PHYSICAL METALLURGY OF ALUMINIUM

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Despite the fact that the production is highly energy intensive. aluminium and its alloys are the most widely used engineering materials next only to iron and steel because of their functional and economical competitiveness. The world over, efforts are on to improve the properties of aluminium/alloys with a view to replacing costly and heavy weight materials in many applications, automobile, space and aerospace for example, for energy saving and economic benefits.

The properties of aluminium alloys heavily depend on structural features and can be enhanced multifold by alloy chemistry, heat treatment and thermo-mechanical processing. This has been possible with the increased insight into the physical metallurgy of aluminium alloys. The basic advantages and applications areas of aluminium are the following :

1. Properties

* Light weight (1/3 density of steel)
* Resistant to weather
* High reflectivity
* Aluminium alloys can equal the strength of steel
* High elasticity; properties do not deteriorate at low temperature
* Readily workable; can be easily thinned to 1/100 mm
* Conducts electricity & heat comparable with copper
* Excellent founding properties

2. Application Areas

Areas - Due to
Transportation- Light-weight, resistance to corrosion
Architecture - Decorative aspects
Package - Resistance to corrosion, decorative aspects
Electrical industry - Good electrical & heat conductivity
Household - Good conductivity, resistance to Corrosion
Chemical & Food industry - Resistance to corrosion

Alloy Classification

Aluminium and its alloys are broadly classified as cast and wrought under the 4 digit classification as per ASTM (American Society for Testing Materials) specifications. Aluminium alloys can again be sub-classified into Heat treatable and Non-heat treatable alloys. The cast alloys are used as cast components with minor machining or heat-treatment. The wrought alloys, on the other hand, are used after the cast ingots are mechanically worked, heat treated or thermo-mechanically processed.

Aluminium Alloys	Alloy No.
Al 99.00% Min. or greater	1xxx
* Copper	2xxx
* Mn (with Mg)	3xxx
* Silicon	4xxx
* Mg	5xxx
* Mg & Si	6xxx
* Zn, Mg	7xxx
* Other elements	8xxx
* Unused series	9xxx

1st digit is indicates the alloy group
2nd & 3rd indicate aluminium purity
digit after decimal place indicate the product form either casting or ingot

Major Alloy System : • Al-Cu alloys : Al-8Cu, Al-10%Cu
- also contains Zn/Si besides Cu
- Heat treatable Al-Cu alloy

* Al-Mg Alloys : Excellent corrosion resistance, good machinability.
  - (Al-4Mg) ; attractive appearance
  - Also contain Zn - die cast
  - Al-7Mg - sand cast
  - Al-10 Mg
* Al-Si alloys : High corrosion resistance, good weldability & low specific gravity
  - Al-5.3% Si : Also contains Mg to strengthen by Mg2Si

* Al-Si-Mg, Al-Si, Al-Si-Mg-Cu
* Al-hyper : Contain Ni, Cu,Mg, V - Engine blocks
  eutectic Si : Outstanding fluidity and machinability
* Al-Zn
* Al-Zn - Bearing and bushes

Minor alloying additions
: Si - Not good for tensile properties
: Fe - Not good ductility
: Be - Used in Al-Mg alloys
: Cr,Mn - improves ductility
: Ni - improves tensile strength at high temperature
: Ti, B,Zr - Grain refinement
: P - Modifies hyper eutectic Al-Si alloys

Bi,Pb,Sn - improves machinability (Chip breakers)

Wrought Alloys	*Alloy No.*
Al 99.00% min. or greater	1xxx
o Cu	2xxx
o Mn	3xxx
o Si	4xxx
o Mg	5xxx
o Mg & Si	6xxx
o Zn	7xxx
o Other elements	8xxx
o Unused series	9xxx

1st digit identifies the alloy group
2nd digit indicates impurities
3rd & 4th digit indicates minimum aluminium content

Wrought Alloys - Al-Mg, Al-Cu, Al-Cu-Mg, Al-Mg-Si, Al-Zn-Mg, Al-Zn-Mg-Cu.

EFFECTS OF ALLOYING ELEMENTS & IMPURITIES ON PROPERTIES

* Density - Mg, Li & Si decrease density of aluminium
  - Cr, Cu, Fe, Mn, Ni, Ti and Zn increase density of Al
  - Si increase density till its solid solubility (S.S) limit (since lattice decreases). Above S.S. the density decreases.

* Thermal expansion - Mg/Zn increases thermal expansion, others decrease.
* Electrical Conductivity - All elements reduce electrical conductivity
* Surface tension- Bi Ca, Li, Mg, Pb, Sb and Sn reduce surface tension.
  - Ag, Cu, Fe, Ge, Mn, Si, Zn have no effect.
* viscosity - Cu, Fe, Ti increase viscosity
  - Zn has no effect on viscosity
  - Mg, Li reduces viscosity

METALLOGRAPHY OF ALUMINIUM ALLOYS

Etching to Reveal Structure

Cast structure consists of grains. Etching causes dissolution of atom layers of metal from individual grains producing steps. The individual grains reflect light to different degrees. This enables the grains and phases to be distinguished (Fig.2a & 2b). Commonly used etching reagents for aluminium/alloys are Keller's reagent, hydro-fluoric acid and sodium hydroxide. Micro and Macro structures can be revealed by suitable etchants.

CAST STRUCTURE

Nucleation & Growth

When the melt reaches the freezing point, nuclei form which increase in size and arrange themselves in certain close packed pattern. The latent heat released by the nuclei is conducted away by the surrounding matrix. The growth of the nuclei stops when the neighbouring crystal meet each other at grain boundaries and form grains. Inside each grain the aluminium atoms (~ 1021 atoms in one grains) arrange in a lattice (Fig.3 & 4). Different grains have different orientation. Grain boundaries are weak areas with regard to chemical corrosion.

In pure aluminium and alloys undercooling occurs before nucleation if the heat is removed faster and no external surfaces are present. In commercial alloys, Ti, B, Fe, etc. are present in fine distribution on which nucleation of aluminium takes place and the undercooling will be minimum.

Ingot Structures (Fig.5)

- Chill zone - Narrow region of fine equiaxed crystals
- Columnar zone - Parallel to heat flow direction
- Equiaxed zone of relatively coarse equiaxed crystals.

Chill Zone

The 1st crystallization takes place near the cold mould wall copiously forming fine grained zone equiaxed in nature.

Columnar Zone

Grains from Chill Zone grow parallel to heat flow direction releasing heat to mould and to the centre, forming long columnar grains.

Equiaxed Central Zone

The central liquid solidifies with fresh nucleation or nuclei derived from chill zone due to convection to form coarse equiaxed grains.

Dendritic Growth

If one looks into the inside of a grain a tree like structure can be seen which are dendrite arms. Cross section of a grain would reveal cells which are sections of dendrite arms. Dendritic growth occurs due to the fact that heat is taken away from corners and edges of cubic nuclei of aluminium.

EQUILIBRIUM DIAGRAM (Fig.6 , 7a & 7b)

There are graphic representation of temperature Vs composition indicating the phases, solidus/liquidus temperatures etc. e.g. Al-Cu, Al-Si. These diagrams are obtained through thermal analysis primarily in liquid to solid transformation. For solid - solid transformation various other methods like dilatometry, metallography, resistivity etc. are employed to get the equilibrium diagrams. The solidification process can be followed with the help of an equilibrium diagram in a homogeneous alloy system. The various phases are designated as α. β. γ. δ. etc.

Lever Rule

Lever Rule will give the fraction of a particular phase.

Eutectic:A liquid transforms to two solids at a fixed temperature.

Al12.5%Si, Al-33%Cu.
Refer Fig.7a.
A-C-beginning of crystallization. Growth of aluminium rich primary crystal (a S.S.)

C-D-Simultaneous growth of two crystal types forming eutectic network around primary aluminium(a)

E-D--Pure eutectic crystallization
D- End of crystallization.

Modification

Process for refining the micro-structure through addition of a third element before casting an alloy e.g.. Na for hypo & eutectic Al-Si alloys and P for hyper eutectic O fir Al-S Alloys. By modification the mechanical properties are significantly enhanced.

GRAIN REFINEMENT

Refining the grain size by heterogeneous or homogeneous nucleation. Fine grain size is desired for excellent room temperature mechanical properties.

TYPES OF EQUILIBRIUM DIAGRAMS

Simple Eutectics	Partly Miscible (Monotectic system,No Known Intermetallics are formed with these elements)
Be IIB	Cd IIB
Si IVB	In IIIB
Zn IIB	T^ IVA
Ga IIIB	Pb IBB
Ge IVB	Bi VB
Sn IVB	Na Ia
	K IA
Hg IIB	Rb IA
	CS IA

Lanthanides, actinides are miscible in liquid state and form complex binary systems with intermetallics.

* Solid solution with peritectics at Al end of phase diagram

  Ti IVA
  V VA
  Cr VIA
  Zr IVA
  Cb VA
  Mo VIA
  Hf IVA
  Ta VA
  W VIA

- o All other metallic elements are completely miscible in liquid state of aluminium
- o Si is completely miscible in liquid Al
- o B has only 0.02% solubility in liquid Al
- o C slightly soluble
- o P & As insoluble
- o S is appreciably soluble
- o SE & Te completely miscible.
- o Except H2 common gases are note soluble in aluminium.
- o No element is completely miscible in aluminium in solid state
- o Zn has the greatest S.S. (66.4 at%)
- o Ag, Mg, Li have greater than 10 at % solid solubility.

HARDENING PROCESSES IN ALUMINIUM/ALUMINIUM ALLOYS

o Work hardening

o Alloy hardening - Solid Solution hardening (used in non heat treatable alloys)
- Precipitation hardening (used in heat treatable alloys)

		Hardening phase
Heat treatable -	Al-Mg-Si (6xxx) -	Mg2Si)
	Al-Cu (2xxx) -	CuAl2
	Al-Zn-Mg (7xxx) -	MgZn2

Non-heat treatable - Al-Mg (5xxx_)
Al (1xxx)
Al-Mn (3xxx)

o Precipitation Hardening (Fig.8)

* Solution Treatment (above solubility curve)
* Quenching (water)
* Ageing - (NA,AA); NA - Natural Ageing
  AA - Artificial Ageing

Precipitation Hardening (Fig. 8)

* Solution Treatment (above solubility curve)

* Quenching (Water)
* Ageing - (NA-AA)

NA - Natural Ageing
AA - Artificial Ageing

Precipitation Stages (Fig.7)

Zone formation due to atomic vibration and clustering of unlike atoms (Al <--> Cu, Mg <--> Zn, Mg <-->Si).
Strengthening due to hindrance to dislocation movement.

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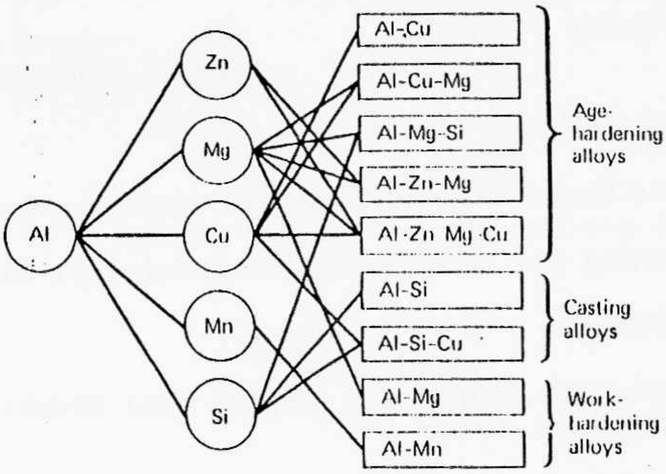
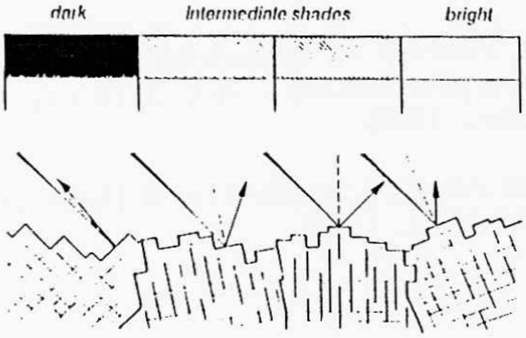


Fig. 1. Principal aluminum alloys.



Reflection of incident light by etched grains. The observer sees from above "steps" in the crystal structure revealed by etching. In the plane of observation, each slope in the crystal surface reflects more or less light into the eye of the observer. The crystal on the far left reflects the light directly back at the source and therefore seems dark. Whereas, the crystals on the far right reflects the light directly in the eye of the observer and appears bright. The schematic section, perpendicular to the etched surface, shows four crystals with their crystallogtraphic planes parallel to the page. Angle of incident light: 45° (M. Schenck).

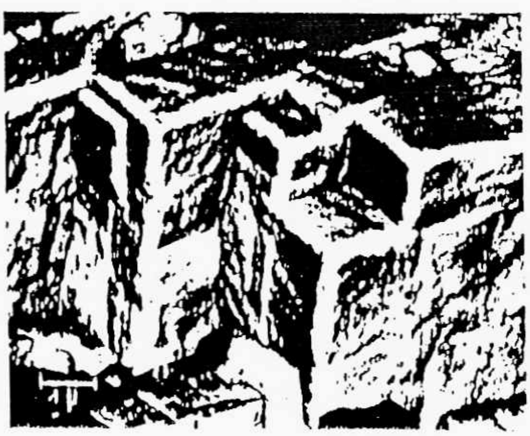
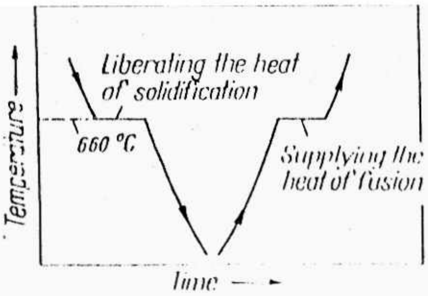


Fig.2a

Etched aluminum surface (99.99% Al). Electron micrograph. One can see that the etchant removed layers of atoms, one after the other, preferentially from crystallographic planes parallel to the faces of the elementary cube. 7 500x



Cooling (solidification) and heating (melting) curves for 99.99% aluminum.

Formation of the cast structure (Rosenhain).

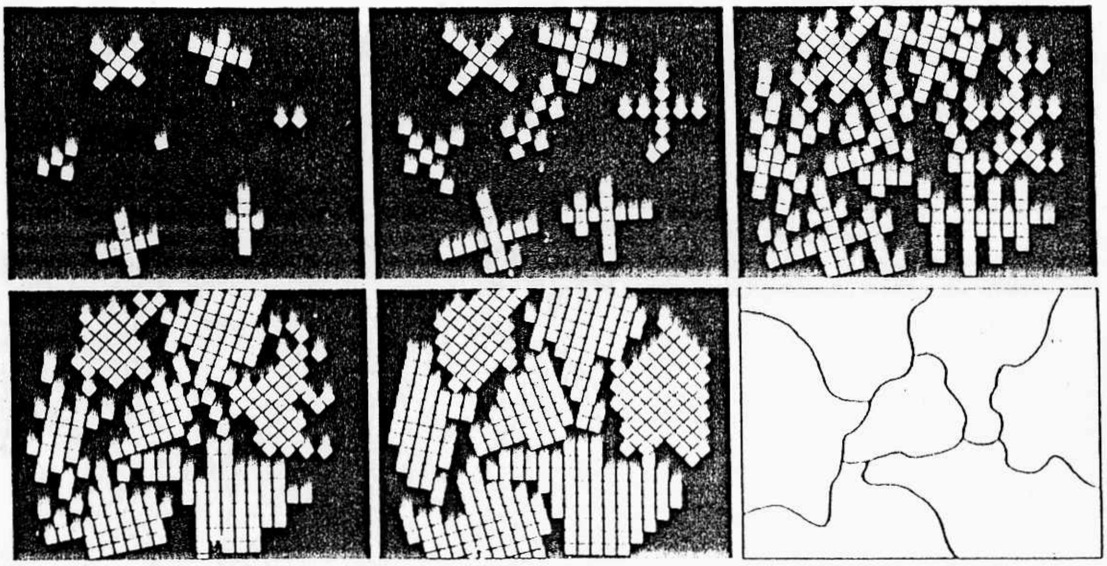
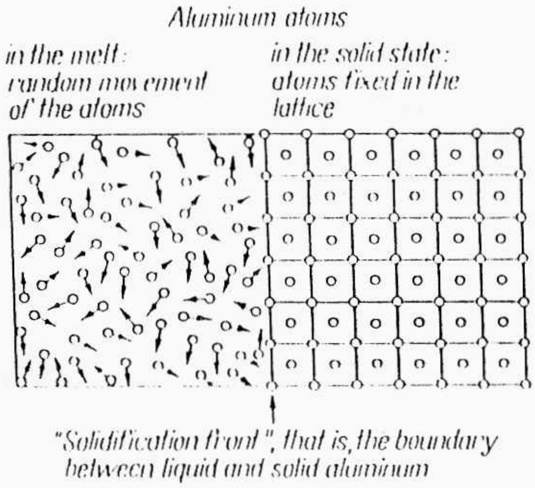


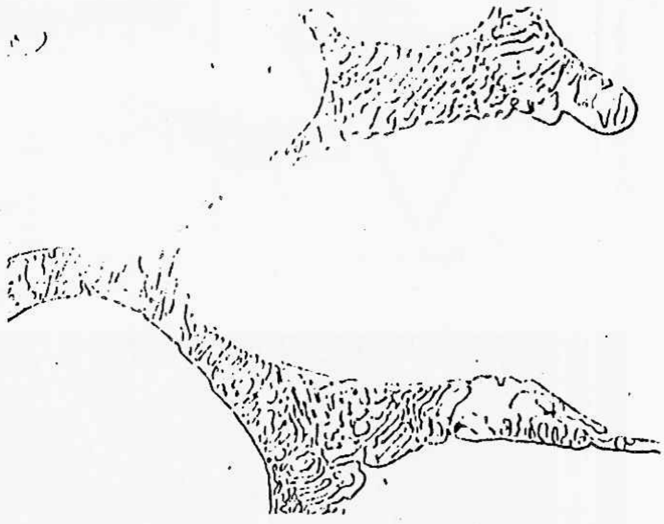
Fig.2b



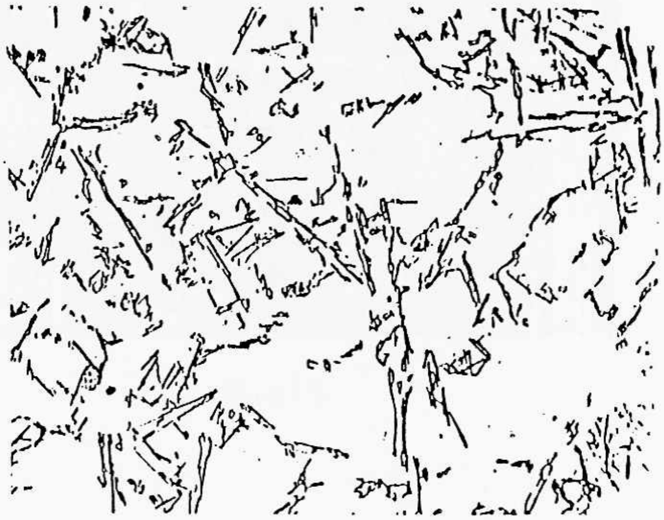
Behavior of atoms during crystallization of aluminum (i. e., during solidification of an aluminum melt).

Fig.3.

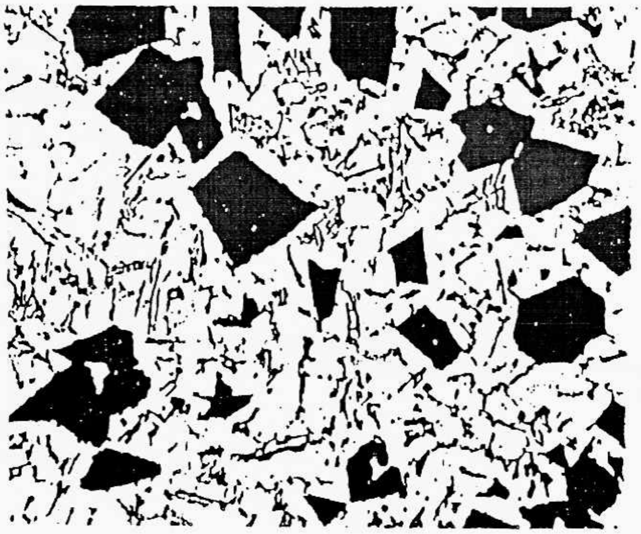
Structure of a hypoeutectic alloy (Hanemann-Schrader). An aluminum-10% copper alloy, eutectic around larger aluminum-rich primary crystals (α-solid solution). 550x.



Aluminum alloy with 8% silicon. Hypoeutectic alloy with aluminum-rich primary crystals. 85x.

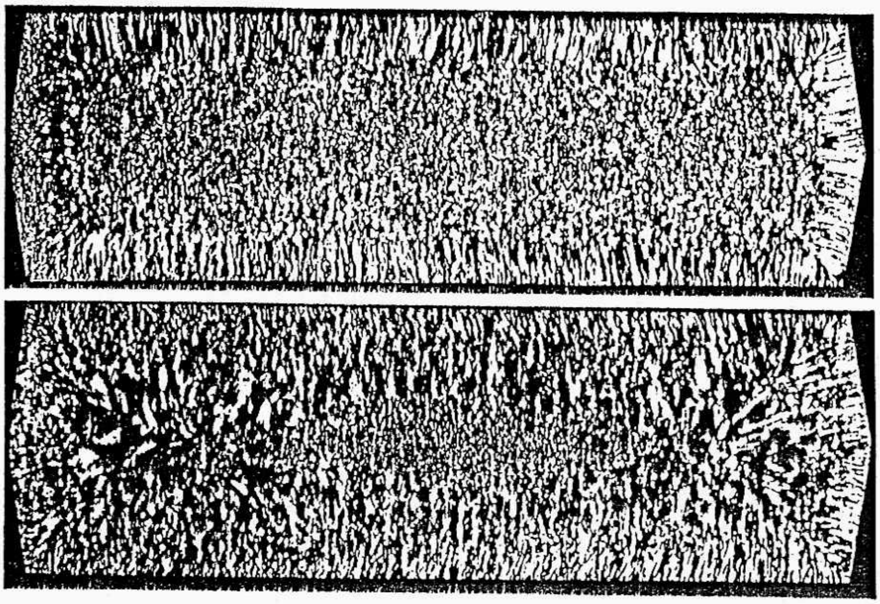


Aluminum alloy with 20% silicon. Hypereutectic alloy with primary silicon crystals. Alusuisse micrograph. See Figure 38 for eutectic alloy structure. 120x.



Structure of sand-cast aluminum-silicon alloys.

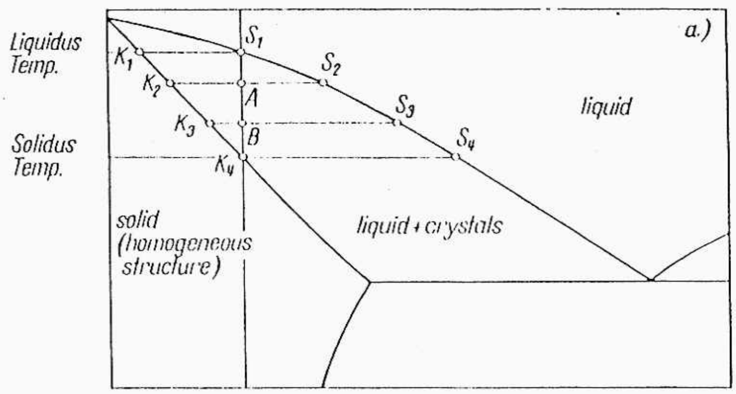
Fig.4.



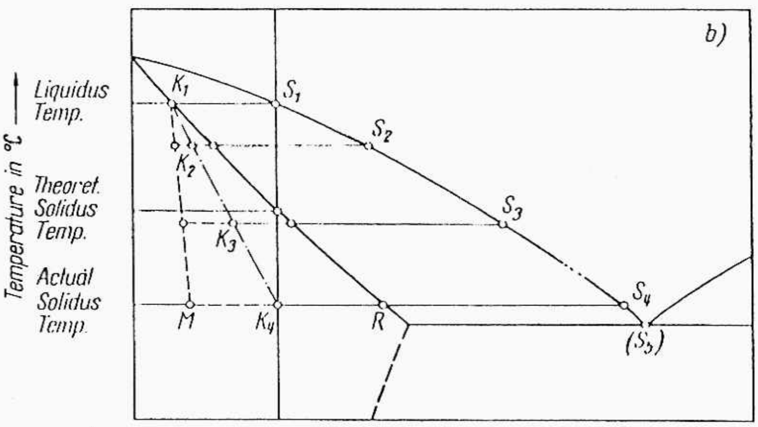
Cross sections through cast, commercial purity aluminum ingots (DC cast in rolling ingot shape). The grain structure has been revealed through etching. Columnar crystals (grains) can be seen in the outer zones, especially in the upper ingot. The columnar grains grow in a direction opposite to the removal of heat.

Fig.5.

Solidification of a homogeneous alloy under equilibrium conditions.



Solidification of a homogeneous alloy under non-equilibrium conditions.



Solidification of a heterogeneous alloy under equilibrium conditions. The β crystals are solid solution crystals, rich in the alloying metal.

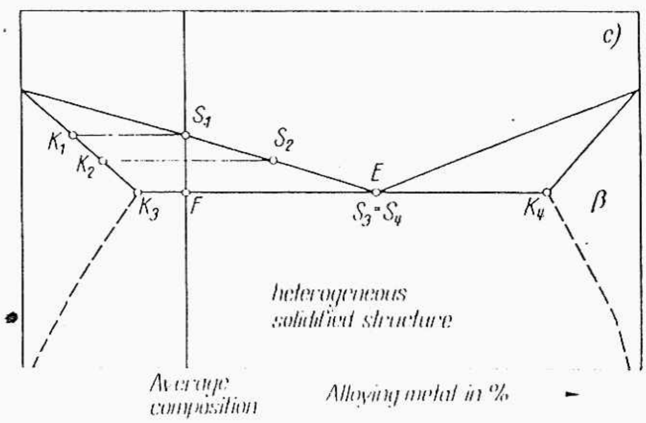


Fig.6

Observing crystallization with the aid of an equilibrium diagram.

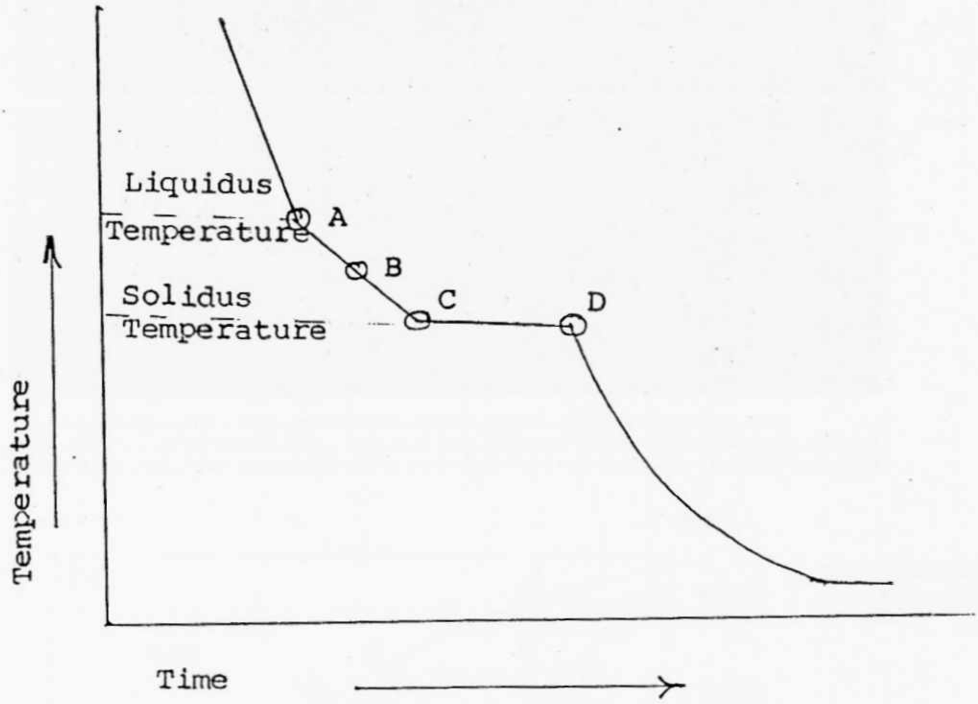


Fig.7a . Schematic solidification curve

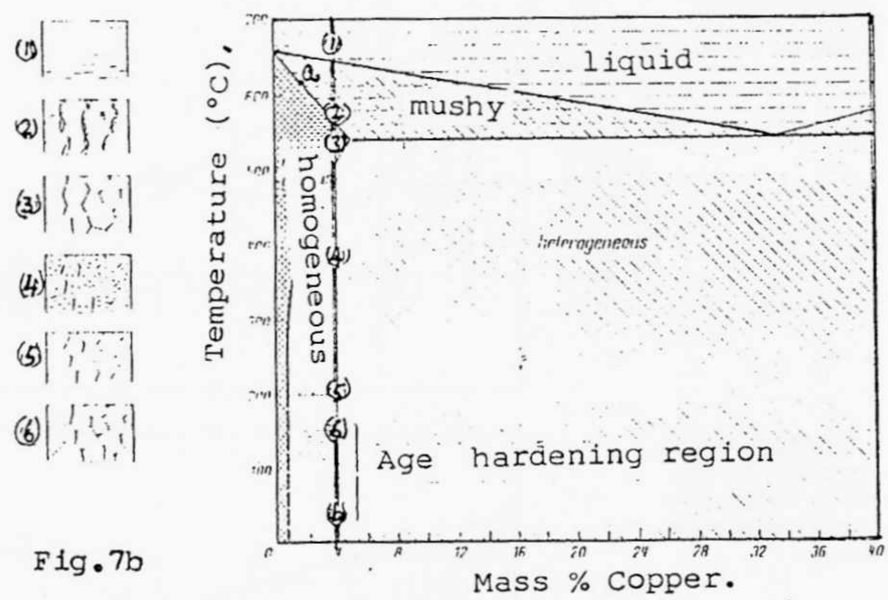


Fig.7b

Relation between equilibrium diagram and structure for the aluminium-copper system. Representation of 4% copper content.

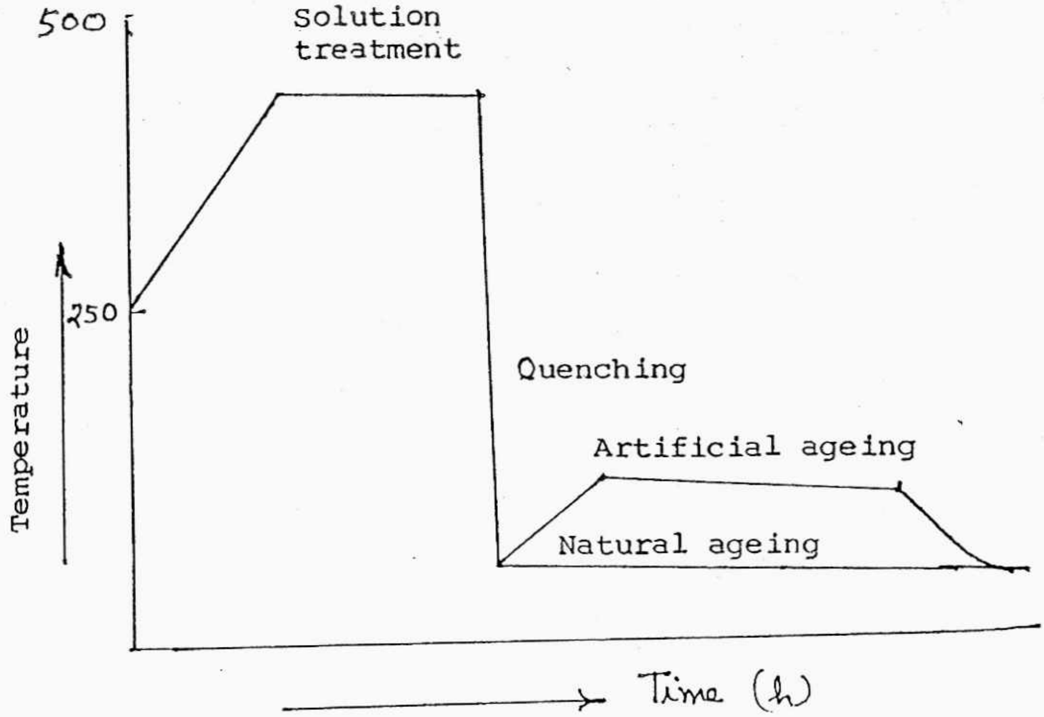


Fig.8. Schematic precipitation hardening of Al-4Cu-2Mg (2024) alloy

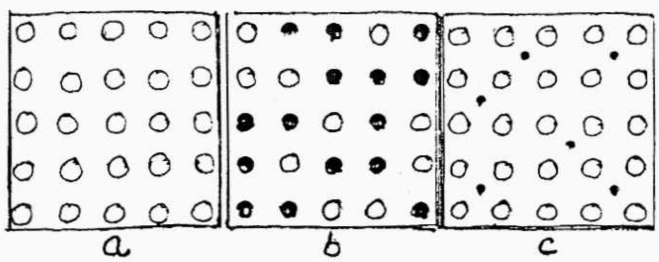


Fig.9a

Atomic arrangement:

(a) Pure Metal (b) Substitutional Solid Solution (Cu/Mg) (c) Interstitial Solid Solution (H_2)

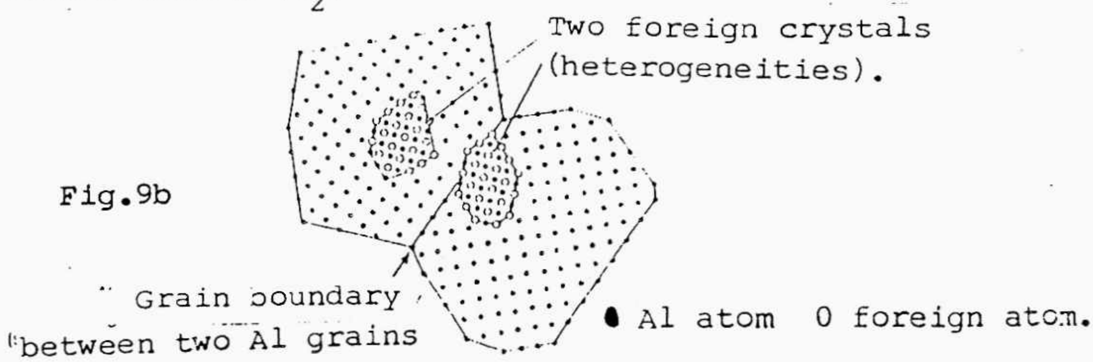


Fig.9b

Atomic arrangement in a heterogeneous structure