

TALAT Lecture 1205

Introduction to Mechanical Properties, Solidification and Casting, Joining and Corrosion of Aluminium and its Alloys

12 pages, 9 Figures

Basic level

prepared by **M H Jacobs** *
Interdisciplinary Research Centre in Materials
The University of Birmingham, UK

Objectives:

To provide background, basic information on mechanical properties and testing, solidification and casting, joining and corrosion of aluminium and its alloys.

Prerequisites:

Basic knowledge of physics and chemistry. Some familiarity with lectures 1201 and 1203.

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1205 Introduction to Mechanical Properties, Solidification and Casting, Joining and Corrosion of Aluminium and its Alloys

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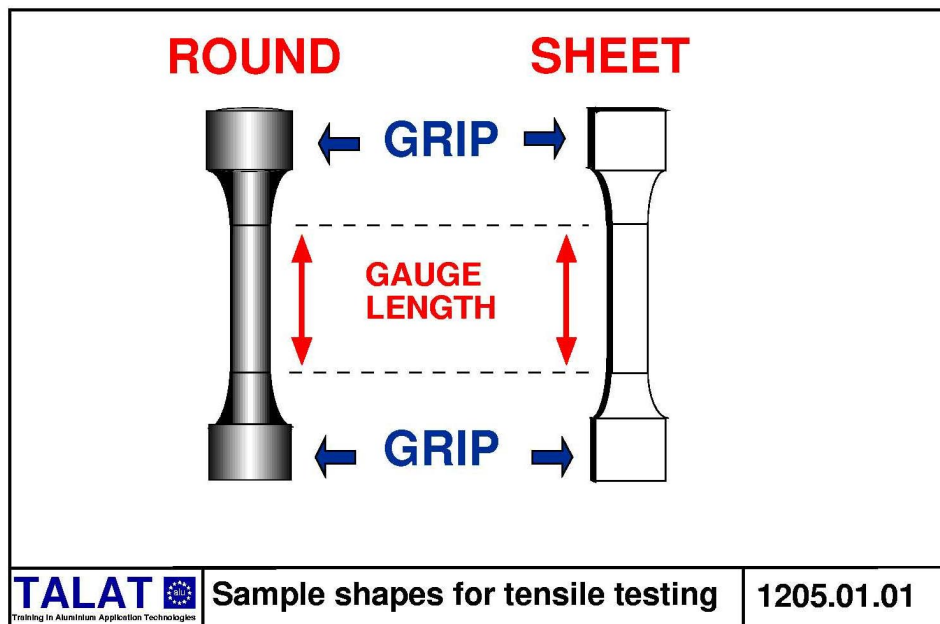
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1205.01 Basics of mechanical properties

1205.01.01 Tensile testing

Most materials are generally supplied to a mechanical property specification. This usually involves data on tensile strength and ductility. Tensile strength is a measure of the material's ability to withstand a load under tension. Ductility is a measure of the material's ability to be permanently stretched, again under tension.

The most common method used to determine tensile strength and ductility is the tensile test. This involves preparing a specially shaped standard test piece that has no sudden changes in cross-sectional area and then pulling it carefully in one direction with a continuously increasing load. The test-piece may be round or rectangular in cross section, [Figure 1205.01.01](#), depending upon the shape of the bulk material; for example, samples with rectangular cross sections are prepared from sheet material. In both cases, the central portion of the test piece is reduced in section to form a gauge length. The reduced section helps to ensure that fracture, when it occurs, does so within the gauge length rather than within the grips where surface imperfections may induce premature failure.



The extension is measured and plotted against load producing a 'load / extension' curve, as illustrated in [Figure 125.01.02](#).

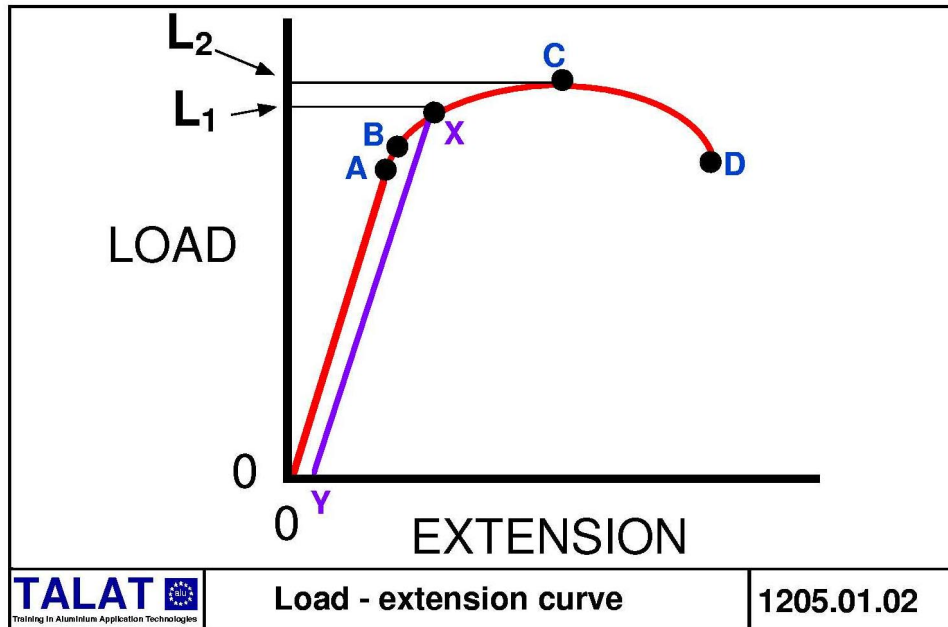
The curve has several distinct sections.

0 → A where the extension is linearly proportional to load. Point A is *the limit of proportionality*.

A → B extension non linearly proportional to load. The extension from O → B is *elastic deformation*, and point B is *the elastic limit*.

B → C the extension is non linearly proportional to load, and is **plastic deformation** uniformly distributed along the length.

C → D extension is plastic but localised.



The point B is important as it marks the change from elastic to plastic behaviour. It can be difficult to locate on the curve, as the change can be gradual. To overcome this a point is added to the curve at X. X is found by measuring a distance Y, along the extension axis and drawing a line parallel to OA. The intersection of this straight line with the curved line is not open to interpretation error. The generally used value for Y is 0.2% of the original length under test.

The load L₁ associated with X, divided by the original cross sectional area, gives the **0.2% proof stress** for the material.

Similarly L₂ divided by the original cross sectional area gives the **tensile strength**.

The **elongation** is given by the total extension divided by the original length (the gauge length) presented as a percentage.

It should be noted that

- **stress** is defined as the load per unit area
(for example, expressed in units of MPa);
- **strain** is the extension of the gauge length divided by the original gauge length (expressed as a fraction).

In the linear elastic part of the load - extension curve, $O \rightarrow A$ in [Figure 1205.01.02](#) there is negligible change in the cross-sectional area of the sample, so we may say that the ratio of stress to strain is a constant, that is :

$\text{stress} / \text{strain} = \text{a constant (E) , known as } \textit{Young's Modulus}.$

The springiness of a material (its *stiffness*) is indicated by its Young's modulus. For most aluminium alloys, irrespective of their metallurgical conditions, the value of Young's Modulus is close to 68 GPa (see [lecture 1204](#) for the special case of lithium-containing alloys, where there is a significant increase in stiffness).

The part of the load-extension curve given by $C \rightarrow D$ in [Figure 1205.01.02](#) represents incipient fracture. Appreciable necking of the sample occurs, leading to fracture. Note that a progressive reduction of cross-sectional area occurs in the necking region; the stress (ie the load per unit area) continues to increase, even though the total load decreases.

The ratio of the cross-sectional area of the fracture surface to that of the original cross-sectional area is known as the *reduction in area*, usually expressed as a percentage.

1205.01.02 Hardness Testing

Hardness testing is a relatively quick and easy way to assess the strength of a material without the need to prepare tensile test samples. For example, it may be a convenient way of investigating the progress of precipitation hardening.

The majority of commercial hardness testers force a small hard metal or ceramic sphere, diamond pyramid or diamond cone into the body of the metal under test by means of an applied load, and a definite hardness number is obtained from the dimensions of the indentation so formed. In practice, the dimension of the indent is referred to a set of values defined in a 'hardness index chart'. Hardness then may be defined as resistance to permanent deformation, and a hardness test can often be considered as a rapid non-destructive estimation of the plastic deformation behaviour of metals.

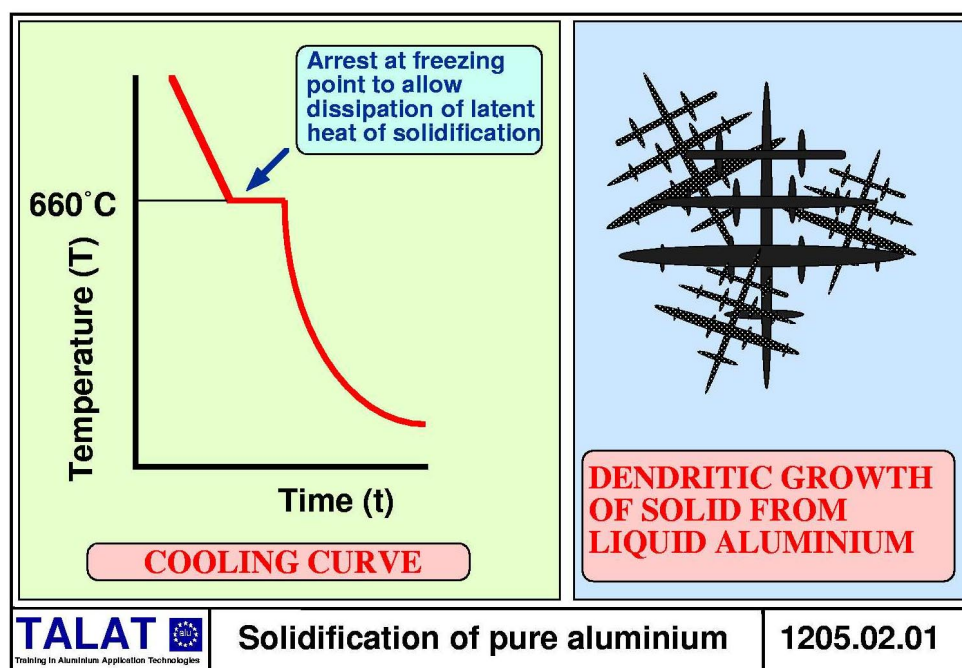
Small indenters are used for microhardness testing, with a special instrument equipped with an optical microscope to view the micro-indent. This provides a very valuable technique for investigation of the relative hardnesses of phases within a microstructure.

Although the term 'hardness' is a comparative consideration of great engineering importance, it is not considered to be a fundamental property of matter. The index of hardness is a manifestation of several related properties of the metal, which may well include a combined effect of yield point, tensile strength, ductility, work-hardening characteristics and resistance to abrasion.

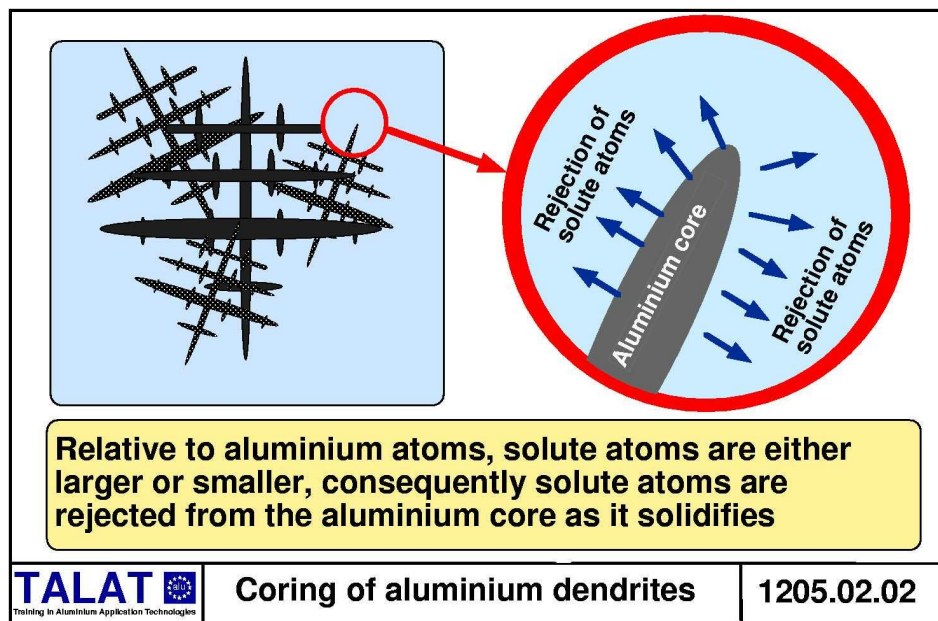
11205.02 Basic solidification and casting metallurgy

1205.02.01 Solidification

The dendritic solidification of pure aluminium is described in [lecture 1203](#) which deals with phase diagrams. For convenience, one of the figures is reproduced here as [Figure 1205.02.01](#), which shows the cooling curve, with an arrest caused by the evolution of latent heat of freezing. The solid forms by a nucleation and growth transformation, with the solid nuclei having a preferred growth directions along $\langle 100 \rangle$ crystallographic directions of the fcc lattice. This gives rise to the formation of dendrites with primary and secondary arms.



In the case of aluminium alloys, the formation of dendrites during solidification is accompanied with coring due to solute rejection. This leads to macrosegregation in the solidified ingot (see [Figure 1205.02.02](#))



The transformation from liquid to solid is accompanied with a reduction in the volume. This has its most dramatic affect on the last liquid to freeze; that is, liquid in the interdendritic pools. This gives rise to inter-dendritic porosity, which is often also called shrinkage porosity.

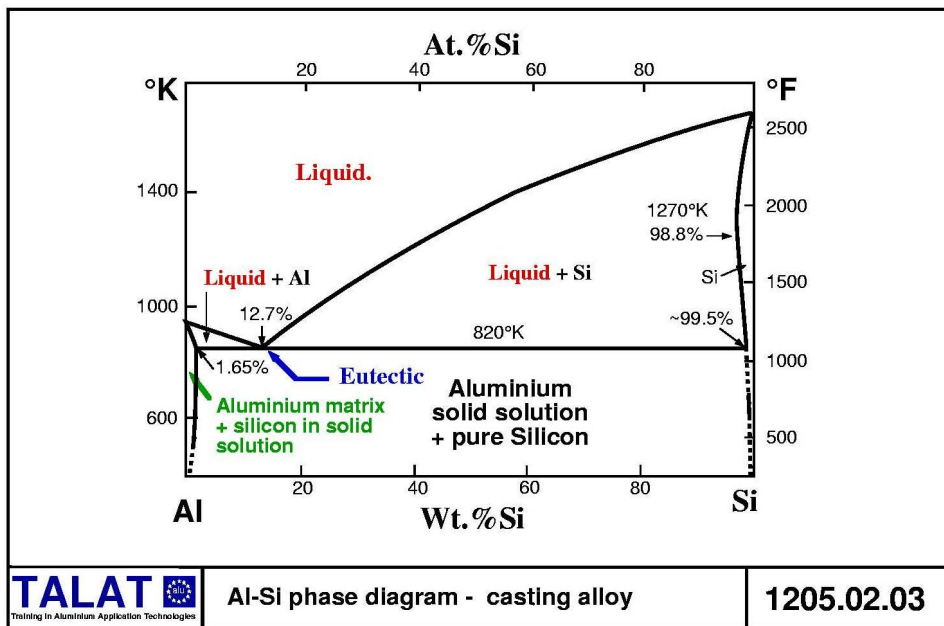
For wrought alloys, the solidified ingot is homogenised in order to even out variations in composition (see [lecture 1201](#)). The incremental or continuous casting associated with the formation of ingots by DC casting means that the incidence of shrinkage porosity should be minimal.

The degree to which a cast aluminium component contains shrinkage porosity is dependent to a large extent upon the casting practice employed.

1205.02.02 Casting

The technology of castings is dealt with in TALAT Chapter 3201 - Introduction to casting technology by J Campbell and R A Harding; also in more depth in the book by J Campbell [1].

The most common casting alloy is based on the eutectic Al-Si system, [Figure 1205.02.03](#). Compositions are usually close to the eutectic composition of 12.7 wt% Si. The mechanical properties of cast pure Al-Si eutectic are not particularly good, but are appreciably improved by 'modification' with sodium in a very small amount, 0.005 - 0.015% [2]. Fluidity is high and shrinkage is low, which aid the production of sound castings. The microstructure consists of almost pure, small laths of silicon in an aluminium-rich solid solution with a little over 1% silicon. Sodium exerts its effect by refining the microstructure.



Unless special precautions are taken to avoid turbulence during the casting operation, surface oxide films readily becomes folded and trapped within the solidifying metal, see TALAT Chapter 3201 and reference [1].

1205.02.03 Classification of casting aluminium alloys

The modern classification is shown in [Figure 1205.02.04](#).

Classification of casting alloys - principal elements	
1xx.x	aluminium > 99.00%
2xx.x	copper
3xx.x	silicon (+ Cu and/or Mg)
4xx.x	silicon
5xx.x	magnesium
6xx.x	not used
7xx.x	zinc
8xx.x	tin
9xx.x	other elements

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Classification of casting alloys

1205.02.04

For the 1xx.x class, the second two digits give the purity and the last digit is 0 for a casting and 1 for an ingot; thus, 150.0 is a casting with 99.50wt% purity (equivalent to the 'old' UK system of LM0).

For the other classes, the first and second digits have no direct significance other than that established by tradition, while the last digit again is 0 for a casting and 1 for an ingot.

Thus, the eutectic alloy Al- 12%Si known as LM6 in the UK 'old system' is 360.0 in the modern system.

At the time of writing, there does not appear to be any moves to adopt a new 'European standard'.

1205.03 Basic joining and brazing

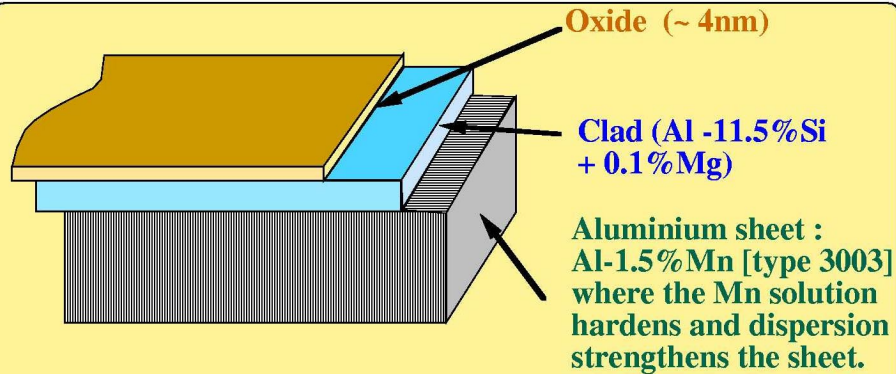
In spite of a tenacious oxide film, aluminium and its alloys can readily be joined. Methods include TIG and MIG and other forms of welding, brazing, mechanical methods such as clinching, riveting and bolting, and adhesive bonding. The technologies are dealt with in detail in lecture series 4000.

In terms of basic metallurgy, there are a few points that should be stressed.

- (a) for TIG and MIG welding, inert gas shielding must be sufficient to prevent oxidation
- (b) for mechanical joining such as lap joints, where sheet metal is bent back on itself to grip and join with a second sheet, it is clear that the alloy type and its heat treatment must be such that it has adequate ductility to withstand the bending operation
- (c) the quality of adhesive bonds will be dependent upon the care taken in surface preparation prior to application of the adhesive.

Vacuum brazing is a technology development driven by the need to manufacture lighter weight automotive radiators and coolers. To this end, special clad sheet has been developed specially for this type of application, **Figure 1205.03.01**. The base aluminium sheet is 3003, an Al-1.5 % Mn alloy where the manganese solution hardens and dispersion strengthens the material. This is clad on one side with a thin layer of 0.1%Mg doped Al-11.5%Si alloy.

Clad Brazing Sheet : used for vacuum brazing of aluminium car radiators



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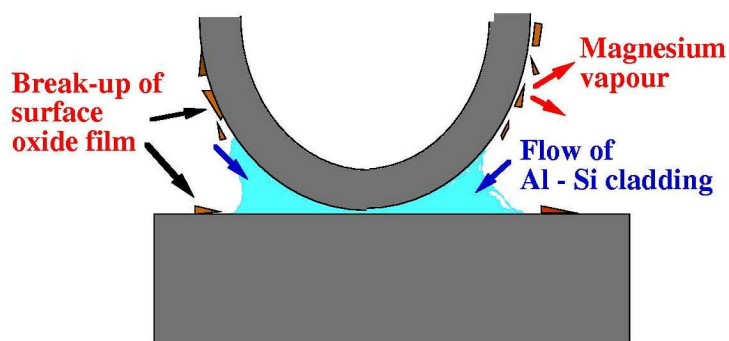
Clad 3003 sheet for Vacuum Brazing

1205.03.01

The radiator is fabricated and assembled as a set of 'loose joints'. The whole assembly - in fact many assemblies in a batch - are placed in a large vacuum furnace, which is evacuated to a high vacuum and simultaneously heated to a temperature just sufficient to melt the cladding but not melt the base sheet. Under these conditions of vacuum and temperature, the magnesium in the cladding evaporates and, in so doing, breaks up the surface oxide film. This allows the molten cladding to flow, driven by capillarity, to form brazed joints everywhere where the sheet materials are in close contact, see diagram [Figure 1205.03.02](#).

VACUUM BRAZING OF A JOINT

Loose joint is heated under vacuum to a temperature where the Mg-doped Al-Si eutectic cladding melts and flows under capillary forces



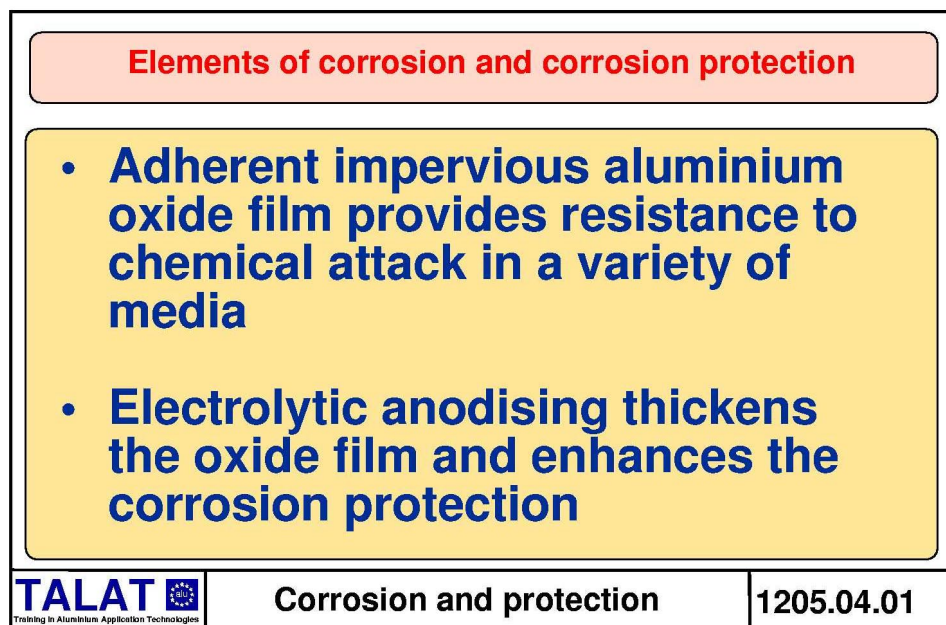
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Vacuum Brazed Joint

1205.03.02

1205.04 Elements of corrosion and corrosion protection

The elements of corrosion and corrosion protection are summarised in [Figure 1205.04.01](#).



As it has been emphasised many times, aluminium is very reactive with oxygen, but it is the very presence of the surface oxide film that provides protection for aluminium and its alloys in a variety of corrosive media. The self-healing, oxidation response of aluminium to accidental abrasion in air adds to its overall resistance to corrosion.

Electrolytic anodising in a dilute solution of sulphuric acid produces a thicker oxide film, which may be dyed for aesthetic enhancement.

A more detailed presentation of principles of corrosion and corrosion protection is given in TALAT lecture 1252.

1205.05 References

1. J Campbell, *Castings*, Butterworth Heinemann, 1991.
2. I J Polmear, *Light Alloys : The Metallurgy of the Light Metals*, Metallurgy and Materials Science Series, Edward Arnold, Second Edition,. 1989.

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