TALAT Lecture 3208

The Finishing of Castings

22 pages, 17 figures

Basic Level

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Objectives:

- To provide an introduction to some of the finer points in the production of high quality castings
- The student will be able to understand the various processes for sealing porosity in badly made castings and to appreciate factors influencing the accuracy of castings, including a basic understanding of how to control and measure casting dimensions

Prerequisites:

- Basic understanding of the foundry industry

Date of Issue: 1994

3208 The Finishing of Castings

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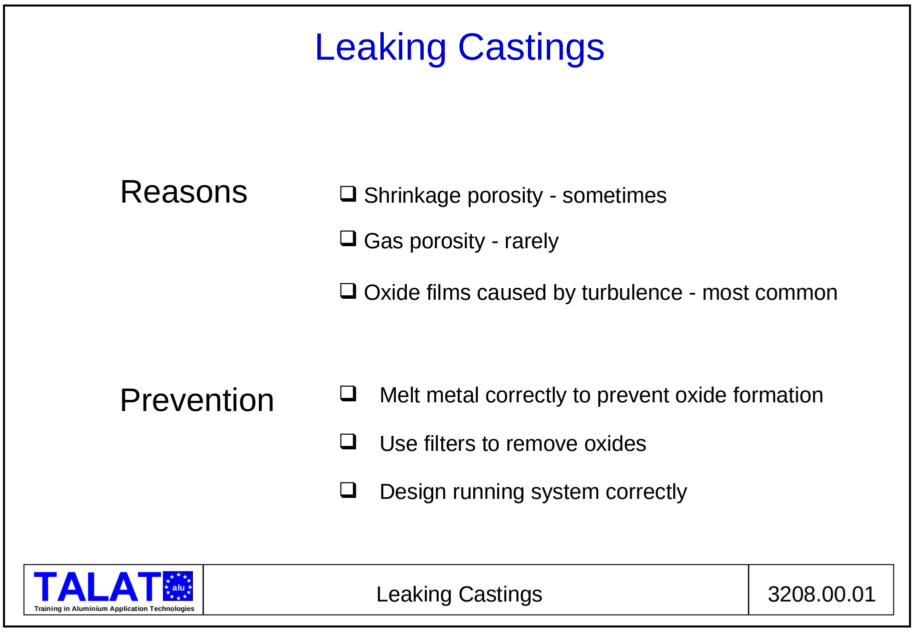
Introduction

The purpose of this lecture is to consider the processes that need to be carried out on castings once they have been removed from the mould and cleaned up. These additional processes are as follows:

1. Rectification. Processes to required to correct any mistakes made during the foundry production phase.
2. Quality Checking (often misleadingly called Quality Control; there can be no control over the quality after the casting is finished, since, of course, control of the quality can only be introduced during manufacture, not afterwards). The checking procedures are designed to verify that the casting has been manufactured to the specified quality requirements, including mechanical properties, leak tightness, dimensions etc.
3. Heat treatment. A significant proportion of aluminium alloy castings is heat treated.

Leakage Problems

Castings have an unenviable reputation for leaking when filled with media such as water, oil or a pressurised gas. This is more of a problem with some metals than others - for example, it is relatively easy to produce fully sound grey iron castings, whereas aluminium alloy castings are more prone to leakage problems. These are sometimes caused by shrinkage porosity - particularly in long freezing range alloys - but only rarely caused by gas porosity (**Figure 3208.00.01**).



Leaking Castings

Reasons

☐ Shrinkage porosity - sometimes

☐ Gas porosity - rarely

☐ Oxide films caused by turbulence - most common

Prevention

☐ Melt metal correctly to prevent oxide formation

☐ Use filters to remove oxides

☐ Design running system correctly

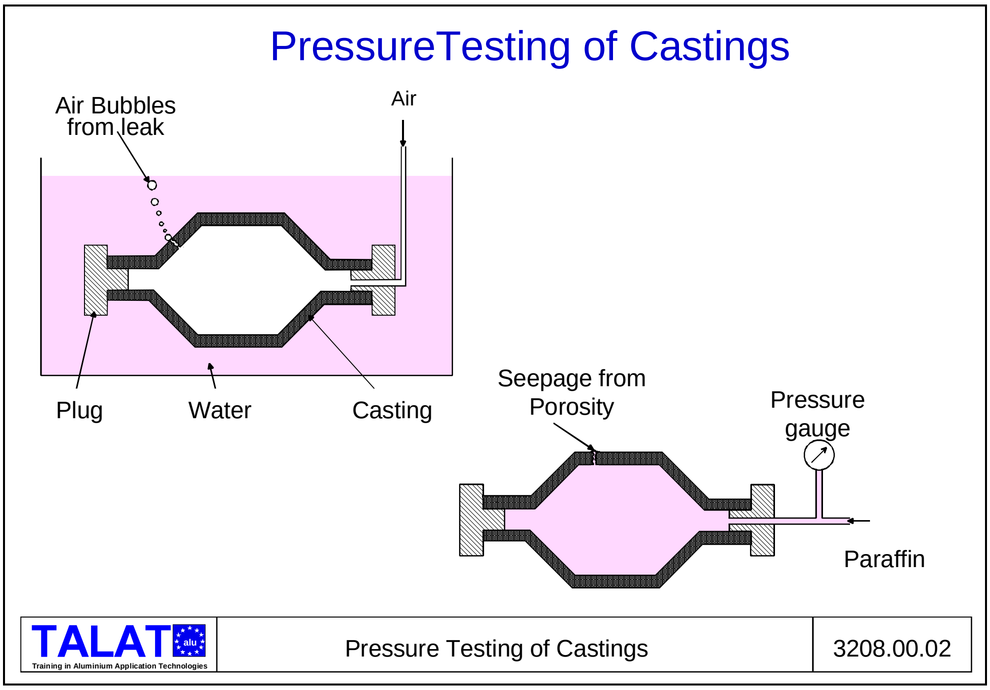
TALAT Training in Aluminium Application Technologies | Leaking Castings | 3208.00.01

The most common reason for leaking castings has already been introduced in **TALAT Lecture 3203**: if the running system is designed such that the mould is filled in a turbulent fashion, the dry oxide films present on the metal in the furnace and ladle or created during pouring are scrambled up and can form through-wall defects which cause leaks when the casting is subsequently subjected to a pressure test.

The obvious solution to this is to take all reasonable steps to ensure that the casting is produced correctly in the first place! In particular, attention needs to be given to melting the metal in such a way that oxides are minimised or have sufficient time to separate before the molten metal is poured into the mould. In addition, various types of filter - such as ceramic foam filters - can be placed in the running system to capture small amounts of oxides which are transferred from the melting furnace. Most importantly, the running system should be designed to promote tranquil filling of the mould cavity at less than the critical velocity, as was discussed in detail in **TALAT Lecture 3203**. Considerable experience shows that if these relatively simple rules are followed, then there is rarely a problem with the pressure tightness of a casting.

However, it has to be recognised that such rules are not yet fully appreciated or correctly applied in many foundries. Indeed, the rules cannot always be easily applied to the all of the complex shapes that foundries are asked to produce. In addition, particularly in the case of a gravity die casting, it is not always easy or economic to modify existing tooling so that it incorporates the optimum design of running system. In the case of pressure die castings, the problems of entrained porosity and folded oxide films are so extensive that such products cannot be recommended for pressure tight applications.

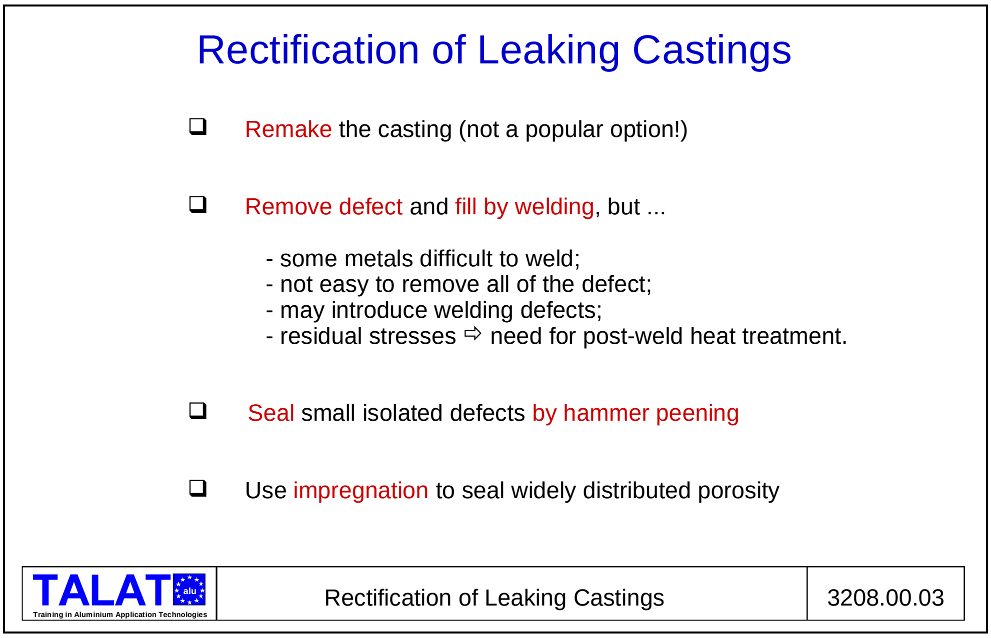
Pressure Testing of Castings



Since it is highly undesirable for castings that are required to hold a pressurised fluid to leak in service, it is common practice for foundries to pressure test castings prior to delivery to the customer (**Figure 3208.00.02**). This is often carried out by plugging all of the cast apertures on the casting and then pressurising the casting with air whilst it is immersed in water. A tell-tale stream of bubbles immediately reveals if the casting contains through-wall porosity. Alternative techniques include filling the casting with a pressurised liquid (such as paraffin, which is a very 'searching' fluid) and either looking for obvious leaks on the outside or, more quantitatively, monitoring the fluid pressure during a pre-determined holding period.

Ideally, castings should be pressure tested in the final machined condition because the machining operation can open up 'blind' porosity, thereby creating a leak path. However, many castings are *not* machined by the foundry, but by the end-user or an intermediary. Therefore it is not surprising that a casting may appear to be sound when tested in the foundry, only to fail once it has been machined and assembled into the final component. (This can lead to disagreement between a foundry and its customer, not least because the latter might invest considerable effort and money in machining a component, only to find that it is unfit for service. The only solution is, of course, to make the casting properly in the first place.)

Rectification of Leaking Castings



Rectification of Leaking Castings

☐ Remake the casting (not a popular option!)

☐ Remove defect and fill by welding, but ...

- some metals difficult to weld;
- not easy to remove all of the defect;
- may introduce welding defects;
- residual stresses ⇨ need for post-weld heat treatment.

☐ Seal small isolated defects by hammer peening

☐ Use impregnation to seal widely distributed porosity

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Rectification of Leaking Castings

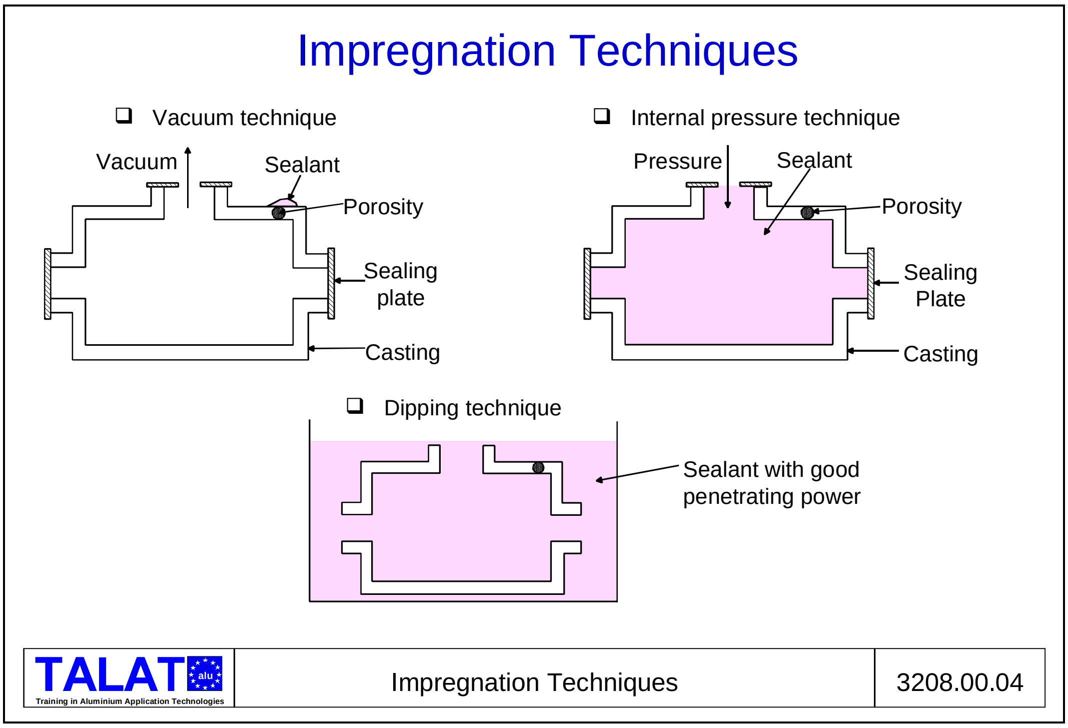
3208.00.03

If the foundryman finds defects during a pressure test, he then has a number of choices (see also **Figure 3208.00.03**):

- He can remake the casting, although this is resisted whenever possible!!

  If the defects are not too widely distributed, the affected area can be machined to remove the defect and the cavity filled by welding. Some of the many limitations to this reclamation welding include:
    - not all metals are easy to weld;
    - it is often difficult to remove all of the defect;
    - welding defects may be introduced;
    - it is normally necessary to carry out a post weld heat treatment to restore the original structure and/or remove residual stresses caused by welding.
- If the defects are limited in size and number, if the metal is relatively ductile and if the service pressures of the casting are not too high, the common practice is to use a special hammer to peen over the defective areas. In effect, the metal is deformed to effect a mechanical seal.
- If the defects are relatively fine and widely distributed, then it may be cost-effective to seal them using one of a number of impregnation techniques.

Impregnation Techniques



Impregnation Techniques

❑ Vacuum technique

❑ Internal pressure technique

❑ Dipping technique

TALAT Training in Aluminium Application Technologies | Impregnation Techniques | 3208.00.04

It is worthwhile giving a few minutes consideration to the various impregnation techniques available (**Figure 3208.00.04**). In its crudest form, a filler can be pushed into holes, although this is rarely an acceptable engineering solution these days. One of the better known examples of its misuse was demonstrated by the Tay Bridge disaster in 1879: severe weather and poor design led to the catastrophic collapse of the bridge and revealed that defects in the poor quality cast iron girders had been filled with lead.

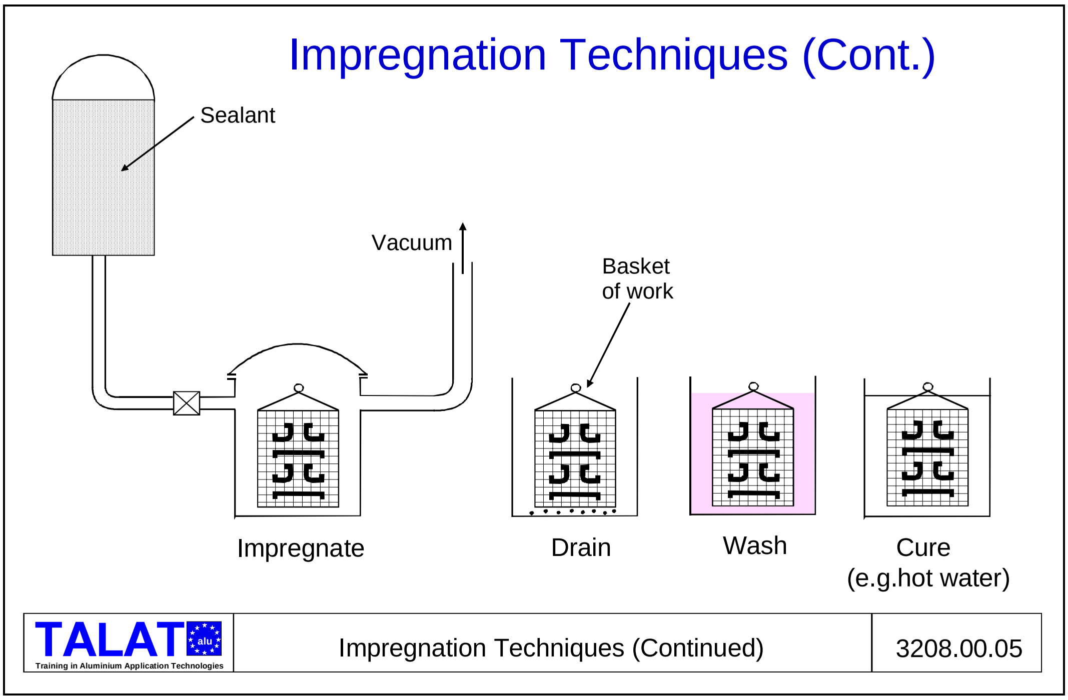
However, there are a number of modern impregnation techniques which are more reliable. All are based on introducing a sealant into the porous area which is normally followed by a curing operation, to produce pressure-tight castings which are capable of holding a fluid (liquid or gas) or retaining a vacuum. There are four techniques available:

1. **Vacuum technique**: All openings in the casting are closed, with the exception of one which is attached to a vacuum pump. The pressure is reduced inside the casting and the sealant applied to the outside so that it is sucked into the porosity. Only through-porosity can be sealed in this way and the technique is slow.

2. **Internal pressure technique**: Again, all openings are closed except one. The casting is filled with the sealant and pressure applied until the sealant starts to seep through the porous areas. Remaining sealant is removed prior to curing. This method is particularly suitable for large castings.

3. **Dipping technique**: Clean, dry castings are dipped in a tank containing a sealant having good penetrating properties for a period of about 15 minutes. They are then removed, drained and air dried for about 12 hours before repeating the pressure test to check whether the impregnation operation has been effective.

4. **Vacuum/pressure impregnation** (**Figure 3208.00.05**): This is probably the most reliable technique and is widely used for batches of small components. Castings are degreased, cleaned and dried and placed in a pressure vessel. A vacuum, typically of less than 8 millibars, is applied to the vessel and sustained for about 10 minutes to draw air from the porosity. The sealant introduced into the vessel, the vacuum released and atmospheric pressure used to force the sealant into the porosity. After a holding time of about 20 minutes, the castings are removed, the excess sealant drained off and the castings then washed. The sealant is then cured using heat, most commonly by immersing the castings in water, or by a special curing agent.


Impregnation Techniques (Cont.)

Impregnation Techniques (Continued)

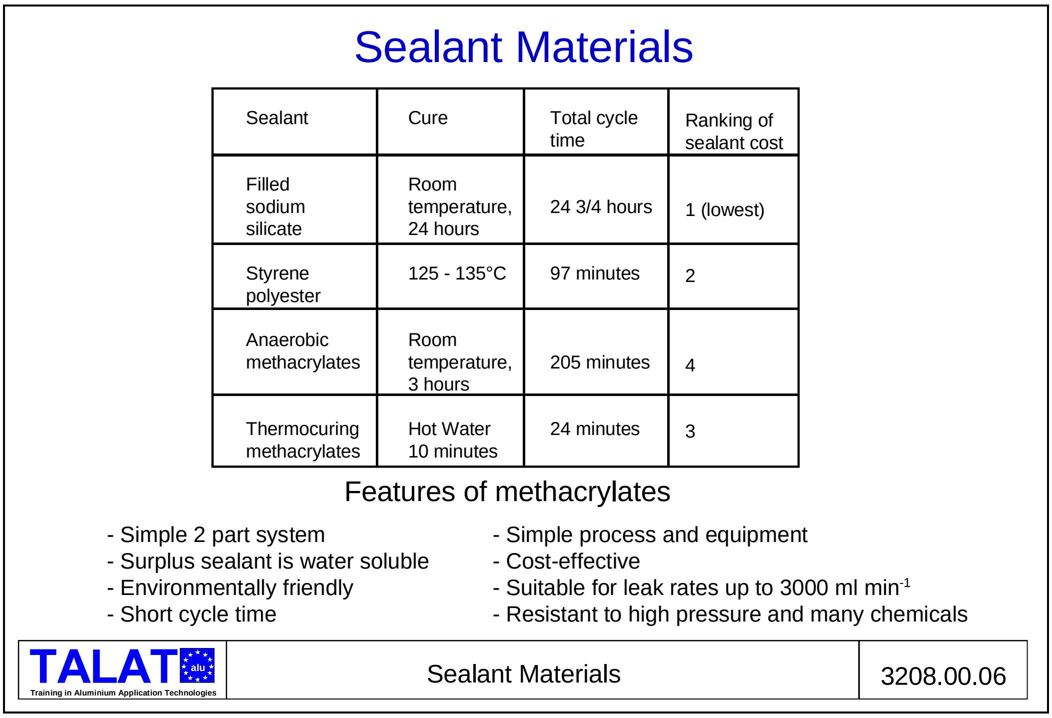
3208.00.05

A number of sealant materials have been or are still used (**Figure 3208.00.06**):

- **Sodium silicate**: this contains a filler such as metallic oxides, calcium carbonate or silica to minimise shrinkage on drying. The main advantage of low cost is normally offset by many disadvantages, including long hardening times (one day at room temperature), high viscosity, ineffectiveness at sealing gross porosity and poor longevity.
- **Styrene-based polyester resins**: these polymerise completely to give a solid sealed area, but again suffer from disadvantages which include high viscosity, environmental problems and high curing temperatures (125-135°C for 45 minutes).
- **Anaerobic methacrylates**: these are liquid in the presence of dissolved oxygen but polymerise once the oxygen is removed under vacuum conditions. These resins have a low viscosity and therefore penetrate porosity well. They also cure to give a 100% solid seal, although this is a lengthy process (2 - 3 hours at room temperature). Other disadvantages include high cost, the need for continuous aeration and refrigeration to prevent premature solidification, and the necessity for continual monitoring of the process by trained personnel.
- **Thermocuring methacrylates**: these are the most recent development (1977) and are steadily growing in importance because of their enhanced technical performance

and ease of use. As the name suggests, they are polymerised by curing at elevated temperature - typically 10 - 15 minutes at 90°C -which is often achieved by immersing the impregnated parts in hot water. These materials have a number of advantages which include:

- They are a simple two-part system (sealant and catalyst);
- The surplus sealant washes away easily with water;
- There are no known environmental problems;
- Short process and cure time;
- Simple process equipment and procedures;
- Although these sealants are more expensive than silicates and polyesters, a lower usage rate and higher productivity means that they are often the most cost-effective.



Sealant Materials

Sealant	Cure	Total cycle time	Ranking of sealant cost
Filled sodium silicate	Room temperature, 24 hours	24 3/4 hours	1 (lowest)
Styrene polyester	125 - 135°C	97 minutes	2
Anaerobic methacrylates	Room temperature, 3 hours	205 minutes	4
Thermocuring methacrylates	Hot Water 10 minutes	24 minutes	3

Features of methacrylates

- Simple 2 part system
- Surplus sealant is water soluble
- Environmentally friendly
- Short cycle time
- Simple process and equipment
- Cost-effective
- Suitable for leak rates up to 3000 ml min^{-1}
- Resistant to high pressure and many chemicals

TALAT Training in Aluminium Application Technologies | Sealant Materials | 3208.00.06

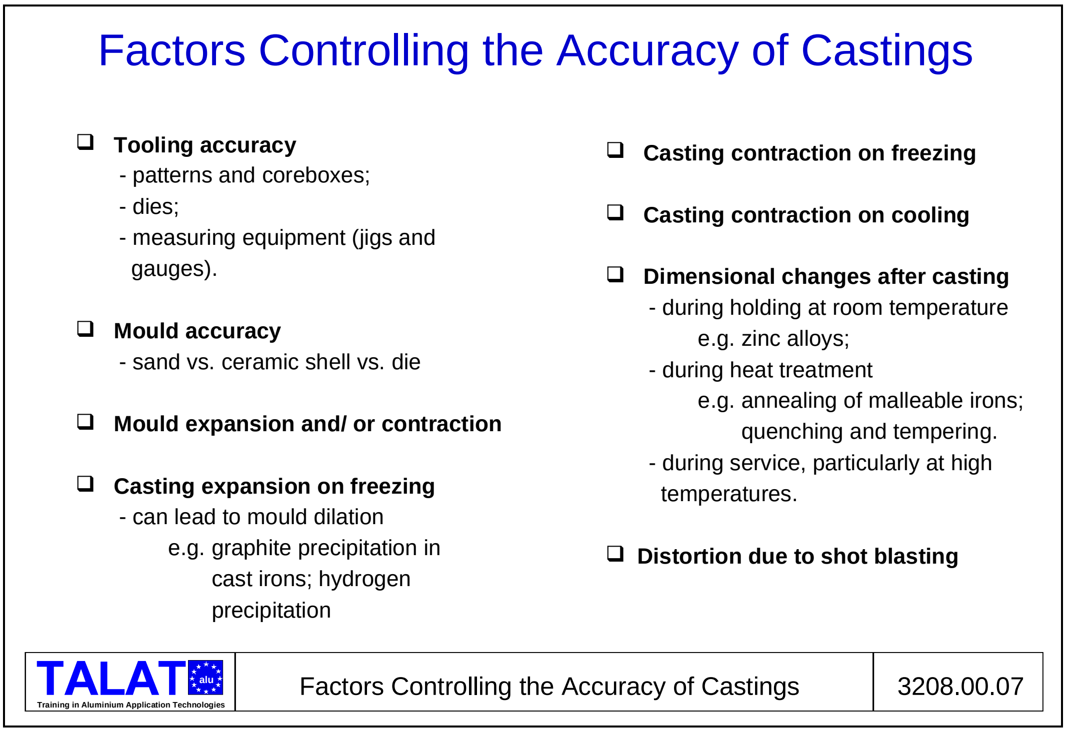
Thermal curing methacrylates can be used to seal both macro-and micro- porosity in a wide range of materials - leak rates of up to 3000 ml per minute can be sealed. The resulting sealed component can withstand high pressure and a wide variety of chemicals.

In some cases, impregnation has become a standard part of the process of producing castings which are required to be leak-tight. This is especially true for pressure die casting operations. However, it must be recognised that this is symptomatic of a failure of the foundry to use a process which is capable of consistently producing high quality castings. If the correct process is used, then impregnation should not be required. It should also be noted that whilst impregnation may successfully prevent leaking, assuming that the pressure and other service conditions are not too extreme, it will do little to restore the mechanical properties in porous regions to those expected in sound material.

Accuracy of Castings

Having considered how to prevent or correct for defects which might affect the ability of a casting to perform adequately in service, we shall now turn to the question of whether it will be accurate enough for its intended purpose. No casting (nor for that matter, any other type of component, such as a high precision machining) is ever *perfect* in terms of its shape and size, but the question must be whether it is within the tolerances specified by the designer.

Controlling Factors



Factors Controlling the Accuracy of Castings

- ☐ **Tooling accuracy**
  - patterns and coreboxes;
  - dies;
  - measuring equipment (jigs and gauges).
- ☐ **Mould accuracy**
  - sand vs. ceramic shell vs. die
- ☐ **Mould expansion and/ or contraction**
- ☐ **Casting expansion on freezing**
  - can lead to mould dilation
    e.g. graphite precipitation in cast irons; hydrogen precipitation
- ☐ **Casting contraction on freezing**
- ☐ **Casting contraction on cooling**
- ☐ **Dimensional changes after casting**
  - during holding at room temperature
    e.g. zinc alloys;
  - during heat treatment
    e.g. annealing of malleable irons;
    quenching and tempering.
  - during service, particularly at high temperatures.
- ☐ **Distortion due to shot blasting**

TALAT	Factors Controlling the Accuracy of Castings	3208.00.07

We will firstly briefly summarise the many factors which control the accuracy of a casting (see also **Figure 3208.00.07**):

- **Tooling accuracy**: This includes the patterns and core boxes, metal dies (when used) and any measuring equipment, such as jigs and gauges. If any of these are wrongly made, they will introduce a systematic error, which should be detectable if sufficient samples are checked. In addition, there may be changes with time: for example, wooden patterns can wear away and also warp, and metal dies can distort in service.

- **Mould accuracy**: Sand is the most commonly used moulding medium and its benefits include the fact that it is used at a more-or-less consistent starting temperature, which means that the mould dimensions will be closely related to those of the pattern. It can also be a very rigid material, particularly if modern high pressure greensand moulding machines or modern cold-setting chemical binders are used, which again promotes good casting accuracy. In some respects, sand moulds should therefore be better than the ceramic moulds used in investment casting.

Ceramic moulds are used at a high temperature, which often promotes plastic deformation of the mould whilst the casting is solidifying, and poor control over the mould temperature can also cause dimensional variation.

Die casting moulds can produce very accurate castings, particularly in zinc alloys. However, with higher melting point alloys, there are increasing thermal shock and fatigue loadings which cause cracking, crazing and distortion, and, in consequence, both dimensional and surface finish problems.

- **Mould expansion and/or contraction**: When a molten metal enters a mould, it is inevitable that heat absorbed by the mould will cause its dimensions to change. Sometimes the mould is heated uniformly, resulting in uniform expansion, but it is more common for heating and the consequential dimensional changes to be non-uniform. The mould wall movement can be outwards or inwards, depending on the casting design and the mould material. The inaccuracies caused by mould wall movement depend on factors such as the coefficient of thermal expansion of the mould material, the heat content of the metal, and the modulus of the casting.

- **Casting expansion**: Although most metals contract on solidification, there are some instances of expansion, the most well known example being cast iron, where the graphite precipitation during solidification leads to enormous pressures being exerted on the mould walls. If the latter are not strong enough, they deform, resulting in an oversize casting. In contrast, if the moulds are sufficiently rigid to withstand most of the expansion pressure, it is possible to counteract any tendency to form shrinkage porosity, resulting in a sound casting which is also reasonably accurate.

  Castings can also expand and dilate the mould if gas precipitation occurs, one example being in aluminium alloys if the hydrogen level is high. In one example, a change in the melting conditions led to an increase in the hydrogen content which produced 3 volume % porosity in the casting and resulted in a 1% increase in the casting length.

- **Casting contraction on freezing**: If the casting is poorly fed, we have already seen (**TALAT Lecture 3206**) that plastic flow of the solidified shell can occur in response to the high hydrostatic stresses built up in the casting. This will normally lead to a localised surface 'sink' or 'draw' in the casting, hence causing a local dimensional inaccuracy in the casting.

- **Casting contraction on cooling**: All metals contract as they cool from the solidus to room temperature. However, the contraction of a shaped casting will be influenced by the constraint of the mould which will in turn be a function of the design of the casting and the rigidity of the mould. For example, an 'L' shaped casting will contract more than an 'H' shaped casting and a solid casting will contract more than a hollow casting, whose contraction will be restrained by its core.

  The skill of pattern making is essentially being able to use experience to predict how a particular casting will solidify, so that the size of the pattern or die can be adjusted accordingly.

  In addition to this uniform contraction, different parts of a given casting can also experience different degrees of constraint from the mould/core, resulting in distortion. A well-known example of this is an open-topped box: whereas the 4 sides will be free to contract uniformly, the contraction of the base will be restrained and can result in a distorted (or even a cracked) casting.

- **Dimensional changes after casting**: Three types of dimensional change can occur in castings once they have reached room temperature.
  - Firstly, some alloys undergo dimensional change at their service temperature if they have not been fully stabilised by an appropriate heat treatment. For example, the common structural casting alloy Al-7%Si-0.4%Mg in the solution treated condition will continue to expand up to a total of approximately 0.1% during their first months or years at room temperature. This is because of the precipitation of the compound Mg2Si. Pre-ageing at a sufficiently high temperature is an effective cure of this dimensional instability.
  - Secondly, other dimensional changes occur during any heat treatment which involves a change of phase. For example, once again, Al-7%Si-0.4%Mg alloy contracts by 0.1 - 0.2% during solution treatment, as alloying elements are taken into solution, and then grows by 0.05 - 0.1% as precipitation occurs.
  - Thirdly, dimensional changes can occur in service, particularly at elevated temperature. For example, in an analogous way in which the well-known growth of grey irons occurs at temperatures as low as 350°C by the continued precipitation of graphite, growth can also occur in Al-17%Si alloy castings if they are used at a high enough service temperature for silicon precipitation to occur. However, this can be prevented by pre-ageing at 230°C for 8 hours.
- **Distortion due to shot blasting**: When castings are cleaned by shot blasting, compressive stresses can be introduced into the surface which can distort castings, particularly those of light section thickness. Excessive shot blasting can also lead to a loss of detail and rounded edges. It is important to distinguish between shot blasting and the *controlled shot peening* of castings in which shot is fired at a casting surface in order to develop a *controlled* residual stress distribution to improve the fatigue performance.

Accuracy Measurements

Having considered the numerous factors which have an effect on the accuracy of a casting, I would now like to consider how we can measure its actual accuracy (**Figure 3208.00.08**). Of course, there is no such thing as *absolute* accuracy, partly because there will always be errors in the measuring equipment and often some errors in the measuring technique. Even the surface finish of the casting will have an effect on its apparent accuracy which should not be overlooked.

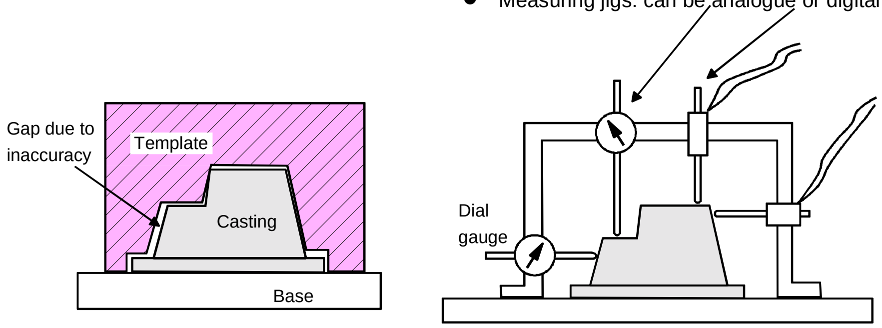
Various techniques are used to check casting accuracy. For initial prototypes or short production runs, the traditional technique of 'marking out' is still widely used. This uses a heavily built co-ordinate measuring machine which is designed to take the loads of a scriber scoring a mark along the surface of the casting. Increasingly nowadays this technique is being replaced by the use of lightweight, computerised three-dimensional co-ordinate measuring machines which simply lightly touch the casting, and record the position of contact electronically.

For long production runs, a traditional technique is to check the contour of a casting by using template gauges. However, these are not to be recommended since they are both expensive to make and difficult to use in any effective way.

'Go/no go' gauges are effective in telling the operator whether particular dimensions of a casting fall within pre-defined limits. However, they are not sufficiently quantitative for effective process control and they are subject to wear which imposes the need for a calibration system. Also, of course, they do not give information such as the drift of actual dimensions, which can be used in a statistical process control (SPC) procedure.

❑ Prototypes and short production runs
- Traditional mark-out equipment
- Three dimensional coordinate measuring machine

❑ Long production runs
- Templates
- Go/no go gauges
- Measuring jigs: can be analogue or digital

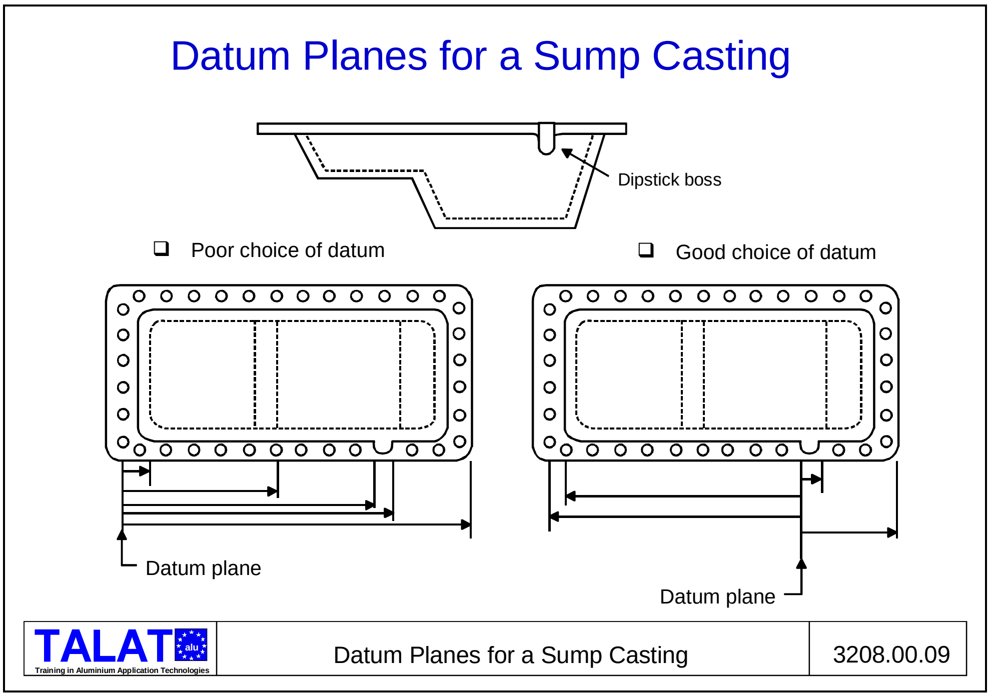


Measurement of Casting Accuracy 3208.00.08

A better approach is to use a measuring jig which straddles the casting and which is fitted with analogue dial gauges or, better still, digital transducers. The goalpost-type jig is first calibrated against a standard casting and the measuring transducers set to zero. Alternatively, the jig is stored in a special cradle which locates against the measuring points, setting them to zero. The jig is therefore stored and protected in its own self-calibrating housing. The jig is then used to measure the production castings and any inaccuracy is instantly displayed as a deviation from zero. If digital transducers are used, the data can be readily stored in a computer-based quality control system and used for SPC purposes.

Determination of Datum Planes

When attempting to measure a casting (or any other component for that matter), it is vitally important that due thought is given to defining suitable datum planes (**Figure 3208.00.09**). Normally, 3 datum planes are used, mutually perpendicular to each other, and dimensions are measured from these.


Datum Planes for a Sump Casting

☐ Poor choice of datum

☐ Good choice of datum

TALAT Training in Aluminium Application Technologies | Datum Planes for a Sump Casting | 3208.00.09

This shows a schematic view of a cast sump for a diesel engine and two ways of defining dimensions. The first method shown is poor for 3 main reasons:

1. The datum is at one end of the casting, whereas if the datum had been defined to be near the centre of the part, the variability resulting from length changes would have been halved.

2. The only feature on the casting whose location is critical is the dipstick boss. If this is misplaced, the dipstick fouls other components in the engine compartment. However, the boss is far from the datum which means that variability in the casting length will result in large proportion of castings being deemed to be unacceptable due to the boss being apparently misplaced. This problem would be reduced by placing the datum at the other end of the casting which is nearer to the boss. If the datum were placed on the boss itself then the problem is eliminated for ever!

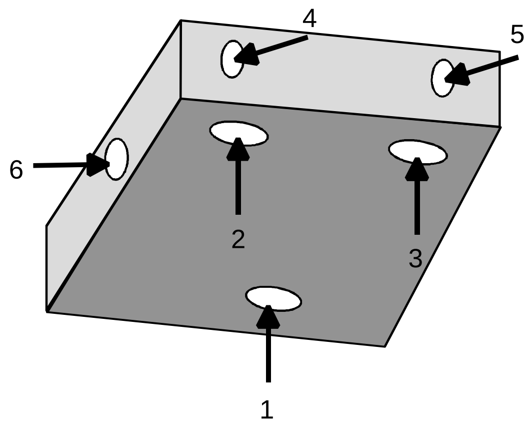
3. The datum is defined relative to a set of machined holes which do not exist on the casting when it is made. As a result, the onus falls on the machinist to decide where to place the holes, sometimes with unfortunate results.

The second method shown is a better way of defining the datum where it is located against an important feature of the casting - the dipstick boss. This results in the boss being correctly placed even if the casting size varies; all the dimensions are allowed to 'float' from this datum. Furthermore, since the datum is closer to the middle of the casting, the errors are almost halved.

It is a rather sad fact of life that considerable effort is often expended to produce an accurate casting which is then scrapped off during the machining stage. For example, an aluminium cylinder head was made using modern casting technology with dimensions of ± 0.1 mm. It was necessary to machine the casting in certain areas in order to achieve higher tolerances and hence the casting was produced with a rather generous machining allowance of 1 mm. In spite of this, the casting failed to 'clean up', i.e. towards the end of machining, there was not enough metal ('machining stock') left on the spring platform in the tappet bores to allow the final dimensions to be obtained. Why was this? The reason is that although the casting conformed to the drawing, it had been poorly located on the machine tool because insufficient thought had been given to the parts of the casting to be used as reference points for unambiguous location of the casting.

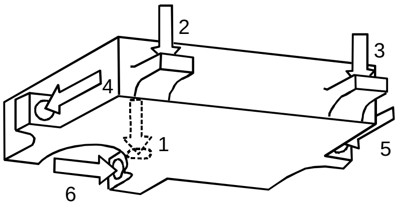
It is firstly worthwhile thinking briefly about how many points are required to locate any object in space. If we take a simple brick-shaped casting as an example, a little thought will show that a total of six points need to be defined - three (1, 2, 3) for one plane, two (4, 5) for another plane at right angles and one (6) for the remaining orthogonal plane (**Figure 3208.00.10**). If less points are used, the casting will not be unambiguously located, and if more points are used, some will be in conflict with each other. For the greatest accuracy, points 1, 2 and 3 should form a large triangle and points 4 and 5 should be as far apart as possible. This then defines the casting 'datums', i.e. the invisible planes which define a zero point in the space which surrounds the casting.

Six Point Location System

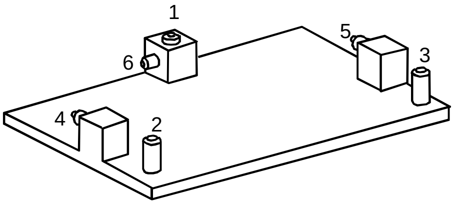


TALAT Training in Aluminium Application Technologies | Six Point Location System | 3208.00.10

However, it is also necessary to define real features on a casting known as 'machining points', 'tooling points' or 'pick-up points'. These are often, but not always, coincident with the casting datums. It is preferable for all six points to be located in one half of the mould, preferably the drag, although this is not essential since the joint between the drag and the cope is usually free from major dimensional error. Sometimes suitable features do not exist on the casting and, in such cases, additional lugs should be added to the casting. Often, such lugs can also serve as points where the casting is supported and clamped onto the machine tool or measuring equipment.



Casting with tooling lugs



Jig used to hold casting

TALAT Training in Aluminium Application Technologies	Example: Unique Positioning of Casting for Machining	3208.00.11

Figure 3208.00.11 shows a cuboidal casting having 3 lugs which are used to provide 6 location points using the approach just described. A further feature of these six points is that all are arranged on centre lines, so as to halve errors in all directions.

This also shows a simple jig for holding this casting and consists of a flat steel plate fitted with simple pegs and blocks. When the casting is placed on the jig, it can be slid about on pegs 1, 2 and 3 which define Plane A, then pushed up against locators 4 and 5 to define Plane B, and then slid along these locators until locator 6 is reached. As a result the casting is located in an unique position relative to the steel base plate.

This 6 point system can act as the basis for integrated manufacturing:

- the pattern maker can define all his measurements relative to the tooling points;
- the foundryman can use the tooling points to check the casting dimensions (as can the final customer, assuming that the tooling points are left in place);
- the machinist can use the same points to pick up the casting for machining.

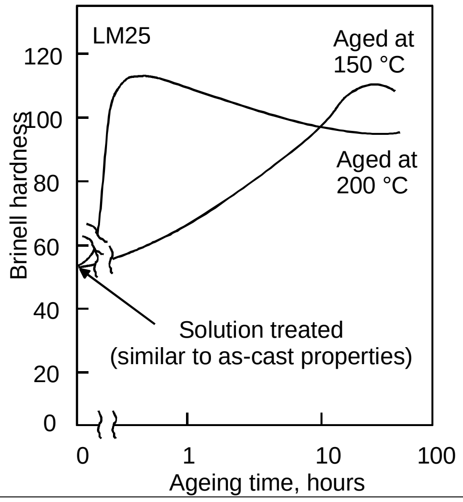
It should be relatively easy to set up this 6 point system, particularly where all operations are on the same site, but may require more perseverance when each operation is carried out by independent businesses.

Heat Treatment

The final topic that I would like to cover briefly is heat treatment (**Figure 3208.00.12**). Large numbers of castings are heat treated and, in some cases, more than one type of heat treatment may be involved.

Effect on Mechanical Properties

Heat Treatment of Castings (I):
Improves Mechanical Properties (Part A)



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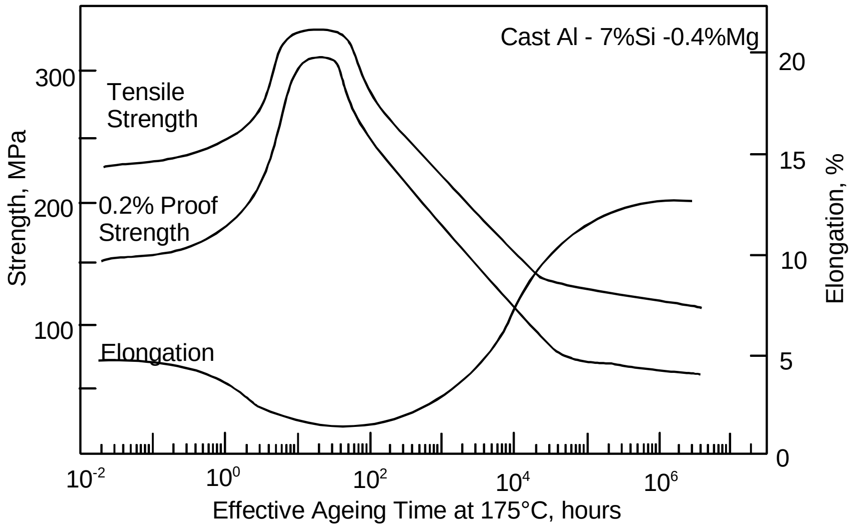
Heat treatments are carried out for a number of reasons. The first of these is to improve the mechanical properties. This is the usual reason for heat treatment. The strength of some alloys can be improved by a factor of two or three above that which is obtained in the as-cast condition.

This shows the effect of solution treatment followed by ageing on the hardness of LM25 alloy (Al - 7%Si - 0.3-0.6%Mg). As would be expected, as the ageing time is increased, the hardness increases as a result of precipitation, reaches a maximum and then decreases due to precipitate coarsening. The time to reach the peak hardness decreases as the ageing temperature increases, but this benefit is offset by a small decrease in the maximum hardness achieved.

Hardness is, of course, only one of a number of mechanical properties of interest to the designer and user of castings. **Figure 3208.00.13** shows how the 0.2% proof strength and tensile strength vary with ageing time and can be seen to follow the same behaviour as the hardness. It can also be seen that the trend in ductility (measured as % elongation) is the mirror image of the trend in strengths.

Heat Treatment of Castings (I):
Improves Mechanical Properties (Part B)



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[It can be noted that the original data for this plot were obtained at a number of different ageing temperatures. They were combined onto a single plot for an ageing temperature of 175°C using an Arrhenius-type equation for diffusion-controlled reactions. This states that:

$$\text{Rate} = A \exp(-Q/RT)$$

where

A is a constant,
Q is an activation energy (137 kJ $\text{mol}^{-1}$for Si in Al - this assumes that Si controls the diffusion process to form Mg_2Si precipitates),
R is the gas constant (8.31 J mol^{-1}) and
T is the absolute temperature.

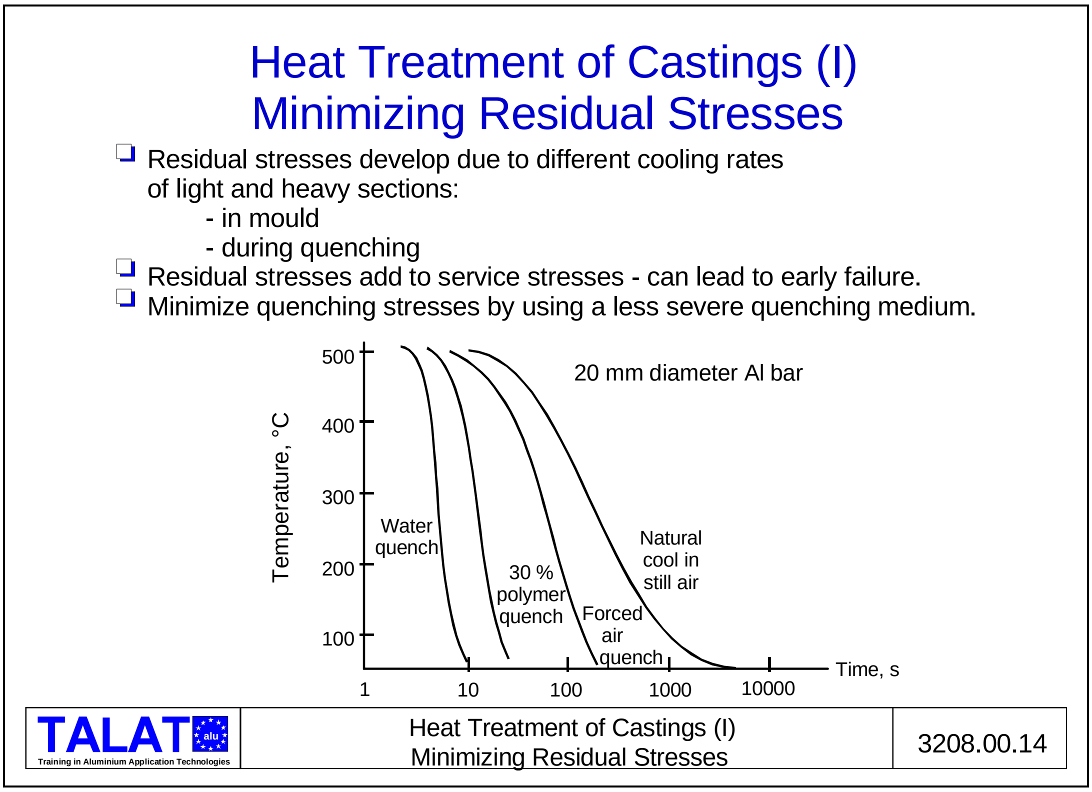
Application of this equation shows that diffusion rate is approximately doubled for every 10°C increase in ageing temperature.]

Effect on Residual Stresses

The second reason for carrying out heat treatment is to relieve residual stresses (**Figure 3208.00.14**). I would firstly like to consider the reasons why stress relief is required.

Larger castings are subject to the problem that some parts cool faster than others, so that stresses are developed during cooling in the mould, and particularly during cooling when water quenching after being held at a solution treatment temperature. In fact the quenching stresses usually are much more important than the casting stresses, especially when it is recalled that the casting stresses are normally relieved during the solution treatment, and the quench is the last rapid cool that the casting experiences.

The problem of residual stress during quenching is especially important for castings as opposed to other products such as forgings. This is because castings can be hollow, with additional important load bearing sections hidden inside the outer walls, protected from the action of the water quench; the huge volumes of steam generated inside the casting from the ingress of a small amount of water prevents the entry of further cooling water. Thus the structural members inside the casting experience slow cooling, after the outside has cooled and contracted. Thus the interior parts of the casting go into tension, to such a high level that failure can sometimes be immediate on quenching. If failure is not immediate, then the stress is retained, to add to service stresses experienced later in its life, thus encouraging early failure in service.



Heat Treatment of Castings (I)
Minimizing Residual Stresses

- Residual stresses develop due to different cooling rates of light and heavy sections:
    - in mould
    - during quenching
- Residual stresses add to service stresses - can lead to early failure.
- Minimize quenching stresses by using a less severe quenching medium.

Heat Treatment of Castings (I)
Minimizing Residual Stresses

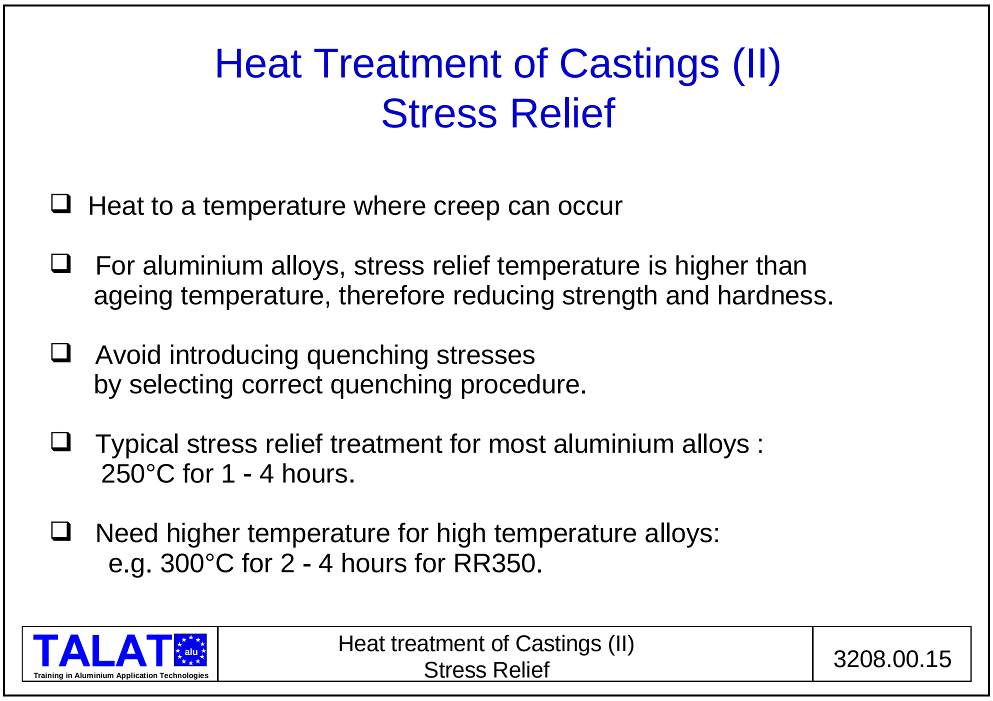
3208.00.14

These problems are reduced by the use of a polymer quench, or even an air quench. These quenching actions are more gentle and more controlled, and consequently give a casting which is substantially free from the danger of residual stress.

Smaller products, usually less than about 100 mm across, are less affected by these problems, as are those components which are largely solid, or can be accessed on all sides by the cooling medium.

We can now consider the various methods of carrying out stress relief (**Figure 3208.00.15**). Years ago castings were stress relieved to some extent by simply leaving them out in the foundry yard for a period of months or years. Another method which has been claimed to work more effectively and quickly is stress relief by the use of vibration.

In general nowadays, however, the only well-researched and proven technique is that of stress relief by the use of a heat treatment at a sufficiently high temperature that creep of the material can occur; the plastic flow caused by the internal stress gradually relieves the stress in the casting.



Heat Treatment of Castings (II)
Stress Relief

- ☐ Heat to a temperature where creep can occur
- ☐ For aluminium alloys, stress relief temperature is higher than ageing temperature, therefore reducing strength and hardness.
- ☐ Avoid introducing quenching stresses by selecting correct quenching procedure.
- ☐ Typical stress relief treatment for most aluminium alloys : 250°C for 1 - 4 hours.
- ☐ Need higher temperature for high temperature alloys: e.g. 300°C for 2 - 4 hours for RR350.

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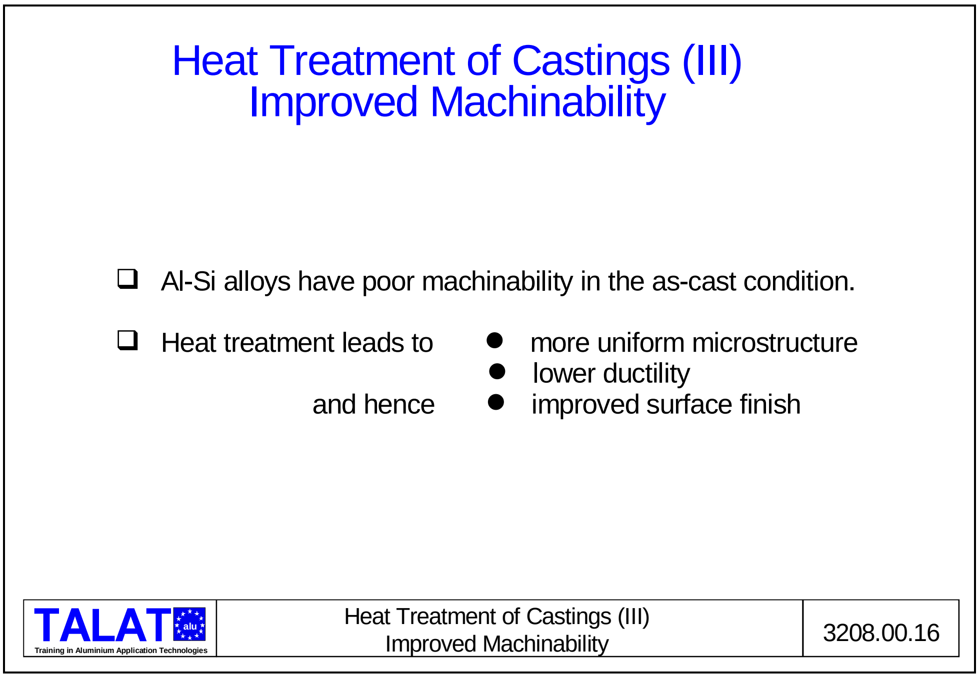
It is important to note that for aluminium alloys the normal ageing treatments are not carried out at a temperature sufficiently high for any useful stress relief to occur. It is unfortunate therefore that aluminium alloys have to be drastically overaged, thus losing most of the strength advantage gained during any prior ageing treatment. Thus castings which have to undergo stress relief will automatically have relatively poor strength and hardness (but good ductility of course). This is the major reason for ensuring that stresses are not put in to the casting by inappropriate quenching procedures in the first place - they can subsequently reduced only at the penalty of the loss of strength.

Typical stress relief treatments are in the range of 250°C for between 1 and 4 hours for many aluminium-based casting alloys to reduce the stress to a small fraction of its original value (the exact degree of reduction of stress does not seem to have been researched so far as the authors are aware). However, for those aluminium alloys designed for high temperature strength (e.g. the creep resistant alloy RR 350) a temperature of 300°C for between 2 and 4 hours is required to reduce the internal stress to below 10 % of its original value.

Effect on Machinability and Corrosion Resistance

There are two further benefits which can be obtained by heat treating castings.

Firstly, it is possible to improve their machinability (**Figure 3208.00.16**). The aluminium-silicon alloys in the as-cast state machine rather poorly, exhibiting a poor surface finish, probably as a result of the large difference in hardness between the aluminium matrix and the silicon-containing eutectic phases. Also, because of the relatively high ductility of the alloy, the cutting tool generates a long curling chip which entangles the machine tool in an inconvenient and even dangerous way. Heat treatment leads to a more uniform microstructural hardness and a reduced ductility, which results in a greatly improved machined finish and the swarf from the cutting action generates fine chips in convenient short lengths.



Heat Treatment of Castings (III)
Improved Machinability

❑ Al-Si alloys have poor machinability in the as-cast condition.

❑ Heat treatment leads to
- more uniform microstructure
- lower ductility

and hence
- improved surface finish

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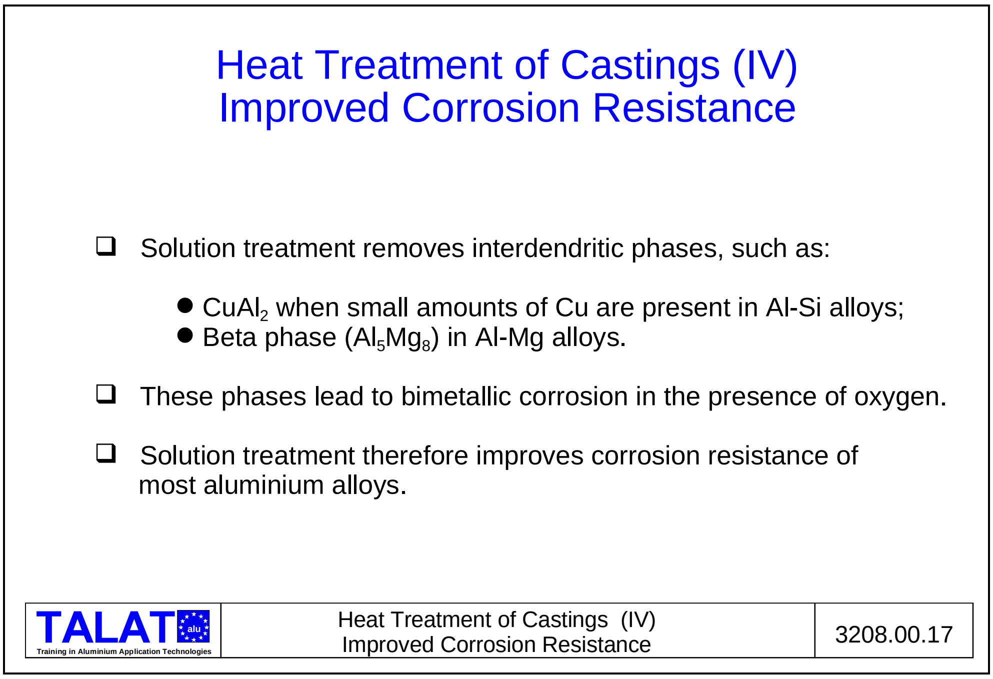
Secondly, it is possible to improve the corrosion resistance of most cast aluminium alloys as a result of solution heat treatment (**Figure 3208.00.17**). This is especially



Heat Treatment of Castings (IV)
Improved Corrosion Resistance

- ❑ Solution treatment removes interdendritic phases, such as:
  - $CuAl_2$ when small amounts of Cu are present in Al-Si alloys;
  - Beta phase (Al_5Mg_8) in Al-Mg alloys.
- ❑ These phases lead to bimetallic corrosion in the presence of oxygen.
- ❑ Solution treatment therefore improves corrosion resistance of most aluminium alloys.

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noticeable in alloys which contain a small amount of copper. When fully in solution this is relatively harmless from the point of view of corrosion. However, when present as an interdendritic phase, of composition perhaps $CuAl_2$, then a bimetallic corrosion couple is set up, in which the cathode is the copper-rich phase, and the anode is the surrounding aluminium-rich matrix, in which the rate of local corrosion is high, leading to rapid pitting in an aqueous environment containing oxygen in solution.

Where there is only a limited supply of oxygen in an environment isolated from the air (e.g. in a central heating installation) then the initial oxygen in solution is quickly consumed and not replaced, so that the corrosion is rapidly halted.

The copper content of the relatively pure Al-7%Si-0.5%Mg and Al-11%Si alloys is kept low to reduce these problems. However, a solution heat treatment will ensure that these problems are reduced further.

The aluminium-magnesium alloys also benefit from solution treatment by the removal of the beta phase (Al_5Mg_8) from grain boundaries. If these phases are not removed the alloy is subject to stress corrosion cracking along the grain boundaries.

There are therefore four reasons why castings are heat treated.

Literature

Campbell, J.: Castings, Butterworth Heinemann, 1991.

Anon: Casting impregnation - a casting tool, Metals and Materials, October 1985, Vol. 1, No. 10, 619 -622.

List of Figures