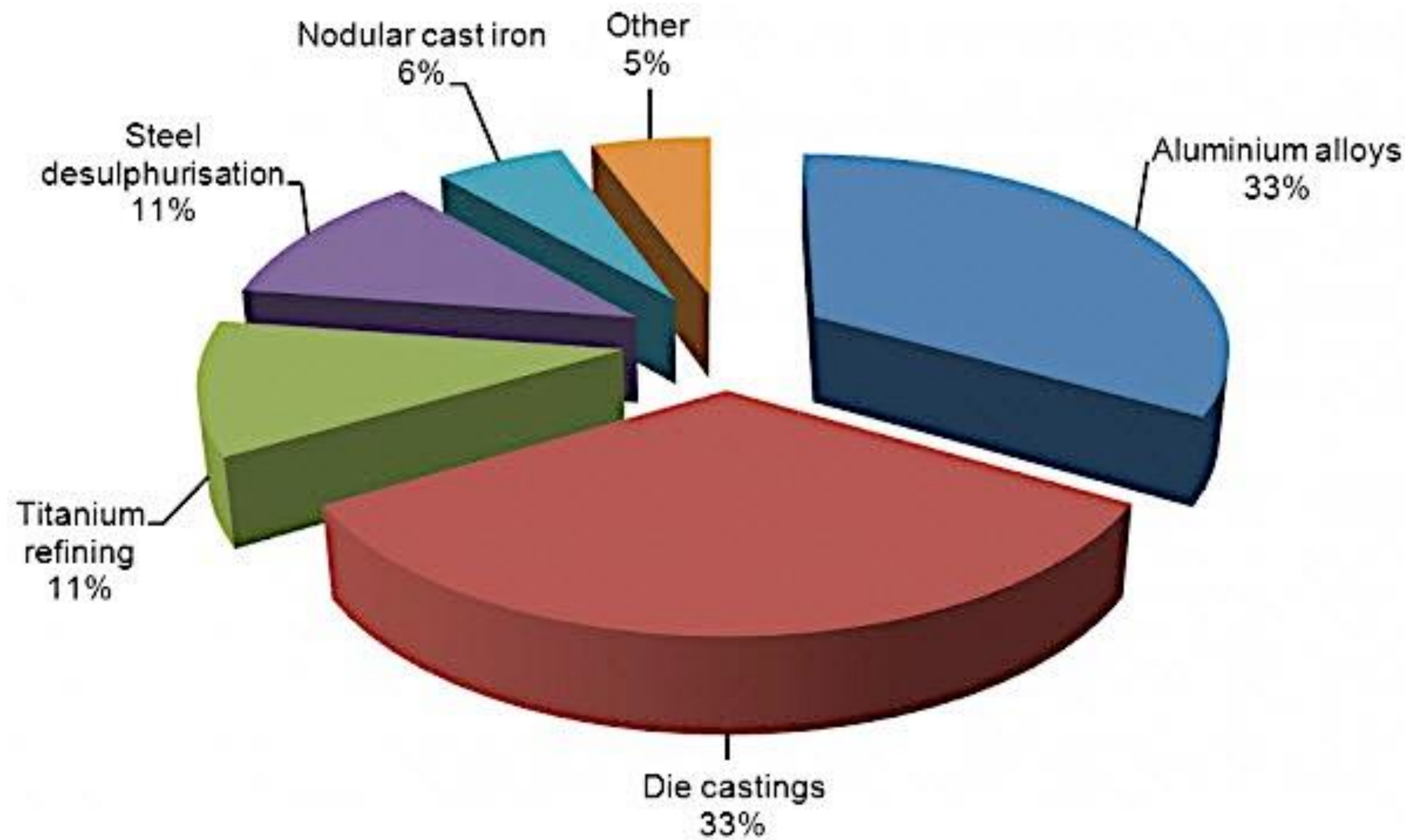
Magnesium and its alloys

- Chief advantages of magnesium are its light weight, ease of machinability and the high strength to weight ratio obtainable with its alloys
- On the basis of equal volume, Al wieghs 1.5 times more, steel weighs 4 times more and Cu and Ni weighs 5 times more than Mg
- Due to its HCP structure, at room temperature the ductility of Mg is lower than FCC metals ➔ cold working of magnesium alloys is difficult
- At higher temperatures the plasticity of magnesium alloys are improved ➔ most fabrication of magnesium is done by hot working between 250–350 °C

Magnesium and its alloys

- Approx. 50% of magnesium produced is used in alloy form for structural purposes in the aircraft and missile industries
- It has found increasing application in photo-engraving due to its light weight and rapid etching characteristic
- It has a strong affinity for oxygen and other chemical oxidizing agents
- Magnesium is often used as deoxidizer and desulphidizer in the production of different alloys
- Magnesium anodes are often used as sacrificial element in the corrosion resistance of ship hulls, underground pipelines etc.

Magnesium and its alloys



http://www.discoveryinvesting.com/blog/2015/8/10/a-closer-look-at-magnesium

Designation of magnesium alloys

- First part of the designation indicates the two principal alloying elements
- Second part indicates the amounts of the two principal alloying elements
- Third part consists of a letter of the alphabet assigned in order as compositions became standard
- Fourth part indicates temper condition – typically a letter followed by a number; separated from the third part of the designation by a hyphen

Designation of magnesium alloys

Letters representing alloying elements

A	Aluminum	M	Manganese
B	Bismuth	N	Nickel
C	Copper	P	Lead
D	Cadmium	Q	Silver
E	Rare earths	R	Chromium
F	Iron	S	Silicon
G	Magnesium	T	Tin
H	Thorium	Y	Antimony
K	Zirconium	Z	Zinc
L	Beryllium		

Considering the magnesium alloy AZ81A-T4:

Al and Zn are the two principal alloying with contents of respectively 8 and 1 wt.%; being the fifth alloy standardized in this series (denoted by A after 81) and it has T4 heat treatment