Aluminium and its alloys

Subjects of interest

- *Why aluminium alloys?*
- *Physical properties of aluminium alloys*
- *Heat treatments of aluminium alloys*
- *Classification of aluminium alloys*
- *Cast aluminium alloys*
- *Wrought aluminium alloys*

Objectives

• This chapter provides fundamental knowledge of different methods of productions / heat treatments of aluminium alloys and the use of various types of cast and wrought aluminium alloys.

• The influences of alloy composition, microstructure and heat treatment on chemical and mechanical properties of aluminium alloys will be discussed in relation to its applications.

Introduction- *Why aluminium alloys?*

- Abundant element of 8% on earth crust and normally found in oxide forms (***Al_2O_3***), i.e., ***bauxite, kaolinite***, nepheline and alunite.
- Found in United states, Italy, France.
- Have been found in Turkey

Bauxite with penny

Bauxite-pebbly

Kaolinite

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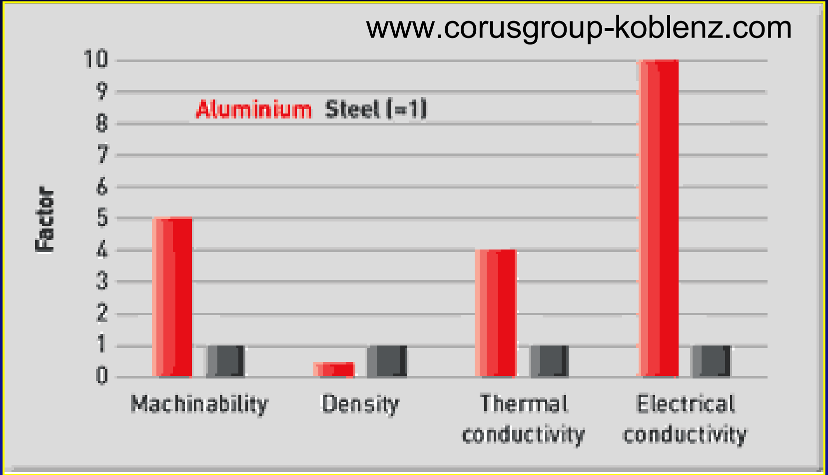
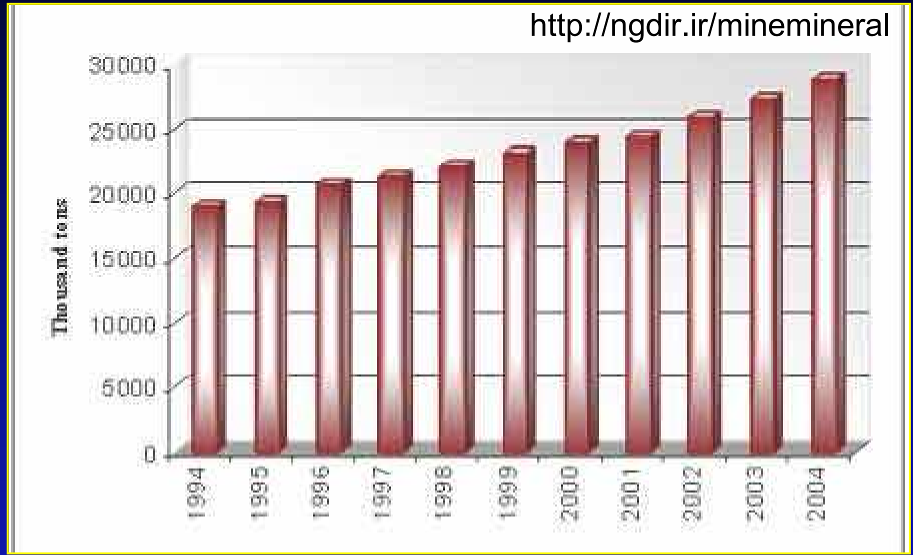
Introduction- *Why aluminium alloys?*

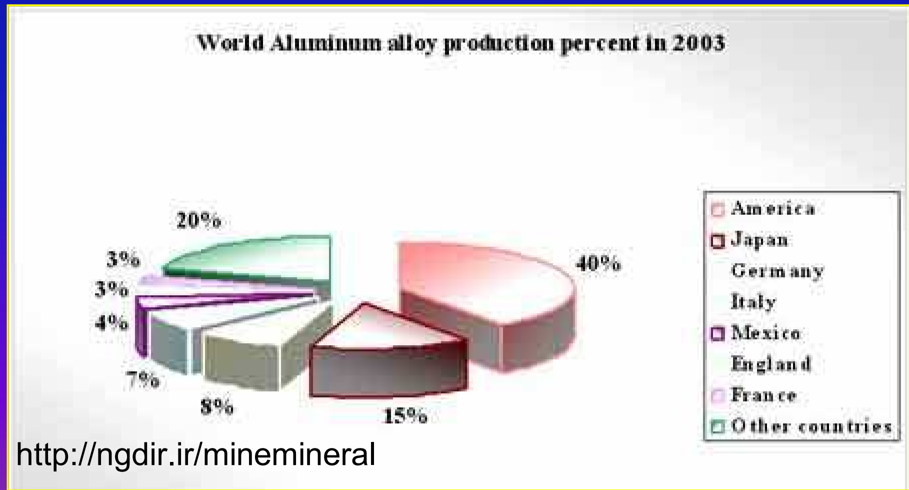


Comparison of Al and steel



Attractive properties

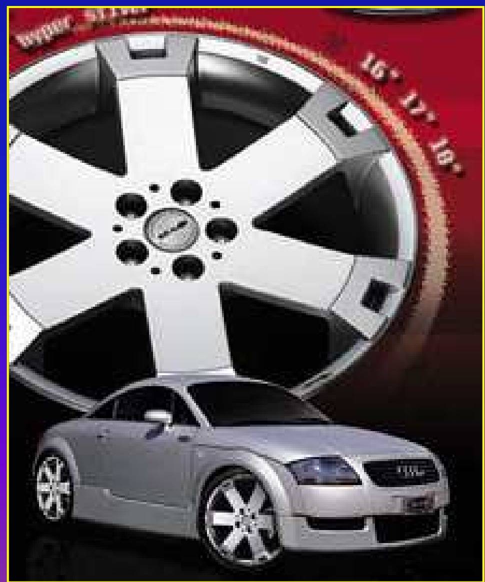
- *High corrosion resistance*
- *Excellent machining properties*
- *Light weight*
- *High thermal/electrical conductivity*
- *High ductility/easily deformable*



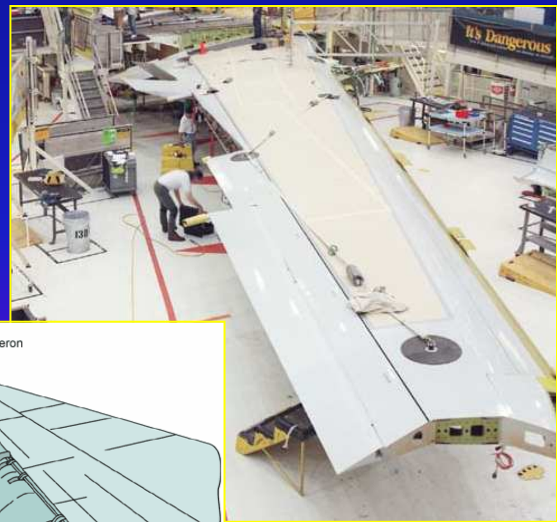
Applications for aluminium alloys

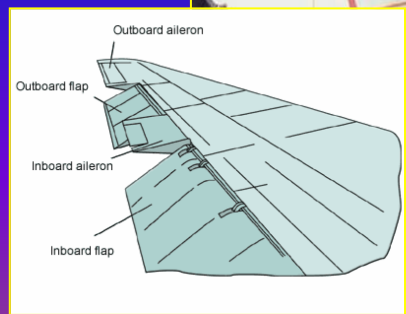
Construction & Equipment

Containers & Packaging



Automotives





Aerospace

Production of Aluminium

France 1855:

• ***H. Sainte-Claire Deville*** first reduced aluminium chloride with sodium.

Austria 1888:

• ***Karl Josef Bayer*** first patented the ***Bayer process*** (digesting crushed bauxite in strong sodium hydroxide solution at temperatures upto 240^{o}C.

Germany :

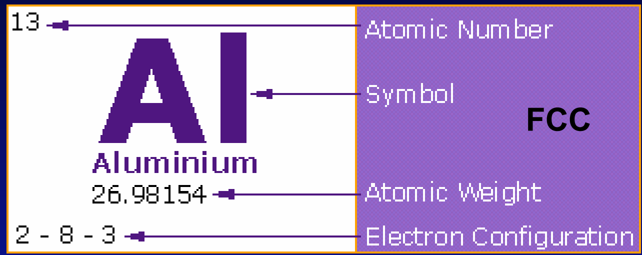
• ***Hall-Héroult*** introduced ***Hall-Héroult process*** by dissolving the aluminain molten cryolite (Na_3AlF_6)

United states 1976:

• ***Alcoa*** commenced a ***chloride-based smelting process*** using alumina combined with chloride.

Aluminum produced by Hall Heroult electrolysis cell contains only a small amount of iron and silicon as main impurity elements. It means that its purity is over 99% Al. It is called as commercial purity aluminium.

Physical metallurgy of aluminium



Density / Specific Gravity (g.cm^{-3} at 20 °C)	2.70
Melting Point (°C)	660
Specific heat at 100 °C, cal.g^{-1}K^{-1} (Jkg^{-1}K^{-1})	0.2241 (938)
Latent heat of fusion, cal.g^{-1} (kJ.kg^{-1})	94.7 (397.0)
Electrical conductivity at 20°C (% of international annealed copper standard)	64.94
Thermal conductivity (cal.sec^{-1}cm^{-1}K^{-1})	0.5
Thermal emmisivity at 100°F (%)	3.0
Reflectivity for light, tungsten filament (%)	90.0

Solubility of elements in aluminium

• ***Mg***, ***Cu, Zn*** and ***Si*** are the most commonly used alloying elements in aluminium, which have sufficient solid solubility.

• ***Cr, Mn*** and ***Zr*** are used primarily to form compounds which control grain structure.

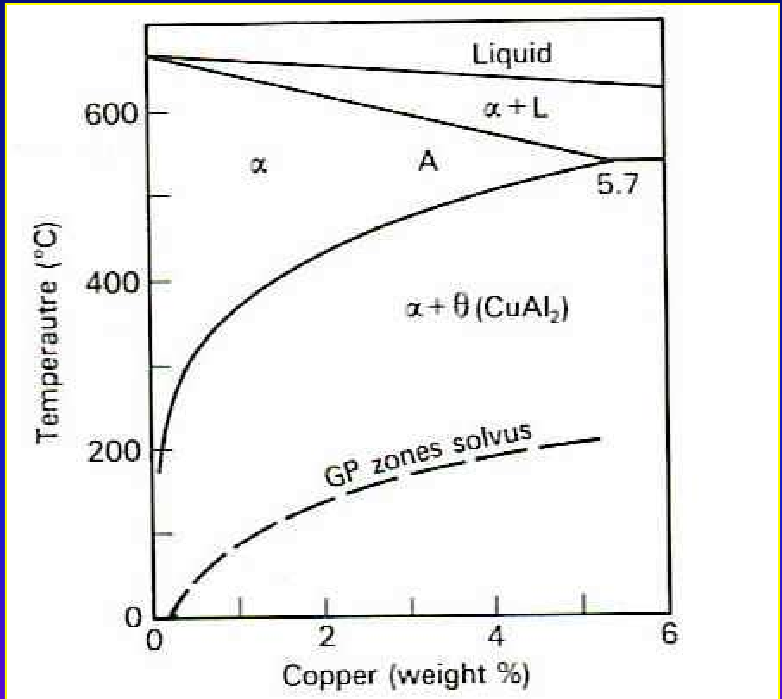
Table 2.1 Solid solubility of elements in aluminium (from Van Horn, K.R. (Ed), *Aluminium*, Volume 1, American Society for Metals, Cleveland, Ohio,1967; Mondolfo, L.F., *Aluminium Alloys: Structure and Properties*, Butterworths, London, 1976)

Element	Temperature (°C)	Maximum solid solubility (wt%)	(at%)
Cadmium	649	0.4	0.09
Cobalt	657	<0.02	<0.01
Copper	548	5.65	2.40
Chromium	661	0.77	0.40
Germanium	424	7.2	2.7
Iron	655	0.05	0.025
Lithium	600	4.2	16.3
Magnesium	450	17.4	18.5
Manganese	658	1.82	0.90
Nickel	640	0.04	0.02
Silicon	577	1.65	1.59
Silver	566	55.6	23.8
Tin	228	~0.06	~0.01
Titanium	665	~1.3	~0.74
Vanadium	661	~0.4	~0.21
Zinc	443	82.8	66.4
Zirconium	660.5	0.28	0.08

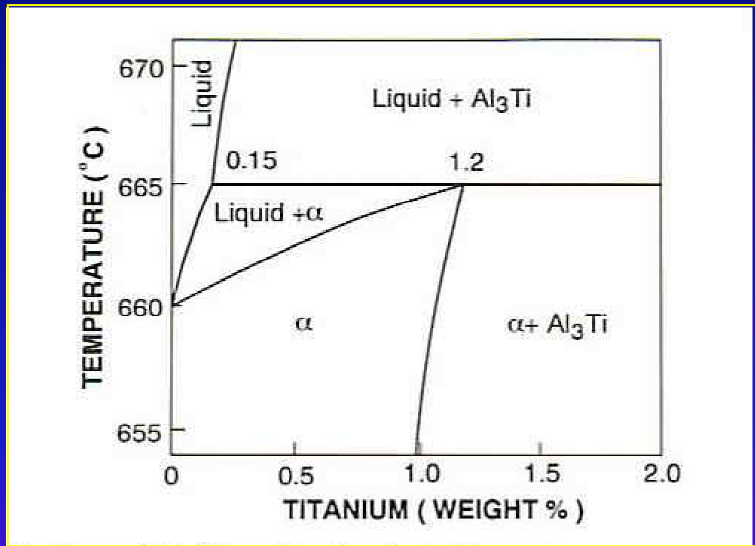
Note:
(i) Maximum solid solubility occurs at eutectic temperatures for all elements except chromium, titanium, vanadium, zinc and zirconium for which it occurs at peritectic temperatures.
(ii) Solid solubility at 20°C is estimated to be approximately 2 wt% for magnesium and zinc, 0.1–0.2 wt% for germanium, lithium and silver and below 0.1% for all other elements.

Phase diagrams of aluminium with various alloying elements

Maximum solid solubility in binary aluminium alloys occurs at eutectic and peritectic temperatures.

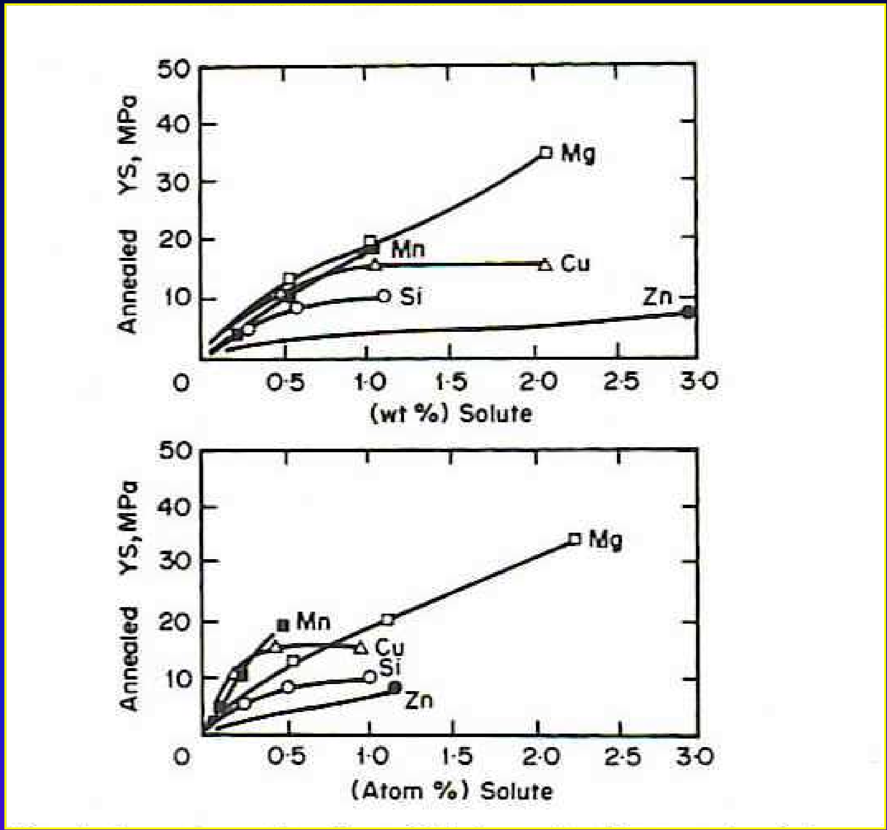


Section of Al-Cu eutectic phase diagram



Section of Al-Ti peritectic phase diagram

Solid solution strengthening of high purity binary aluminium alloys



Note: Zinc has high solubility but contributes to only mall solid solution strengthening.

- ***Annealed high-purity aluminium*** has very low yield strength (7-11 MPa), but can be strengthened by ***solid solution hardening***.
- ***Mn*** and ***Cu*** are the most effective strengtheners at 0.5%, but tend to form ***Al_6Mn precipitates*** and insoluble ***Al-Cu-Fe constituents*** respectively.
- ***Mg*** is the most effective strengthener on the weight basis due to its ***high solubility***.

Heat treatments in aluminium alloys

Principles of age-hardening

- ***Age hardening*** requires a decrease in ***solid solubility*** of the ***alloying elements*** with decreasing temperature.

Heat treatment usually involves the three following stages:

1. Solution treatment at relatively high temperature to dissolve the alloying elements.
2. Rapid cooling or quenching usually to room temperature to obtain ***supersaturated solid solution (SSSS)*** of these elements in aluminium.
3. Controlled decomposition of the ***SSSS*** to form a finely dispersed precipitates, normally accompanied with ageing at appropriate temperatures.

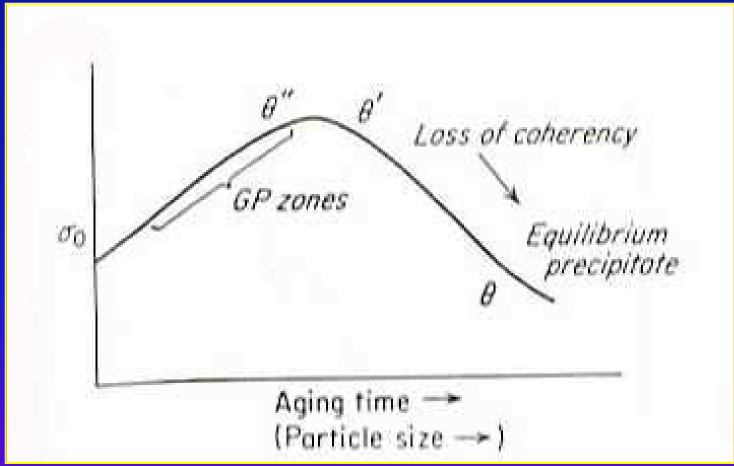
Decomposition of supersaturated solid solutions

Decomposition of SSSS is complex and normally involves several stages;

The formation of →

- Equilibrium phase
- Guinier-Preston (GP) zones
- Intermediate precipitates

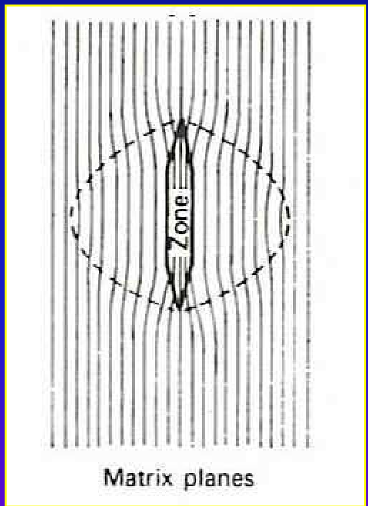
The presence of a critical dispersion of ***GP zones*** or an ***intermediate precipitates***, or both contributes to the ***maximum hardening*** in commercial alloys.



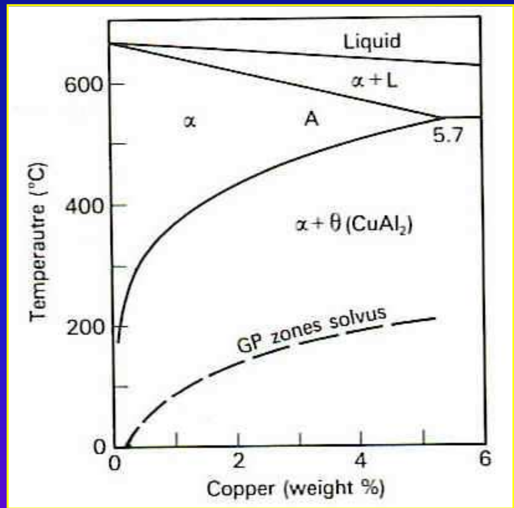
Variation of yield stress with ageing time

1) The GP zone

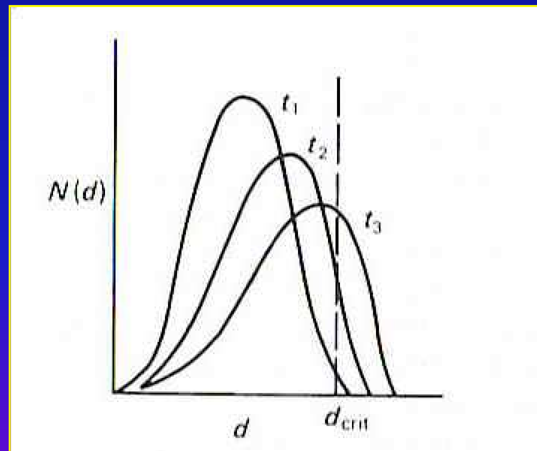
- The ***GP zones*** are ***ordered***, solute-rich clusters of atoms, and ***coherent*** with the matrix, *fig (a).* The ***GP zones*** are normally finely distributed in the matrix, which contribute to ***hardening***.
- The ***GP zone solvus*** shown as a metastable line in the equilibrium diagram *(fig b)* which defines the ***upper temperature limit of stability*** of the ***GP zones***. The GP zone size distribution varies with ageing time, *fig (c).*



(a) Schematic of the distortion of matrix lattice plane near the coherent GP zone.



(b) Section of Al-Cu eutectic phase diagram

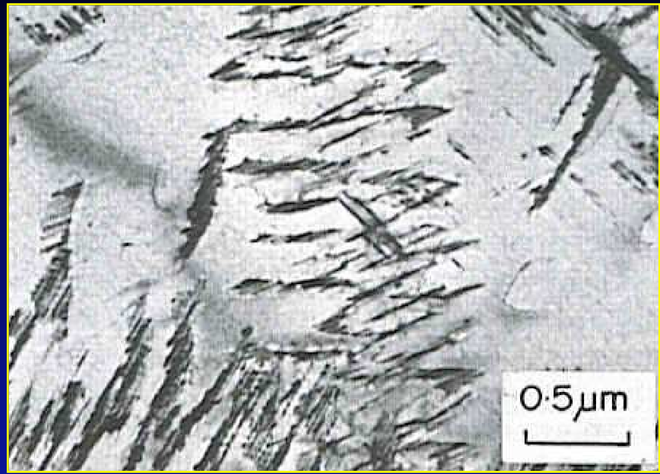


(c) Schematic of the variation of GP zone size distribution with ageing time.

2) Intermediate precipitates

• ***Intermediate precipitates*** have a definite composition and crystal structure and are of ***much a larger size*** than that of ***GP zones***.

• Intermediate precipitates are partly ***coherent*** with the matrix and can nucleate at the sites of stable ***GP zones*** or ***dislocations***.



TEM of rods of S-phase (Al2-Cu-Mg) precipitates heterogeneously distributed on dislocation lines.

3) Equilibrium precipitates

• The final ***equilibrium precipitates*** occur when ***the intermediate precipitates loss its coherecy with the matrix***.

• They are formed only at relatively high ageing temperatures and appear as coarsely dispersed precipitates → ***little hardening effect***.

Designations of wrought aluminium alloys

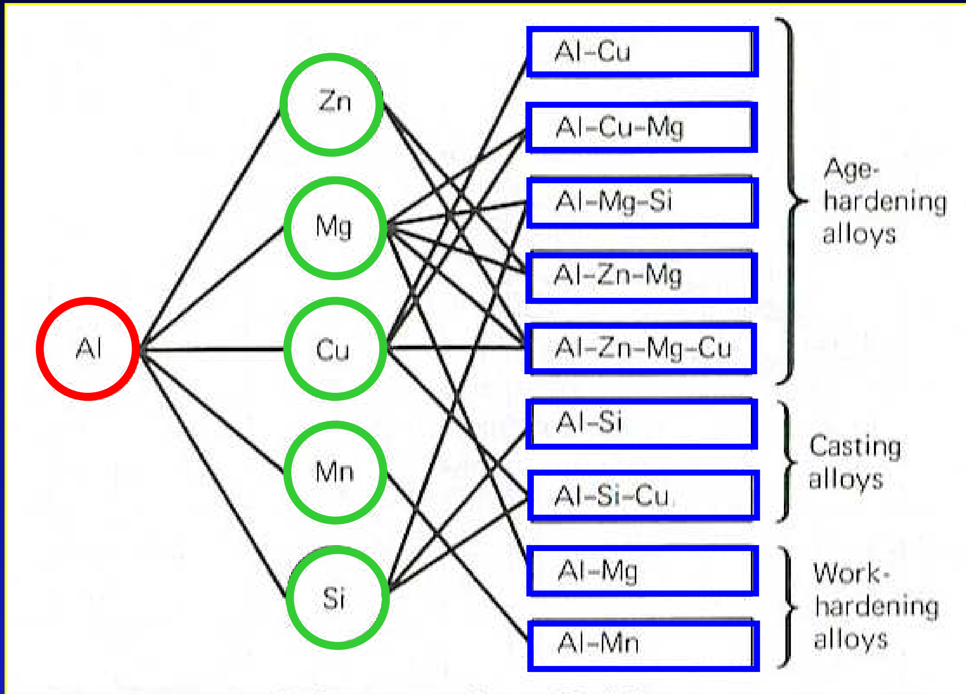
Non-heat-treatable alloys

- 1xxx series (Super-purity and commercial-purity aluminium)
- 3xxx series (Al-Mn and Al-Mn-Mg alloys)
- 5xxx series (Al-Mg alloys)
- 8xxx series (Miscellaneous alloys)

Heat-treatable alloys

- 2xxx series (Al-Cu and Al-Cu-Mg alloys)
- 6xxx series (Al-Mg-Si alloys)
- 7xxx series (Al-Zn-Mg and Al-Zn-Mg-Cu alloys)

Roles of alloying elements



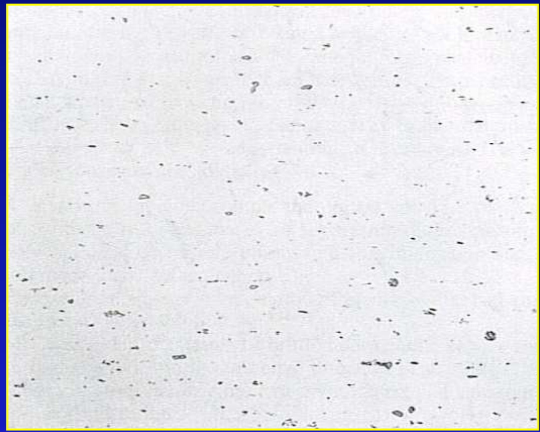
- ***Zn, Mg, Cu, Mn, Si*** are mainly used for principal commercial aluminium alloys.
- Most elements have a ***very low solid solubility*** in ***Al*** and are segregated to the dendrite cell boundaries during casting.

- ***Second-phase particles*** (~10 mm) are formed if high amount of these elements is added and remain as particles after processing.
- These particles contribute to little improvement in ***strength*** but lower ***toughness*** and ***corrosion resistance***.

Super-purity and commercial-purity aluminium (1xxx series)

- **Super-purity (SP) aluminium (99.99%)**
- **Commercial-purity (CP) aluminium (upto 1% impurities or minor additions)**

- ***Fe*** and ***Si*** are always present as impurity and form refined ***$FeAl_3$, Fe_3SiAl_{12} or $Fe_2Si_2Al_9$*** constituents.



1100 sheet showing fragmented and redistributed constituent due to mechanical working

Properties:

- Low tensile strength (90 MPa in *CP 1100*)
- Yield stress of only 7-11 MPa.

Applications:

- Electrical conductors
- Chemical process equipment
- Foils
- Decorative finishes.

Aluminium conductors (bare)

Al-Mn and Al-Mn-Mg alloys (3xxx series)

- **Al-Mn alloys (upto 1.25% Mn)**

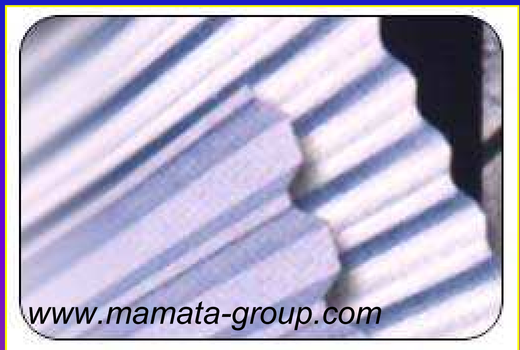
Greater amount leads to large primary Al_6Mn particles)→ deleterious local ductility).

Properties:

- Moderate strength, i.e., σ_{TS} ~ 110 MPa in ***annealed 3003.***
- High ductility
- Excellent corrosion resistance

Applications:

- Foil
- Roofing sheet



- **Al-Mn-Mg alloys**

(provide solid solution strengthening) and widely used in a variety of strain-hardened tempers.

Properties:

- Moderate strength, i.e., σ_{TS} ~ 180 MPa in ***annealed 3004.***
- Readily fabricated
- Excellent corrosion resistance

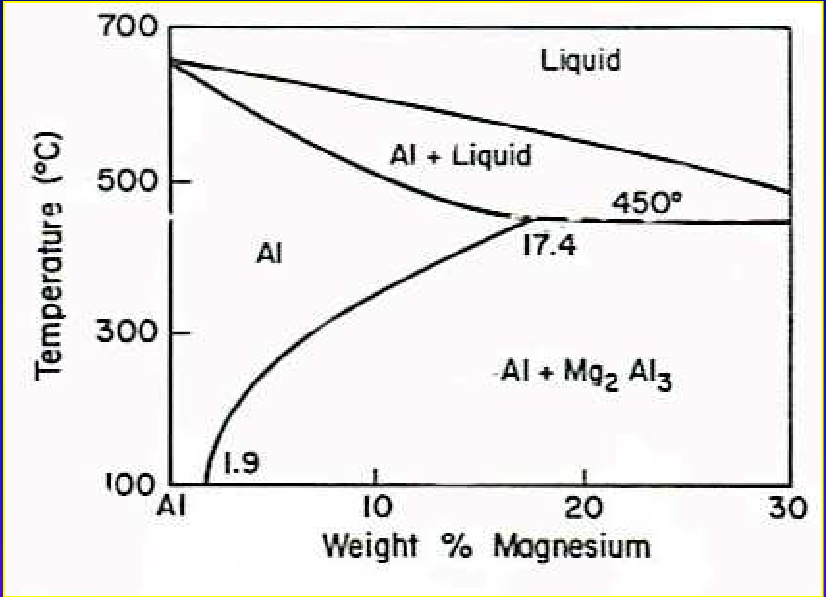
Applications:

- Manufacturing beverage cans

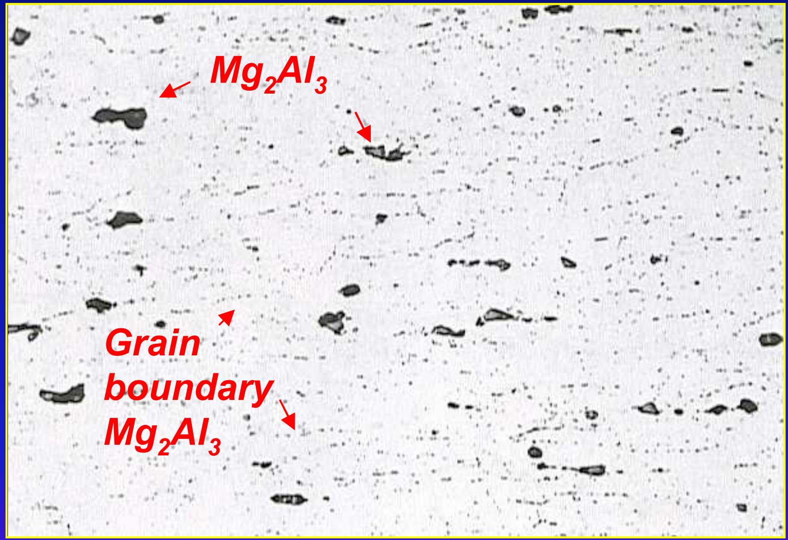
aluminium.matter.org.uk

Al-Mg alloys (5xxx series)

- ***Mg*** (***T_m*** = 651°C, ***HCP*** structure)
- ***Small solubility*** of 3% at RT and 15.35 at 451°C (eutectic).
- Eutectic reaction gives ***K*** phase (***FCC***) and β phase (***Al_3Mg_2***)



Phase equilibrium diagram of Al-Mg



5086-H34 sheet showing the constituent distribution and discontinuous Mg_2Al_3 grain boundary particles

Al-Mg alloys (5xxx series)

• Mg additions (0.8-5%) provide solid solutions and give a wide range of alloy compositions → strength properties

Properties:

- Al-0.8Mg (5005): σ_y 40 MPa, σ_{TS} 125 MPa
- Al-(4.7-5.5)Mg (5456): σ_y 160, σ_{TS} 310 MPa
- High rate of work hardening
- High corrosion resistance
- Bright surface finish

Applications:

- Transportation structural plates
- Large tanks for petrol, milk, grain
- Pressure vessel
- Architectural components

Aluminium transportation plates

Aluminium fuel tank

Miscellaneous alloys (8xxx series)

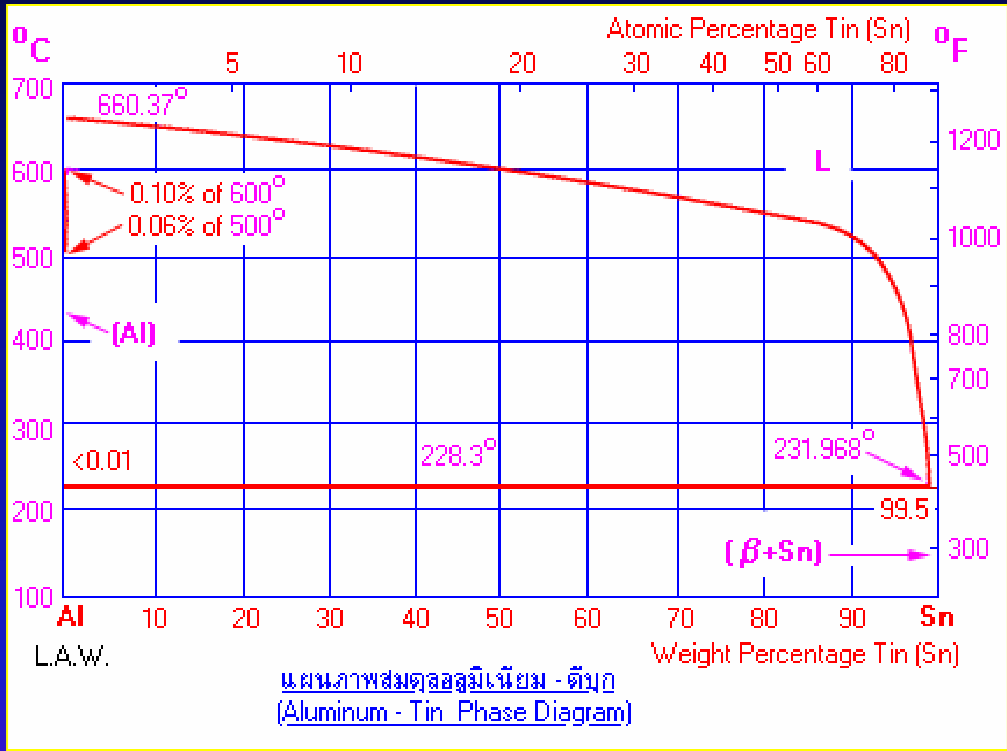
- **This series contains several dilute alloys**

Properties:

- High corrosion resistance at high temp & pressure
- Deep drawing

Applications:

- Al-1.1Ni-0.6Fr (8001) - nuclear energy installations.
- Al-0.75Fe-0.7Si (8011) - bottle caps.
- Al-Sn (up to 7%) soft bearings



Al-Cu alloys (2xxx series)

- ***Cu*** (T_m = 1085°C, ***FCC*** structure)
- Good solubility upto 5.65% at 548°C (eutectic).
- Eutectic reaction gives α phase (5.65%Cu) - ***ductile*** and θ phase (***$CuAl_2$***-52.75%Cu) – ***brittle***.

$$L \leftrightarrow \alpha + \theta$$

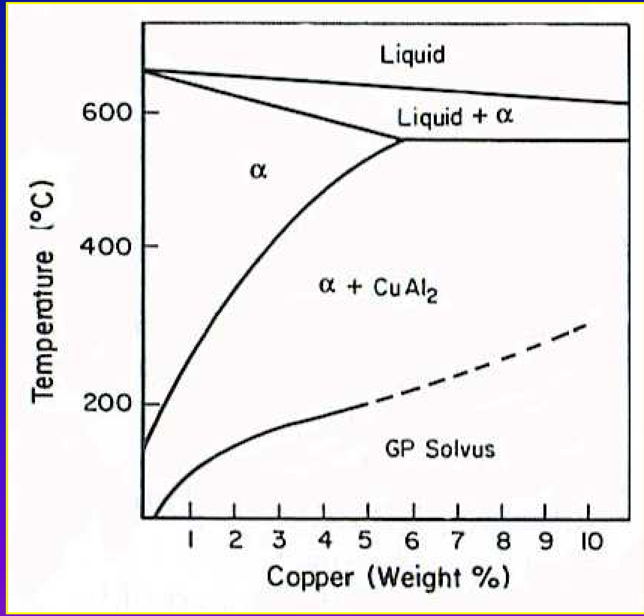
- Eutectic phase consists of alternate lamella structure of α and θ phases, resembling ***pearlite*** in carbon steels, which give high strength but brittle.

Hypoeutectic

- ***> 5% Cu***, cooling is in equilibrium, grain boundaries of α phase surrounded by ***(α+θ)*** eutectic phase – reduced toughness.
- ***< 5% Cu***, α phase in some cases surrounded by θ phase.

Hypereutectic

- ***Cu*** → 33%, too brittle due to high amount of θ phase.



Equilibrium phase diagram of Cu-Al

Al-Cu alloys (2xxx series)

• Precipitation hardening – by forming θ phase in α matrix, gives high strength and toughness.

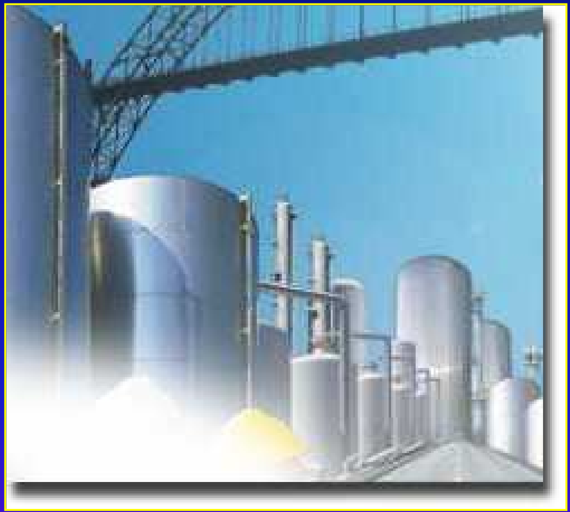
Properties:

• High strength (2119: σ_{TS} 505 MPa).
• Good creep strength at high temp.
• High toughness at cryogenic temp.
• Good machinability.

Welding wires

Applications:

• Fuel tanks



Fuel tanks

Al-Cu-Mg alloys (2xxx series)

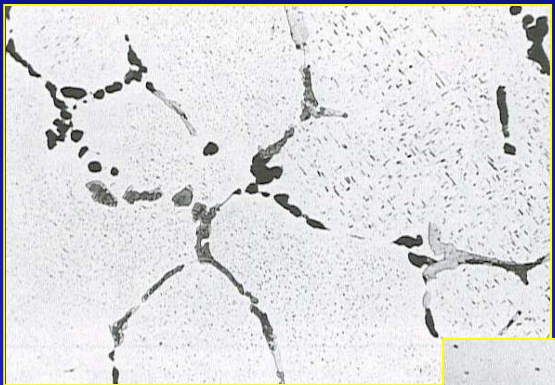
• **Miner amount of Mg (0.2%) modifies the precipitation process, resulting in greater age-hardening.**

Properties:

• High strength (2024: σ_{TS} 520 MPa).
• high toughness.

Applications:

• pistons, rivets for aircraft constructions



2024 heated ingot showing soluble Al_2CuMg.

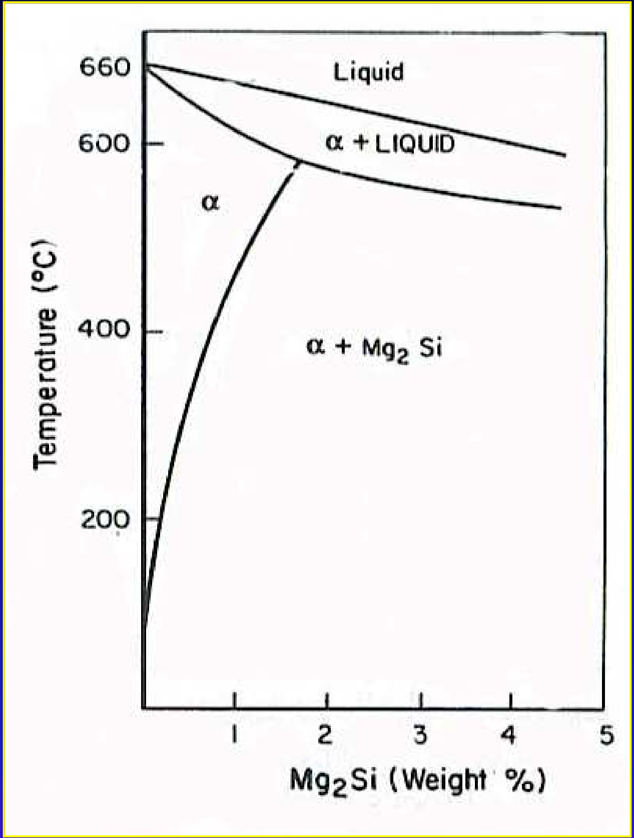
2024-T4 (solution heat treated) plate showing redistribution of constituents due to mechanical working.

Airplane structure

Aluminium pistons and devices for thermal shock used in airplane

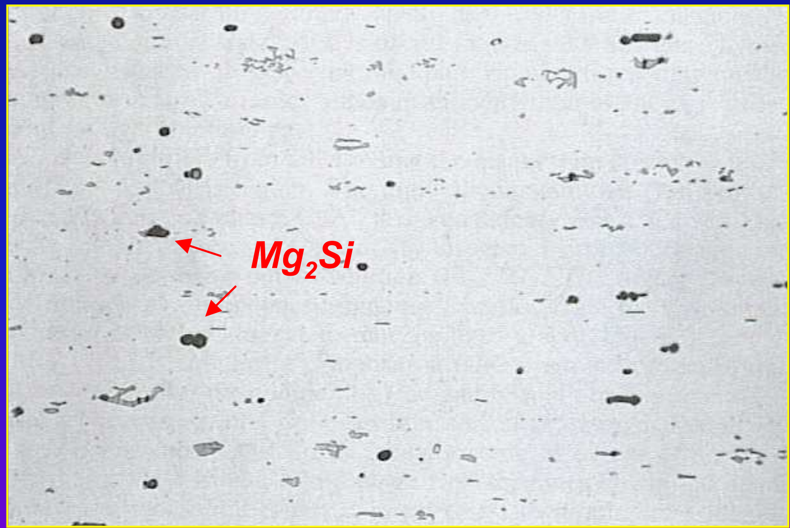
Al-Mg-Si alloys (6xxx series)

- ***Mg*** and ***Si*** are added in balanced amount to form ***Mg_2Si***.
- Excess amount of ***Si*** → brittle.
- Congruent ***Mg_2Si*** has properties similar to pure metal can dissolve in α phase upto 1.85% at 595^{o}C (eutectic) and reduces to 0.2% at 200^{o}C.



$$L \leftrightarrow \alpha + Mg_2Si + (Si)$$

Pseudo-binary Al-Mg_2Si diagram



6061-T6 sheet showing excess soluble Mg_2Si particles as redistributed by mechanical working (dark phase)

Al-Mg-Si alloys (6xxx series)

Mg + Si (0.8-1.2%)

Properties:

- Medium-strength structural alloys (most widely used 6063-T6, σ_y 215 MPa, σ_{TS} 245).
- Readily extruded
- Colour anodized.

Applications:

- Architectural & decorative finishes.
- Automotive trim.

Al 6005 satellite dish

Al 6009 car body

Al 6061 Structural component

Electric train

Al 6063 Large water pipe

Al-Mg-Si alloys (6xxx series)

Mg + Si (> 1.4%)

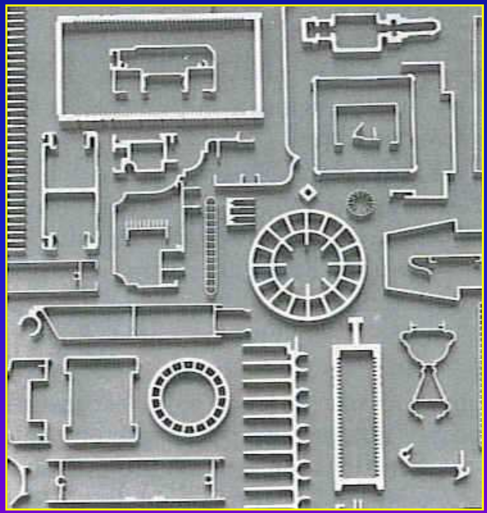
• Some alloys contain excess amount of ***Si*** (to form ***Mg_2Si***), which promotes additional response to age-hardening by
1) Refining the size of Mg_2Si particles
2) Precipitating as silicon.

Properties:

• Higher strength on ageing, 6013 - Al-Mg-Si-Cu, σ_y 330 MPa(T6) and 415 (MPa) T8.

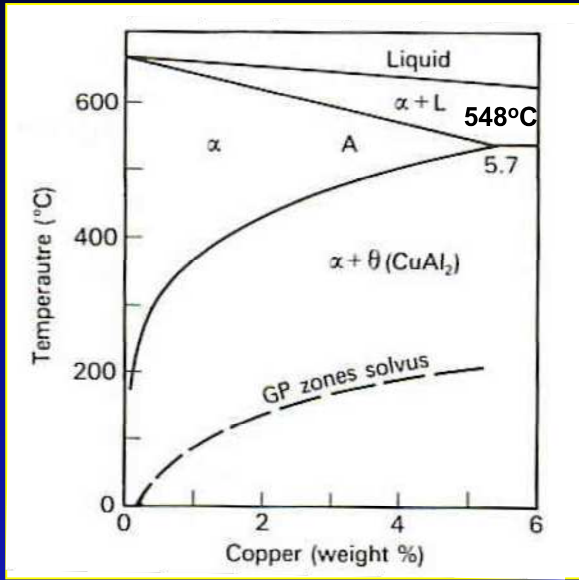
Applications:

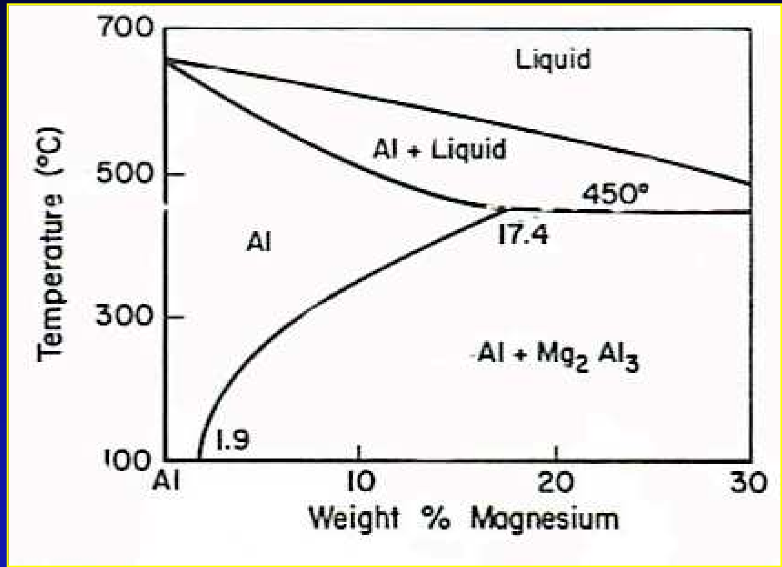
• Aircraft, automotive
• Recreation applications
• Extruded sections



Extruded sections

Age-hardening for Al-Cu and Al-Mg alloys

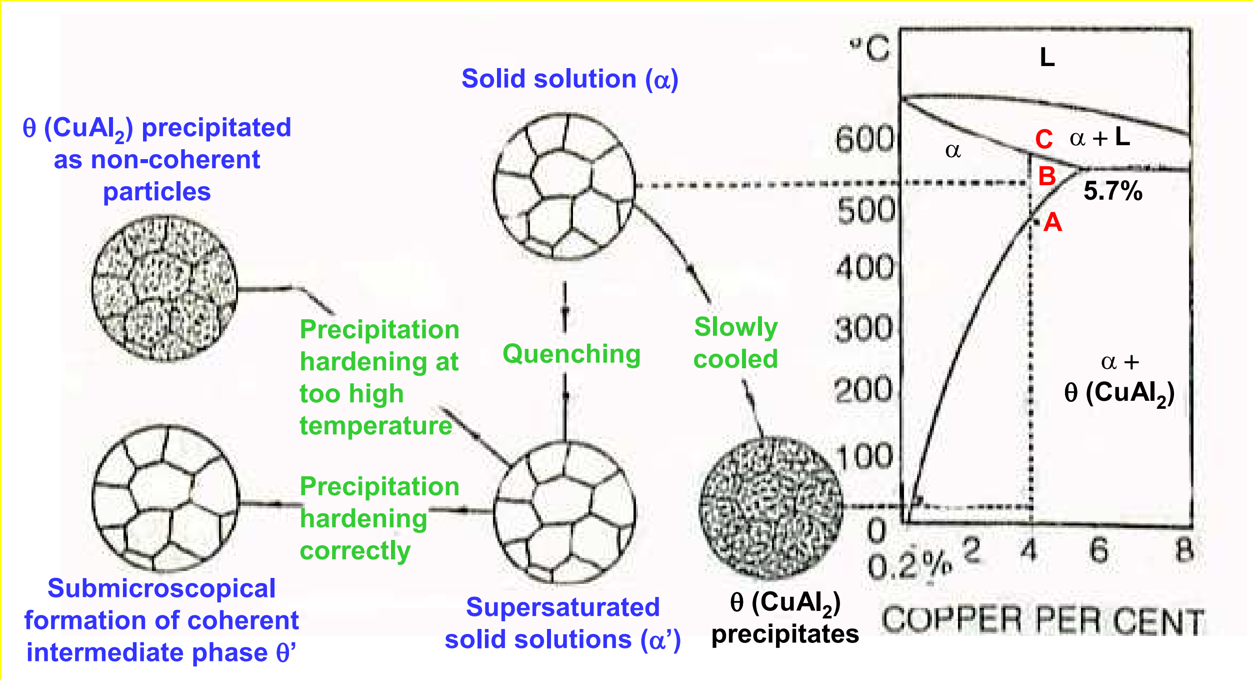




• Alloys with < 0.5% ***Cu*** or <1.4% ***Mg*** in ***Al-Cu*** and ***Al-Mg*** alloys respectively cannot be ***aged-hardened***.

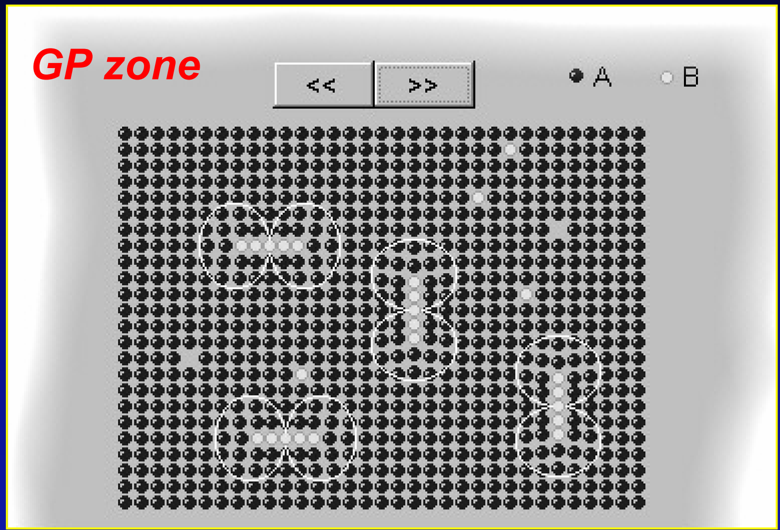
• ***Aged hardening*** of alloys with > 5.7% ***Cu*** or < 17.4% ***Mg*** in ***Al-Cu*** and ***Al-Mg*** alloys respectively are less effective (less hardness).

Example: Age-hardening in Al-Cu alloys



- ***Equilibrium cooling*** of 4% ***Cu*** down to ***RT*** gives $\alpha + \theta\ (CuAl_2)$ which are non-coherent precipitates with the matrix (starting at ***A***).
- ***Quenching*** from just above point ***A*** down to ***RT*** will give ***supersaturated solid solution (α' phase)*** where higher amount of ***Cu*** can be dissolved in the matrix. → non-equilibrium.
- ***$CuAl_2$*** will precipitates from the α' phase if leave it for ~ 6 days (trying to get back to equilibrium) and this leads to ***higher strength***.

Age-hardening mechanism in Al-Cu alloys

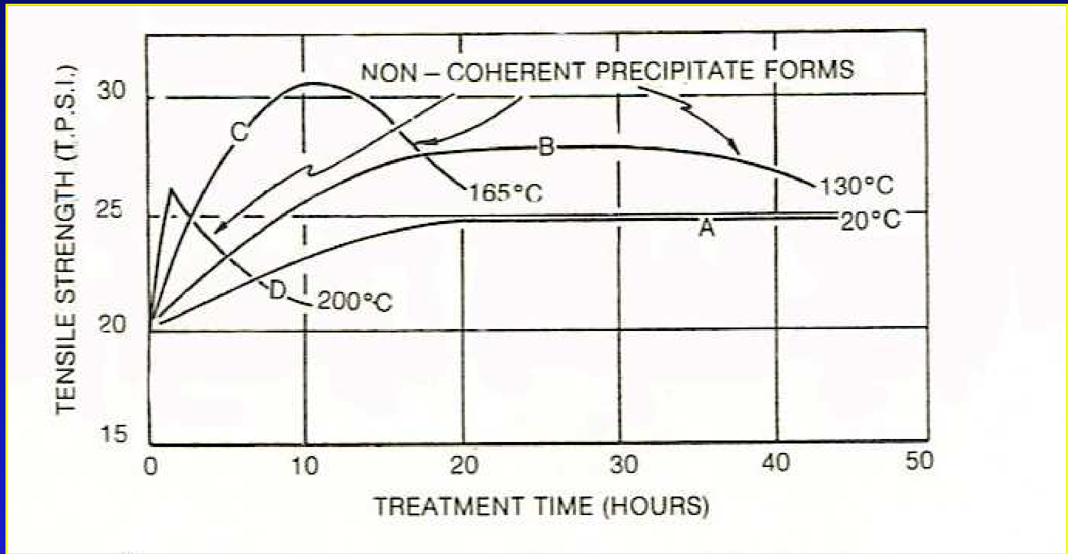


SSSS → GP zone → θ' → θ

- ***Coherent precipitates*** or *θ'* provide distortion within the atom lattice which affect dislocation movement. → improved mechanical properties.

- ***Coherent θ'*** changes to ***non-coherent precipitates θ*** with increasing ageing time (try to get back to equilibrium) → less strength due to no distortion within the lattice. (***Over aging***)

Effects of time and temperature of precipitates – treatment on the structure and tensile strength of a suitable alloy



• ***Ageing*** at ***T*** = 165°C provides the optimum strength due to homogeneous distribution of high amount of θ'.

Al-Zn-Mg and Al-Zn-Mg-Cu alloys (7xxx series)

• **High response to age-hardening especially with Cu addition (0.3%) to also give stress corrosion cracking resistance.**

Properties:

• Strength is insensitive to cooling rate → suitable for ***welding***.
• ***Yield strength*** might be double to ***Al-Mg*** and ***Al-Mg-Si*** alloys (~ upto 600 MPa).
• ***Stress corrosion cracking resistance*** in ***Al-Zn-Mg-Cu*** alloys.

Al 7039 aircraft construction

Applications:

• Light weight military bridge
• Aircraft construction.

Al 7075 Component in motorcycle

Al 7005 post box

Melting of aluminium

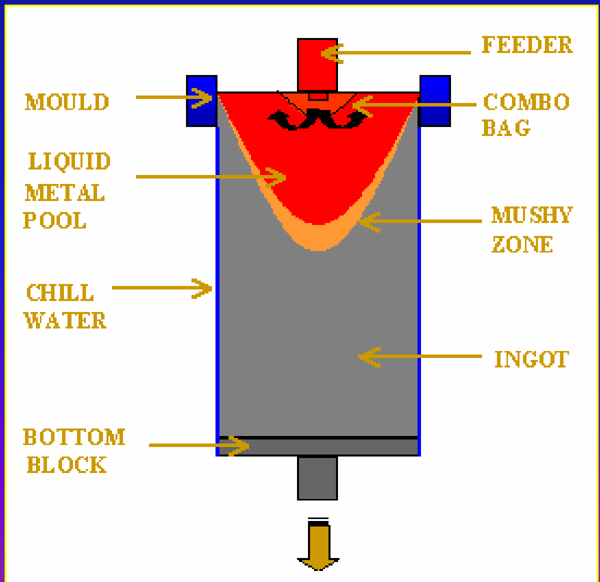
Direct-chill casting process

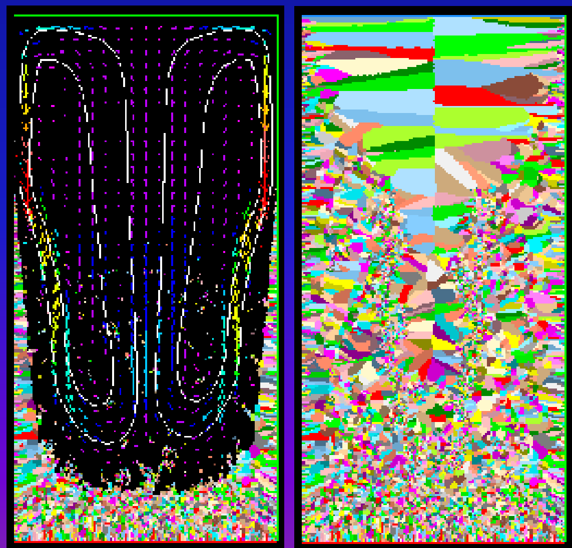
• Uniform ingot structure is obtained by ***direct-chill (DC) casting*** most common in vertical than horizontal process.

• Molten alloy is poured into water-cooled moulds having retractable bases.

• During the ***solidification process,*** metal solidifies at the ***bottom block*** with subsequent solidification of the rest occurs rapidly by means of chill water.

Direct-chill casting process (vertical)





Grain growth during solidification

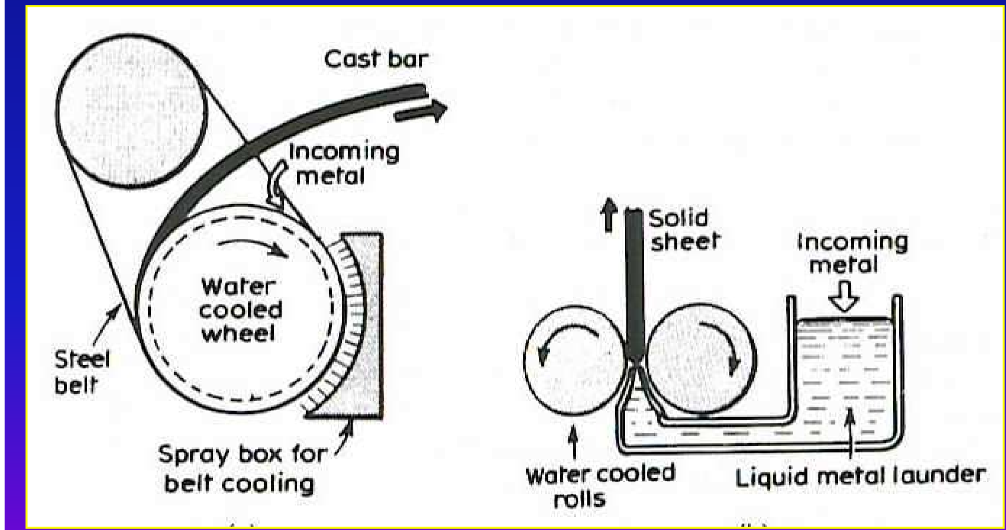
<u>Note:</u> the ingot obtained may be rectangular or round depending on further working processes: rolling, forging or extrusion.

Continuous casting process

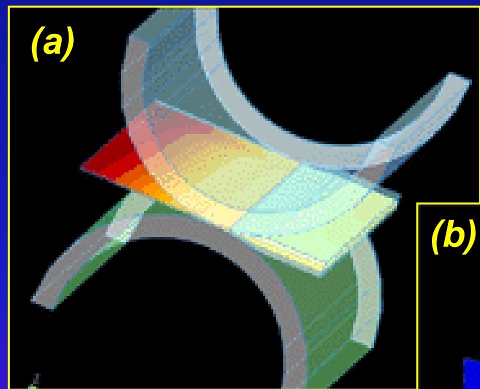
- The process produces ***continuous thin slabs*** and sheets with sizes to those required in final products. → reducing great amount of ***investment cost*** required to reduce in sizes from large ingot.

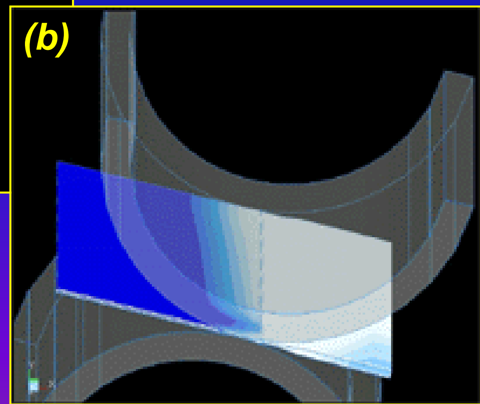
- ***Continuous casting of aluminium alloys*** involves complex surface cooling patterns, due to the alternation of rolls and spray zones.

- Sets of ***water-cooled rolls*** are rotated continuously to produce slab.



Continuous casting process





Thermal field (a) and solid fraction (b)

Metallurgical factors affecting melting of aluminium

Molten aluminium is susceptible to:

1) ***Excess absorption of hydrogen gas*** (embrittlement)
2) ***Oxidation*** of the melt to form complex oxides of ***Mg, Na, Ca, Sr*** (affecting mechanical properties) as films or particles
3) ***Inclusions*** in forms of borides, oxides, carbides and non-metallic particle, i.e.,Al_2C_3 (found in all ***Al alloys***). → stress concentration.

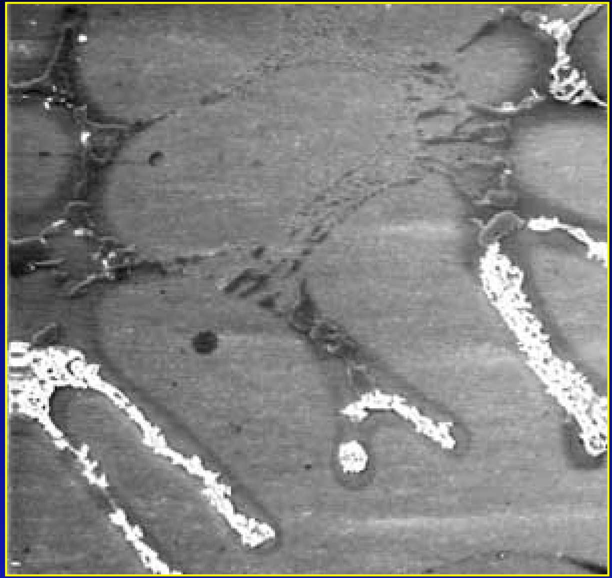
Control of metallurgical structure

Primary factors are ;

1) Dendritic cell size or dendrite arm spacing,
2) Form and distribution of microstructural phase
3) Grain size.

Fine grain size or structures are desirable, leading to improvements of;

- feeding characteristics
- tear resistance
- mechanical properties
- pressure tightness
- response to thermal treatment
- chemical, electrochemical and mechanical finishing.



As-cast microstructure

Grain refiners:

- master alloys of Ti
- Al-3-5%Ti refiners
- Al-Ti-0.2-1%B refiners (Ti:B ~ 5:50)

Grain refinement by inoculation

Grain refiners used are;

- master alloys of Ti
- Al-3-5%Ti refiners
- Al-Ti-0.2-1%B refiners
  (Ti:B ~ 5:50)

$$Al_{(liq)} + TiAl_{3(crys)} \rightarrow \alpha - Al \;\; alloy \;\; solid \;\; solution$$

- ***$TiAl_3$*** crystals act as ***nuclei*** for grains to grow.
- Multiple nucleation of averagely eight sites may occur on each particle.
- ***TiB_2*** also offers grain refinement effect.

Petal-like $TiAl_3$ particles in α-Al solid solution

Homogenisation of DC ingots

Homogenisation of DC ingots at temperatures 450-600^{o}C prior to working processes is common in aluminium alloys in order to:

1) Reducing micro-segregation
2) Removing non-equilibrium, low melting point eutectics that may cause cracking during subsequent working.
3) Controlling excess amount of precipitates that are dissolved during solidification.

- During homogenisation, alloying elements will diffuse from ***GBs*** and ***other solute-rich regions*** to ***grain centres***.
- ***Diffusion time*** depends on ***diffusion distance*** (grain size, dendrite arm spacing) and the ***diffusion rate*** of alloying elements.

$$\boxed{x = \sqrt{Dt}} \quad \text{...Eq. 10}$$

where

x = mean distance
D = diffusion coefficient
t = time

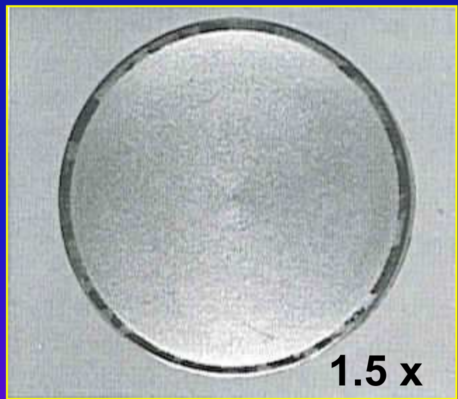
<u>Note:</u> homogenisation time varies from 6-24 hrs, depending on conditions and alloy systems.

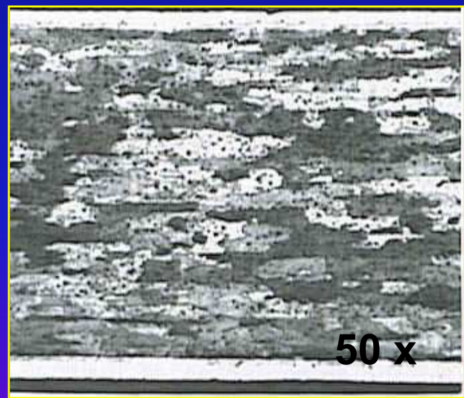
Fabrication of DC ingots

• After homogenisation, the ingot is ***hot-worked*** to ***break down the cast structure*** (coarse grain structure), giving **uniform grain size** as well as constituent size and distribution.

• ***Cold working*** is followed especially to ***strengthen*** alloys which do not response to precipitate hardening. This might be followed by ***immediate annealing*** at T ~ 345-415^{o}C.

X-section of extruded bar having coarse recrystallised grains around the periphery





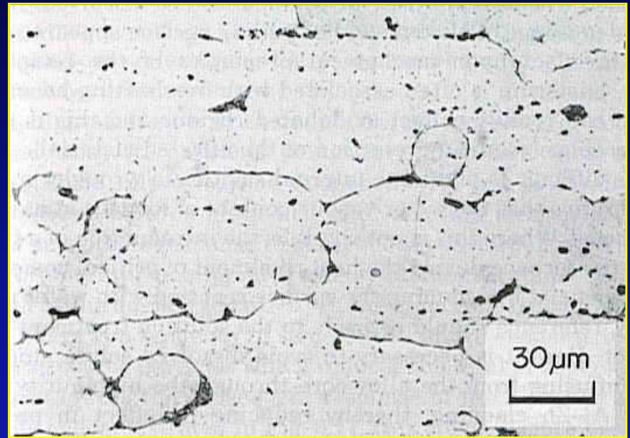
X-section of a high-strength alloy sheet roll-clad with pure aluminium

Thermal treatment

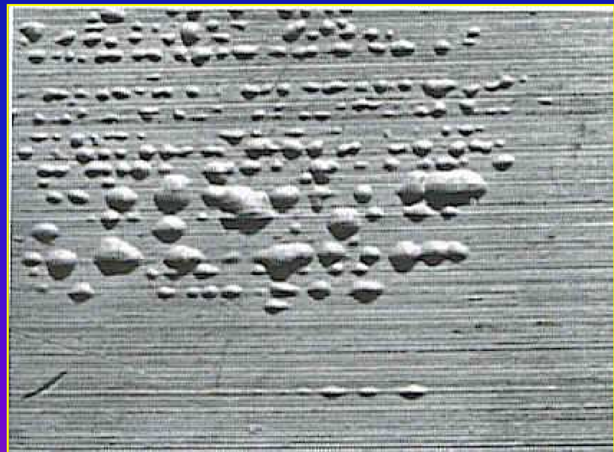
Thermal treatment is performed to develop ***desirable mechanical properties*** required for service performance.

Solution treatment

- Solution treatment should be ideally carried out at temperatures within the ***single phase*** to obtain ***complete solution*** of most of the alloying elements.
- However, this temperature should not be over the ***solidus temperature*** to avoid ***overheating***, i.e., liquation of compounds and at GBs, as well as ***grain growth*** → ***affecting mechanical properties.***
    - ***Absorbed hydrogen atoms*** can recombine at internal cavities to form pockets of gas or ***blistering***. → should minimise ***water vapour*** in the furnace or ***cladding***.



Liquation along GBs due to overheating of an Al-Cu-Mg alloy during ST

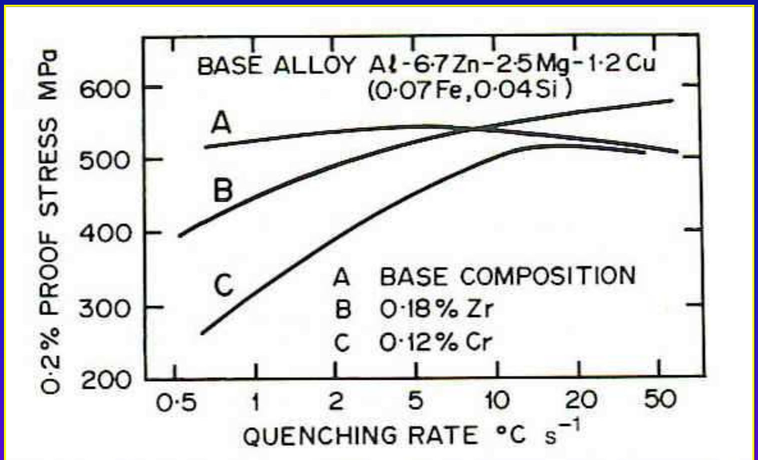


Blistering on Al alloy surface, heat-treated in a humid atmosphere

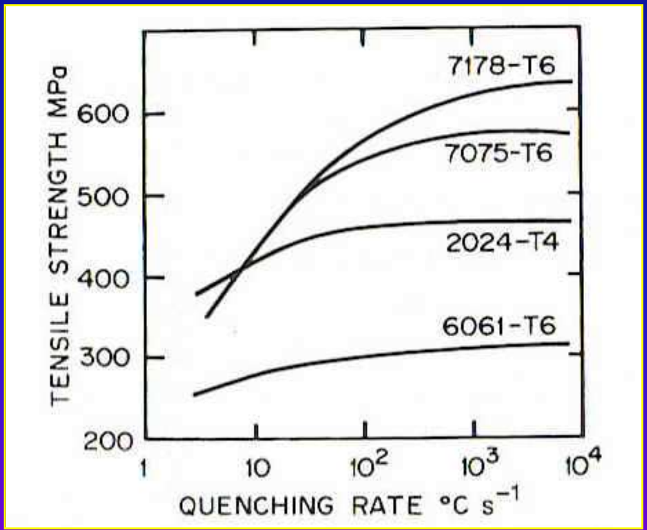
Quenching

*The alloy is **quenched after solution treatment** normally to room temperature to achieve **maximum supersaturated alloying elements** for subsequent ageing.*

1) Cold-water quenching : for high cooling rate especially in thick sections, but gives distortions (***residual or quenching stresses***) in thin sections. → can be relaxed (20-40%) during ***ageing***.



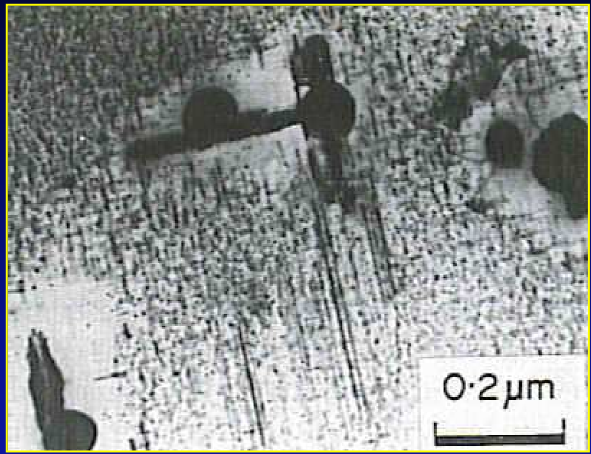
The effect of minor additions of Cr and Zr on the quench sensitivity



Tensile strength as a function of quenching rate in T_{crit} ~ 290-400°C

Quenching

2) Hot or boiling water quenching as well as air-cooled quenching: slower rates of cooling and quenching stresses, showing ***acceptable response to subsequent ageing*** – also depending on quench sensitivity of each alloy systems. However this might cause ***heterogeneous nucleation of coarse particles***.



Heterogeneous nucleation of large particles in slow-quenched and aged Al-Mg-Si alloy.

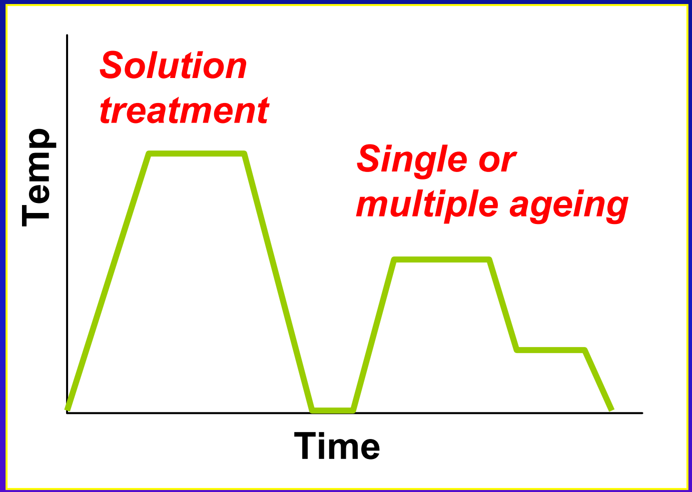
3) Salt-bath quenching : (at 180°C and holding for a time before cooling to room temperature.) for ***high-strength Al-Zn-Mg-Cu alloys***. Provides ***rapid cooling rate*** but ***reduced residual stresses***.

Age-hardening

Age-hardening *is the final stage to optimise properties in the heat-treatable aluminium alloys.*

- Natural ageing – at room temperature
- Artificial ageing – at elevated temperatures (100-190^{o}C)

- ***Ageing temperature and time*** depend upon alloy systems and the final required properties.



- ***Single-step ageing:*** to develop high strength ~ 8-24 hrs.
- ***Multiple ageing:*** to give specific properties such as stress-corrosion resistance, toughness.

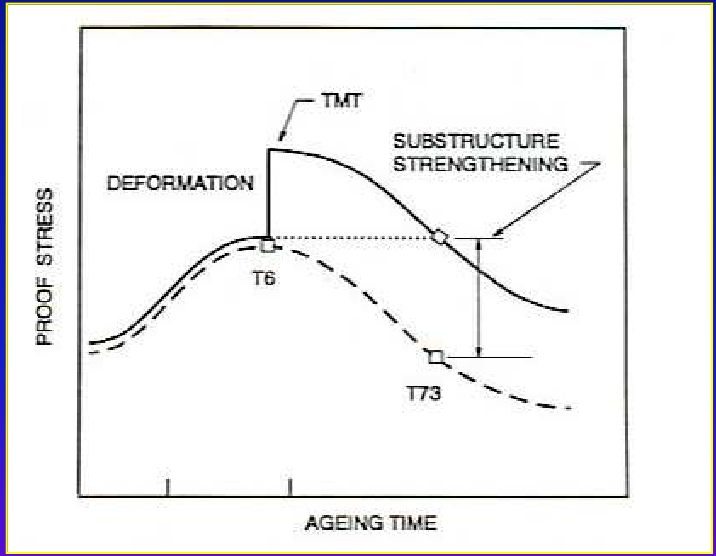
Note: RT ageing provide incubation or nuclei for the growth of GP zone in the subsequent elevated temperature ageing.

Thermo-mechanical processing

Thermo-mechanical treatment (TMT) *is the combination of* ***plastic deformation*** *and* ***heat treatment*** *to provide high strength properties.*

There are ***two types of TMT*** for high strength aluminium alloys.

1) Intermediate TMT : The deformation is applied to give very fine recrystallised grains ***prior to solution treatment***.



2) Final TMT : the deformation is applied ***after solution treatment*** and may involve cold or warm working before, during or after ageing.

Cast aluminium alloys

Properties required for good casting

- Low melting temperature
- Low solubility of gases except H_2
- Good fluidity
- Good surface finishes

Disadvantage

- High solidification shrinkage (3.5-8.5%)

Factors controlling properties

- Melting and pouring practices
- Impurity levels
- Grain size
- Solidification rate

Cast aluminium alloys are widely used for transport applications,
Ex: Cast engine block

Note: Innovations and development are mainly oriented to the automobile sector which is the most important market for castings.

Designations of cast aluminium alloys

United States Aluminium Association system

- Using four-digit system.

1xx.x	*Al, 99.00% or greater*
	Al alloys grouped by major alloying elements
2xx.x	*Cu*
3xx.x	*Si with added Cu and/or Mg*
4xx.x	*Si*
5xx.x	*Mg*
7xx.x	*Zn*
8xx.x	*Sn*
9xx.x	*Other elements*
6xx.x	*Unused series*

1xx.x series

- Second two digits indicate the minimum percentage of Al, Ex: 150.x → 99.50% Al.
- Last digit (after decimal point) indicates product forms.

1 = casting, 2 = ingot

2xx.x to 9xx.x series

- Second two digits identify the different aluminium alloys.
- Last digit (after decimal point) indicates product forms.

Note: The 6xx.x series is allocated to Al-Si-Mg alloys in Australia.

British System

- Designation of ***cast Al alloy*** in ***British system*** is covered by the ***British Standard 1490***.

M	***As-cast***
TB	***Solution treated and naturally aged***
TB7	***Solution treated and stabilised***
TE	***Artificially aged after casting***
TF	***Solution treated and artificial aged***
TF7	***Solution treated, artificially aged and stabilised***
TS	***Thermally stress-relieved***

Casting techniques

The most common aluminium casting techniques are;

1) ***Sand casting***
2) ***Die casting***
   - ***gravity casting***
   - ***high pressure die casting***
   - ***low pressure die casting***
   - ***vacuum die casting***
   - ***squeeze casting***

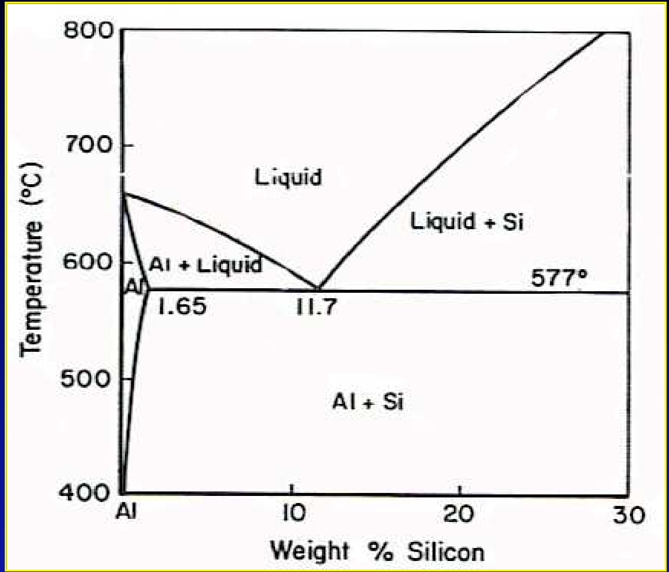
Selection of casting process *depends upon alloy composition which is related to controlled characteristics such as solidification range, fluidity, susceptibility to hot-cracking.*

Castability	**3xx.x > 4xx.x > 5xx.x > 2xx.x > 7xx.x**
	Si,Cu,Mg Si Mg Cu Zn

Alloys based on the Al-Si system

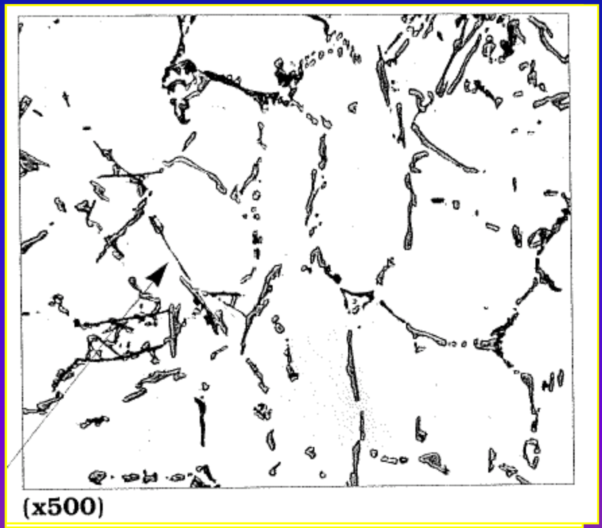
The most important group and constitute for 85-90% of the total aluminium casting.

- ***Eutectic (Al – 12.7%Si)*** is formed just over 1% ***Si*** addition, which contains a coarse microstructure of large plates or needles of ***Si*** in a continuous ***Al*** matrix.
- Large ***Si*** plates → low ductility and brittleness.



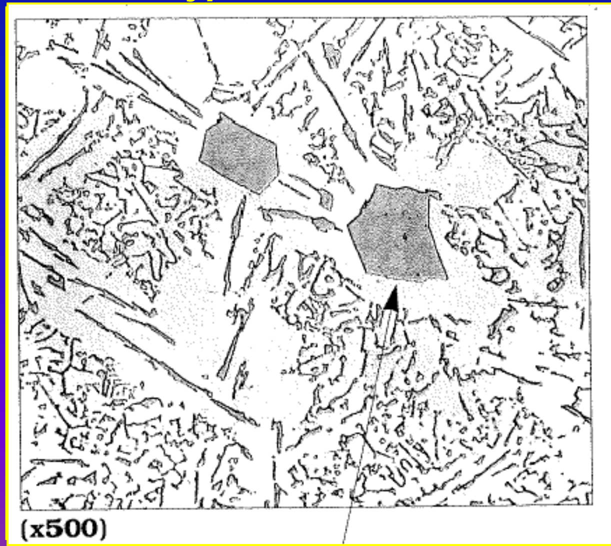
Equilibrium binary Al-Si phase diagram

Hypoeutectic Al-Si



Eutectic Al-Si

Hypereutectic Al-Si



aluminium.matter.org.uk

Composition of common Al-Si casting alloys

Alloy	Method(b)	Si	Cu	Mg	Fe	Zn	Others
		Elements (wt. %)					
319.0	S, P	6.0	3.5	<0.10	<1.0	<1.0	
332.0	P	9.5	3.0	1.0	1.2	1.0	
355.0	S, P	5.0	1.25	0.5	<0.06	<0.35	
A356.0	S, P	7.0	<0.20	0.35	<0.2	<0.1	
A357.0	S, P	7.0	<0.20	0.55	<0.2	<0.1	0.05 Be
380.0	D	8.5	3.5	<0.1	<1.3	<3.0	
383.0	D	10.0	2.5	0.10	1.3	3.0	0.15 Sn
384.0	D	11.0	2.0	<0.3	<1.3	<3.0	0.35 Sn
390.0	D	17.0	4.5	0.55	<1.3	<0.1	<0.1 Mg
413.0	D	12.0	<0.1	<0.10	<2.0	-	
443.0	S, P	5.25	<0.3	<0.05	<0.8	<0.5	

(a) Remainder: Aluminum and other impurities
(b) S, Sand Casting; P, Permanent Mold Casting;
D, High Pressure Die Casting

<u>Note:</u> Available with hypoeutectic and less commonly hypereutectic compositions.

Properties:

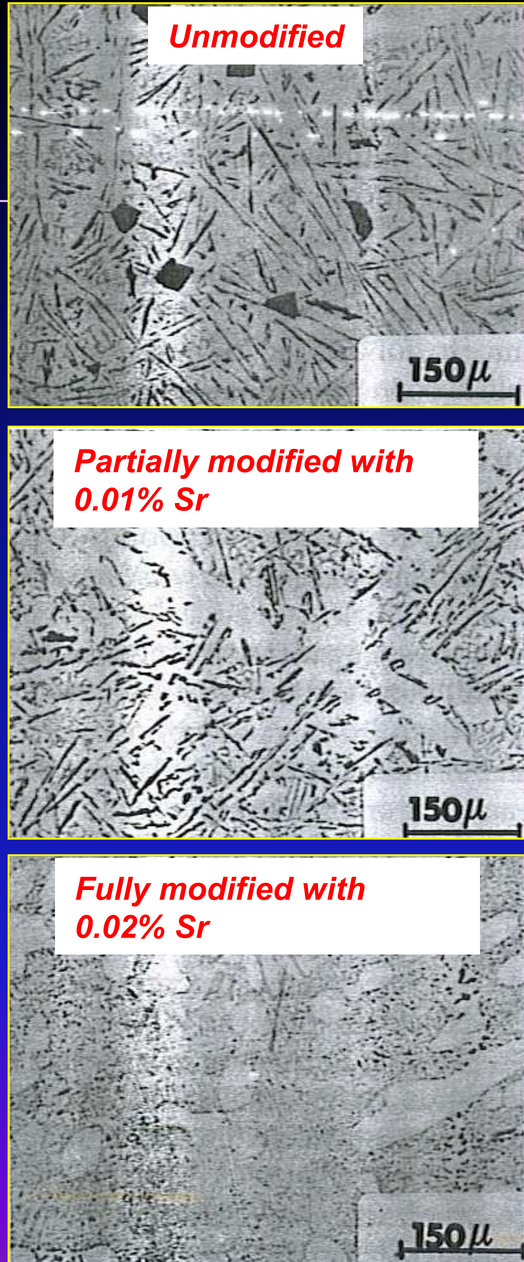
- Good castability and high fluidity due to Al-Si eutectic
- High corrosion resistance
- Good weldability.
- Low solidification shrinkage.
- Machining difficulty in hypereutectic.

Modification of microstructure

- Apart from fast cooling to refine the microstructure, ***modification*** can be carried out by adding certain ***alkali fluorides*** to the melt prior to pouring.
- Additions of ***Sr*** or ***Na*** change ***eutectic microstructure*** from needle-like or lamellar to ***fibrous***.
- Higher concentration of 0.02% ***Sr*** fully modifies to fibrous structure.

- ***Grain refinement*** improves resistance to ***hot tearing***, decreases ***porosity*** and increases ***mass feeding***.

<u>Note:</u> Higher Si content requires more modifying agent.

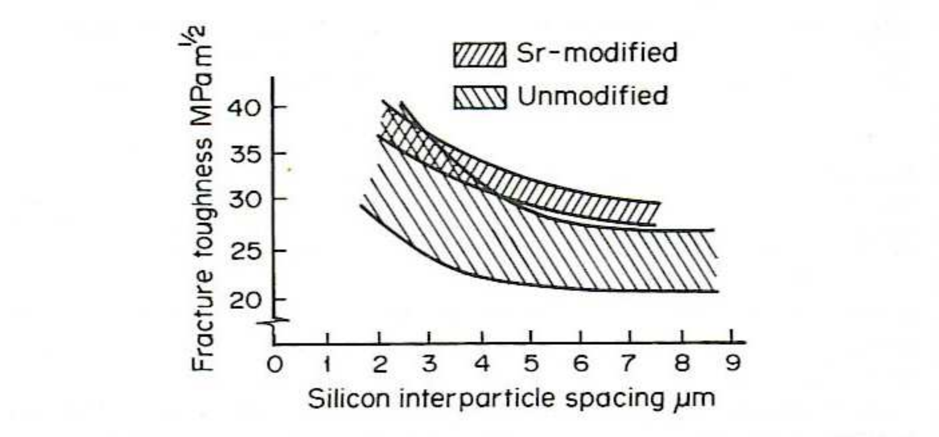


Microstructures of 413 alloy (Al-Si eutectic alloy) and modified with Sr

Mechanical property improvement due to refined microstructure

Condition	Tensile strength (MPa)	Elongation (%)	Hardness (Rockwell B)
Normal sand cast	125	2	50
Modified sand cast	195	13	58
Normal chill cast	195	3.5	63
Modified chill cast	220	8	72

Mechanical properties of Al-13%Si alloy



Fracture toughness of alloy A357 (Al-7Si-0.5Mg) with and without Sr modification

Tensile strength ↑

% Elongation ↑

Hardness ↑

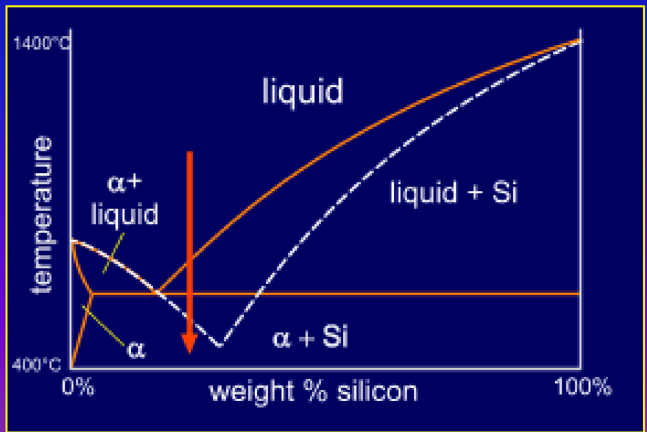
Fracture toughness ↑

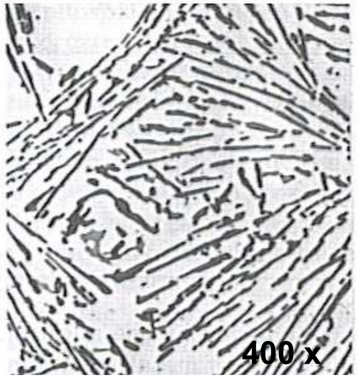
Note: Cast Al alloys normally have inferior mechanical properties to those of wrought Al-alloys.

Example: Modification with Na

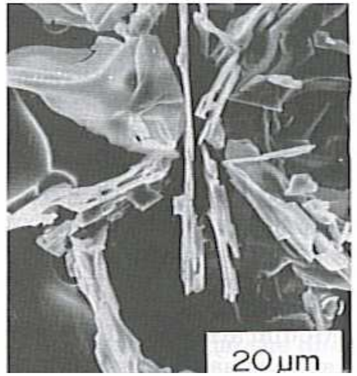
- ***Modification mechanism*** by ***Na addition*** are still controversial.
- The effect of ***Na*** on the nucleation and growth of ***eutectic silicon*** during solidification.
- ***Na*** restricts growth of ***Si*** particles by segregation at periphery of ***Si plates*** and ***prohibiting growth***.
- Excess amount of ***P*** → large particles of silicon resulting ***poor mechanical properties***.

Al-Si +Na

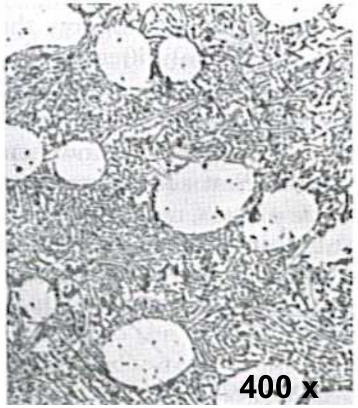




(a) 12% Si unmodified.



(b) 12% Si unmodified (SEM).



(c) 12% Si modified with Na.

(d) 12% Si with excess P.

<u>Ex:</u> 0.005-0.01% Na or 0.02%Sr are required for modification for 7% Si.

Variables determining microstructure

1) Type of modifier used

- Na is more powerful than Sr.

2) Amount of modifier used

- A critical level is required to obtain a full modification.
- Too high level → over modification.
- Modifier fading → need top up.

3) Impurities present in the melt

- ***P*** makes modification more difficult.
- ***Mg*** was found to make modification easier.

4) Freezing rate

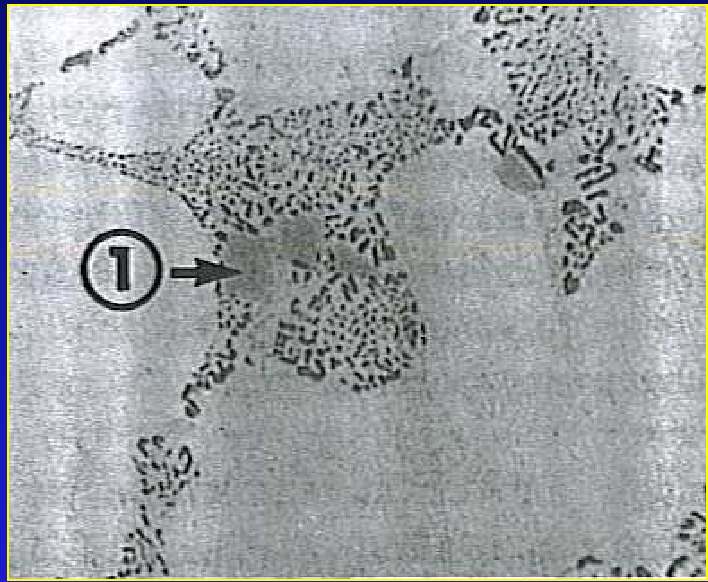
- Higher solidification rates assist the modification process.

5) Si content of the alloy

- Higher amount of existing ***Si*** requires greater amount of modifier to obtain complete modification.

Over modification

- ***Over modification*** occurs when Na concentration exceeds 0.018 – 0.020%.
- ***Coarsening of Si*** takes place associated with bands of primary aluminium.
- ***Na*** is rejected in front of the solidifying interface and form ***AlSiNa*** which serves as nucleation sites for ***coarse silicon particles***.
- Excess amount of ***Sr*** also cause over modification by ***coarsening of the silicon structure***.



Al_4SrSi_2 phase (1) caused by over modification of 356 alloy (x270)

Al-Si-Cu, Al-Si-Mg alloys

Cu and Mg additions provide much greater strengthening effect.

Al-Si-Cu alloys

3 -10.5% Si
1.5 - 4.5% Cu

- ***Cu*** addition increases ***strength*** and ***machinability*** but reduces castability, ductility and corrosion resistance.
- Higher ***Si*** alloys are used for ***pressure die casting*** while lower ***Si*** and higher ***Cu*** alloys are used for ***sand and permanent mould casting.***

Applications:

- Automative cylinder heads/blocks in place of cast iron.

<u>Note:</u> more complex compositions for special properties. i.e., elevated temperature properties.

<u>EX:</u> Al-12Si-1Cu-1Mg-2Si and Al-17Si-4Cu-0.55Mg).

Pistons and air compressor. 390.0 (Al-Si-Cu)

Pistons and connection rods. 319.0 (Al-Si-Mg)

Al-Cu alloy

- ***Strength*** and ***hardness*** at ***T*** up to 250^{o}C is achieved from a combination of ***precipitation hardening*** together with ***dispersion hardening*** by intermetallic compounds.
- Strength is higher than other ***cast Al alloys*** and comparable to ***wrought Al alloys***.

Properties:

- σ_y 345-480 MPa and σ_{TS} 415-550 MPa due to high response to ***ageing***, with 5-10% elongation.

Applications:

- Elevated temperature applications. Ex: ***Al-4Cu-2Ni-1.5Mg*** for diesel engine pistons and air-cooled cylinder heads for aircraft.

Aerospace housing (201.0)

Flywheel housing (295.0)

Note: Have casting problem with hot-tearing

Al-Mg alloys

- ***Al-Mg*** alloys are less preferable than ***Al-Si*** in casting and require practice during melting and pouring due to ***oxidation problem***.
- Mg content ~ 4 - 10%.
- Most are sand cast.

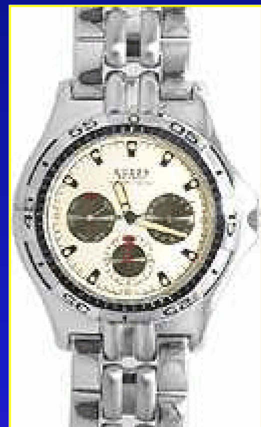
Properties:

- High resistance to corrosion
- Good machinability
- Attractive anodised surface.
- Little or no response to heat treatment.

Applications:

- Chemical and sewage
- Kitchen utensils.

Kitchen utensils



Watch body

Al-Zn-Mg alloys

- Binary ***Al-Zn*** alloys are obsolete except for use of ***sacrificial anode for steel structure protection***.
- Normally ***sand cast*** because permanent moulds tends to cause hot-cracking.

Properties:

- σ_y 115-260 MPa and σ_{TS} 120-310 MPa.

Applications:

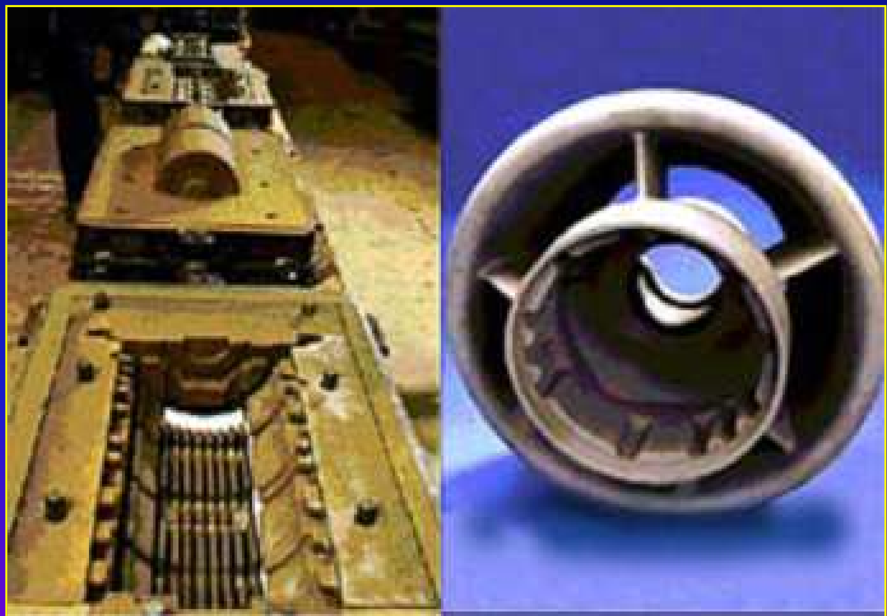
- High eutectic melting point.
- Good machinability.
- Dimensional stability.
- Corrosion resistance.
- Not suitable for high temperature applications due to rapid softening.

Casting processes

- *Sand casting*
- *Die casting*
- *Semi-solid casting (Thixo-casting)*
- *Squeeze casting*
- *Cosworth casting*
- *Improved low pressure casting*

Sand casting

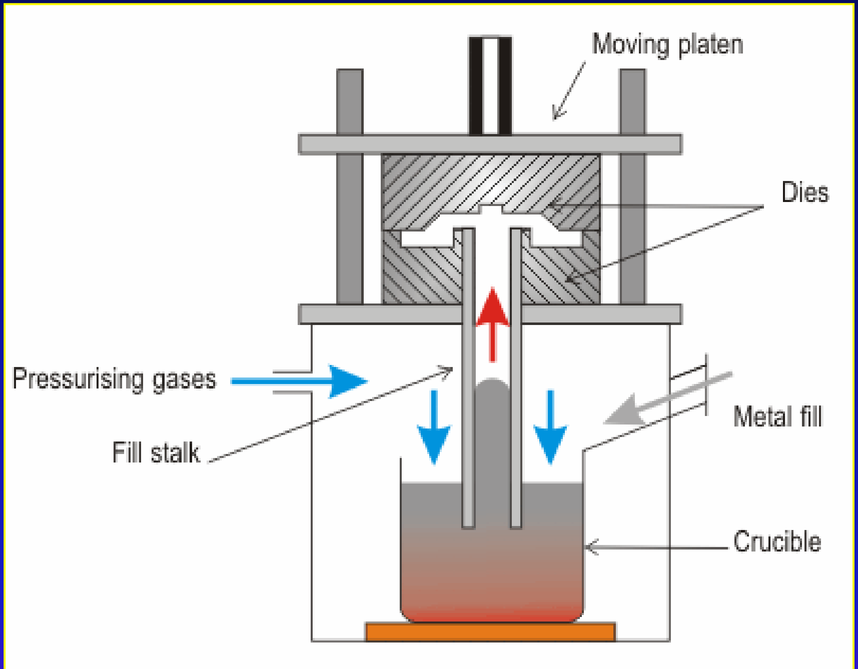
- Versatile – complex designs, sizes, shapes
- Sand – silica sand, zirconia sand, olivine
- Sand mould is destroyed after each use and reusable
- Bonding of sand mould is a key step.
- Size and shape of sand also control the quality of the cast.



Half mould with cores and an example of a cast air intake for a turbocharger

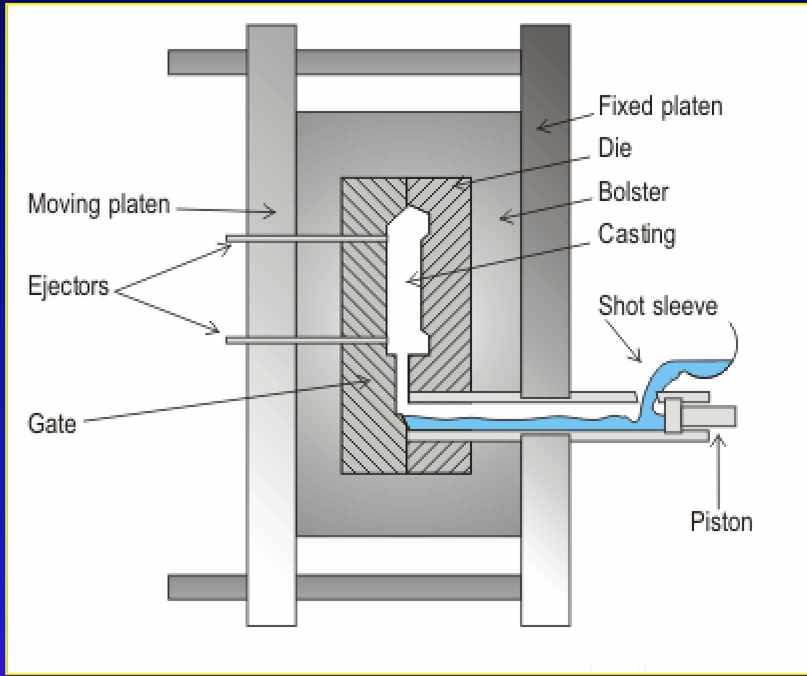
Die casting processes

• Liquid metal is pushed into a die cavity either by ram, gas or a pump and either by means of high or low pressure.



Low pressure die casting

Liquid metal enters die at relatively low velocity.



High pressure die casting

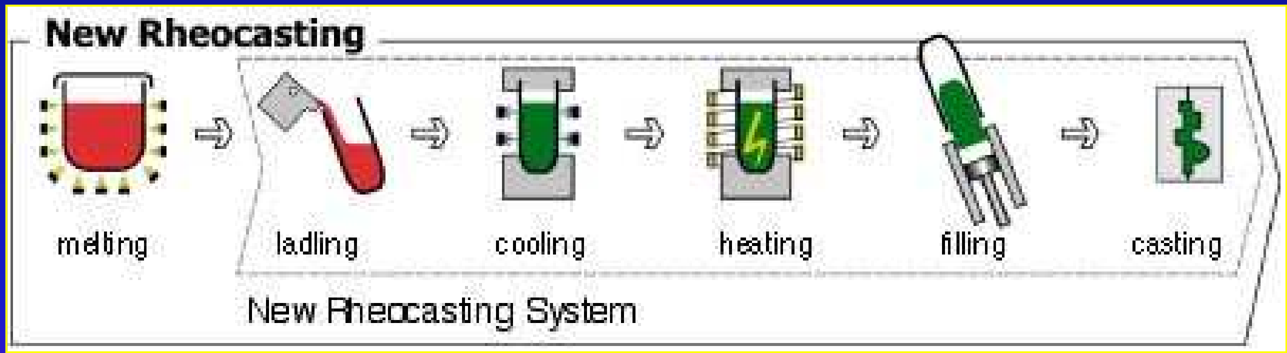
Liquid metal enters die at high velocity.-no sand cores are normally used.

Semi-solid processing (Thixo-casting)

• The use of ***agitation*** during solidification to break down ***dendrites*** can improve ***fluidity*** although the solid content has reached 60%.

• Broken down dendrites result in very fine grain size.

• Semi-solid slurry has thixotropy characteristics (agitating ↑ viscosity ↓)



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Note: Use for the production of automotive components such as master brake cylinders, pistons, compressors

Advantages of semi-solid casting

1) Reduced capital investment and operating cost due to

- Contained process of melting.
- Less energy required due to no complete melting.
- Reduced cycle time and minimised scrap.

2) Reduced shrinkage and cracking

- The alloy is party solidified during casting.

3) Lower operating and pouring temperature

- Improve the life of metal dies.

4) Readily produced composite materials (Compocasting)

- Fibres or solid particles can be added into the feedstock.

Squeeze casting

• The process involves ***working*** or ***processing*** the ***liquid metal*** in a hydraulic press during solidification.

• The use of pressure (~200 MPa) which is higher than conventional casting helps to ***fill up pores*** by the flow of the melt.

• Promote intimate contact between casting and mould walls. → improve heat extraction → ***grain refinement***.

Advantages:

• Improvement in ductility

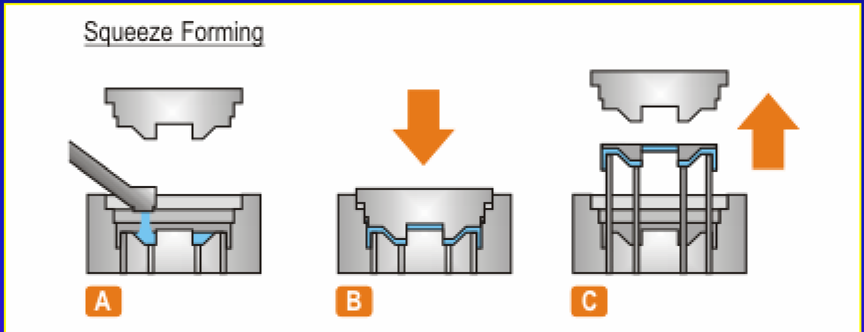
• Provide isotropic properties where (wrought products suffer from directionality.

• Liquid metal can be infiltrated into a mesh or pad of fibres (or particulates) to produce composite materials. → used to manufacture pistons in for cars.

Direct squeeze casting

• Pour metered amount of liquid metal into a die and then pressurise to solidify the metal via the second moving half of the die.

• Runners and feeding systems are not required. → good cast yield.

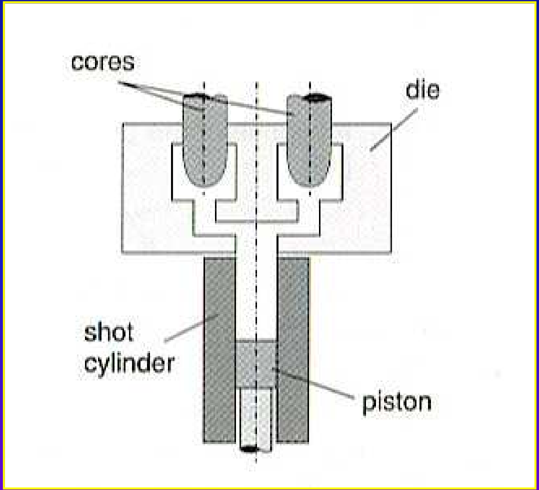


Direct squeeze casting

Indirect squeeze casting

• Pour the liquid metal into a shot sleeve and inject vertically into the die by a piston, which sustains the pressure during solidification.

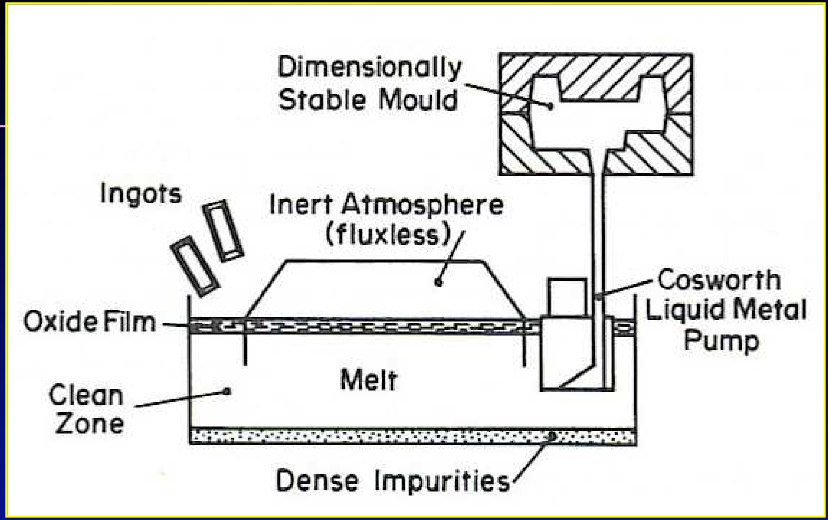
• Runners and feeding systems are not required. → good cast yield.



Indirect squeeze casting

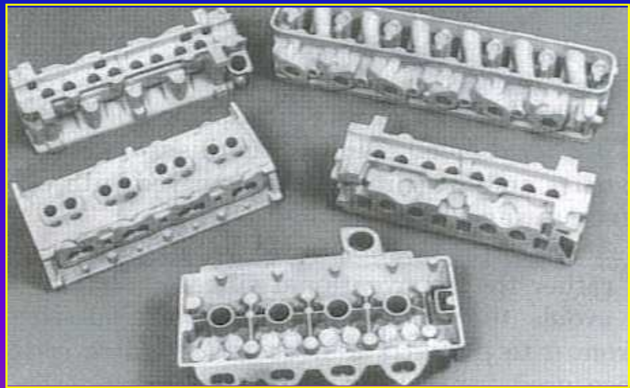
Cosworth Process

- The **Cosworth Process** allow quiescent transfer of metal from the stage of the ingots to the final filling of the mould.



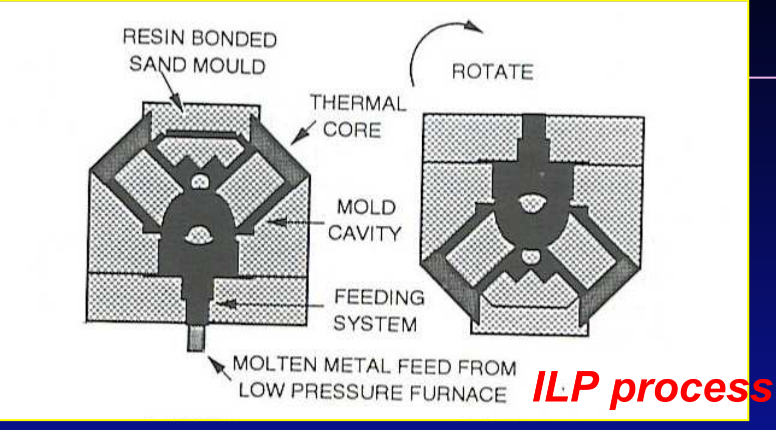
A casting unit in Cosworth Process

- Minimising the undesirable effect of ***dispersing fine oxide particles*** and ***inclusions*** through the melt.
- Oxides/inclusions are separated by ***floating*** or ***sinking***
- No flux or chemicals additions. → atmosphere protection.
- The mould is permeable to allow air to escape. → improve tensile strength and ductility.
- Use reclaimable zircon sand rather than silicon sand for mould and core making. → stable mould volume → dimensional tolerance.



Cylinder head castings produced by Cosworkth Process

Improved low pressure casting (ILP) process



ILP process

• ***Automotive Precision casting process*** developed in Australia.

• Molten metal transfer is ***vertical*** through a riser tube into the bottom of the mould cavity.

• Molten metal is ***degassed*** and ***filtered*** in the casting furnace due to a ***pressurised atmosphere of nitrogen***.→ quiescent, computer-controlled filling of the mould.

• The mould is sealed immediately after filling to allow ***solidification*** to occur remotely from the casting unit.

• ***High productivity*** → cycle time ~ 60 s.

• The ***metal cores*** are made from ***resin-bonded silica*** sand for mould which promotes rapid unidirectional solidification. → optimal properties.

Reduced dendrite arm spacing and overall microshrinkage.

Comparison of mechanical properties of 357 Al alloy produced by different casting process

Process	0.2% proof stress MPa	Tensile strength MPa	Elongation %
Sand cast	200	226	1.6
Chill cast	248	313	6.9
Squeeze cast	283	347	9.3
Cosworth	242	312	9.8

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