Controlling the structure of cast aluminium alloys

The structure of cast aluminium alloys needs to be controlled if the highest mechanical properties are to be obtained. In the case of silicon containing alloys this generally involves refinement to produce a fine grain size together with modification to change the size and form of the silicon eutectic.

Grain refinement

In the highest quality aluminium castings the structure is fine grained and as uniform as possible. Such a uniform fine grained structure produces improved mechanical properties, together with better feeding characteristics and less likelihood of such defects as porosity and tears. A casting with heavy sections and thus a slow solidification rate can have a grain size up to about 12 mm diameter. By comparison a fine grained structure would typically contain grains no larger than about 1 mm in diameter.

Three factors principally influence grain size in aluminium alloys.

Solidification rate

A rapid solidification rate produces a fine grained structure. High levels of nucleation occur at rapid solidification rates, producing a large number of sites or nuclei from which crystals can form. This effectively means that castings produced in steel or cast iron dies will have a finer grain size than those produced in sand moulds. Similarly, thin sections will have a finer grain size than thick sections, because of their more rapid solidification.

Pouring temperature

The effects of pouring temperature are inter-related with the type of moulding material. High pouring temperatures produce a larger grain size because the time between pouring and the start of solidification is extended, thereby increasing the temperature of the mould wall and slowing down the rate of solidification. In practice the lowest sensible pouring temperature should be used, bearing in mind the need to avoid the production of a defective casting.

Addition of grain refining elements

Grain refinement can be achieved by deliberate additions of elements such as titanium and boron, typically as potassium titanium fluoride and potassium borofluoride salts, in tablet form. However, the process of using salt tablets is far from ideal as illustrated in Table 1 and grain refining master alloys such as titanium aluminium (TiAl) and titanium boron aluminium (TiBAI) are more commonly used. Alloys typically used in the foundry industry are 5% TiAl and 5% Ti, 1% Al added to give residuals of about 0.1% Ti and 0.025% B. TiBAI is such a powerful grain refiner that in some instances levels of addition of only 0.02% Ti are effective.

The addition of titanium master alloys produces titanium carbides and aluminium borides. These compounds act as nucleating sites and are far more potent when present together. Typical improvements in mechanical properties, obtained from the grain refinement, are as follows:

<table>
<thead>
<tr>
<th></th>
<th>UTS N/mm²</th>
<th>E%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated AISi5Cu3</td>
<td>164</td>
<td>2.5</td>
</tr>
<tr>
<td>Grain refined with 0.02% Ti as 5/1 TiBAI</td>
<td>182</td>
<td>2.8</td>
</tr>
<tr>
<td>Minimum specified requirement</td>
<td>160</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Table 1  Comparison of salt tablets and TiBAI as grain refiners in the foundry

<table>
<thead>
<tr>
<th>Recovery</th>
<th>TiBAI rod</th>
<th>Salt tablets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact time</td>
<td>High and consistent</td>
<td>Variable and operator dependent</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Short (30 seconds)</td>
<td>Long (5-10 minutes)</td>
</tr>
<tr>
<td>Fade</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Dissolution</td>
<td>Fast (&lt;30 seconds)</td>
<td>1:1.5 hrs.</td>
</tr>
<tr>
<td>Addition</td>
<td>Clean and fume free</td>
<td>Slow (2-5 minutes)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fumes and flux residues</td>
</tr>
</tbody>
</table>

Modification of aluminium alloys

When the aluminium alloys cool and solidify the aluminium/silicon eutectic, which normally contains 11.7% Si, produces a coarse, lamellar plate-like structure within the matrix which is detrimental to strength and which has an adverse effect on machinability because of its hardness. The speed of cooling and solidification has an effect on the formation of the eutectic phase, slow cooling favouring the formation of a coarse structure. Modification refines this structure to produce superior mechanical properties, castability and machinability. Typical properties of a modified alloy are as follows:

<table>
<thead>
<tr>
<th>UTS N/mm²</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated AISi5Cu3</td>
<td>164</td>
</tr>
<tr>
<td>Grain refined 0.02% Ti as 5/TiBAI and modified 0.03% Sr as 10% SrAl</td>
<td>185</td>
</tr>
</tbody>
</table>

The most common alloys which are modified are those which are approximately eutectic, i.e. those in the 10-13% silicon range, such as AISi12. Modification is sometimes applied to the lower silicon alloys in the 3-6% Si range as AISi5Cu3 which although not strictly necessary, does have the advantage of increasing mechanical properties particularly when the alloy is poured in reasonably heavy sections in sand moulds where slow cooling results.

Alloys containing 18-26% Si, i.e. those which are strongly hyper-eutectic, are wear resisting by virtue of the presence of the silicon particles. Even when modified some coarse plates of silicon are present, thus providing the required wear resistance in these materials.

Elements used for modification

Four elements are commonly used for modification and each has a specific usage, advantages and disadvantages. These are sodium, strontium, antimony and phosphorus. Sodium and strontium are true modifiers producing the structure shown in Fig. 1, compared with the unmodified structure illustrated in Fig. 2.

Antimony and phosphorus are not true modifiers but are strictly grain refiners, producing a granular structure intermediate between the two shown in Figs 1 and 2.

Fig. 1  Modified AISi12

Fig. 2  Unmodified AISi12
Modification with sodium
Modification with sodium can be carried out using sodium salts such as sodium fluoride, but is more commonly achieved by using the pure metal as a tablet encapsulated in aluminium foil. Factors of importance are:

- An addition rate to achieve 0.005-0.02% residual sodium – Recoveries can be variable at around 20%
- Avoidance of levels in excess of 0.02% which produce an 'overmodified' structure similar to the unmodified structure shown in Fig. 2
- Treatment time for modification is about 5 mins.
- Fade occurs with time
- Phosphorus contamination above about 0.0009%, causes deterioration of the structure

Modification with strontium
Strontium salts such as chloride, fluoride or bromide can be used but the addition of master alloys such as AISr4 is far more common. Strontium has some distinct advantages over sodium but modification takes longer to achieve. Important factors are:

- An optimum addition range of 0.02-0.03%
- Recoveries of about 90%
- Modification is longer lasting
- There is no evidence of over modification
- Treatment times are 20-30 mins
- Phosphorus contamination above 0.0009%, causes structural deterioration.

Modification with antimony
Antimony is considered a permanent modifier and for this reason is normally added to the ingot by the supplier to a residual level between 0.1-0.2% using AISb4. Important factors are:

- Antimony is strictly a grain refiner
- Loss on remelting is minimal
- Antimony is more dense than aluminium and can segregate when molten metal is held or in castings with long solidification times.

Modification with phosphorus
Although phosphorus destroys the effects of sodium or strontium modification it can be used to modify (or more strictly grain refine) the hyper-eutectic aluminium alloys in the 16% + Si range. Important factors are:

- Modification is normally with 15% PCu
- Residual levels typically between 0.03-0.04%
- Great care required with scrap and returns of this material, to avoid phosphorus contamination of other alloys.