TALAT Lecture 2101.01

Understanding Aluminium as a Material

23 pages, 21 figures

Basic Level

prepared by Sigurd Støren, The Norwegian Institute of Technology, Trondheim and by Skanaluminium, Oslo

Objectives:
This chapter is an introduction to aluminium alloys, fabrication methods and properties. The goals are:
- To provide information about:
  - ⇒ the classification of aluminium alloys, new alloys and composites
  - ⇒ shaping processes, processing chains and component shapes
  - ⇒ microstructure and the interaction between microstructure and properties.
- To promote understanding of the fact that the correct choice of materials demands knowledge of alloys, shaping processes and microstructure and the interaction among them

Prerequisites:
The lecture is recommended for those situations, where a brief, general background information about aluminium is needed as an introduction of other subject areas of aluminium application technologies.

This lecture is part of the self-contained course „Aluminium in Product Development“ which is treated under TALAT lectures 2100. It was originally developed by Skanaluminium, Oslo, and is reproduced for TALAT with kind permission of Skanaluminium. The translation from Norwegian into English was funded within the TALAT project.

Date of Issue: 1994

2101.01 Understanding Aluminium as a Material

Interaction between Material Characteristics and Design

A good product is one whose functions and properties are realised through harmonic interaction between form, material and processing chain.

There is no automatic or even particularly easy way to achieve such harmonic interaction. While a designer must have a good understanding of a product's function and the user's needs, he must also be familiar with the opportunities and limitations inherent in the various materials and processing chains. It is essential to become totally engrossed in all aspects of the problem in order to "invent" a product.

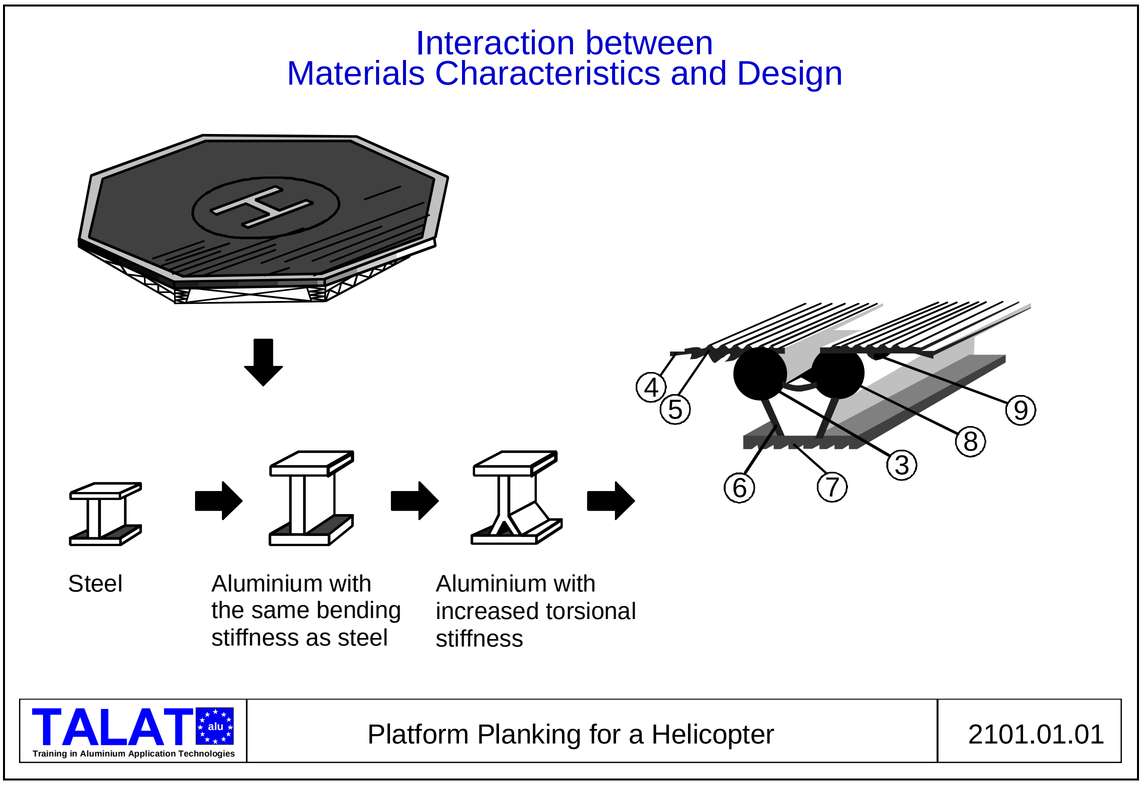
This chapter presents the most important aluminium alloys and processing chains used for industrial products and supporting structures.

Let us look first at a product, or rather a part of a product, which exhibits harmony between function, form, material and processing chain.

Figure 2101.01.01 shows the development of platform planking for a helicopter pad. The planking was originally made of rolled steel shapes that were welded together. They were dimensioned to resist bending and torsion stress. Various potential aluminium solutions were examined with a view to reducing weight. With extruded aluminium sections, the depth had to be increased by about 40 per cent to achieve a 60 per cent weight reduction without sacrificing bending stiffness. The extrusion process itself and heat treatable aluminium alloys make it possible to manufacture complex, thin-walled cross-sections with a strength equal to that of ordinary structural steel. The torsional stiffness can be improved by exploiting the advantages of hollow sections. A designer who is familiar with extrusion techniques will be able to go even further, however. The extrusion process makes it possible to integrate a number of secondary functions into the design of the platform planking. For example, an extruded solution can:

1) resist bending stress (floor thickness)
2) resist spot stress (wall thickness)
3) resist torsion stress (hollow section)
4) facilitate joining ("groove and tongue", tack welding)
5) prevent skidding (grooves)
6) provide drainage for fuel spill and rainwater
7) allow airing to prevent crevice corrosion
8) conduct fire extinguishing foam
9) accommodate de-icer cables.

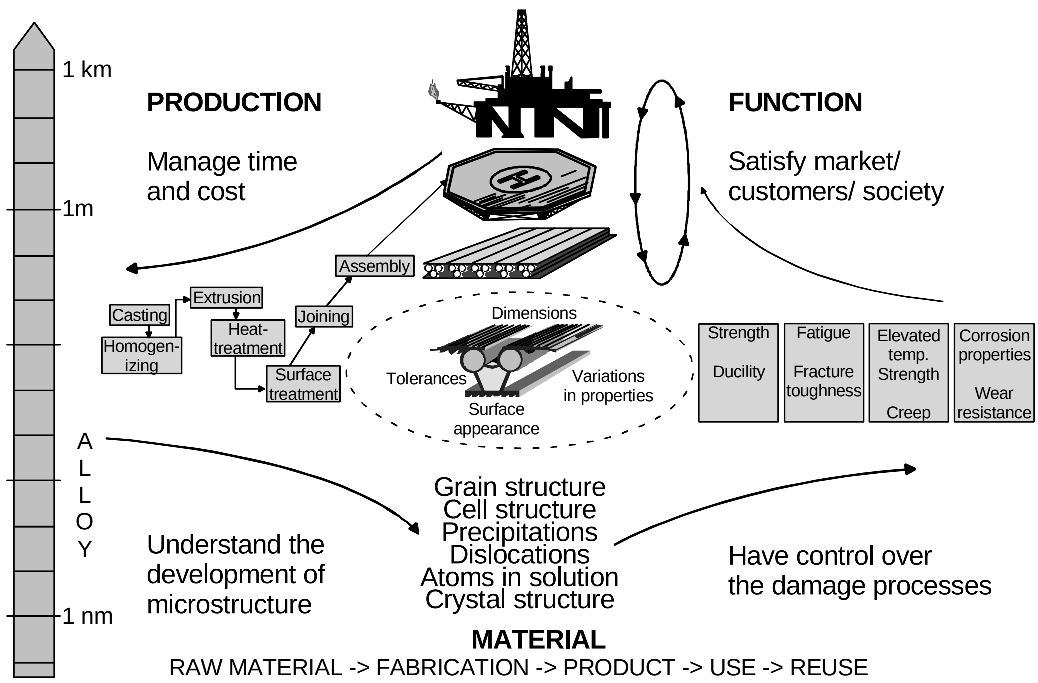
Yet before such a solution can be accepted, we must ensure that the alloys selected provide the required properties and that the solution is superior with a view to facilitating production, lower costs, safety, useful life, life cycle costs, etc.



An Illustration of the Interaction

The production development team must conduct such overall assessments early in the design phase.

Figure 2101.01.02 offers an example of a "map" which may help us make such overall assessments. The horizontal axis describes the product's total life, from raw material to disposal and recycling. The vertical axis is a logarithmic scale from 1 nm (10^{-9}m, the size of an atom) to 1 km (10^{3}m, the size of a manufacturing plant). Each component of the product, illustrated here by the platform planking, can be compared with this "map" to evaluate the processing chain used, the microstructure achieved through the choice of alloy, the thermo-mechanical process history, and the properties achieved as a consequence of these. The interaction of the component with the product's other components during assembly, use and possibly dismantling will also be clear from the illustration. Such a "map" can be drawn up for each component. Viewed together, the "maps" will constitute a "product model" that provides systematic documentation of all the information about the product, its components, their production, fabrication, use and re-use.



TALAT	Product Model	2101.01.02

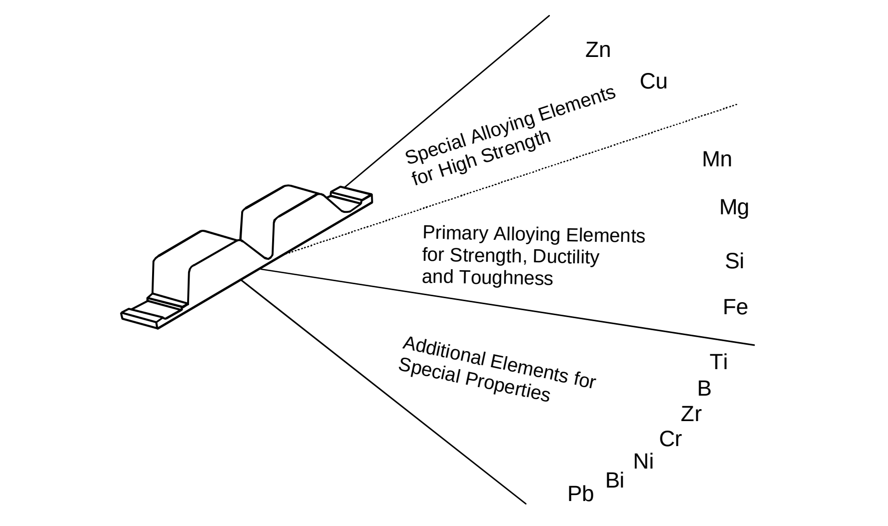
Such "maps" or "visualisations" are important for understanding the connection between a whole and its parts. They represent an effective "mental tool" which helps us work systematically to gain the insight, understanding and perception we seek.

Alloying Elements and Types of Alloys

The most important alloying elements used to impart particular properties to aluminium are silicon (Si), magnesium (Mg), manganese (Mn), copper (Cu) and zinc (Zn).

All commercial alloys contain roughly 0.1 - 0.4 per cent iron (Fe) by weight. The iron content may be viewed as an impurity in the metal. It depends on the raw materials (alumina) and the electrolytic reduction process. Iron is occasionally used to give the material special qualities (e.g. the properties of aluminium foil).

Other alloying elements often used in combination with one or more of the major alloying elements include bismuth (Bi), boron (B), chromium (Cr), lead (Pb), nickel (Ni), titanium (Ti) and zirconium (Zr). These elements are usually used in small amounts (<0.1 per cent by weight, although B, Pb and Cr may comprise up to 0.5 per cent) to tailor alloys for special purposes by imbuing them with properties such as castability, machinability, heat-resistance, corrosion-resistance, tensile strength, etc. (see **Figure 2101.01.03**).



TALAT	Alloying Elements	2101.01.03

The Classification of Aluminium Alloys

There are a number of different systems for classifying aluminium alloys. We will be using the standard set by the American Aluminum Association (AA), which is the most frequently used international standard. In some cases, we will use the ISO standard whose designations specify the content of the major alloying elements as percentages by weight.The new European Norms (EN) will also be based on the two standards mentioned above.

Figure 2101.01.04 presents the AA's list of major alloying elements. The first digit in the AA designations classifies the alloys by major alloying element(s). A distinction is made between wrought alloys and cast alloys. The figure also specifies the mechanisms that contribute to the strength of the alloy class (atoms in solution, work hardening and precipitation hardening). A distinction is also made between non-heat treatable alloys and heat treatable alloys.The non-heat treatable alloys obtain their strength from the alloying elements in solid solution and different degrees of cold deformation and annealing.

Alloy Designation System

	AA	Major Alloying Element	Atoms in Solution	Work Hardening	Precipitation Hardening	
Wrought Alloys	1xxx	None		X		Non-Heat Treatable Alloys
	3xxx	Mn				
	4xxx	Si	X	X		
	5xxx	Mg				
	6xxx	Mg + Si				Heat Treatable Alloys
	2xxx	Cu	X	(X)	X	
	7xxx	Zn				
	8xxx	Other				
Casting Alloys	1xx.x	Min. 99% Al				Non-Heat Treatable Alloys
	4xx.x	Si				
	5xx.x	Mg	X			
	3xx.x	Si + Mg (Cu)				Heat Treatable Alloys
	2xx.x	Cu				
	7xx.x	Zn	X		X	
	8xx.x	Sn				
	9xx.x	Unused				

Source: Aluminium Association, Washington, D.C.

TALAT Training in Aluminium Application Technologies | Alloy Designation System | 2101.01.04

Figure 2101.01.05 provides an overview of the standard combinations of work hardening and annealing. Heat-treatable alloys obtain their strength primarily from precipitation hardening.The figure also shows the designations of the standard solution heat-treatment and aging processes.

Temper Designation for Aluminium Alloys

XXXX-F: as-Fabricated XXXX-O: Annealed (Wrought Alloys)

XXXX	H1	Work-Hardened Only		Non-Heat Treatable Alloys
	H2	Work-Hardened and Partially Annealed		
	H3	Work-Hardened and Stabilized by Low Temperature Treatment		
XXXX	HX2	Quarter-Hard	Degree of Cold Working	
	HX4	Half-Hard		
	HX6	Three-Quarter-Hard		
	HX8	Full-Hard		
	T2	Cooled from an Elevated Temp. and Naturally Aged		Heat Treatable Alloys
	T4	Solution Heat-Treated and Naturally Aged		
	T5	Cooled from an Elevated Temperature Shaping Process and Artificially Aged		
	T6	Solution Heat Treated and Artificially Aged		

TALAT Training in Aluminium Application Technologies | Temper Designation for Aluminium Alloys | 2101.01.05

Figure 2101.01.06 is a list of the most common commercial alloys available from all suppliers.These alloys have been used extensively and their properties are well documented.They may be referred to as "generic alloys" and it is always a good idea to take one of them as a point of departure during the concept phase of the product development process. If a special combination of properties is required, special alloys should be examined in consultation with a supplier (see, for example, the product example involving the "compressed air tank" in TALAT lecture 2102.04).

One of the generic alloys in the 7000 series, AlZn6MgCu, is especially strong. It is a so-called "aviation alloy", primarily used in aircraft. However, high costs, reduced weldability and the risk of corrosion mean that these aviation alloys are rarely used in building construction or for marine applications or other types of transport.

Commercial Aluminium Alloys

European Standard ISO	American Standard AA	Swedish Standard SS	Norwegian Standard NS	Properties	Applications
Al99.5	AA 1050	4007	17010	Wrought Alloys Non-Heated Treatable	Sheets and Bars
AlMn1	AA 3103	4054	17405		
AlMg2.5	AA 5052	4120	17210		
AlMg4.5Mn0.7	AA 5083	4140	17215		
AlMgSi	AA 6060	4103	17310	Wrought Alloys Heat Treatable	Extrusions, Tubing and Forgings
AlSi1MgMn	AA 6082	4212	17305		
AlSi1Mg	AA 6351				
AlZn5.5MgCu	AA 7075				
AlSi12	A 413	4261 / 63	17510	Casting Alloy, Non-Heat Treatable	Mould Casting
AlSi7Mg	356	4244	17525 }		
AlSi10Mg	361	4253	17520 }	Casting Alloy, Heat Treatable	
MgAZ91D			17709		

TALAT	Commercial Aluminium Alloys	2101.01.06

A magnesium alloy, MgAZ91 (alloyed with 9 per cent Al and 1 per cent Zn by weight), is among the generic casting alloys. It is natural to view magnesium as an alternative light metal casting alloy. The alloy's low density, good ductility and good machinability may sometimes provide the best solution. The main alloying elements in the other generic alloys are Si, Mg and/or Mn. The figure also shows the semi-finishing processes typically associated with the different classes of alloy.

New Alloys and Composites

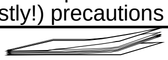
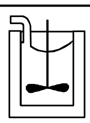
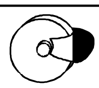
New alloys and composites are being developed all the time. **Figure 2101.01.07** shows some of the most interesting alloys and aluminium-based composites currently under development.

The addition of lithium (density 534 kg/m^3) offers a new type of aviation alloy with a lower density, higher modulus of elasticity and higher strength than the traditional aviation alloys. High production costs will no doubt limit the use of these alloys to the fields of aviation, space and defence.

Rapid quenching from melt to particles, wire or thin rod can cause the content of certain alloying elements (iron, nickel) to increase far beyond what is considered "normal". When such rapidly solidified alloys are compressed and extruded or forged, we get a material with high strength and excellent heat resistance. However, high production costs suggest that these alloys will probably be limited to special applications.

Improved fatigue-resistance and fracture toughness can be achieved at a lighter weight than conventional alloys by making a laminate of high tensile aluminium alloy and a polymer (e.g. many layers of 0.3 mm AA7075 and 0.2 mm aramid epoxy).

New Aluminium Alloys and Aluminium-based Composites

Material System		Typical Application(s)	Special Properties	Challenges
Aluminium-Lithium-alloys	Conventional processes, but high reactivity of Li requires special (costly!) precautions	Aircraft Components	High strength, low density, high modulus of elasticity	Cost Recycling
Laminate AA 7075 Al + Aramid	 Thin sheets (0.2mm) of aluminium and Aramid in alternative layers, glued together	Aircraft High Efficiency Transport on Road, Railway and Sea	High fatigue resistance and fracture toughness. Low weight	Cost Recycling
Rapid solidified alloys	 Rapid solidified to granulate, wire or thin stamps. compressing	Engine Parts	High strength at elevated temperature	Cost Recycling
Particle reinforced aluminium SiC-particles + Al-Si-Mg-matrix	 Mixing of the particles into the Al-melt. Conventional processing	 Disc - Brakes	High wear resistance high modulus of elasticity	Machining Recycling

TALAT — New Aluminium Alloys and Aluminium-based Composites — 2101.01.07

Another exciting development involves particle reinforced aluminium. Particles of silicon carbide (SiC) or aluminium oxide (Al_2O_3) ranging from 5 - 20 µm in size are mixed into the melt (10 - 25 per cent by volume) before casting. Standard shaping methods like mould casting, extruding or forging may be used. Particle reinforcement results in a higher modulus of elasticity, enhanced heat resistance, improved wear resistance and better fatigue resistance. Prototypes of components and products, such as the brake disks, are currently under development.

Despite these interesting development trends, it is important to point out that the traditional alloys dominate the market in actual practice. The challenge lies in taking advantage of the opportunities inherent in the easily accessible standard alloys by choosing the appropriate combination of shape, alloy, processes and production procedures for the function that the product or component is to perform. At the same time, we must bear in mind that new alloys and processes sometimes result in unexpected, competitive solutions.

Shaping Processes, Processing Chains and Component Shapes

Different product designs and properties are achieved through deformation and heat treatment. The most important processing chains used to manufacture individual aluminium parts may be divided into three:

- Rolling and shaping sheets and strip.
- Extruding and processing sections, tubing and forging stock.
- Mould casting.

These processing chains are sometimes followed by subsequent machining, welding and surface treatment.

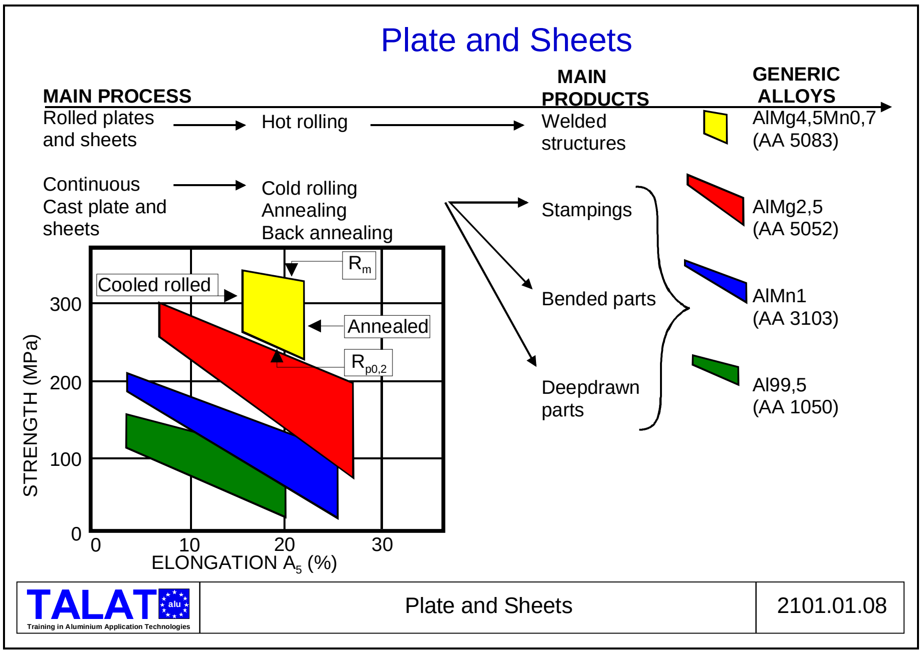
There is a close connection between alloys and processing chains, so the different alloys generally have their own special processing chains. The specific choice of shaping methods and alloys is described more fully under the discussion of the product examples in TALAT lectures 2102.01 - 2102.04.

Sheet Products and Sheet Alloys

Sheets and strip are made from cast and homogenised ingots. Homogenisation involves equalising the differences in the concentration of the elements in the cast ingot by keeping it at a constant temperature of approx. 585°C for up to 24 hours. Hot rolling reduces the ingot to its final gauge for heavy plate or to coils for cold rolling. The coils for cold rolling can also be cast directly in continuous strip casting machines. The cast coils, 2-6 mm thick, are reduced further by cold-rolling to their final gauge (thin sheets and strip).

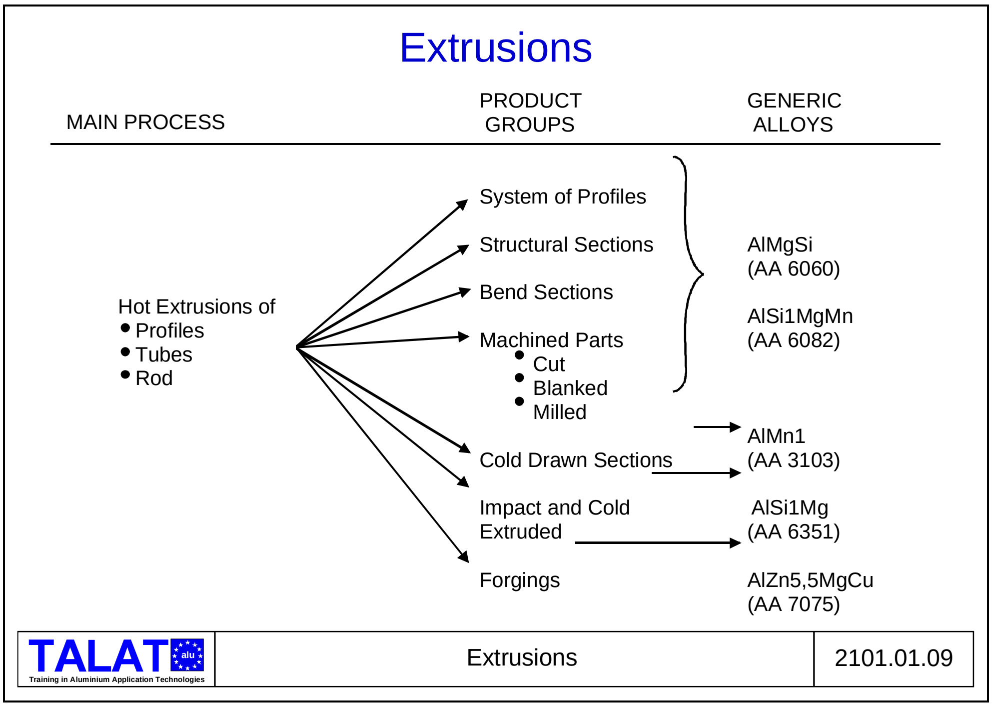
Most rolled products for design and structural applications are made from unalloyed aluminium or alloys containing Mn and/or Mg. We have selected four common alloys.

Figure 2101.01.08 specifies the processing chains typcially used with these alloys. An alloy designated AA5083 is often used in larger structures by welding sheets or plates to produce wide panels. The diagram covering strength and ductility shows that this alloy maintains its strength, even in an annealed state. This is because the alloying elements in solid solution are a more important strengthening mechanism than work hardening in this alloy. For some other alloys there are far greater differences in strength and ductility between the annealed and full-hard state. One must select the correct combination of sheet thickness, strength and hardness, based on processing and the component's area of application.

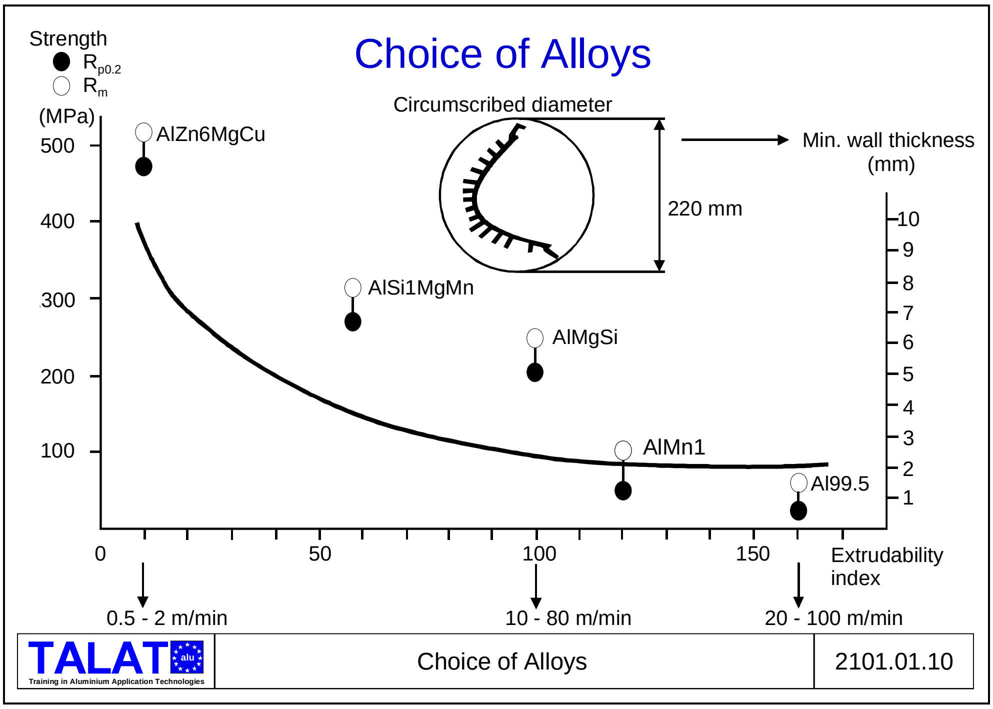


Extruded and Impact-Extruded Components and Alloys

Cast, homogenised ingots ("logs") are pre-heated and cut into appropriate lengths ("billets"). These are extruded in a hydraulic press at initial temperatures of 450 - 490°C into custom extrusions, standard extrusions or into tubing or rods for drawing, impact extruding or forging. **Figure 2101.01.09** shows alternative processing chains and products from the extrusion press, as well as a list of common alloys.



The material selection diagram (**Figure 2101.01.10**) shows the connection between the circumscribed diameter of the section, the minimum wall thickness, the alloy's extrudability and the strengths of the various alloys.

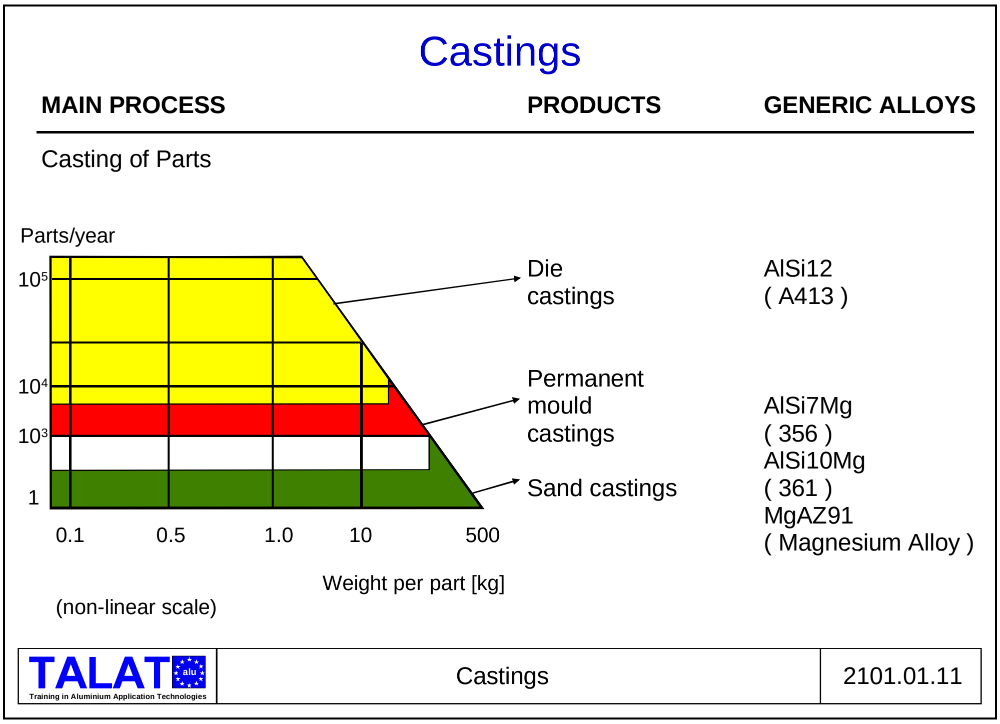


Al99.5 (AA1050) and AlMn1 (AA3103) are not heat treatable. ince extrusion is a hot forming process, these alloys will have very low strength. ubsequent cold drawing of tubes or wire will let us achieve strength attributes comparable to those achieved by cold rolling. These alloys are readily extrudable and can be manufactured as thin-walled sections. However, heat treatable alloys are usually used for extrusions. The diagram

shows that the high-strength alloy AlZn6MgCu is difficult to extrude and has a minimum wall thickness of 8-9 mm. Accordingly, it is expensive to produce and makes it difficult to exploit the combination of high strength and thin wall thickness. By selecting alloys hardened with magnesium and silicon, on the other hand, a good balance can be achieved between strength, minimum wall thickness and extrudability. Consequently, AlMgSi is one of the most commonly used extrusion alloys. The somewhat more heavily alloyed AlSi1MgMn is even stronger. The less heavily alloyed AlSi1Mg (AA6351) is often chosen for subsequent cold forging (see **TALAT Lecture 2102.02**) to achieve an optimal combination of extrudability and strength.

Cast Components and Alloys

There are three main methods used for casting aluminium alloys: Sand casting, gravity die-casting and pressure die-casting (see **Figure 2101.01.11,** also **TALAT Lecture 2102.03**).



The alloys usually have a high silicon content, which reduces the viscosity of the molten metal when it is cast. Pressure die-cast components cannot be heat treated, so non-heat treatable alloys are selected, represented here by AlSi12. Gravity die-casting and sand casting often use the heat treatable alloys AlSi7Mg and AlSi10Mg. As mentioned earlier, it is natural to include another heat treatable alloy, MgAZ91, among the "generic alloys". The diagram shows the relationship between the unit weight of the castings and the areas recommended for the respective casting methods.

After casting and heat treatment, the castings are generally subjected to machining and surface treatment before completion. Machinability is therefore an important property for cast alloys.

The Interaction between Microstructure and Properties

Thus far we have examined several important processing chains for the fabrication of aluminium components. The process determines not only the shape of the component, but also its microstructure. In turn, the microstructure determines the component's attributes. We shall now proceed to examine this in more detail.

Certain properties of aluminium are largely independent of the content of alloying elements and the processing chain. Examples are the modulus of elasticity, E = 70 GPa, the density, s = 2700 kg/m^3, and the thermal expansion coefficient, 24 x 10^{-6}/K.

Most other properties are very sensitive to the material's microstructure and composition. As indicated in **Figure 2101.01.02**, it is natural to divide these properties into four categories:

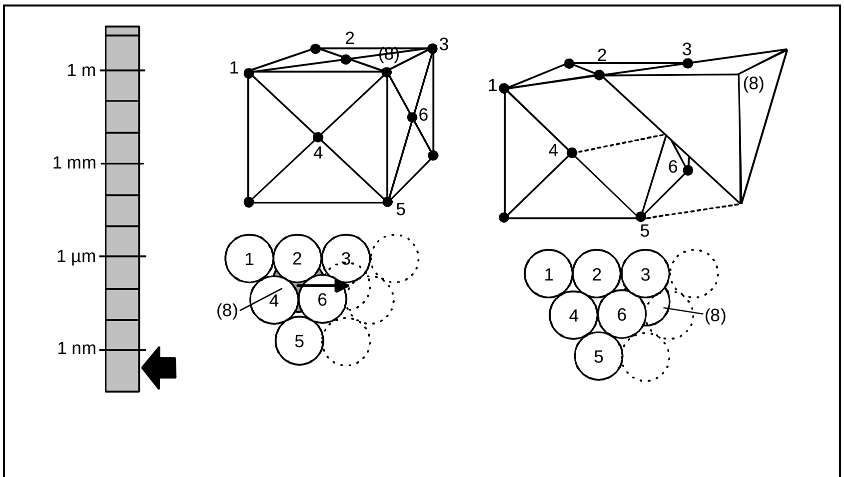
- Strength, ductility and formability (volume properties)
- Fatigue resistance and fracture toughness (local properties or crack front properties)
- High temperature resistance and creep resistance (thermomechanical properties)
- Corrosion resistance, wear resistance and surface condition (surface properties).

Since the alloy composition, the shaping processes and heat-treatment determine the microstructure, and the microstructure in turn determines the properties mentioned above, it is imperative for the designer to be familiar with these relationships. If the designer views microstructure as part of a component's structural design, it will also be easier seek the help of metallurgists and process experts when needed. ou will now be taken on a "guided tour" through the microstructure of aluminium alloys. We will begin with atomic structure and conclude with grain structure. This spans a dimensional range from the size of an atom, 4 x 10^{-10}m (0.4 nm) to the size of a grain, 4 x 10^{-5}m (40 µm), i.e. 5 orders of magnitude. This is the range in which the materials' properties are formed.

Atomic Structure

Aluminium has a face-centred cubic lattice structure. This means the atoms are arranged so that they form the corners of a cube, with one atom in the centre of each face (**Figure 2101.01.12)**. The length of a side is about 0.4 nm, as indicated by the arrow pointing to the logarithmic size scale. The atoms' relative position in the lattice-arrangement will remain the same as long as there is no plastic deformation of the material. If the material is strained enough to cause plastic deformation, certain crystal planes slip in particular directions. This is indicated in the figure by the slip that takes place in the plane parallel to plane 1-2-3-4-5-6. Atom number 8, located on the slip plane, moves from one "depression" in the plane below to the next "depression".

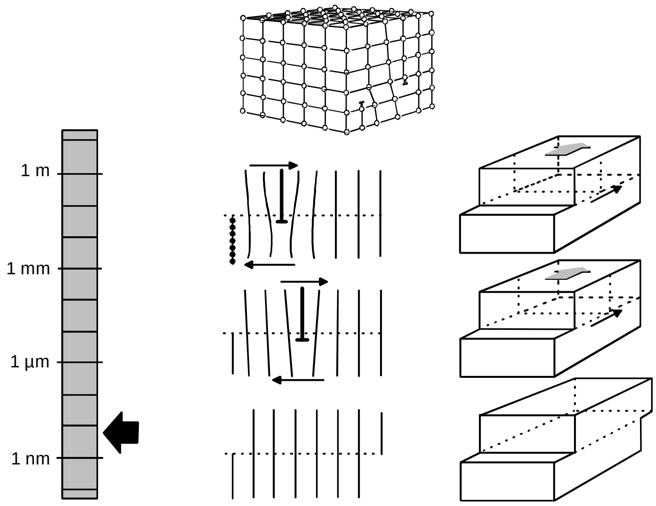
A slip caused by all the atoms in the slip plane shifting simultaneously would theoretically call for a yield stress of approximately 4,000 MPa and result in absolutely brittle material. Aluminium alloys generally have a yield stress between 40 to 700 MPa. he most important commercial alloys are found in the 150 - 350 MPa range, values which result in highly ductile, workable metals.



TALAT | Aluminium Atomic Structure | 2101.01.12

Dislocations

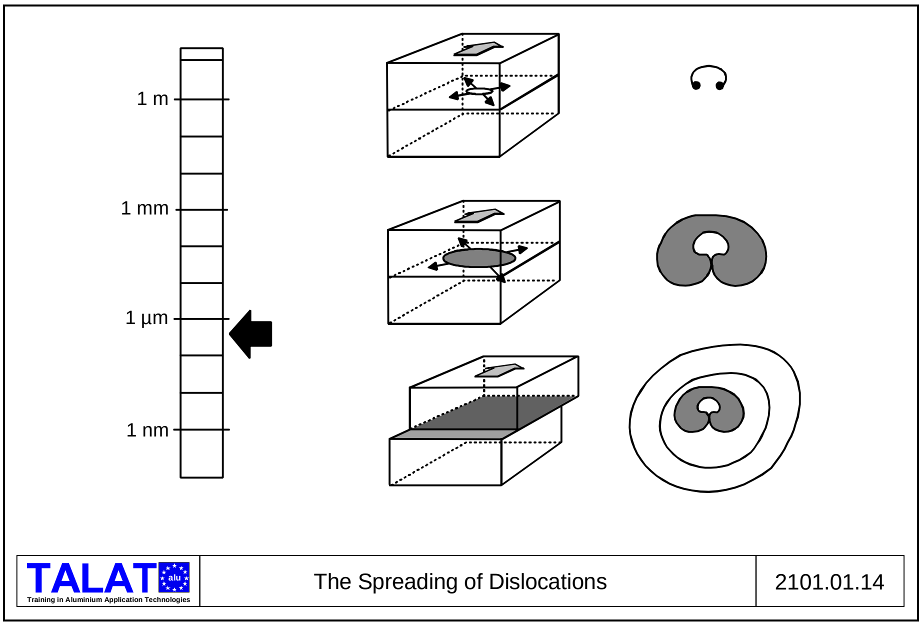
Figure 2101.01.13 presents a schematic illustration of an imperfect crystal structure. Certain planes of atoms end in the middle of the crystal. The line that forms along the edge of such an extra plane is called a dislocation. This edge or dislocation can move in particular atomic planes and directions. f the extra atomic plane bonds to the lower part of the neighbouring plane, the upper part of that neighbouring plane will become the extra plane; the dislocation has migrated precisely as far as atom 8 in **Figure 2101.01.12**. In that way, the dislocation moves along the slip plane, where new atoms continuously add momentum to its movement. Once it passes through an entire crystal, the upper part of the crystal will have slipped a length comparable to the migration made by atom 8. The direction and length of this movement is called Burger's vector. The crystal has sustained a plastic deformation.



TALAT Dislocations 2101.01.13

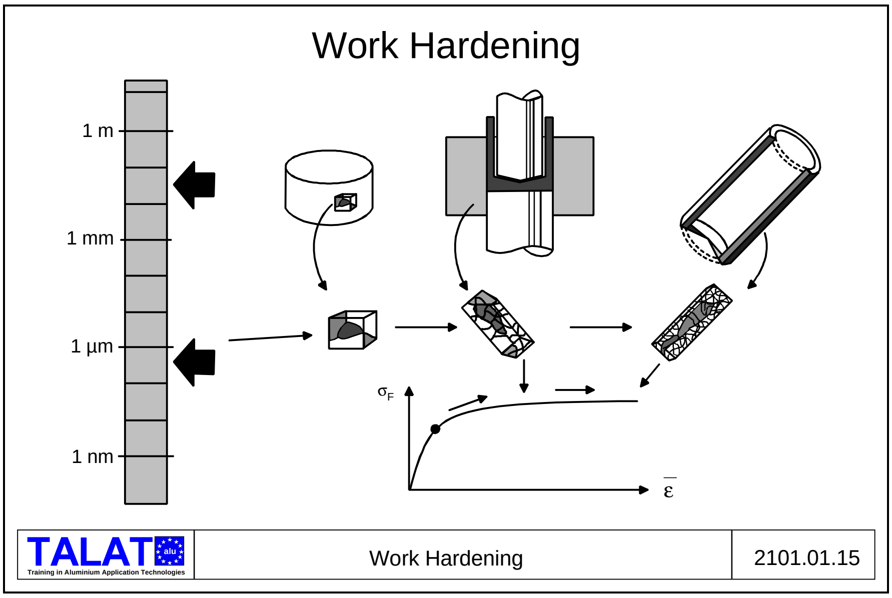
New dislocations are formed continually during plastic deformation. They start at one point and spread out in a ripple pattern, as illustrated in **Figure 2101.01.14**. This facilitates continual plastic deformation. Measurements indicate that the yield stress of super pure aluminium would be about 4 MPa.

A metal's strength and ductility can be explained on the basis of the migrations of the dislocations. By adding alloying elements, selecting process parameters for casting, mechanical working, heat treatment, joining and surface treatment, the microstructure can be "manipulated" to obtain the best possible combination of properties in the component. The mechanisms that affect resistance to the migration of dislocations in an alloy will now be reviewed.



Work Hardening

Figure 2101.01.15 illustrates a cold metal process called cold forging or impact extrusion (see also TALAT lecture 2102.02). A cylindrical blank is cut from an extruded rod. The blank has undergone soft annealing so it has the lowest possible flow resistance in its initial state. That means it features few dislocations. The blank is placed in a die and a punch presses the metal upwards, past the top of the punch, to form a cup-shaped component. This is called "indirect extrusion". If we look at a material element in the blank, we will see it consists of crystals with a diameter of approximately 40 µm. When subjected to plastic deformation during the extrusion operation, dislocation sources such as those shown in **Figure 2101.01.14** will be formed inside each grain under the influence of external forces, and a stream of dislocations will ripple out from each source, migrating along many slip planes. The number of dislocations that are or have been in movement and their speed are determined by the punch speed and how much the material element is deformed. Dislocations originating from various sources intersect in different planes, forming "vases" of dislocations which prevent further movement. The metal is strengthened by the deformations.

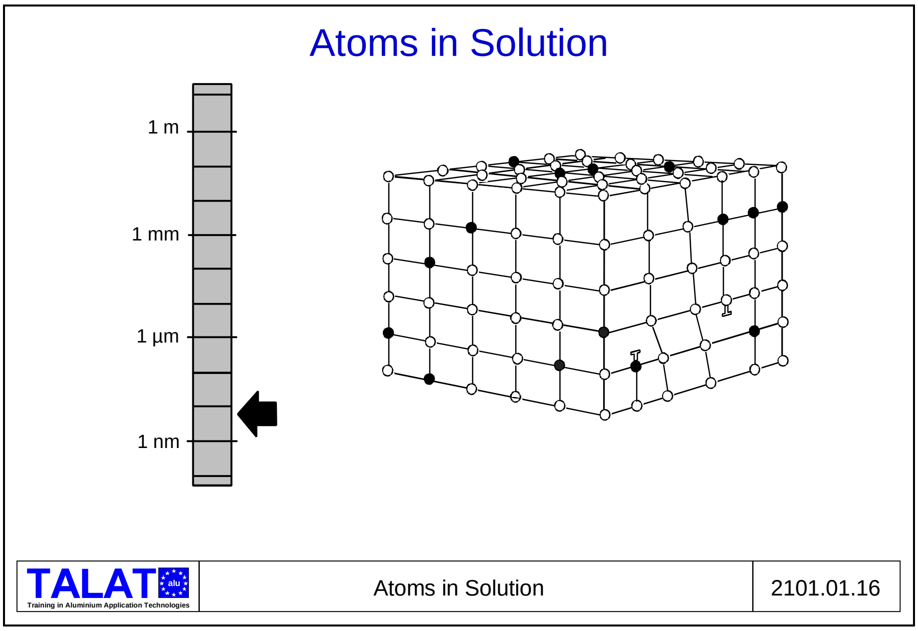


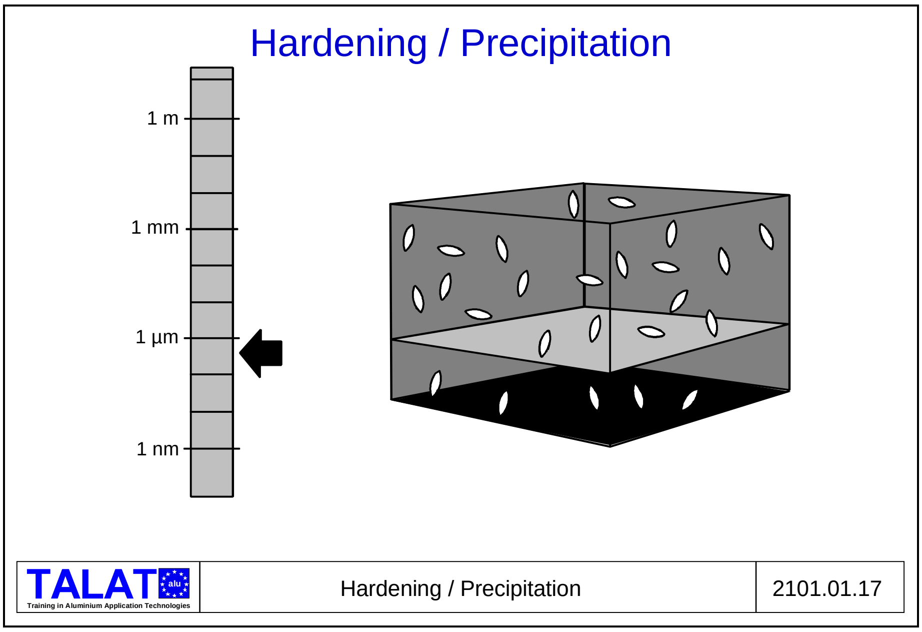
When sufficiently heavy deformations occur, the vases are arranged into a network, forming *cells* bounded by areas congested with locked dislocations, while the cells contain few dislocations that can move relatively freely. The diameters of the cells range from 3 - 5 µm. Within the bounds of the cells, dislocations disappear as extra planes merge into whole atomic planes. Depending on temperature and the speed of deformation, the heavy deformations will reach a state of equilibrium between the formation of new dislocations and the annihilation of old ones. Thus the work hardening has reached the saturation point. The curve will flatten out as indicated in **Figure 2101.01.15**.

Heating will cause a component's locked dislocations to melt together and disappear (annealing). However, since no new dislocations will be formed, we will obtain a "recovered" structure with a lower strength. It is possible to achieve the desired combination of strength and ductility through a controlled heating process called partial annealing or back annealing.

Atoms in Solution

When atoms from another metal replace aluminium atoms in a crystal lattice, we say the alloying element is in solid solution. Manganese and magnesium are typical examples of alloying elements in solution in aluminium. These atoms do not quite fit into the lattice, meaning the surrounding aluminium atoms are displaced slightly (**Figure 2101.01.16**). This impedes the migration of dislocations through the crystal. The foreign atoms in solution add to the strength of the alloy.





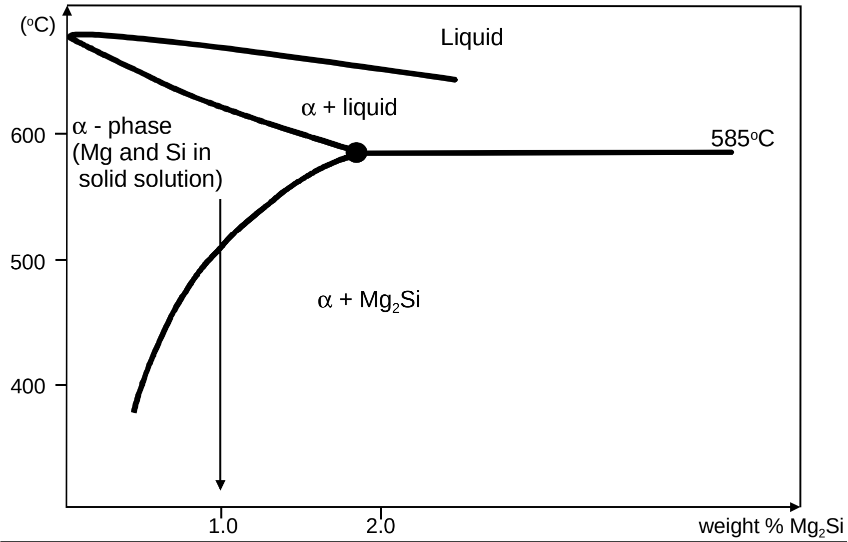
Precipitation of Particles

Figure 2101.01.17 shows particles (or thin bars) precipitated in the crystal lattice. Such particles are formed when alloying elements in solution are oversaturated (solution heat-treatment) and precipitated (aging). For example, magnesium and silicon in solid solution are precipitated as an intermetallic compound in the form of needles or bars with a length of just a few tenths of a micrometre and a thickness of approximately 10 nm.

Solution Heat-treatment

Solution heat-treatment can take place when the amount of the alloying elements in solution is reduced in proportion to temperature. We can see this from the phase diagram for the Al-Mg-Si system.

Figure 2101.01.18 shows a cross-section of the diagram based on percentage weight of Mg_2Si along the horizontal axis. In the "a-phase" area, Mg and Si are in solid solution. When an alloy containing approximately 1 per cent of Mg2Si (by weight) is quenched rapidly from a temperature of roughly 570 °C to room temperature, the alloying elements will not have time to diffuse and form particles. The aluminium metal becomes oversaturated with magnesium and silicon in solid solution.

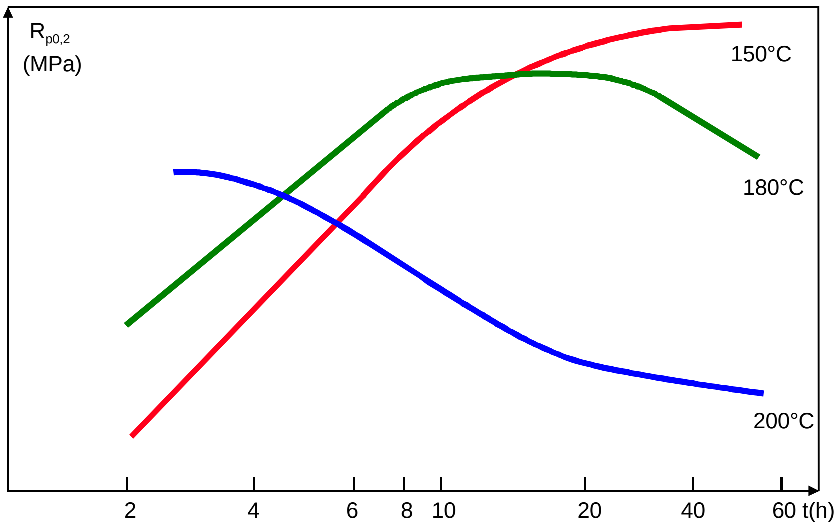


TALAT	Phase Diagram Al-Mg-Si System	2101.01.18

Artificial Ageing

Artificial ageing involves heating the alloy to roughly 180 °C for a few hours. This will facilitate a controlled diffusion (migration) of the dissolved silicon and magnesium atoms towards the areas where the intermetallic Mg_2Si phase begins to precipitate. At the same time, the surrounding crystal lattice will be slightly deformed because the precipitates do not quite fit into the structure. The hard needles precipitated, combined with the deformation of the surrounding lattice structure, mean that considerable external forces are required for a dislocation to pass through such areas. Consequently, the material's flow stress, $R_{p0.2}$, in-creases significantly. If the alloy is kept at this high temperature for too long, the contact between the particles and the surrounding lattice will decrease, reducing the deformations in the lattice while some particles grow and others disappear. We say the alloy has been overaged, and the flow stress declines

again. **Figure 2101.01.19** demonstrates this phenomenon at different aging temperatures.
In time, ageing may also take place at room temperature. This applies to zinc (Zn) and magnesium (Mg) alloys in particular and, to a far lesser extent, to Al-Mg-Si alloys. As time passes, alloys in a naturally aged state will always exhibit some variation in their properties.



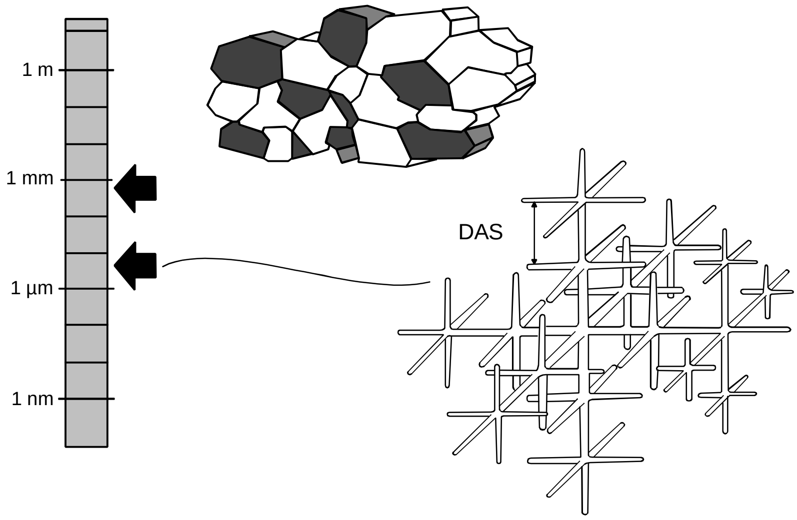
TALAT | Variation in Flow Stress at Different Temperatures | 2101.01.19

Grains and Dendrites

When the metal solidifies, the solidification process begins with small solid particles in the melt. Particles (seed crystals) with a diameter of a few µm are added to aluminium melt to provide sufficient nuclei for solidification. Each grain grows into a crystal shaped like a dendrite (see **Figure 2101.01.20**). A dendrite is formed when the growth speed of the crystal becomes especially great in certain directions, forming tree-like branching patterns. Each dendrite grows until it encounters neighbouring grains. The metal between the arms solidifies and the metal that solidifies last frequently has a different composition of alloying elements and impurities than the metal that solidified earlier. This process forms an alloy's cast structure. The more nuclei formed, the smaller the grains. The particles added as seed crystals are therefore called grain refiners. The distance between the arms of the dendrite (DAS = Dendrite Arm Spacing) is determined by the speed of solidification. Grain size, dendrite spacing, pores and the amount of impurities are of decisive importance to the properties of the cast metal. The grains in a cast structure are usually in the 200 - 1,000 range, while the dendrite arm spacing generally varies from 10 - 40 µm.

Wrought alloys are hot rolled or extruded after being cast and homogenised. The cast structure will then be broken up and a new grain structure will be formed by recrystallization. Meanwhile, micropores, impurities and deposits of alloying elements along the grain boundaries and between the dendrite arms will be dissolved and distributed during homogenisation and the subsequent hot working process. In extruded materials, grain sizes commonly reach 30 - 50 µm.

Further processing through a combination of cold deformation and heat-treatment will result in more precise control of grain size, the structure of precipitated particles, dislocations, impurities and the alloying elements in solution.



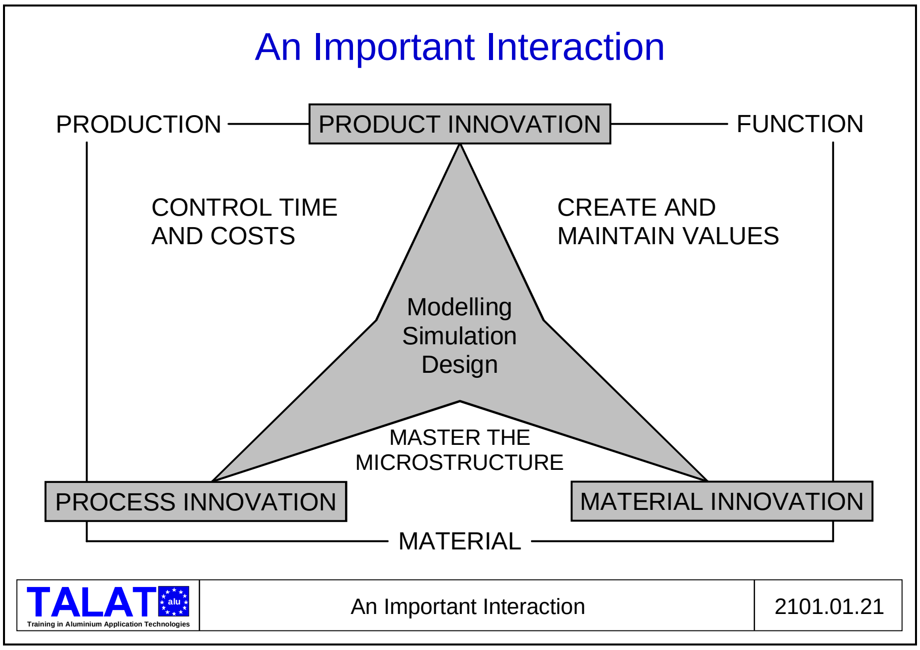
TALAT Training in Aluminium Application Technologies	Grains and Dendrites	2101.01.20

Factors and Sources of Innovation

The interaction between processing chain, component shape, microstructure and the component's properties is a source of innovation. Shaping, processing, joining and surface treatment are used for more than just giving a component a shape and a surface. In combination with casting parameters and thermal treatment, these processes allow us to control an alloy's microstructure and achieve an optimal combination of properties for any given purpose (see **Figure 2101.01.21**).

- Knowledge of the parts combined with an understanding of the whole results in freedom of design.
- Freedom of design paves the way for innovation.
- Innovation makes it possible for us to meet the challenges of the future.

We shall examine four product examples in TALAT lectures 2102.01 - .04 and discuss in more detail the phenomena mentioned here.



Literature

Hatch, John E.: *"Aluminium, Properties and Physical Metallurgy"*, American Society for Metals, 1984. ISBN 0-87179-176-6.

Altenpohl, D.: *"Aluminum Viewed from Within"*, Aluminium-Verlag, Düsseldorf, 1982.

ISBN 3-87017-138-3.

Mondolfo, L-M.: *"Aluminium Alloys: Structure and Properties"*, Butterworths, London, 1976.

van Lancker, M.: *"Metallurgy of Aluminium Alloys"*, Chapman and Hall Ltd., London, 1967.

"ALUMINUM Standards and Data 1986, Metric SI", Aluminum Association, 818 Connecticut Ave., Washington D.C. 20006

"Aluminium-Taschenbuch", Aluminium-Verlag, Düsseldorf, 1983. ISBN 3-87017-169-3.

Thundal, Björn: *"Aluminium"*, kap. 7 - 11, Almqvist & Wiksell, 1991, ISBN 91-21-58813-9.

"Materialkendskap.Aluminium", Etteruddannelse i Materialteknologi, kursus A1, Dansk Teknologisk Institut Forlaget, 1991, ISBN 87-7756-148-1 (telefon +45 42 99 66 11, lokal 3901).

MATEDS, PC-based materials property database, approx. 150 wrought and cast alloys, 50 different properties and procedures for materials selection. For information contact Skanaluminium, Oslo, tel +47 22 96 10 80.

ALUSELECT, PC-based materials property database, 28 wrought alloys, 50 properties, developed by EAA (European Aluminium Association, Brussels).

List of Figures