Metallographic Investigation and Solidification-Structure Modelling of Al Micro Castings

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Abstract

Producing micro-castings through vacuum investment casting is known to be associated with high cooling rates due to small scale of the castings. High cooling rates together with alloy composition might be the main factors affecting the final metallographic structure of castings' alloys during the solidification process. When using Al-Si-Mg casting alloys, the size of the dendritic structure can be used for a non-destructive test to assess the mechanical properties and overall quality of the castings. Also the ability of the alloys to be structured by different mechanical and energy assisted processes is highly dependant on their metallographic structure. This paper investigates the structural changes occurring when shifting from conventional size castings to micro-castings. An empirical model describing the degree of dendrite cell refinement as a function of micro-castings aspect ratio is proposed. Additionally, the paper reports the changes in porosity and Si particles morphology observed on micro-castings produced with different flask temperatures. MHV measurements were also performed for different aspect ratio of the cast micro-features.

Keywords: micro-casting, dendrite cell refinement, investment casting.

1. Introduction

The capability of the Vacuum Rapid Investment Casting (VRIC) to produce complex micro and meso-micro components was studied in details in [1-3]. It was shown that features with size less than 150 µm, ribs with aspect ratio (AR) higher than 50, and surface roughness in the range of 5 µm could be reproduced with accuracy of 10% or less. This makes the technology quite promising in Rapid Prototyping (RP) micro features and components especially by applying RP techniques to produce accurate sacrificial patterns or casting clusters through direct shell processes.

However, our knowledge is still limited in regards to microstructure and properties of these castings. It is not clear how the extreme cooling conditions associated with this technology affect the structure and mechanical properties of the components. Also, it is important to verify to what extent the existing solidification theories are valid when micro size casting channels are utilised. The importance of answering those questions arises from the emergence of new application areas, e.g. the use of aluminium (Al-Si-Mg) castings in microelectronics cooling devices, and heat exchangers [4]. Since the material morphology of the castings affects their machining response [5-6], it is also important to obtain information on as-cast microstructure of micro components and thus reduce uncertainty that this introduces to their further structuring with mechanical and energy assisted processes.

It is well known that the solidification conditions of cast metals have a direct relationship to their metallographic structure and mechanical properties [7-8]. Over the years, extensive research has been done to assess the influence of casting parameters on the mechanical properties of Al alloys [9-11]. The work of Spear & Gardner [10] showed that the dendrite cell size measurement could be used to describe their structural refinement. They concluded that both alloy composition and solidification rate were major factors influencing the dendrite cell refinement. The dendrite cell size of Al casting alloys could be related to the solidification rate using the following equation:

\[
\lambda = C \cdot R^\phi ,
\]

where: \(\lambda\) - dendrite cell size (DCS) in [µm]; \(R\) - K/s-solidification rate; \(C\) and \(\phi\) - constants. They also concluded that a decrease of dendrite cell size leads to an increase of the tensile ductility of the castings.

This work has been more recently re-examined by Wang & Cáceres [11] in the light of the current understanding of the relationship between microstructure and plastic deformation of Al-7Si-0.4Mg alloys. It was concluded that although DCS provided a means of linking mechanical properties to solidification conditions, they played only a limited role in determining the tensile ductility of these alloys. This was attributed to the fact that the size, shape and distribution of the eutectic Si particles is also an important factor affecting the tensile behaviour of these alloys [11-12].

In general, for unmodified alloys under normal cooling conditions, Si particles are polyhedral and are in the form of coarse acicular needles [12]. These Si particles are large and brittle and act as crack initiators that consequently lower the ductility of the castings [11-13]. However, when fast cooling rates are applied (>10 K/s), eutectic Si particles undergo a morphological change and are present in the microstructure as small individual particles [14-15]. Such eutectic type is called fibrous eutectic [16].

Due to the poor thermal conductivity of the ceramic shells in investment casting, the cooling rates are low during the solidification process, which often produces equiaxed and coarse structures that lower the mechanical properties of the castings [7-8]. With the decrease of the casting channels, especially at micro scale, the cooling rates increase even further and extreme values can be achieved [17].

In this research, an experimental study is conducted to investigate the degree of dendrite refinement when producing micro components using Al-Si-Mg casting alloys. An empirical model is proposed to describe the evolution of DCS in walls with different thicknesses as a function of their AR for a given mould/metal materials and processing parameters.
2. Experimental designs and settings

In order to assess and compare the potentially different solidification conditions that can be present when casting walls with different thickness (T) and AR, two sets of experiments were conducted in this study. The first set of trials included casting of plates with T of 10, 7, 5 and 2.5 mm and AR of 10. These are typical dimensions of castings produced at macro scale. To consider the heat flow transfer problem as a one dimensional one [7], T of the plates was selected to be at least 3 times smaller than their widths (W), and the feeding was done only from one side of the samples as shown in Fig. 1a. The second set of experiments was performed on test parts incorporating thin ribs, micro features, having a range of thicknesses starting from 1 mm down to 250 µm with a maximum AR of 50 (Fig1.b). In particular, the thicknesses of the ribs were 1, 0.75, 0.5, 0.45, 0.3 and 0.25 mm. Again, the ratio W/T > 3.

Lost patterns were built using a thermal phase change inkjet system, ThermoJet [3]. To cast them, they were embedded in a gypsum-bonded investment, M028 from Hoben. Finally, the castings were produced in a single shot using an induction melting vacuum investment casting unit, MPA 300, with inert gas overpressure facilities. Flask temperatures of 250°C and 450°C and pouring temperature of 715ºC were used in this study.

The test parts were sectioned along their length, L, to perform a metallographic analysis of their microstructure. The plates with thicknesses bellow 5 mm and the ribs were cut employing electro-discharged machining to prevent any structural changes of the samples. The samples were then cast into acrylic resin and polished using diamond polishing slurries.

The metallographic analysis was done using image analysis software, Omnimet. The changes of the DCS and Si particles morphology of the samples together with their porosity were assessed as a function of the ribs’ AR.

3. Results and discussion

3.1 Conventional castings: the plates

A set of conventional castings was produced in order to use them as a reference in this experimental study. In Fig. 2, the results of the conducted quantitative metallographic analyse of material microstructure are given. The analysis confirmed that the changes in the solidification rates of investment castings at macro scale were only a result of the varying process parameters and the thickness of the castings. This was in agreement with the general solidification theory for castings and ingots into insulated moulds [7]. In particular, the following generic observations were made:

- A higher mould temperature reduces the solidification rate and leads to a coarser alloy microstructure;
- Thinner sections solidify faster than thicker ones which results in smaller DCS.

3.2. Meso/micro castings: the plates with thin ribs

The second set of experiments included casting meso and micro features, in particular the thin ribs. The pictures in Figure 3 depict the dependence of dendrite cell refinement in the ribs on AR and mould temperature. In contrast to the first set of trials the resulting microstructure was strongly dependent on the ribs’ AR. This represented a fundamental difference in the solidification behaviour of castings incorporating meso/micro features. Thus, such scale effect requires the classical approaches to be re-examined and new models to be introduced. Based on the results from the trials, an attempt is made in this study to describe the evolution of DCS in the ribs with different thicknesses as a function of their AR.

After testing of a number of models, exponential decay with plateau was chosen to perform the nonlinear regression analysis of the experimental data:

\[
DCS = \text{Plateau} + \text{Span} \cdot e^{-k \cdot \text{AR}}
\]

The model has three parameters, \(\text{Span}\), \(k\) and \(\text{Plateau}\) that can be associated with different physical aspects of the casting process. In particular, the \(\text{Span}\) describes quantitatively the degree of cells’ refinement encountered in each specimen in respect to its overall size and complexity. The coefficient \(k\), represents the

![Fig. 1 Test parts: a) a cross sectioned plate; b) a plate incorporating ribs with AR of 50. Note: The arrow shows the location of the feeding](image)

![Fig. 2 DCS as a function of the plate thickness: a) flask 450°C; b) flask 250°C](image)
slope of the curve and reflects the changes in the degree of under-cooling achieved during solidification. *Plateau* is a threshold value that defines the refinement limit for the existing functional dependence between DCS and AR of the features. These parameters are dependent on the thermodynamic characteristics and the freezing range of the casting alloy, and also on its ability to form dispersive structures under the specific cooling down conditions for a given investment material.

In Fig. 4 model plots and the goodness of fit for ribs in the range from 0.5 to 0.25 mm thick is given. The models defined in this way describe relatively well the evolution of DCS observed in this experimental study. However, it should be considered only as a simplification of the actual complex relations between the process parameters and final material microstructure. Further research is required to understand better their complex interdependence. Apart from DCS, AR and mould temperature had a significant effect on the eutectic morphology. The shape of the Si particles changed dramatically from lamellae structures to a more rounded type of eutectic as shown in Fig 4.

3.3 Empirical Model

The data sets obtained for different rib thicknesses and flask temperatures were independently analysed using a nonlinear regression analysis. It was observed that the three parameters *Plateau*, *Span* and *k*, remained almost unchanged within the range from 0.5 to 0.25 mm. Taking into account the focus of this experimental study, this reduced range can be considered more representative of the specific conditions that arise when casting meso/micro features than the whole range of ribs’ thicknesses investigated, in particular from 1 to 0.25 mm. Therefore, to develop an empirical model of DCS evolution in features at this scale as a function of their AR the average values of these parameters for the ribs in the range from 0.5 to 0.25 mm were used. These average values are presented in Figure 4. As the figure shows, the empirical model developed in this way correlates very well to the experimental results within the range from 0.5 to 0.25 mm. This was confirmed by the goodness of the model fit by calculating the coefficient of correlation $R^2$ and the best fit estimate of the standard deviation of the residuals $S_{xy}$. At the same time, for the ribs in the range from 1 to 0.75 mm, the model deviation from the measured data was considerable. This confirms one more time that the casting conditions in these two sub-ranges differ significantly and only the low range should be considered representative of DCS evolution in meso/micro features as a function of their AR.

3.4 Apparent Porosity and Hardness

While performing the metallographic analysis, the porosity as the ratio between the pores’ area and the total surface area revealed after polishing the samples was calculated. The measurements were taken both from the ribs and the casting core for each flask temperature. Results are summarised in Table 1.

![Fig. 3 The dendrite refinement of 0.3 mm thick ribs at flask temperature of 450°C, a) AR 0 and b) AR 40, and at flask temperature of 250°C, c) AR 0 and d) AR 40 (x400 magnification)](image1)

![Fig. 4 Model plot and goodness of fit for the ribs in range 0.5-0.25 mm. Flask temperatures: a) 250°C; b) 450°C)](image2)

![Fig 5. Si morphology in the eutectic. a) AR=1 & flask temperature 450°C (x400 magnification); b) AR=40 & flask temperature 250°C (x400).)](image3)
As a consequence of this microstructure refinement and the more evenly distributed porosity, an increase of the micro hardness from 52 MHV in the rib base to 61 MHV on their tips was observed. In addition, it is expected that the improved structural integrity of meso/micro features will lead to their better machining response to various mechanical and energy assisted processes.

Table 1 Samples’ porosity

<table>
<thead>
<tr>
<th>Flask temperature</th>
<th>250°C</th>
<th>450°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casting core [%]</td>
<td>0.7</td>
<td>5.14</td>
</tr>
<tr>
<td>Ribs [%]</td>
<td>0.084</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Conclusions

Based on the conducted experimental study the following conclusions can be derived:

1. The microstructure refinement in castings incorporating meso/micro scale features is significant. In particular, the smallest dendrite size measured in features with a thickness of 250 µm was less than 5 µm. The grain refinement of the casting alloys should be expected to facilitate the replication process and also to reduce the shape instability of the channel type features.

2. The influence of features’ AR on resulting material microstructure is significant when casting meso/micro scale components. For example, the increase of AR from 0 to 50 in the ribs with a thickness in the range from 250 to 500 µm led to more than 3 times reduction of DCS. In macro scale castings AR does not affect the metal microstructure. This phenomenon could be explained with the significant increase of the cooling rates when reducing the feature sizes that are highly dependent on mould thermal properties and processing temperatures.

3. The porosity distribution in meso/micro features of the castings was more uniform. This is due to almost simultaneous solidification of casting alloys in such features. In particular, the apparent porosity in meso/micro features was reduced to less than 0.1 % while in the core of the castings it was typically around 1 to 5 %.

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References