TALAT Lecture 1255

Metallurgical Background to Alloy Selection and Specifications for Wrought, Cast and Special Applications

16 pages, 17 Figures

Advanced level I

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Objectives:

Outline of the metallurgical principles of alloy selection and specifications.

Prerequisites:

Basic knowledge of physics and chemistry. Familiarity with the contents of Lectures 1201 through 1205.

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1255 Metallurgical Background to Alloy Selection and Specifications for Wrought, Cast and Special Applications

Contents (17 Figures)

1255.01 Wrought alloys

The majority of aluminium used in engineering applications is in the wrought form [1]; that is, as rolled plate, sheet and foil, extrusions, tube, bar and wire (the remainder are casting alloys and alloys produced by special processing - we will consider these later in this TALAT lecture).

The number of alloys available to the engineer is large, but can be divided into two main groups; ***non-heat treatable alloys and heat treatable alloys***. Before looking at the characteristics of these two classes of wrought alloy, let us first define the modern method of designation of wrought alloys and their processing.

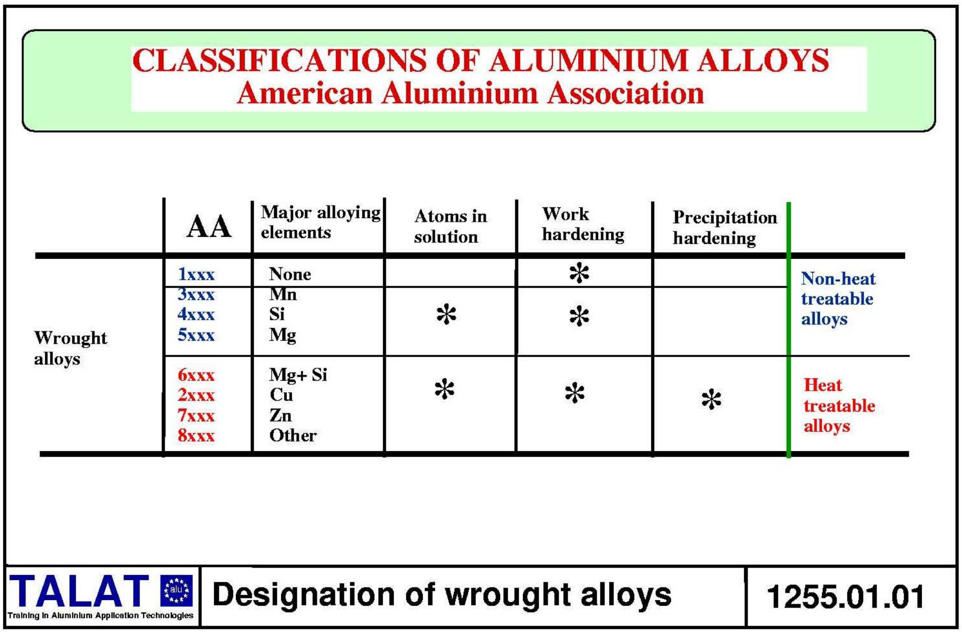
1255.01.01 Designation of wrought alloys

The International Designation System for wrought alloys is reproduced below in Table 1 and also in **Figure 1255.01.01**.

AA Designation	Major alloying elements	
1xxx	None	) Non - heat treatable
3xxx	Mn	)
4xxx	Si	) Non - heat treatable
5xxx	Mg	)
2xxx	Cu	)
6xxx	Mg + Si	) Heat treatable
7xxx	Zn	)
8xxx	Other	)

Table 1. Designation of wrought aluminium alloys.

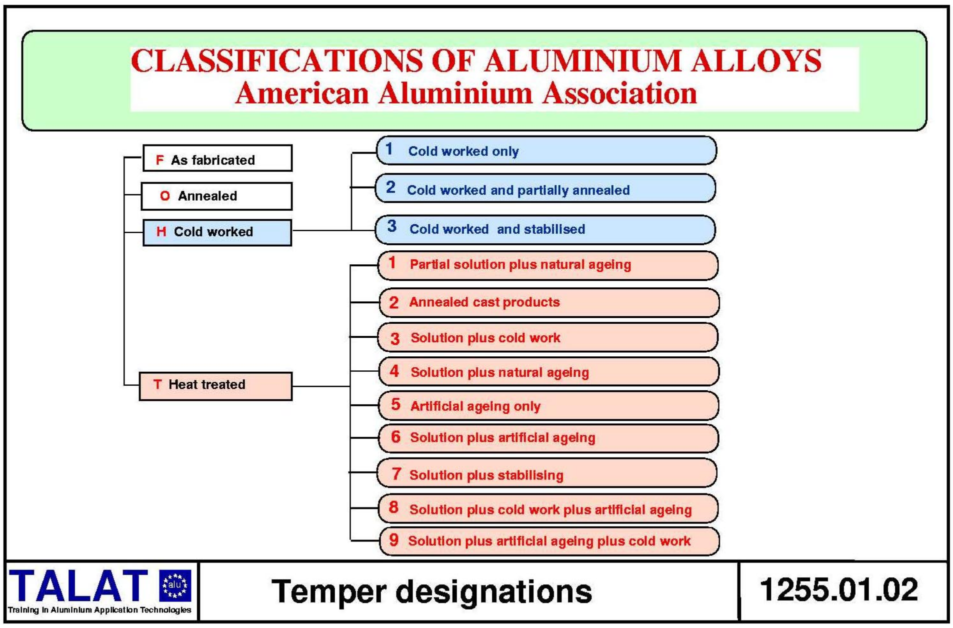
In this four digit classification system, the first digit identifies the major alloying elements(s). The remaining three digits are used as serial numbers to identify particular alloy types. For the 1xxx series there is some logic in the designations; for example, in alloys of commercial purity, the xxx signifies the degree of purity - 1080 signifies aluminium of purity 99.80 wt%. For the remaining wrought alloys the xxx in the designation has no systematic code and the reader is referred to texts such as that provided by the Aluminium Federation [2].



	AA	Major alloying elements	Atoms in solution	Work hardening	Precipitation hardening	
Wrought alloys	1xxx	None		*		Non-heat treatable alloys
	3xxx 4xxx 5xxx	Mn Si Mg	*	*		
	6xxx 2xxx 7xxx 8xxx	Mg+ Si Cu Zn Other	*	*	*	Heat treatable alloys

The processing condition of an aluminium alloy is given by its temper designation, which is a convention for describing the basic treatment or condition of the alloy (Note : here the term 'temper' has a different meaning to the very specific heat treatment of 'tempering' as applied to steels).

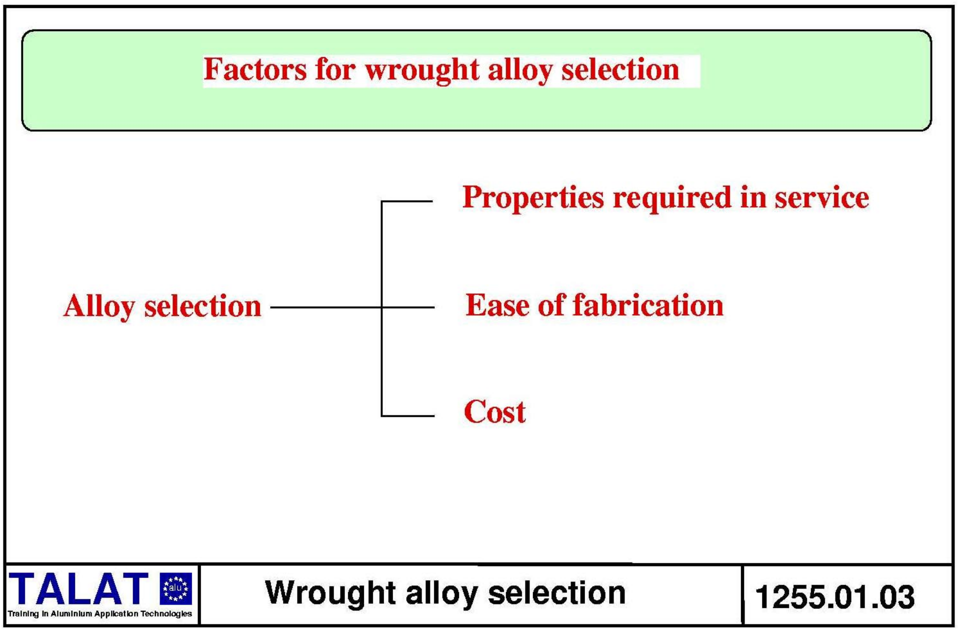
Temper designations for aluminium alloys as per the American Aluminium Association are given in **Figure 1255.01.02**. Unfortunately, variations of this classification persist in the UK and Europe (see [1] and [2]).



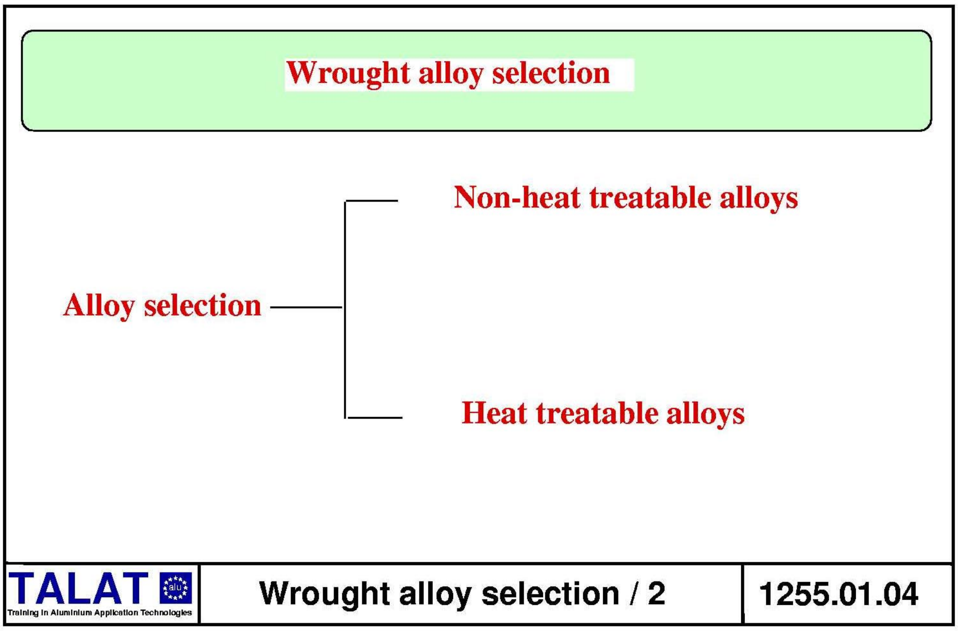
1255.01.02 Wrought alloy selection

Wrought aluminium alloys are selected, **Figure 1255.01.03** on the basis of

- the properties required during service;
- the ease of forming and fabrication;
- and last but not least, the overall cost of alloy type, availability, heat treatment processing and finishing.

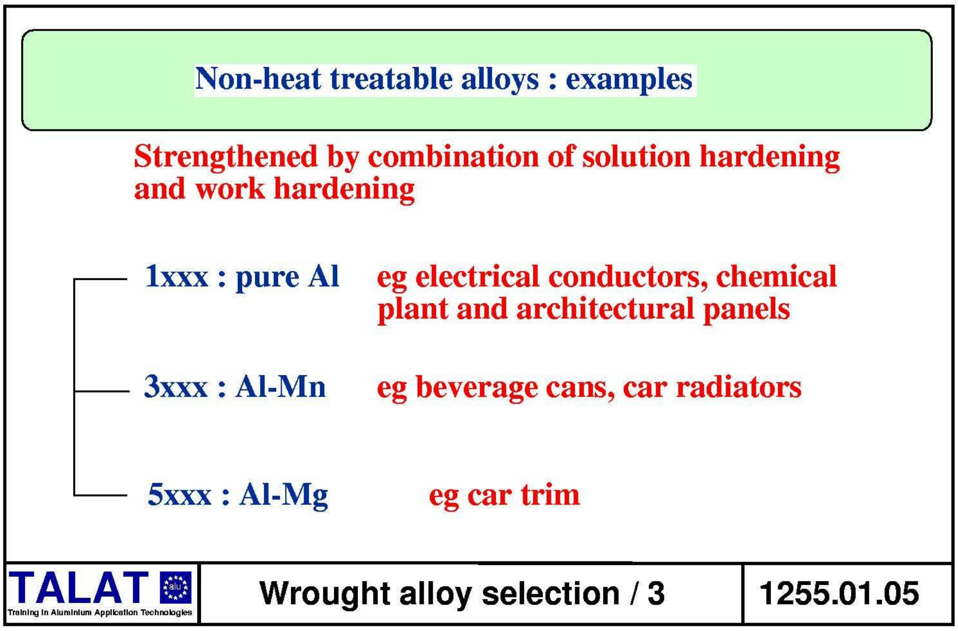


The alloys may be divided into two groups, non-heat treatable alloys and heat treatable alloys, **Figure 1255.01.04**.



1255.01.02.01 Non-heat treatable alloys

These alloys, **Figure 1255.01.05**, are hardened by solution hardening and/or by work hardening, but they do not respond to heat treatment by precipitation hardening.



Pure aluminium (1xxx series) finds applications in electrical conductors, certain plant for chemical engineering and for architectural panels. Tensile properties are low in the annealed condition (~ 50MPa) and can be doubled by cold work.

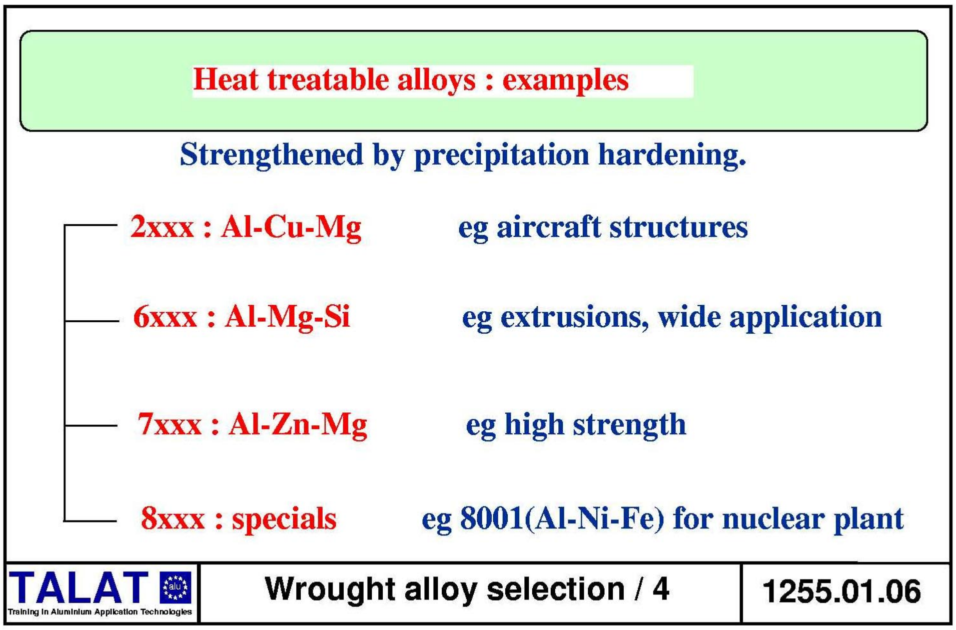
Alloys selected from the 3xxx series alloys, based on Al-Mn , such as 3003, are used as sheet material, for example for aluminium car radiator corrugations. They are used in applications which require medium strength (~ 180 MPa) together with good ductility (i.e. ease of forming) and good corrosion resistance. For example, 3004, with Mn and Mg, for beverage cans [1].
Alloys from the 5xxx series, based on Al-Mg, are used [1] as structural plate for transport applications, and with alloys made from high-purity aluminium may be polished to a bright finish for automotive trim and architectural panels.

1255.01.02.02 Heat treatable alloys

The alloy series are 2xxx, 6xxx, 7xxx and 8xxx, so the choice for selection is large. All depend upon precipitation hardening in order to develop their optimum properties, **Figure 1255.01.06**.

The 2xxx series, particularly those based on Al-Cu-Mg have found application in aircraft structures [1].

Al-Mg-Si alloys (6xxx) series are used extensively as medium strength extrusions with a wide field of application.

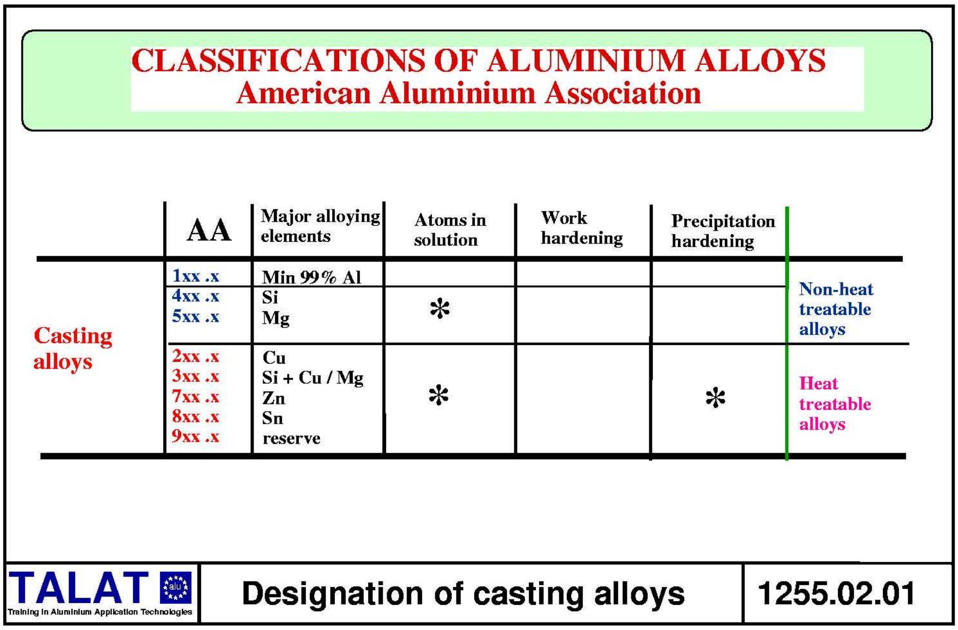


he Al-Zn-Mg alloys (7xxx series) offer high strength [1] for demanding applications.

Special heat treatable alloys in the 8xxx series include 8001 (Al-1.1Ni-0.6Fe) for nuclear plant [1] where it resists corrosion in water at high temperatures and pressures, and 8011 (Al-0.75Fe-0.7Si) with excellent deep drawing properties for bottle tops [1].

1255.02 Cast alloys

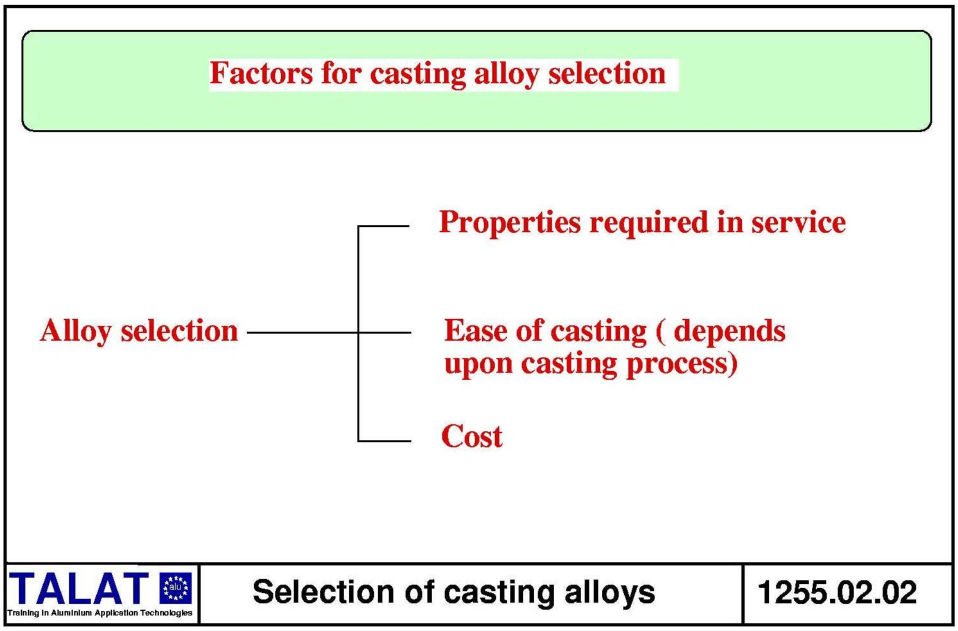
Designations of casting alloys as classified by the American Aluminium Association are given in **Figure 1255.02.01** and Table 2.



The use of other designations is common-place, for example the LM series in the UK - see [1] and [3].

As with wrought alloys, casting alloys may also be divided into those with are non-heat treatable and those which are heat treatable.

Selection of casting alloys, **Figure 1255.02.02** depends upon the type of casting process and the properties required by the application, see TALAT lecture 3201, Introduction to Casting Technology.



AA Designation	Major alloying elements	
1xx.x	None	)
4xx.x	Si	) Non - heat treatable
5xx.x	Mg	)
2xx.x	Cu	)
3xx.x	Si + Cu / Mg	)
7xx.x	Zn	) Heat treatable
8xx.x	Sn	)
9xx.x	Other	)

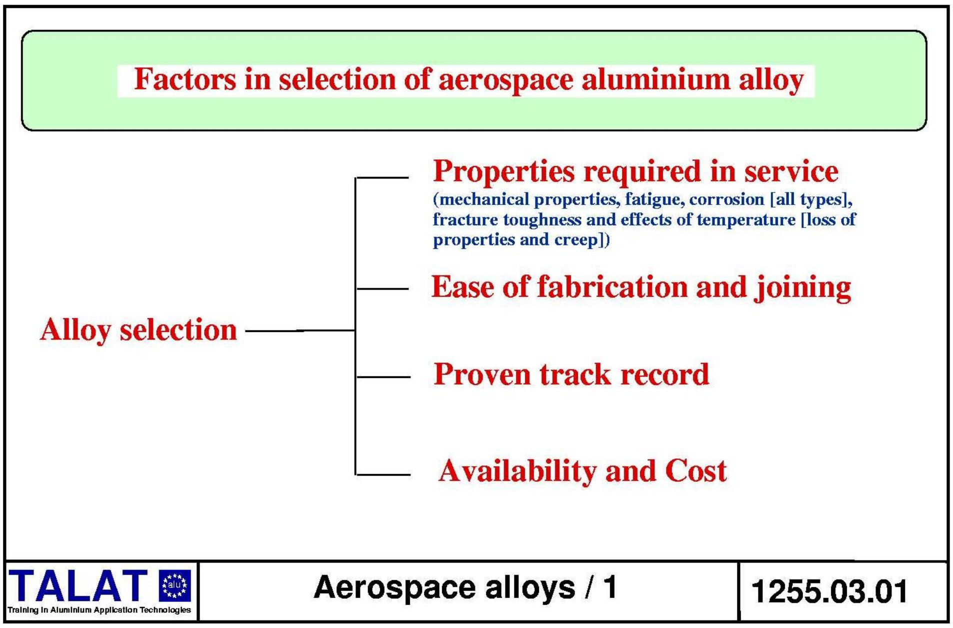
Table 2. Designation of casting aluminium alloys.

Casting aluminium alloys based on those to which silicon is added as the main alloying element are probably the most important for engineering applications. This is because of the high fluidity provided by alloys with near eutectic composition. The castings have high corrosion resistance, combined with a low coefficient of thermal expansion and good weldability [1].

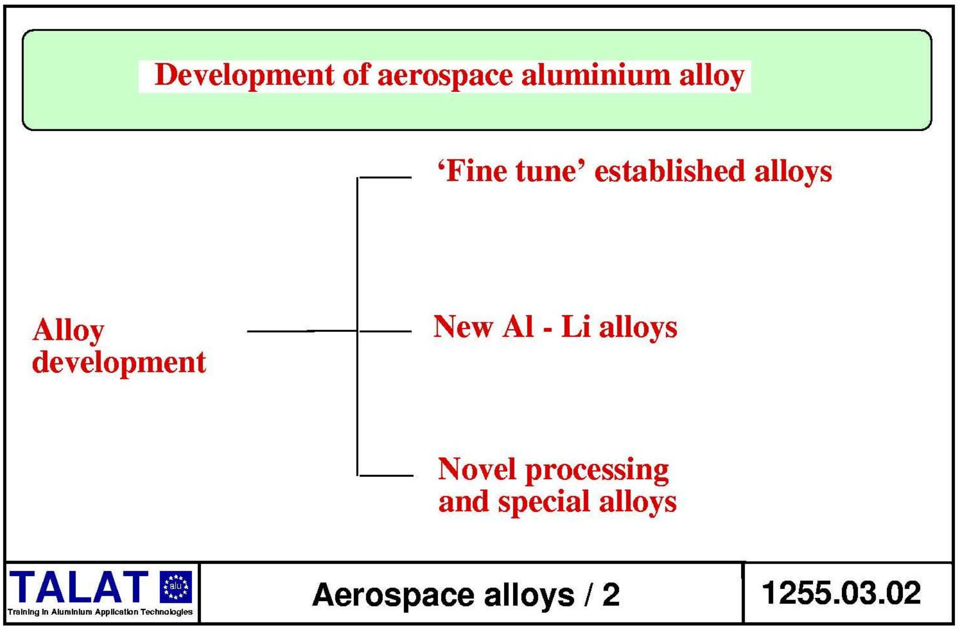
1255.03 Aerospace alloys

An excellent summary of the essential role of aluminium alloys in the aerospace industry is presented in the Aluminium File [4]. The special demands of civil and military air travel have placed the aerospace industry at the forefront of the technologies of lightweight materials, and aluminium alloys have an important role in this field of high performance application. In [4] it is said that “high strength combined with aluminium’s low density offers obvious advantages to other uses but factors such as toughness, fatigue performance and sensitivity to environmental effects must be taken into account when considering aircraft alloys for applications which differ from their original purpose. Of prime importance is the need for minimum weight consistent with safety, initial fabrication costs plus cost of ownership for the required service life”.

Aluminium alloys are used for many aerospace applications, mainly for the airframe structure, including the skin material. Again as reported in [4], “airframes are subject to combinations of both static and dynamic stresses depending on the part in question and they operate in a range of internal and external environments. They are subject to temperature changes caused by the atmosphere and speed. Also, should any defect occur during flight, the material used must be capable of tolerating its effect until the fault can be detected and identified at inspection. Furthermore, the demands of such damage tolerance vary depending on the component in question. Consequently, the additional material properties to be adjusted around the required mechanical properties, or perhaps vice versa, are fatigue, stress corrosion, pitting corrosion, exfoliation corrosion, galvanic corrosion, fracture toughness and the effects of temperature. Also, fabrication factors - machining, forming and joining - have to be taken into account” - **Figure 1255.03.01**. Also, it must be emphasised that the aerospace industry, quite rightly for our safety, requires any new material or new variant of a material to be thoroughly tested, proven and certified before it is ever considered for service. This means that the lead times before the introduction of any new material are necessarily long.



The aluminium industry has responded to these demands in three ways, **Figure 1255.03.02**: firstly, by 'fine tuning' existing alloys to provide the performance characteristics required for specific applications; secondly, by development of new alloys - for example, those which contain Lithium for further weight reduction and improved specific stiffness; and thirdly, by developing special alloys by novel processing techniques. The first two approaches are described in the remainder of this chapter, the third on the production and application of special alloys by novel processing is given its own section below - because it has wider application than just aerospace.



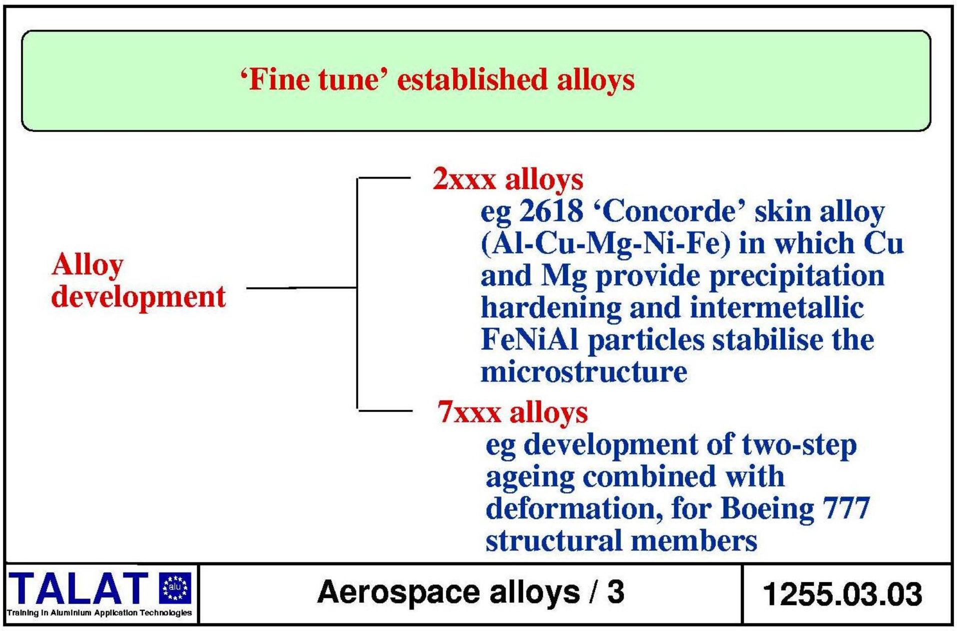
1255.03.01 Fine tuning of established alloys

It should be noted that aircraft development during World War 2 stimulated the introduction of high strength 7xxx series aluminium alloys based on Al-Zn-Mg-Cu, with tensile strengths exceeding 500MPa.

Since that time [5], further developments of the 7xxx alloys for strength-critical areas, and development of the 2xxx series alloys for damage-critical areas, have taken place, **Figure 1255.03.03**.

In the case of the 7xxx developments, these have been concentrated [5] on improving service reliability by enhancement of resistance to stress-corrosion cracking and fracture toughness via fine tuning of heat treatment and small changes to alloy composition rather than any major improvement in tensile strength. This has been achieved [5] by the optimisation of two-step ageing treatments (see TALAT **Lecture 1204**), in some cases by combining ageing with deformation to achieve a measure of strengthening from dislocation hardening. Commercial considerations have restricted disclosure of the details of such processing, but it is interesting to note that it is reported [5] that a 7055 alloy (Al-8Zn-2.05Mg-2.3Cu-0.16Zn-0.15Femax-

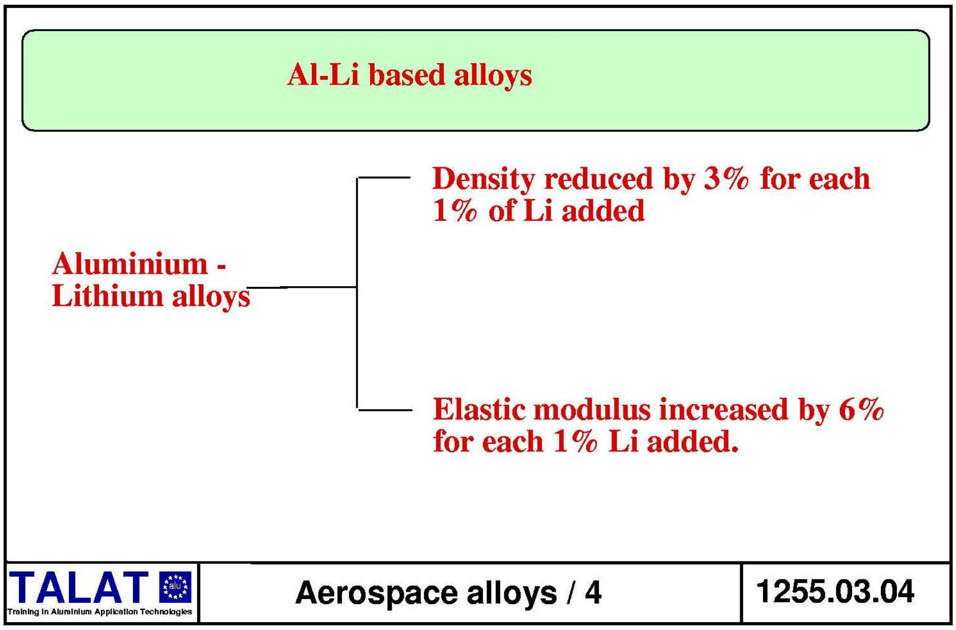
$0.10Si_{max}$) has been used for structural members of the Boeing 777 giving a weight saving ~ 635kg.



2xxx series alloys continue to be used as aircraft structural materials, for example as fuselage skins. Enhanced fracture toughness has been achieved by improvements in alloy cleanness, for example, lower levels of iron and silicon. Alloy 2618 (Al-2.2Cu-1.5Mg-1Ni-1Fe) is used as the fuselage skin of Concorde, with the Cu and Mg providing precipitation hardening and $FeNiAl_9$ dispersoid particles stabilising the microstructure [1].

1255.03.02 Aluminium-Lithium based alloys

The addition of lithium to aluminium alloys both reduces weight (density is reduced by 3% for each 1%Li added) and increases the stiffness (the elastic modulus is increased by 6% for each 1% Li added [5], **Figure 1255.03.04**. This attractive combination of enhanced properties has stimulated much research into these alloys, and this continues. Low fracture toughness has been a problem, attributed to grain boundary segregation of sodium and potassium - measures have been taken to clean melt alloys to achieve material with less than 1 ppm of Na and K impurity levels [5].



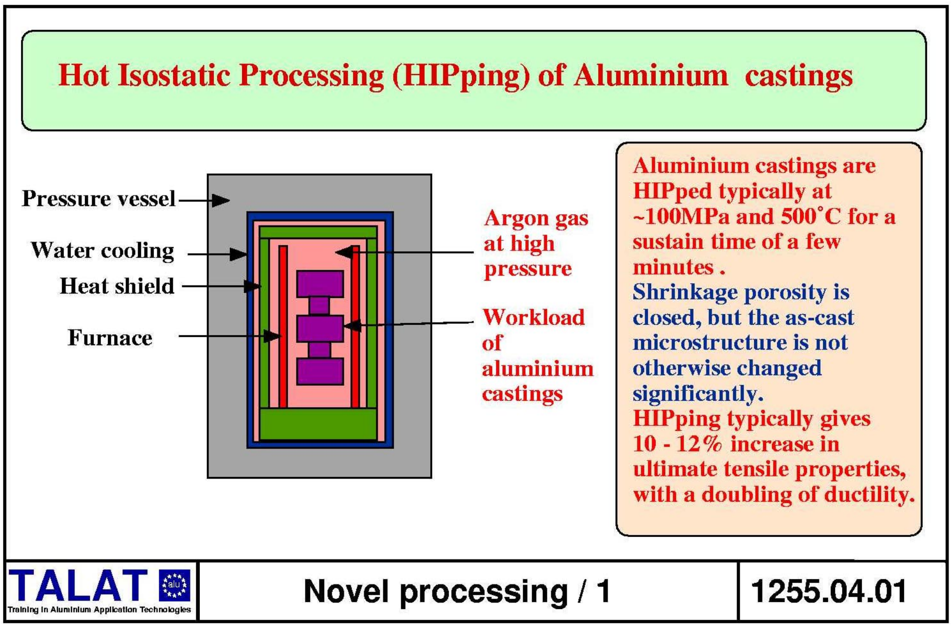
1255.04 Novel processing and special alloys

Following the revolution in scientific understanding of the metallurgy of aluminium alloys in the 1960s that occurred as a result of the application of the transmission electron microscope to the investigation of microstructure, there was a period of consolidation and optimisation that led to the family of alloys that we know today. It is not unreasonable to say that the bounds of metallurgy imposed by equilibrium phase diagrams have been thoroughly explored. This should not imply that there will always be scope for 'fine tuning', as we have seen for aerospace alloys above. Maybe a similar 'fine tuning' will be promoted by the drive towards the aluminium automobile. None the less, the bounds of equilibrium metallurgy will only be stretched so far, and this has been recognised over the last four decades. However, we have not reached the end of the road; new processes have been, or are being, developed either to compensate for the limitations imposed by 'equilibrium metallurgy' or to exploit 'non-equilibrium' processes. In this section we will look at examples of technologies in these categories.

1255.04.01 Hot Isostatic Processing of Aluminium Castings

Hot isostatic pressing (HIPping) involves [6] the application to a component of processing conditions of elevated temperature and a very high gas pressure, say ~ 100MPa (about 1000 bar or atmospheres) in a special hot isostatic processing plant, **Figure 1255.04.01**. Thus, a very high isostatic gas pressure is applied to the component to be treated which, provided the temperature is high enough for plastic deformation and creep to occur, will consolidate with any pores being closed.

HIP processing is applied to aluminium castings, commonly at ~ 500°C for a few minutes at a gas pressure ~ 100MPa. Shrinkage porosity is closed, but the as-cast microstructure is not significantly changed. The beneficial reason for HIPping is that the ultimate tensile strength of a casting may be increased by 10-20%, and the ductility may be doubled [6].



Hence, HIPping may be seen as a method of counteracting the natural interdendritic porosity that occurs during solidification of an aluminium casting.

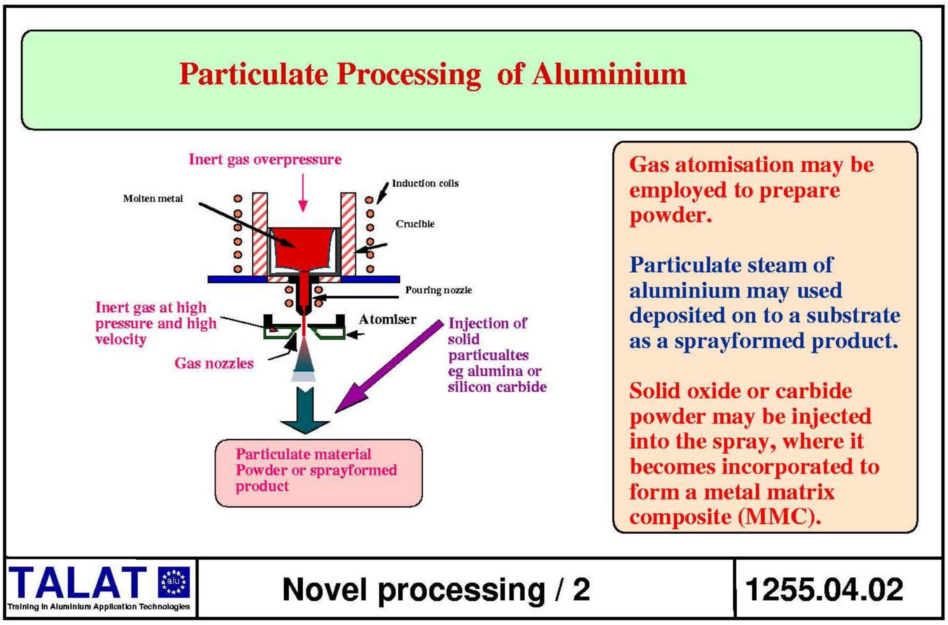
Very large HIPping plant is now in commercial operation [6], which reduces the unit cost to a level which makes it a worthwhile for the enhanced mechanical properties obtained.

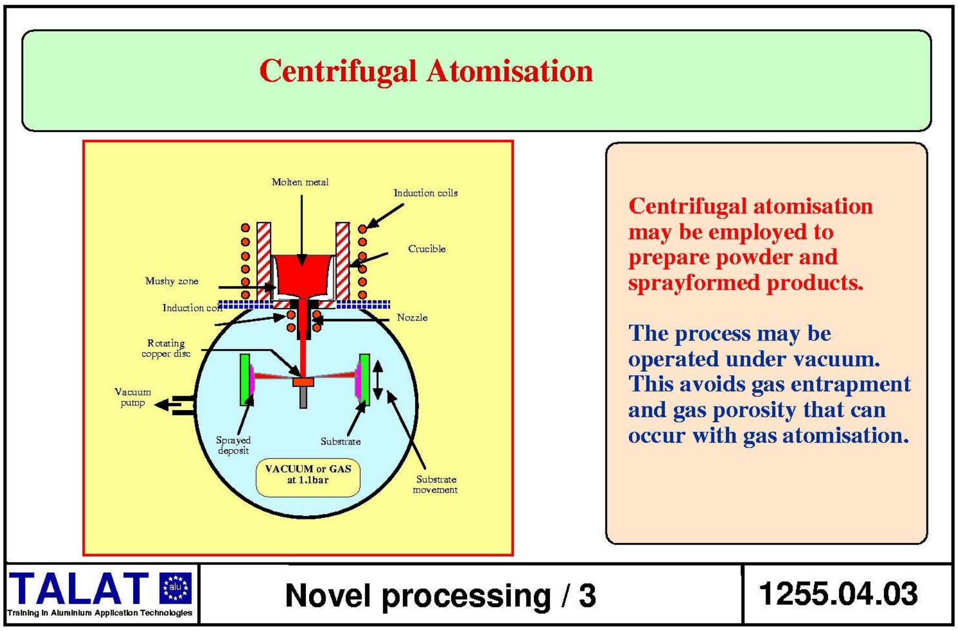
It must be pointed out however, that HIPping must not be seen as a way of correcting bad casting practice. Currently, computer modelling is very successfully being applied to the design of casting systems in order to obtain the highest integrity of cast product. Also, the avoidance of trapped, folded oxide films is paramount [7], which again comes down to devising good casting practice.

1255.04.02 Particulate processing

Aluminium alloys may be processed to prepare powder and sprayformed products by gas atomisation, **Figure 1255.04.02**, and by centrifugal atomisation, **Figure 1255.04.03**.

Atomisation caused rapid solidification, and this may be usefully employed to increase the amount of solute retained in solid solution; for example, alloys with high lithium contents up to ~ 5% may be made in this way.
The injection of oxide or carbide powder into a sprayformed product is one method of manufacturing a metal matrix composite (MMC). Other methods of making MMCs include infiltration of a porous ceramic with molten aluminium and stirring of particulates into molten aluminium.





1255.04.03 Particulate Metal Matrix Composites

Special attention has been paid [5] to composites of aluminium alloys such as 2014 (Al-Cu-Mg-Mn) and 6061 (Al-Mg-Si) with silicon carbide or alumina particles or fibres, **Figure 1255.04.04**. 6061-SiC MMCs have been developed as extrusions with up to 20 volume % SiC as short fibres; this gives high tensile strength (~500MPa) and a high elastic modulus at 120GPa compared with 70GPa for 6061.

Metal Matrix Composites (MMCs)

MMCs may be manufactured by injection of oxide or carbide powders into the aluminium particulate stream during atomisation and sprayforming. Powders may also be added to molten aluminium alloys.

MMCs have been made with a number of aluminium alloys as the matrix; eg Al-Cu-Mg-Mn and Al-Mg-Si.

Al-Mg-Si alloy 6061 has been developed with 20 volume % silicon carbide to make extrusions with high tensile strength at ~500MPa and high elastic modulus at ~ 120GPa (compared with 6061 at 70GPa).

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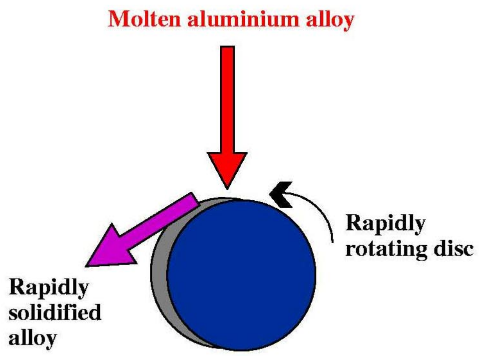
1255.04.04 Rapid solidification processing (RSP)

Rapid solidification may be achieved by atomisation or injection of a molten stream of aluminium alloy on to a cold rotating disc, **Figure 1255.04.05**. Cooling rates are the order of 10^6°C s^{-1}.

Rapid Solidification Processing (RSP)



Cooling rate ~ 10^6 °C /second

Very fine scale, metastable microstructures are produced.

Many RSP alloys are based on Al-Fe.

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Al-Fe with Fe contents around 8% are commonly used as the base for RSP aluminium alloys. Fe has virtually no equilibrium solubility in Al, see **TALAT lecture 1203** and **Figure 1203.01.09**. However, by very rapid solidification the Fe may be forced into high metastable solid solution, which then precipitates fine-scale metastable phases which confer useful mechanical properties on the alloy - particularly higher strength at elevated temperatures of around 300°C to 400°C [1].

1255.05 References

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1255.06 List of Figures