

TALAT Lecture 1201

Introduction to Aluminium as an Engineering Material

23 pages, 26 figures (also available as overheads)

Basic Level

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Objectives

To provide an introduction to metallurgical concepts necessary to understand how structural features of aluminium alloys are influenced by alloy composition, processing and heat treatment, and the basic affects of these parameters on the mechanical properties, and hence engineering applications, of the alloys. It is assumed that the reader has some elementary knowledge of physics, chemistry and mathematics.

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1201 Introduction to Aluminium as an Engineering Material

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1201.01. Basic mechanical and physical properties

1201.01.01 Background

The chemical element aluminium (symbol Al) is a metal, which in its pure, bulk form is relatively soft, light and abundant - 8.07% of the Earth's crust compared, for example, with the familiar metal iron at 5.06% (see [TALAT 1101](#), [Figure 1101.01.01](#)). Only oxygen and silicon (as sand) are more abundant in the Earth's crust, and yet it was only a century ago that aluminium was discovered as the most common of metals (see [TALAT 1501.01](#); History and production process of aluminium). We are all familiar with the bronze and iron ages that considerably predate the discovery of aluminium - so why was aluminium so late in appearing on the scene? The answer, as for the pre-historic copper and bronze ages (bronze is a metallic mixture of copper and tin) and later iron and steel (a mixture of iron and a small quantity of carbon), relates to man's technological capability not only to extract the material from the Earth's crust but also to process the material into a useful product.

Man's discoveries and exploitation of metals

- Copper Age to Bronze Age to Iron Age to Steel and finally Aluminium

Copper may be found as lumps in the ground. In pre-historic times, around 8,000 BC, it was discovered that copper may be beaten cold into a useful tool (today we call this cold work hardening). Later, it was found that the use of fire to heat copper softened (today we call this annealing) and this made it easier to fashion into a tool and implements such as cups. Later still, it was found that further addition of heat allowed the copper to melt (at 1,083.4°C), whereupon it can be cast into a variety of useful shapes. However, as a fighting weapon, a copper knife, although much less brittle than flint, very rapidly lost its cutting edge.

Tin also may be found in the ground. Around 2,000 BC it was discovered that if a mixture copper and tin (today we call this an alloy) was melted and cast, the product - bronze - was much harder than pure copper. This remarkable discovery set the pattern for the major progress in civilisation known as the Bronze Age.

Copper and tin are relatively scarce in the Earth's crust compared with iron, which is abundant but in the form of iron oxide. One cannot but wonder what inspired the discovery, around 1,000 BC that by heating iron ore together with charcoal (carbon) gives metallic iron, and hence the birth of the Iron Age [the carbon combines preferentially with the oxygen from the iron oxide - carbon dioxide gas is given off, leaving metallic iron]. Iron, and later steel (an iron alloy with a small amount of carbon), became dominant as a structural material and today is still the most widely used metallic material because of its high strength and relatively low cost - it is, however, heavy and very susceptible to corrosion (rusting).

Aluminium oxide is also very abundant in the Earth's crust. However, the chemical affinity between aluminium and oxygen is very much stronger than that between iron and oxygen. Consequently, aluminium as a metal was not discovered until relatively recently and requires a large amount of energy to extract it from its ore.


The great affinity of oxygen for aluminium (which produces a chemical compound, alumina Al_2O_3) means that the element aluminium is present in the Earth's crust incorporated in a mineral, Bauxite ore. The technical challenge at the end of the last century was to extract aluminium metal from Bauxite. The solution - the "Hall – Héroult" process (see [TALAT 1501.01](#)) - was the development of an electrolytic process, which is still used today. A large quantity of electricity is required, and it was the development of cheaper electricity (particularly hydroelectric power) at the turn of the last century, that made the industrial production of aluminium a commercial proposition. The incentive to recycle aluminium is considerable because, compared with the energy required for primary electrolytic extraction, only a few percent of that energy level is required to remelt scrap material. Nonetheless, as a general rule, aluminium is more expensive than steel; hence, for a given application, the selection of aluminium over steel (or any other competitive material) will rely upon one or

more of the many attributes of aluminium which make it a better choice for a particular application. Lightness in weight, the characteristic to be readily formed into useful shapes, good corrosion resistance, and high electrical and heat conductivities are just some of the potentially valuable attributes.

1201.01.02 Commercially pure aluminium

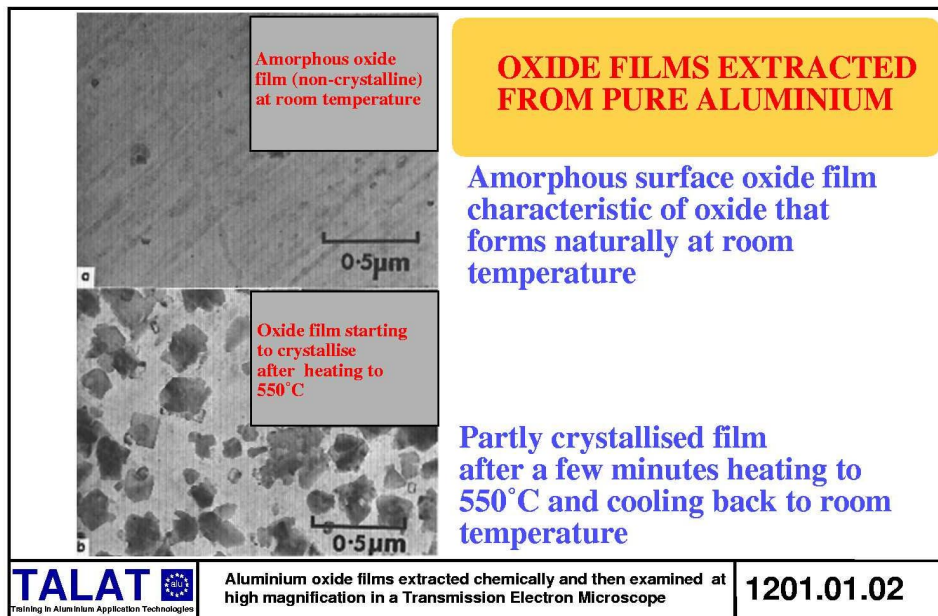
Commercially pure aluminium is the product of the electrolytic cell process. It contains a low level of impurities, usually much less than 1%. Commercially pure aluminium is light in weight ($2,700 \text{ kg.m}^{-3}$ compared with iron at $7,870 \text{ kg.m}^{-3}$) and melts at 660°C .

A lump of aluminium that has been heated to just below the melting point and allowed to cool slowly (annealed) is light in weight, is not very strong, is soft and ductile, is corrosion resistant and has high thermal and electrical conductivities - see [Figure 1201.01.01](#) for data. If the lump is mechanically deformed at room temperature, then it becomes noticeably harder and less ductile - the material has been “**work hardened**”; the mechanism of work hardening will be explained later in this section. The mechanical and physical properties of commercially pure aluminium may be also be changed by deliberate additions of other elements, for example, copper (Cu), magnesium (Mg), silicon (Si) - the products are **alloys** and the aim of industrially useful alloys is to enhance their properties and hence make them more suitable for fabrication into useful products. Again, the mechanisms involved will be the subject of much discussion later in this chapter. Such alloy additions are small in amount (typically up to a few percent); consequently they have only a very small effect on the density, which remains low at typically 2800 kg.m^{-3} . An exception is additions lithium (Li), density 540 kg.m^{-3} , of up to a few percent and specially developed for aerospace applications, where the aluminium-lithium alloy density is lower at $2200\text{-}2700 \text{ kg.m}^{-3}$. Also, alloys of aluminium with small additions of lithium are stiffer than other aluminium alloys, which is a feature of benefit to some applications (see section on aerospace alloys, TALAT lecture 1255).

PURE ALUMINIUM		
Annealed pure aluminium is: <ul style="list-style-type: none"> • not very strong • soft and ductile • light in weight • corrosion resistant • of high thermal and electrical conductivities 	Typical mechanical properties are:	
	Annealed	Moderate cold work
	0.2% Yield Strength	15 MPa 50 MPa
	UTS	50 MPa 100 MPa
	Elongation †	50% 50%
	Hardness	130 Hv 230 Hv
	† maximum elongation before breaking	
		1201.01.01

The extremely strong affinity of aluminium for oxygen means that, at room temperature in normal air conditions, a lump of aluminium will instantaneously form a very thin layer of surface oxide. This is only a few atom layers thick; however, it is very stable and provides good protection against chemical attack.

The surface oxide film formed at room temperature is amorphous (this means that the component atoms are not arranged in a regular array). Upon heating to elevated temperature, say around 550 °C, the amorphous film starts to crystallise - small regions of aluminium oxide re-arrange their atoms into a more stable, regular arrangement - small **crystals** are formed. Stripping of the films allows them to be examined at very high magnification in a **transmission electron microscope** (see later section on metallographic techniques); this allows the structure of the films to be determined - **Figure 1201.01.02**. The small aluminium oxide crystals formed at an elevated temperature are of a size and separation to cause optical interference effects (diffraction) in normal white light - thus, such a sample may appear bluish through brown to black, as opposed to the familiar reflective “silvery” colour of aluminium.



Aluminium oxide (also called alumina) is a brittle, ceramic material that has a very high melting point of 1,773 °C. This means that when a lump of aluminium is melted, the alumina film remains solid and, unless special measures are adopted, it breaks up and, because of turbulence in the liquid, readily becomes incorporated inside the liquid where it remains during subsequent freezing (**solidification**). The alumina films are folded back on them-selves and are poorly bonded and, as such, present regions of weakness in the solidified aluminium. Unless special precautions are adopted, entrapped oxide films can be a serious problem in components cast from aluminium alloys - see TALAT lecture 3202 (**Figure 3202.00.01**).

1201.02 Crystal structure and defects

1201.02.01 Crystals and atomic bonding

Aluminium is a metallic material, composed of atoms which are arranged in a specific three-dimensional array - a **crystal**. The way in which the atoms of all materials are bonded is determined by their atomic structure. The box below provides brief descriptions of various types of bonding and some simple crystal structures.

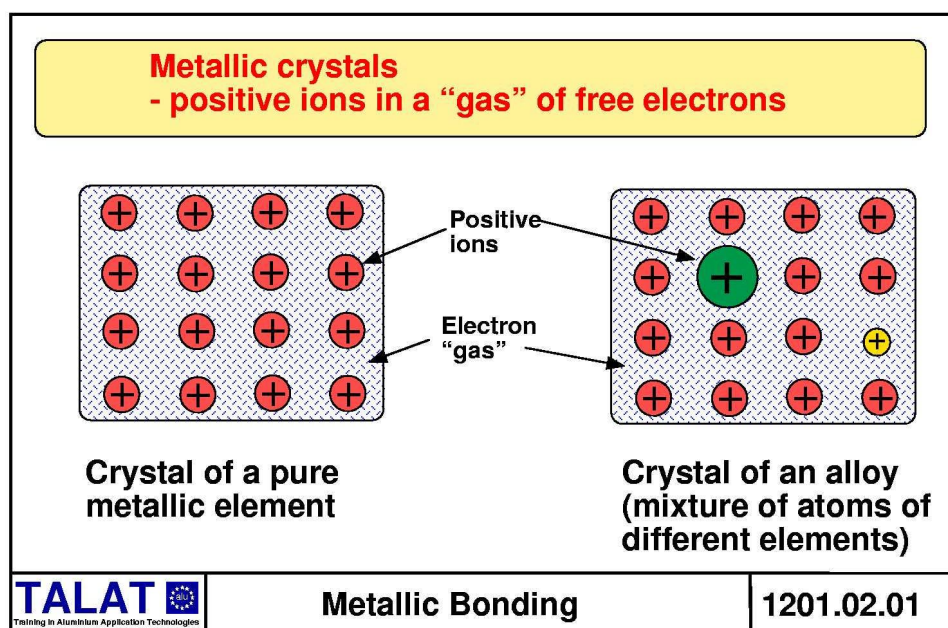
Atoms, bonding and crystal structures

Most solid matter is crystalline. The atoms of which it is composed form a regular pattern which is repeated throughout space; this is the **crystal structure**. Since solid matter has strength, it is clear that there must be a force, the atomic bond, holding each atom to its neighbours in the crystal. Bonding is of three basic types: **Metallic bonding**; **Covalent bonding** and **Ionic bonding**. Let us look at the characteristics of each in turn.

Metallic bonding

In metallic bonding, an electron is lost by one type of atom and gained by another. Electrons carry a negative charge. An atom will lose one or more atoms if it has this number in its outer shell; this is the chemical definition of a metal.

Suppose some metal atoms are brought together, each having spare electrons in their outer shells. What holds them together? Again it is a matter of sharing but not one atom with another but more on a communal basis! The way a metal is best viewed is of a system of positive charges or ions (the atoms which have lost electrons so-called positive ions) surrounded by a cloud of negatively-charged electrons - sometimes called 'electron-gas' - see [Figure 1201.02.01](#) - which shows pictorially metallic bonding with positive ions surrounded by an 'electron-gas'. The mutual attraction between the positively charged ions and negative 'electron-gas' provides the bond.



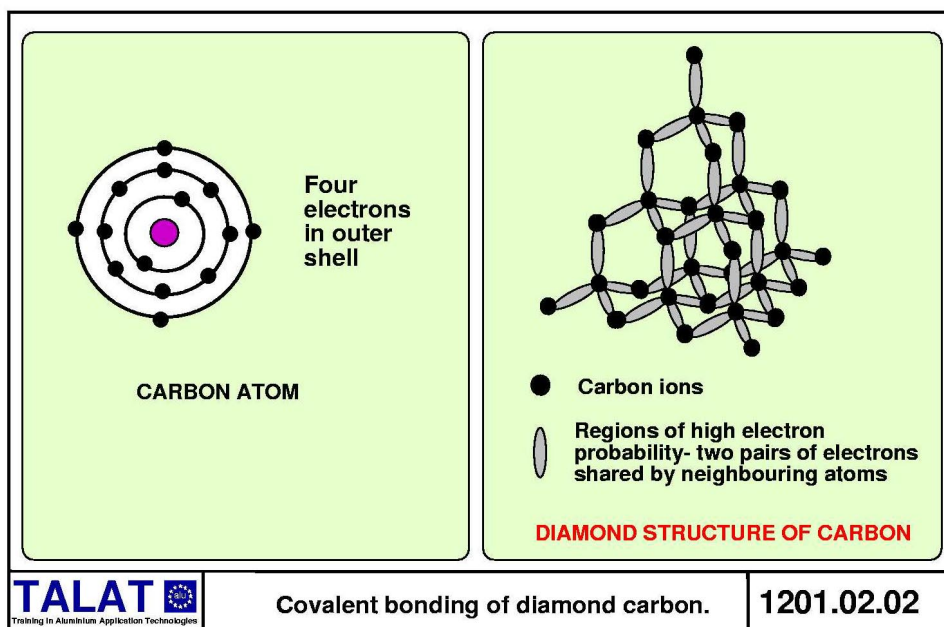
The free electrons in the "electron gas" of a metal are relatively free to move. Under the influence of a voltage potential, an electron current flows. Hence, metals are good conductors of electricity.

It is important to note that mixtures of metallic atoms occur commonly - these are known as **alloys**. There are many different alloys of aluminium. There are also a number of different classes of aluminium alloy; these will be discussed later in this lecture series. In all cases of metallic alloys, the simple picture of positive metal ions in an electron gas holds true. The positive metal ions may assemble into special arrays as a result of a particular heat treatment or special mechanical treatment - this gives rise to crystal structures with special features, for example **grain structures** and more general **microstructures**; we will look at these features later in this lecture.

Covalent bonding

Electron shells can be made complete by sharing electrons. Carbon is an example; this has 4 electrons in the outer shell and shares these to make the stable shell of 8.

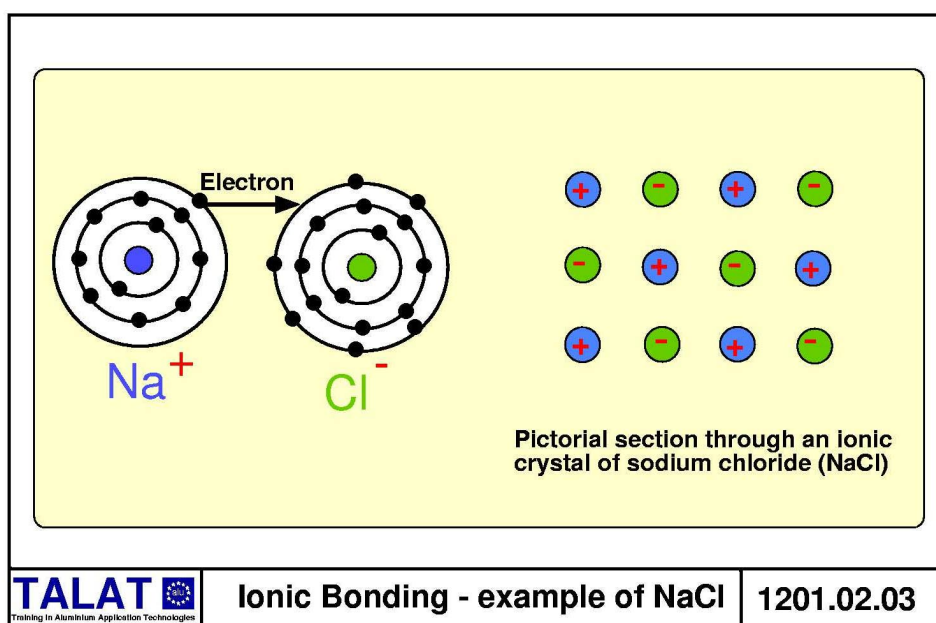
The diamond structure of carbon is shown in [Figure 1201.02.02](#). This shows a three dimensional representation with the bonds shown as the region of high electron probability. The strength of the covalent bonds is what accounts for the great hardness of diamond. atoms. The strong bonding of the electrons also means that there are no free electrons to carry an electrical current: diamond is an electrical insulator.



Mixtures of atoms - compounds - can have covalent bonds. Organic materials are mostly covalently bonded, e.g. plastics, which are mostly good electrical insulators.

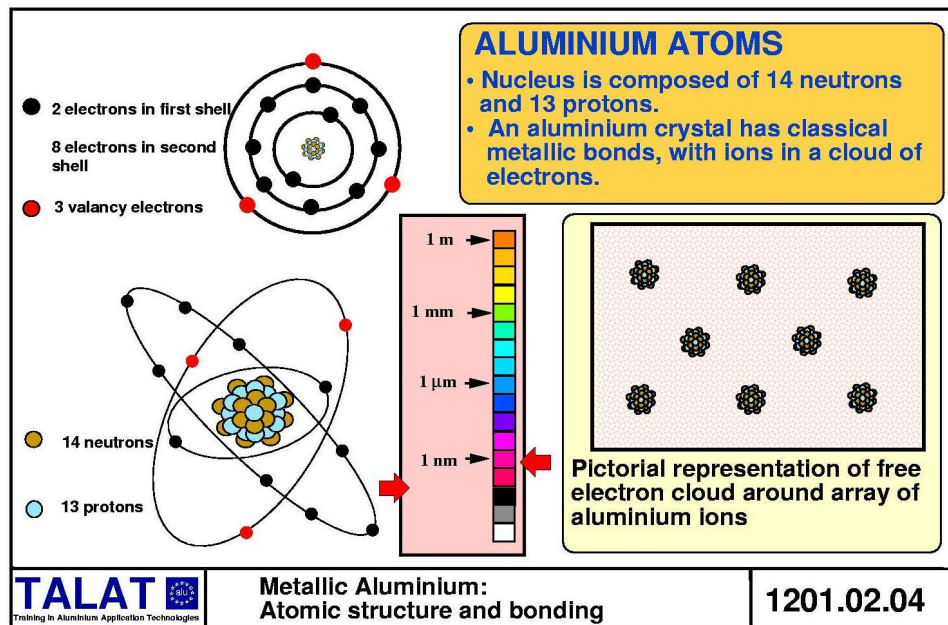
Ionic bonding

Non-metals, in contrast, have almost full outer electron shells and become more stable by gaining one or more electrons. Consider sodium (Na) and chlorine (Cl) - see [Figure 1201.02.03](#). As electrons carry a negative charge the Na atom becomes positively charged and the Cl negatively charged. Opposite charges attract and this is the basis of the bond - in this case producing NaCl, common salt.



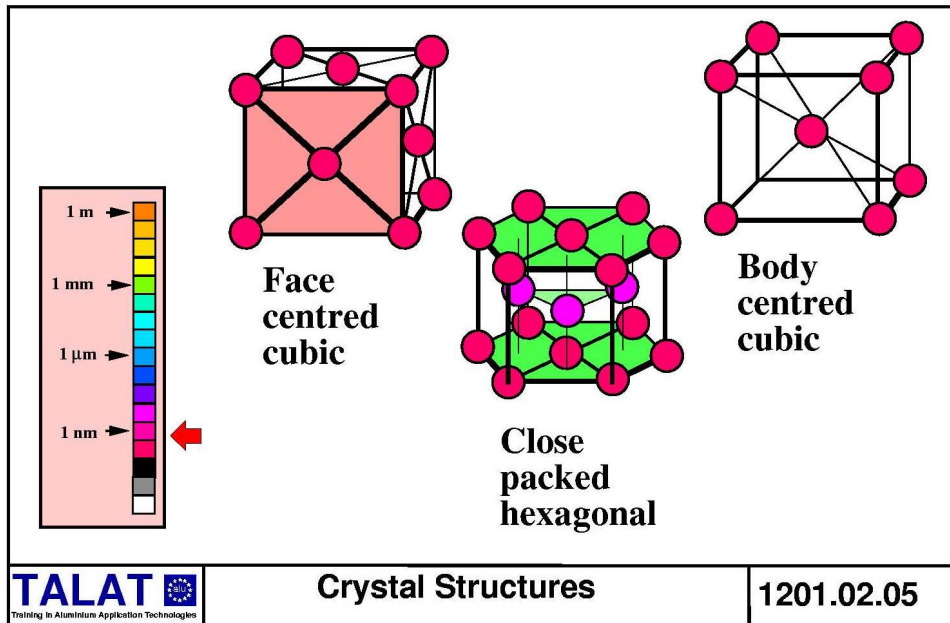
1201.02.02 Atomic structure of aluminium

Let us return to the specific case of aluminium. The atomic number of an aluminium atom is 13; by definition this is because it has 13 protons in its nucleus, together with 14 neutrons. The atomic structure is shown pictorially in [Figure 1201.02.04](#). The outer electron shell - the valency shell - contains three electrons; these contribute to the “free electron gas” of aluminium crystals and give such crystals excellent electrical conductivity. As a general rule, the electrical conductivity is reduced by the addition to aluminium of impurities and by the deliberate addition of other elements to form aluminium alloys.



1201.02.03 Crystal structures

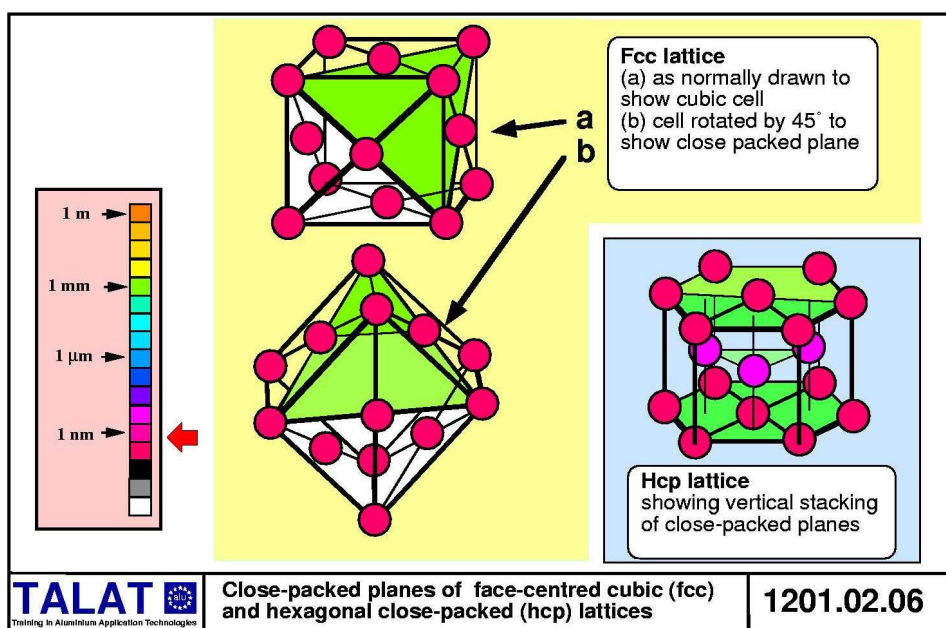
As already indicated above, aluminium atoms assemble into an array to form a crystal lattice. The crystal lattice has a face-centred cubic structure (often abbreviated to fcc). Aluminium, in common with most other metals and their alloys, pack atoms together in a highly compacted way - mostly, this is achieved by one of three different lattices, face-centred cubic, close-packed hexagonal or body-centred cubic - see [Figure 1201.02.05](#).



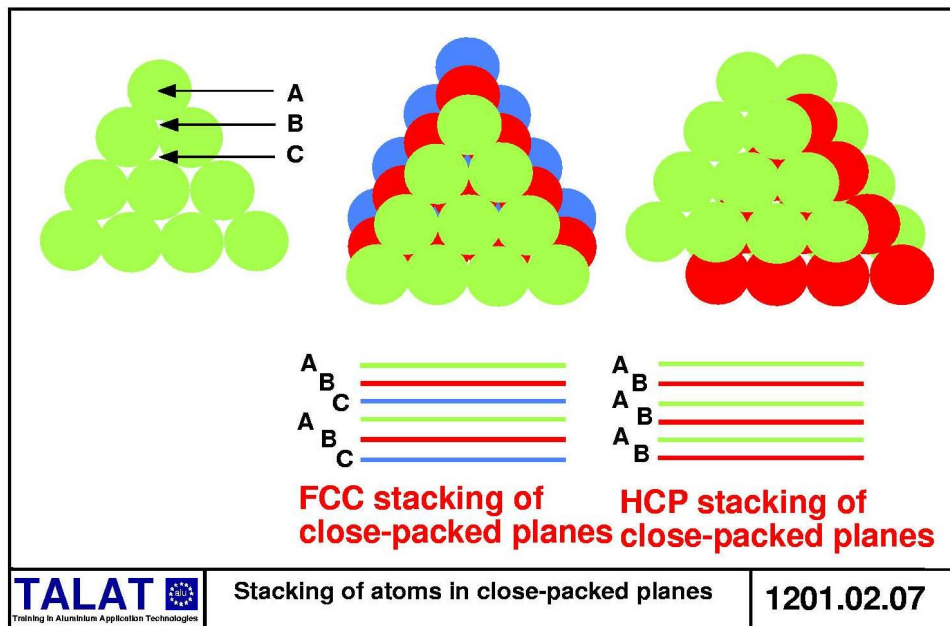
1201.02.04 Some comments on crystal structures of materials

As we saw above, covalently-bonded materials must have their atoms arranged to allow electron sharing; this leads to some very complicated structures - for example, plastic polymers and bio-medical materials. Ionic crystals have, as their priority, the requirement that positive and negatively charged particles are neighbours.

The metallic bond, however, makes no such demands and, as a result, the atoms can pack together in the most efficient way. This leads to close-packed structures of which there are two types, face-centred cubic (fcc) and close-packed hexagonal (cph), **Figure 1201.02.05**. Another common structure is body centred cubic (bcc), which is also illustrated in **Figure 1201.02.05**.



Although the fcc and hcp look very different, they are, in fact, both made up by stacking close-packed layers, one on top of another. This is illustrated in [Figure 1201.02.06](#). Probably a rather simpler picture is to consider rafts of close-packed atoms, which may be stacked on top of each other. These rafts may be stacked in two distinctly different sequences, ABCABC and ABABAB (or ACACAC), as illustrated in [Figure 1201.02.07](#); the former is fcc stacking, and the latter is hcp. [This is readily demonstrated with small spheres, e.g. rafts of glued table tennis balls].



The **slip** of one raft of atoms over a neighbouring raft is the mechanism by which a crystal can change its shape - that is, by the application of a sufficient force to a crystal, it responds by changing its shape. This is known as **plastic deformation**. The plane on which the slip occurs is determined by the geometry of the crystal structure. The geometry involved is relatively simple for crystals based on cubic symmetry, for which crystal planes and crystal directions may be defined in terms of **Miller indices**, see box below.

Miller indices

Three axes, x, y and z, are defined which are parallel to the edges of a cube whose cell edges are of unit length - see [Figure 1201.02.08](#). The convention to define a crystal plane is as follows:-

1. Determine the intercept of the plane along the three axes x, y and z..
2. Take the reciprocal of each intercept.
3. The three resulting numbers are the Miller indices of the plane.

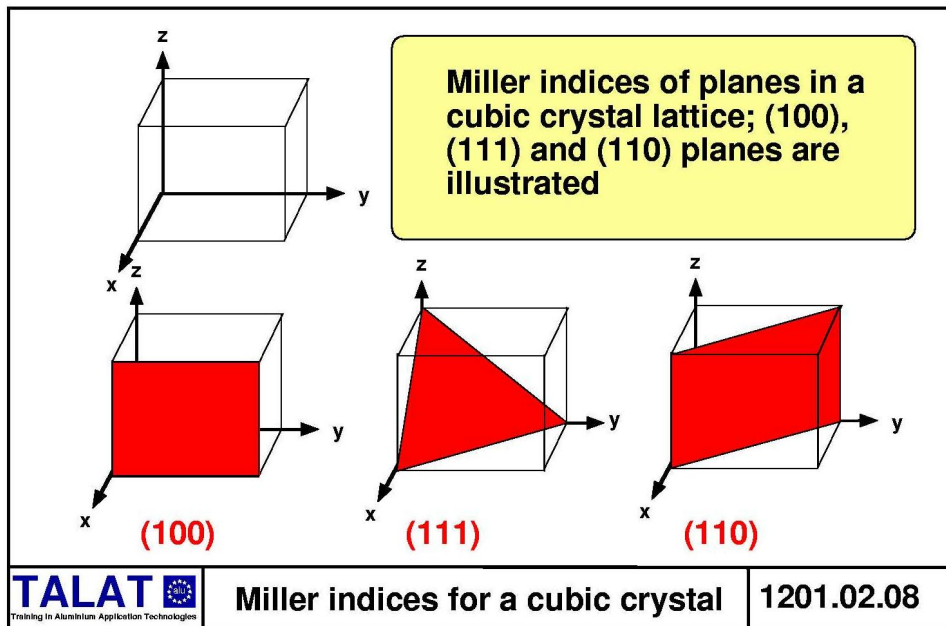
As an example, consider one of the faces of the cube shown in [Figure 1201.02.08](#). The intercepts are

- 1 along the x-axis
- infinity along the y axes
- infinity along the z axis.

Take the reciprocal of each intercept to obtain the integers 1, 0 and 0.

The convention is to enclose these integers in brackets - (100) - to define the plane, again see [Figure 1201.02.08](#). Clearly, other faces of the cube will be represented by (010), (001) and so on. Such a family of planes is denoted by {100}.

Note that the close-packed planes are {111}, and these are the slip planes.



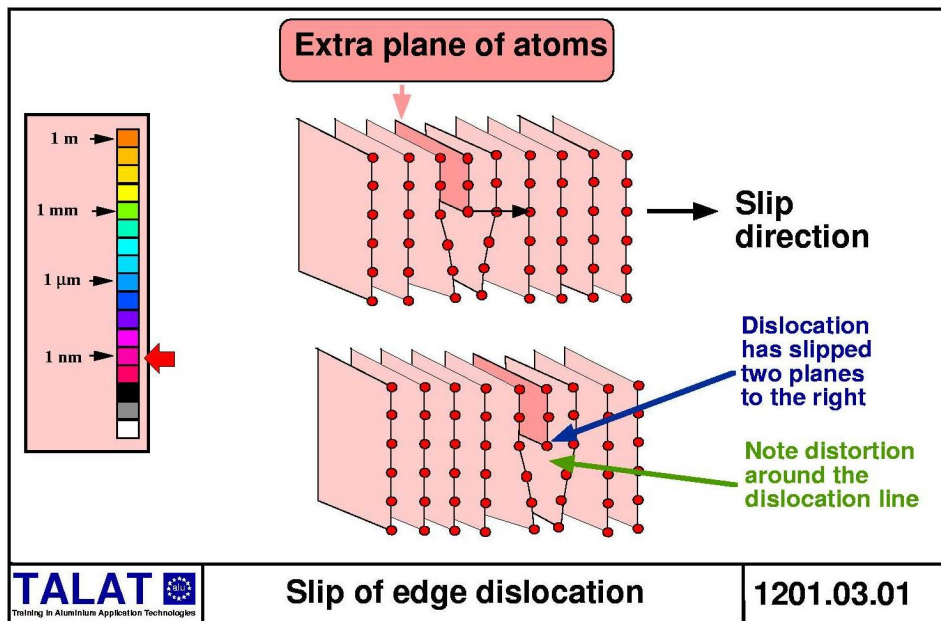
Directions in the cubic crystal are defined in 'square brackets' as the normals to the planes; for example, the direction along the x- axis is $[100]$. A family of equivalent 'cube' directions is denoted as $\langle 100 \rangle$.

1201.03 Plastic deformation, slip and dislocations in single crystals.

1201.03.01 Slip and dislocations

Deformation by slip in aluminium mostly occurs on $\{111\}$ planes and along $\langle 110 \rangle$ directions. In practice, the energy that would be required to move a complete raft of close-packed atoms all in one go would be impossibly large, and this never happens. Instead, slip occurs by the movement of so-called line defects in the crystal, known as dislocations. The science of dislocations is a huge and complicated subject, so for details the interested reader is referred to specialised texts [1]. Nonetheless, the basic principle of slip by dislocation movement is easy to illustrate by reference to a so-called 'edge dislocation'. The arrangement of atoms is shown in [Figure 1201.03.01](#). The dislocation line is the boundary of an extra plane of atoms. Slip occurs by the movement of this extra plane along the slip plane; hence, deformation is a localised process and the energy required is very much less. Note, however, the very localised distortion of the atomic lattice around the dislocation; the lattice is said to be in a state of strain, with some atoms further apart than normal, and some atoms closer than normal.

In practice, any macroscopic shape change requires movement of very large numbers of dislocations. However, because dislocation movement in a pure aluminium crystal requires only a small energy, macroscopic deformation is relatively easy - we perceive the material to be soft.



1201.03.02 Other features and defects in aluminium single crystals.

In the real world, very high purity aluminium is a rarity; normally aluminium material contains at least a small amount of impurities and, for most engineering applications, the material contains deliberate additions of alloying elements. The main impurities in commercially- pure aluminium are iron and silicon. Iron has a very low solubility in aluminium (0.05wt% maximum at 665°C), hence an impurity level higher than this results in particles of aluminium-iron intermetallic which are insoluble. Some elements, notably copper (Cu), lithium (Li), magnesium (Mg), manganese (Mn), silicon (Si) and zinc (Zn) dissolve, each up to a certain limit which is temperature dependent, in the aluminium lattice they form so-called **solid solutions** see [Figure 1201.03.02](#).

Element	Temperature (°C)	Maximum solubility* (wt%)	Atom size † (nm)
Aluminium	-	-	0.29
Copper	548	5.65	0.26
Iron	655	0.05	0.25
Lithium	600	4.2	0.30
Magnesium	450	17.4	0.32
Manganese	658	1.82	0.25
Silicon	577	1.65	0.23
Zinc	443	70.0	0.28

* Data from *Light Alloys*, I J Polmear, Metallurgy & Materials Science Series, Arnold, London, 1989, p.18
† Data estimated from *Structure of Metals*, W Hume-Rothery and G V Raynor, Inst of Metals Monograph & Report Series No 1, 3rd Edition, London, 1954, p.62

TALAT Training in Aluminium Application Technologies

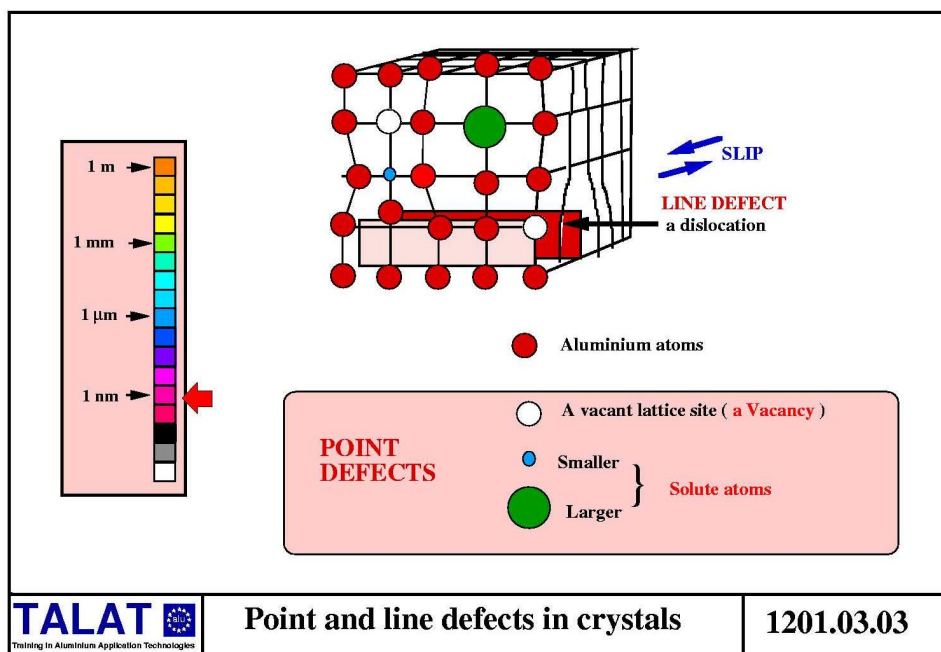
**Solubilities of elements in aluminium.
Estimates of atom sizes.**

1201.03.02

In a solid solution, the ‘foreign’ atom substitutes for an aluminium atom - see [Figure 1201.03.03](#). These foreign atoms are known as solute atoms; they have atom sizes that are different from the atom size of aluminium (see [Figure 1201.03.02](#)). This means that solute atoms introduce a distortion into the aluminium lattice - see [Figure 1201.03.03](#)- a feature that has a controlling influence on how the solid solution - the alloy - responds to heat treatment and to mechanical working; we will return to the important feature later in this chapter. Some lattice sites are not occupied by any atom - the sites are vacant. The point defect caused by the vacant lattice site is called a vacancy. The equilibrium concentration of vacancies is very temperature dependent. The concentration of single vacancies, C_v , in equilibrium in a pure metal at a temperature $T^\circ\text{K}$ is given by [2]

$$C_v = \text{constant} \times \exp\left(-\frac{E_f}{kT}\right)$$

where E_f is the energy of formation of a single vacancy and k is Boltzmann’s constant. The equilibrium concentration varies [3] from about 2×10^{-3} / atom (i.e. 2 lattice sites in every 1,000) at just below the melting point, to 1×10^{-12} / atom (i.e. 1 lattice site in 1,000,000,000,000 at room temperature). However, if a sample of aluminium is cooled rapidly, a high, non-equilibrium level of vacancies can be retained in the structure; this has important implications to the metallurgy of aluminium alloys - we will return to this when we discuss the mechanism of precipitation hardening in [section 1201.04](#).



Vacancies are also important because they facilitate the mechanism of the diffusion of solute atoms in an aluminium alloy lattice - see [Figure 1201.03.04](#). In the illustration, the small solute atom diffuses upwards, and the large solute atom diffuses downwards.

(a) (b) (c)

(d) (e) (f)

● Aluminium atoms
○ A vacant lattice site (a Vacancy)
● Smaller } Solute atoms
● Larger }

TALAT Training in Aluminium Application Technologies

Solute / vacancy diffusion

1201.03.04

1201.03.03 Grain features of bulk aluminium and its alloys.

Although it is possible by special procedures to grow large single crystals of pure aluminium and aluminium solid solutions, in most situations where aluminium is processed and applied as an engineering material, the bulk material (as with other engineering materials) is composed of an agglomeration of a large number of crystals, **so-called grains** - so next, we must look at the formation and characteristics of multi-grained materials.

Dendrites on the surface of a pore in cast Al-7wt%Si-0.5%Mg

(SEM micrograph from PhD thesis by AKMB Rashid, The University of Birmingham, 1993)

Diagram of dendrites, showing primary and secondary arms

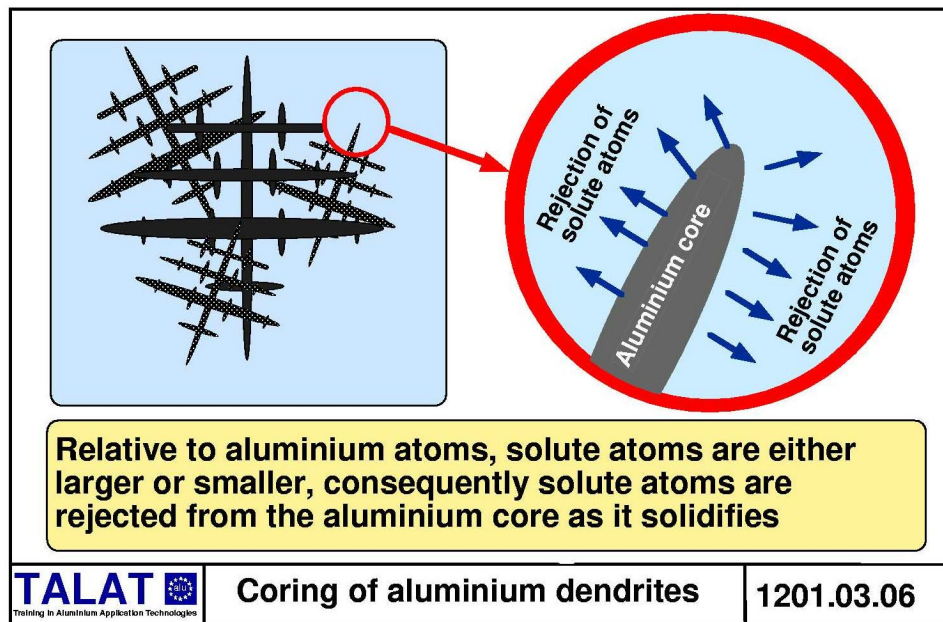
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Dendrites in cast Al-Si-Mg alloy

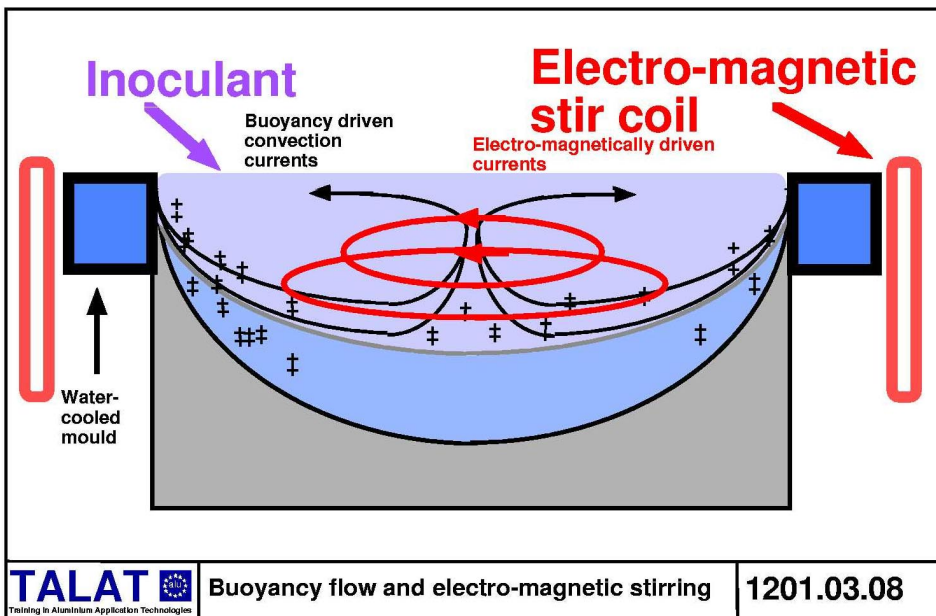
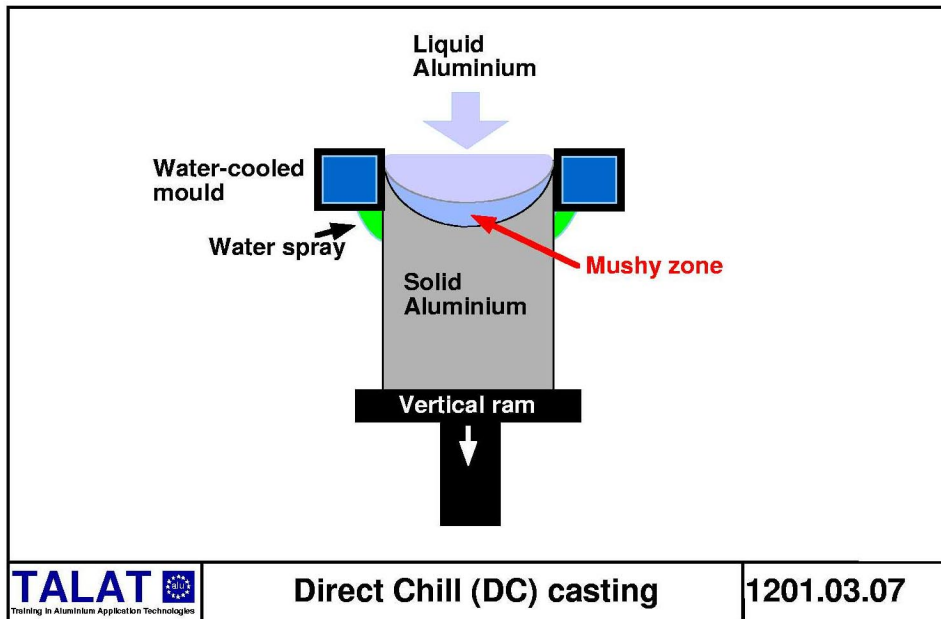
1201.03.05

Let us start by considering the freezing (solidification) of an aluminium alloy. As the liquid cools to, and then below, the freezing point, small crystals of solid start to grow within the liquid. The solid crystal grows at different rates in different lattice directions - in aluminium, as for all fcc metals, the preferred growth directions are the cube $\langle 100 \rangle$ directions, and the

crystal takes on a characteristic, so-called ‘dendritic’ morphology; branching takes place, to produce crystals as illustrated in [Figure 1201.03.05](#). If the liquid contains dissolved solute atoms which, as a general rule will be either smaller or larger than the aluminium atoms, these solute atoms will not easily fit into the growing crystal and are therefore rejected into the surrounding liquid - the solute atoms are **microsegregated** into the inter-dendritic regions, [Figure 1201.03.06](#). Hence, the solid formed is not uniform in composition, but is microsegregated on a scale determined by the sizes of the dendrites. The sizes of the dendrites are controlled by the conditions of freezing, that is, by the method by which the bulk material is cast.



[Figure 1201.03.07](#) shows the arrangement for vertical, direct chill (DC) cast of aluminium alloys - a variant of this produces horizontal cast bars [4]. Liquid aluminium alloy is poured into a water-cooled mould. The liquid starts to solidify - the mixture of solid dendrites and solute-enriched liquid is known as the ‘mushy zone’. Solid aluminium alloy is withdrawn downwards on a vertical hydraulic ram. Metallurgically important processes occur within the cooling liquid and in the mushy zone - [Figure 1201.03.08](#). A steep temperature gradient from the surface of the water-cooled mould extends inwards to the centre-line. This sets up buoyancy-driven convection currents that cause dendrites to flow downwards, along the region in the vicinity of the mushy zone and the liquid - the interface between the 100% liquid and the mushy zone is called the ‘liquidus’ surface, and the interface between the mushy zone and the 100% solid is called the ‘solidus’ surface. This flow of dendrites, coupled with the fact that dendrites will grow preferentially parallel to the temperature gradients leads to elongated crystal grains growing towards the centre line; also solute atoms get redistributed over large distances, which leads to **macrosegregation**. Sometimes an electromagnetic coil is placed around the mould, which induces eddy currents in the liquid and tends to counter the buoyancy flow. Also, it is common practice in industry to add an inoculant, whose purpose is appreciably to increase the nucleation of dendrites, and so reduce the scales of microsegregation and macrosegregation.

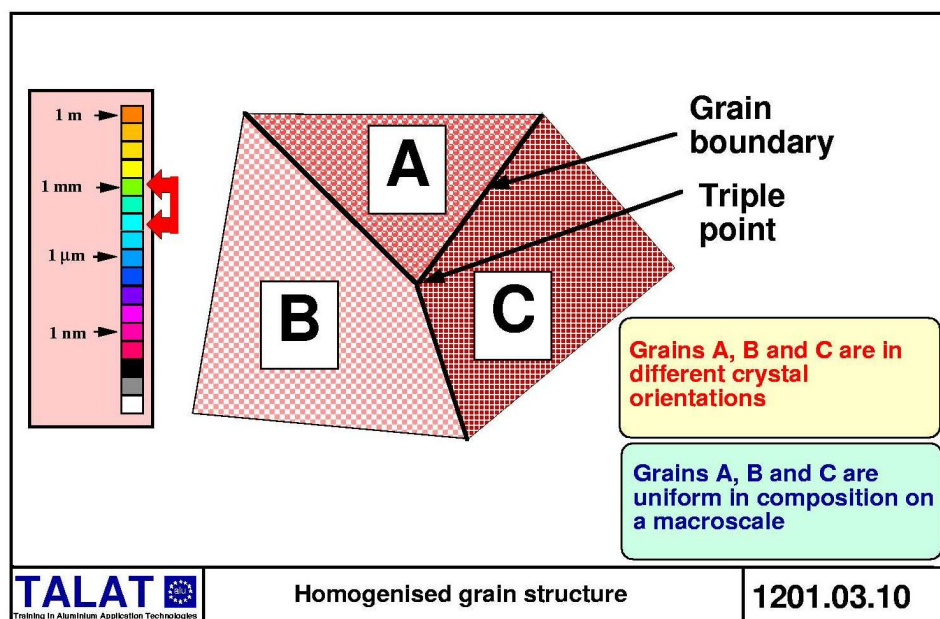
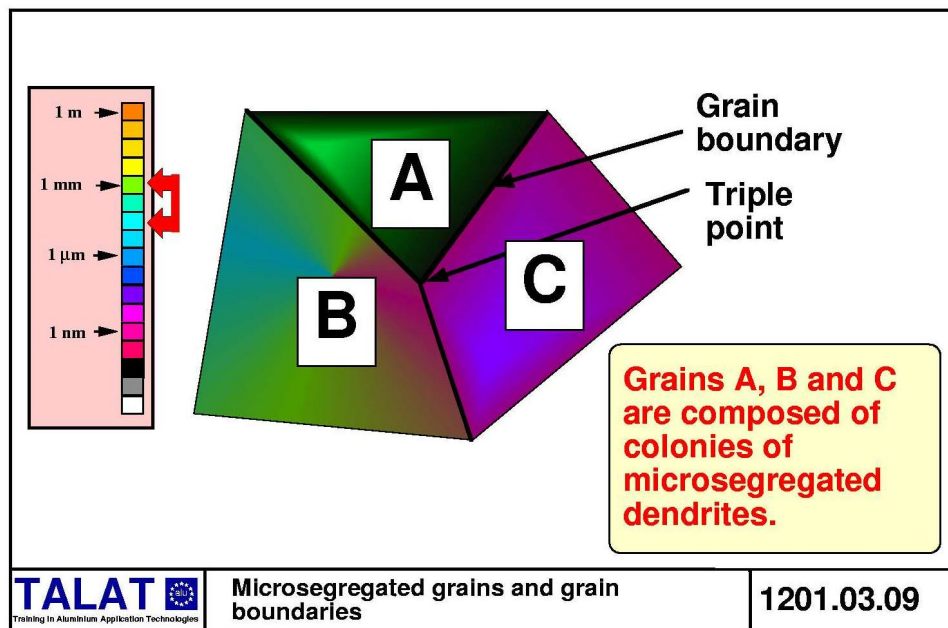


Grain refinement of aluminium [4].

Because uniformity of grain size and chemical composition is so desirable - this produces a consistent, uniform engineering product of isotropic properties - it is usual to add small amounts of an inoculant of Al-Ti or Al-Ti-B to the melt in order to promote refinement. Two theories have been advanced to explain the mechanism of grain refinement: (1) small particles of either TiC or TiB₂ are added to the melt and these act as seeds for dendrite growth; and (2), as so-called peritectic reaction, as follows:

Liquid aluminium + TiAl₃ reacts and goes to α- alloy solid solution.
Dendrites grow from the TiAl₃ coated with solid solution.

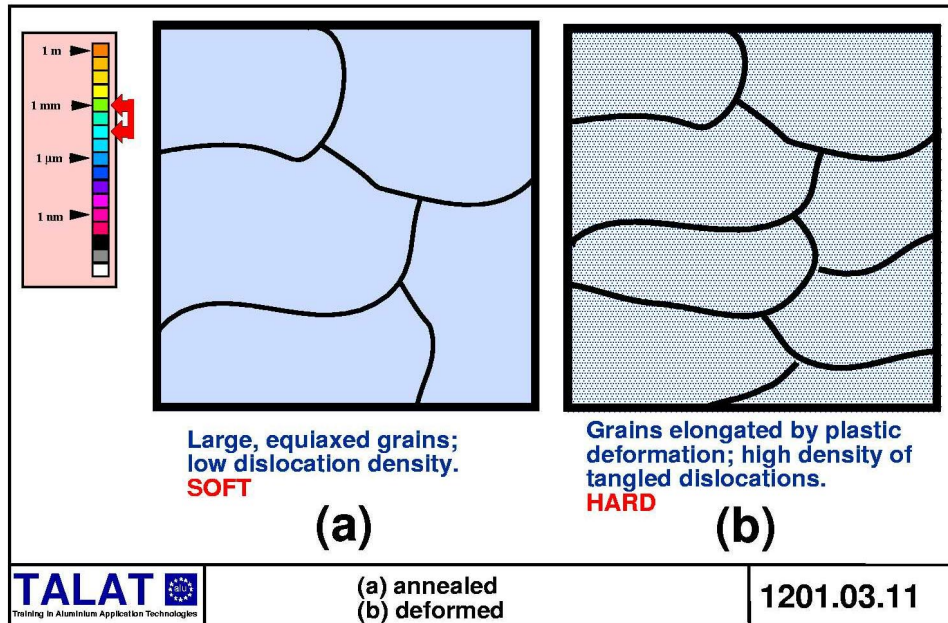
Fully solid cast material consists of colonies of dendrites, separated by grain boundaries. The grains are microsegregated, **Figure 1201.03.09**. Heat treatment of the solid at a temperature just below the melting point (**homogenisation**) allows concentration gradients in the solute compositions to even out by diffusion, and grains of uniform composition are formed, **Figure**



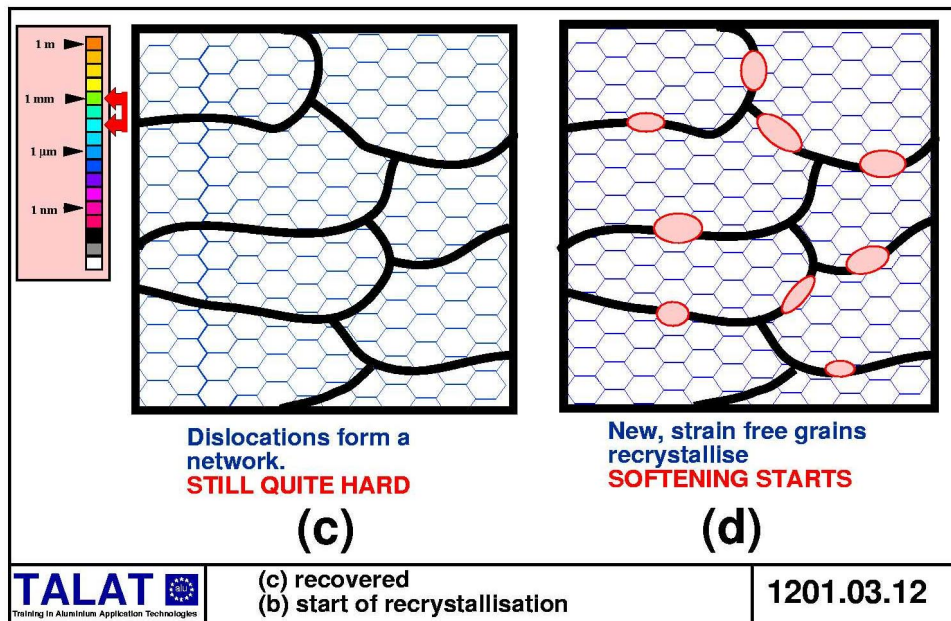
The boundaries between grains are in a state of local, high disorder and are of higher energy relative to the regular lattice of grain interiors. Thermodynamic principles say that systems always tend to minimise their total energy; consequently, a sustained annealing treatment leads to growth of grains to lower the total grain boundary area. This same principle is the main driver that determines how a material responds to deformation (working) and further heat treatments.

1201.03.04 Plastic deformation, recrystallisation and grain growth

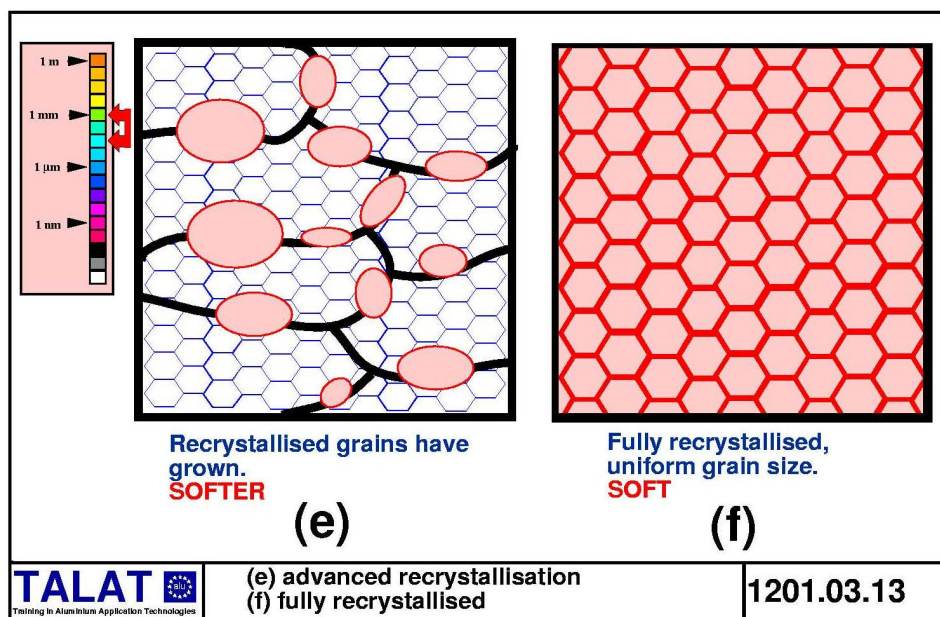
Let us take as our starting point a slab of commercially pure aluminium that has been fully annealed and homogenised, with a relatively large grain size - say of the order of a millimetre, see (a) in [Figure 1201.03.11](#). The grains are reasonably uniform in size (equi-axed) and of low dislocation density; hence, the material is soft and easily deformed. If the material is mechanically worked at room temperature, it hardens noticeably - this is called **work hardening**. The plastic deformation creates a multitude of dislocations, [Figure 1201.03.11](#), whose ability to slip becomes progressively more difficult because of resistance from neighbouring dislocations - macroscopically the material becomes 'hard'.



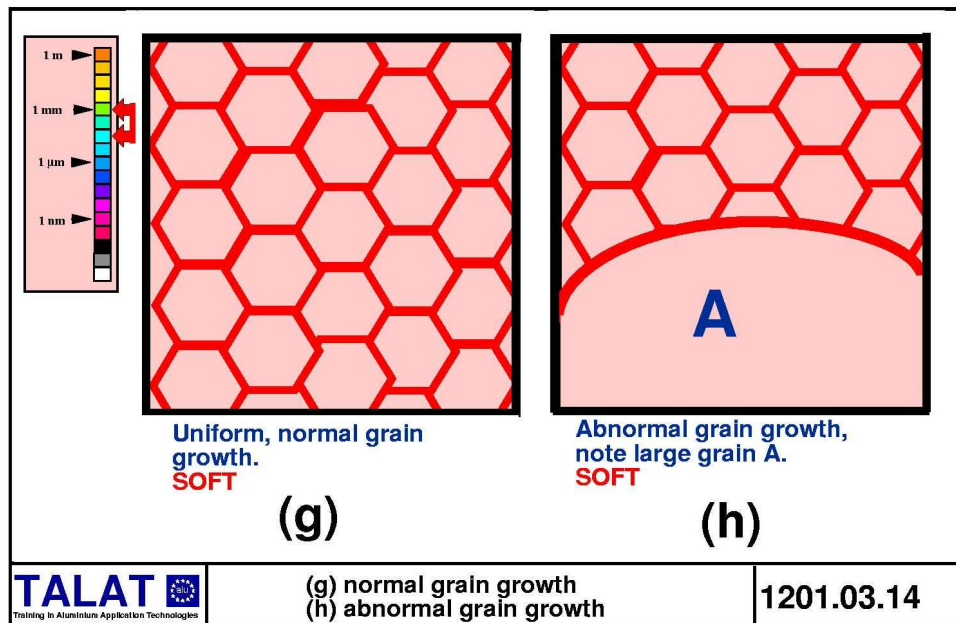
Recovery. If the temperature of the slab is now raised to around 250°C, the dislocations will form a network structure of cells (polygonisation), [Figure 1201.03.12](#). The process is called recovery and the material will start to soften slightly.



Recrystallisation. If the temperature of the slab is raised further, new strain free crystals are nucleated; recrystallisation has commenced, [Figure 1201.03.12](#), and the material starts to soften. This process continues until the whole of the material has recrystallised and softened, [Figure 1201.03.13](#).

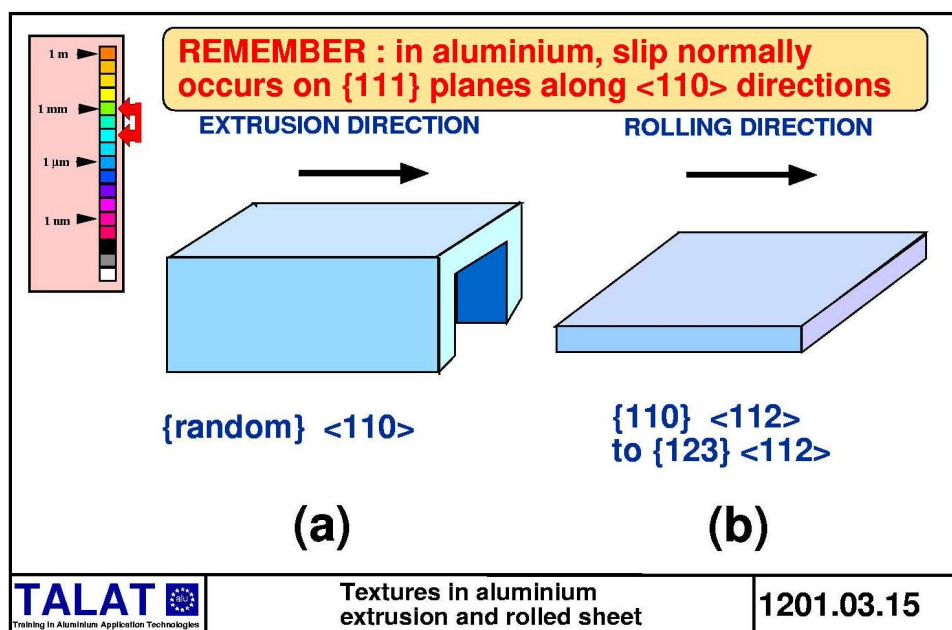


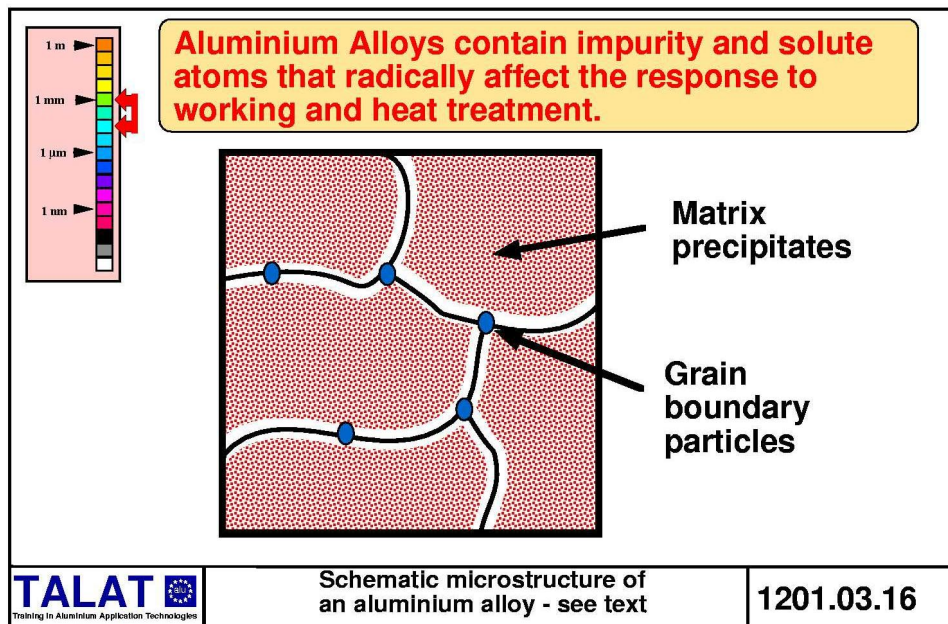
Primary and secondary grain growth. If a fully recrystallised material is held at elevated temperature for a period of time, then the grains grow, [Figure 1201.03.14](#). Initially the growth is reasonably uniform but later, a small number of grains grow preferentially and abnormal grain growth sets in, [Figure 1201.03.14](#).



Texture. Plastic deformation of aluminium normally occurs by slip on $\{111\}$ planes in $\langle 110 \rangle$ directions.

Aluminium wire and extruded bar have a ‘fibre’ texture[4], with $\langle 110 \rangle$ directions parallel to the axis of the wire and extrusion, [Figure 1201.03.15](#). The texture of rolled sheet is more complicated [4], with $\langle 112 \rangle$ parallel to the rolling direction and certain preferred grain orientations, [Figure 1201.03.16](#).





1201.03.05 Structural transformations in aluminium alloys

In contrast to pure aluminium, aluminium alloys contain solute additions which can markedly effect grain structures and particularly the microstructures within the grains, **Figure 1201.03.16**. This in turn strongly influences the responses of alloys to working and heat treatment. Both crystal structure and microstructure influence mechanical properties. Slip is inhibited by grain boundaries, which are disordered regions, (and so small grains improve strength). Slip can also be made difficult by dispersing particles of another phase throughout the matrix. To understand the metallurgy of this we must first look at methods by which the structures can be investigated (**Metallography of Aluminium Alloys, TALAT lecture 1202**), then we must see how the structures present (phases) depend upon composition and temperature (**Phase Diagrams, TALAT lecture 1203**). This will then lead us on to the very important subject of **Precipitation Hardening**, which will be treated in **TALAT lecture 1204**.

1201.04 References

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3. L E Mondolfo, *Aluminium Alloys - Structure and Properties*, Butterworths, 1976, pp.22-23.
4. I J , *Light Alloys - Metallurgy of the Light Metals*, Metallurgy and Materials Sciences Series, Edward Arnold, 2nd Edition 1989, p55.
5. F J Humphreys and M Hatherly, *Recrystallization and Related Annealing Phenomena*, Pergamon, 1995.

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