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Porosity Formation and Eutectic Growth in Al-Si-Cu-Mg Alloys Containing Iron and Manganese

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Abstract

The effects of iron and manganese on the solidification of the Al-Si eutectic were examined by quenching. In unmodified alloys with low iron levels, eutectic solidification is characterised by the formation of a large number of small eutectic grains. Iron reduces eutectic nucleation, resulting in fewer and larger eutectic grains. Manganese additions reverse this trend. The effect of iron becomes less apparent as the copper content increases. It is proposed that permeability and porosity are affected by these changes in microstructural evolution and the presence of intermetallics in the interdendritic regions.

1. Introduction

Iron is known to have a detrimental influence on the castability of Al-Si foundry alloys. High levels of porosity have been associated with the formation of large β-Al_5FeSi platelets prior to the Al-Si eutectic reaction [1-4]. It has been suggested that porosity increases because β-Al_5FeSi platelets block interdendritic flow channels [1].

Taylor [2] proposed a model for iron-related porosity formation based on the observation of a minimum in porosity at intermediate iron contents in Al-5%Si-0.5%Mg-1%Cu castings. At high iron levels, β-Al_5FeSi forms prior to the Al-Si eutectic reaction. At low iron levels, β-Al_5FeSi forms after the Al-Si eutectic. While at a specific intermediate iron content (the critical iron content), β-Al_5FeSi forms as a ternary eutectic constituent with aluminium and silicon. Taylor [2] suggested that the eutectic silicon nucleates on large pre-eutectic β-Al_5FeSi platelets, leading to reduced interdendritic permeability. At low iron contents, the eutectic silicon nucleates prior to the formation of β-Al_5FeSi. The most permeable structure results from the nucleation of many small eutectic grains on small β-Al_5FeSi platelets at the critical iron content. However, Taylor's model does not explain the behaviour of alloys with different silicon and copper concentrations where no minimum in porosity at the critical iron content is observed [3,4].

In the presence of sufficient manganese, porosity decreases and the iron-bearing intermetallic phase changes to α-$Al_{15}(Fe,Mn)_3Si_2$; a phase with a script-like morphology. It has been suggested that the relative "compactness" of α-$Al_{15}(Fe,Mn)_3Si_2$ compared to β-Al_5FeSi is responsible for reducing porosity [5,6]. However, large intermetallics, whether α-$Al_{15}(Fe,Mn)_3Si_2$ or β-Al_5FeSi, would be expected to obstruct feed paths in proportion to their volume fraction. Hence, the mechanism responsible for manganese decreasing porosity is unclear. The Al-Si eutectic accounts for 50-90% of the volume of typical Al-Si foundry alloys and is therefore, likely to control porosity. This work aims to investigate the effects of iron and manganese on Al-Si eutectic solidification and porosity levels in Al-Si foundry alloys.

2. Experimental Methods

Sand-cast plates with a centrally-located boss were used to investigate the effects of iron and manganese on porosity formation. A schematic of the plate casting is shown in Figure 1. The castings are gravity poured using an optimised bottom gate. A minimum of four castings was made for each alloy variant. Porosity levels in the castings were measured using Archimedes' method. The porosity data were analysed using 90% confidence intervals calculated from Student's t-distribution, to account for the small number of samples.

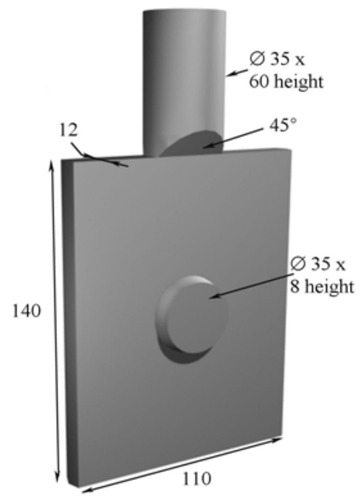

Figure 1: Schematic diagram of the plate casting. Dimensions are in mm.

The base alloy was non-grain-refined and unmodified Al-9%Si-0.5%Mg. Two copper contents were examined (0 and 3%) along with three iron contents (0.1, 0.6 (the critical iron content for 9%Si), and 1%). Manganese additions of 0.5% were made to some alloys with 1%Fe. The melts were degassed with argon for 30 minutes at a flow rate of 3.5 litres per minute. Ransley chill cast samples were used to determine the melt hydrogen content. The measured hydrogen concentrations were low and found to be uncorrelated with the porosity levels.

The evolution of the Al-Si eutectic was investigated by interrupting solidification just after eutectic nucleation. Small, tapered stainless steel cups, with dimensions of 30mm diameter at the top, 20mm diameter at the bottom, and a height of 30mm were used to produce the quench samples. A stainless steel-sheathed N type thermocouple was used to log cooling curves and first time-derivative curves. In addition to the alloys used for the porosity experiments, iron and manganese were added to binary Al-9%Si alloys, to give Al-9%Si-0.6%Fe, Al-9%Si-1%Fe and Al-9%Si-1%Fe-0.5%Mn alloys. Metallographic specimens were prepared from the quenched samples. The area density of eutectic nucleation events was calculated by manually counting the number of eutectic grains in ten randomly selected 1090 μm x 1385 μm fields.

3. Results and Discussion

Examples of quenched microstructures for alloys based on binary Al-9%Si are presented in Figure 2. Figure 2 appears to show that the Al-Si eutectic nucleation frequency decreases with increasing iron concentration, while the addition of 0.5%Mn to the alloy with 1%Fe causes the eutectic nucleation frequency to revert to a similar level as Al-9%Si-0.6%Fe.

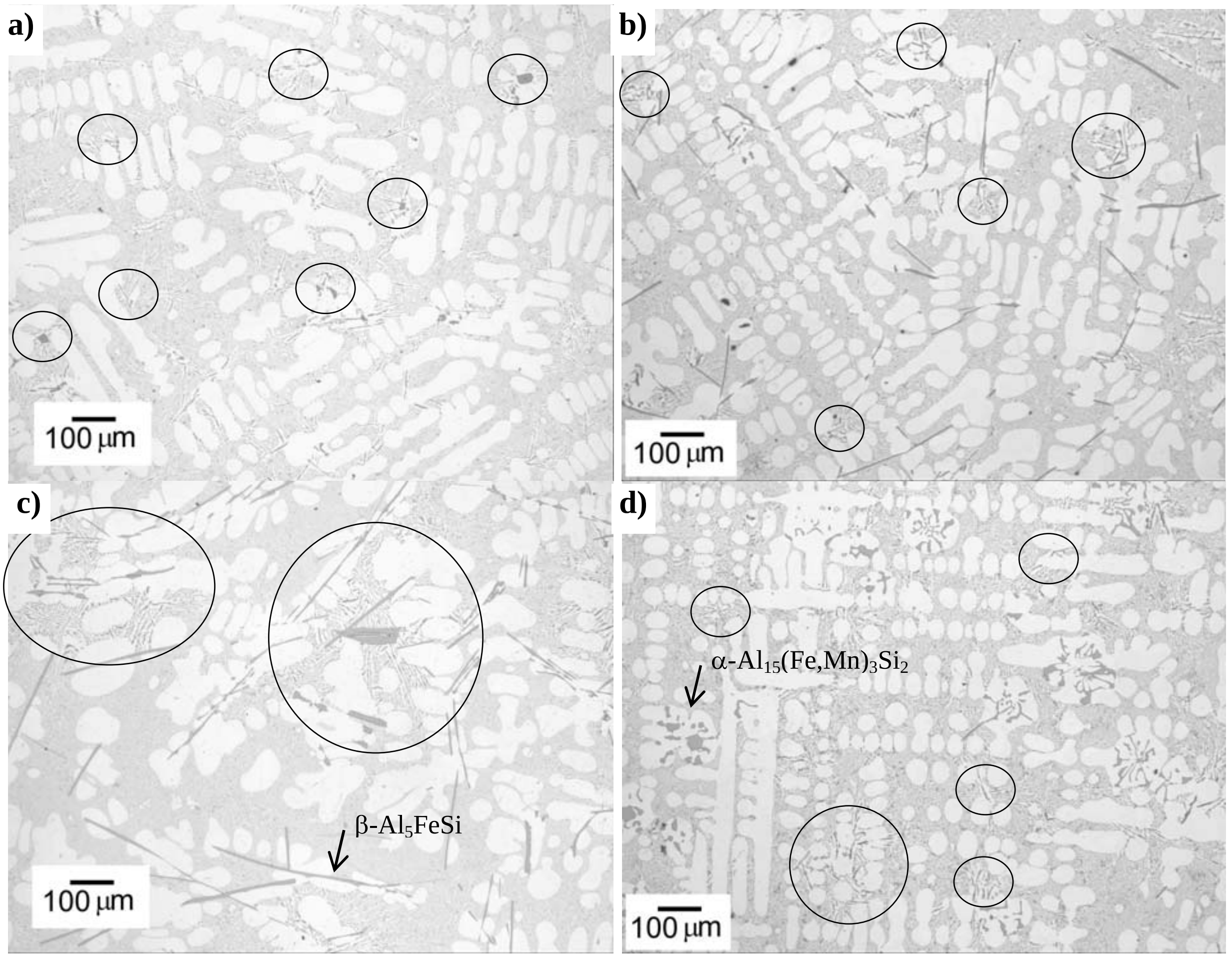

Figure 2: Microstructure of samples quenched after nucleation of the Al-Si eutectic. Examples of eutectic grains are outlined by circles. (a) Al-9%Si (b) Al-9%Si-0.6%Fe (c) Al-9%Si-1%Fe (c) Al-9%Si-1%Fe-0.5%Mn.

The trends observed in Figure 2 are also observed for iron-containing alloys based on Al-9%Si-0.5%Mg and Al-9%Si-0.5%Mg-3%Cu. However, the effect of iron is not as strong in the copper-containing alloy. The measurements of the area density of nucleation events presented in Figure 3 confirm the trends observed in Figure 2. Magnesium appears to have no effect on the nucleation density of eutectic grains because the Al-9%Si-(Fe) and Al-9%Si-0.5%Mg-(Fe) alloys show similar behaviour. The addition of 3%Cu increases the nucleation density in the alloys with 1%Fe and 0.5%Mn while having no effect on the 0.1%Fe alloy. In other words, iron does not decrease the eutectic nucleation density in the copper-containing alloys as much as in the copper-free alloys. The number of nucleation events in the 0.6%Fe variants of Al-9%Si-0.5%Mg and Al-9%Si-0.5%Mg-3%Cu were not measured but are expected to follow the same trend as in the Al-9%Si alloy and therefore, be between the 0.1 and 1%Fe variants, resulting in a similar number of nucleation events as Al-9%Si-0.6%Fe.

Iron, copper and magnesium segregate during the solidification of the Al-Si eutectic, causing constitutional undercooling ahead of the eutectic/liquid interface [7]. The segregation of manganese is negligible [8]. Therefore, iron, copper and magnesium may be expected to increase the number of nucleation events. However, iron additions decrease the number of eutectic nucleation events and manganese additions reverse this trend. Eutectic silicon is known to nucleate on AlP particles [9], suggesting that β-Al_5FeSi and AlP particles may interact in the liquid. Therefore, the increased number of nucleation events after manganese addition, may be due to increased availability of AlP because of the preferential formation of α-$Al_{15}(Fe,Mn)_3Si_2$ instead of β-Al_5FeSi.

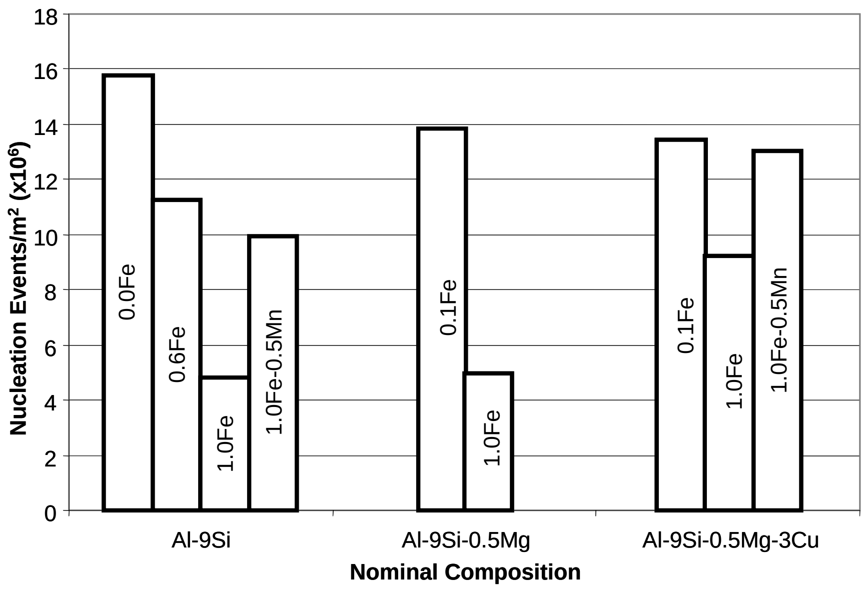

Figure 3: Frequency of Al-Si eutectic nucleation events measured in a range of quenched samples. Estimates of the nucleation frequency in Al-9%Si-0.5%Mg-0.6%Fe and Al-9%Si-0.5%Mg-3%Cu-0.6%Fe alloys have been made based on trends in the data of Al-9%Si-(Fe).

Figure 4 shows the effect of iron, manganese and copper on the formation of porosity in the sand-cast plates. The copper-free alloys (light grey in Figure 4) show a slight increase in porosity as the iron content increases from 0.1% to 0.6%. A further increase in the iron content to 1% causes a significant increase in porosity. An addition of 0.5%Mn reduces porosity to approximately the same level as in the 0.6%Fe alloy. In the copper-containing alloys (dark grey in Figure 4) an increase in iron content from 0.1% to 0.6% causes an increase in porosity. A further increase in iron concentration to 1% increases porosity. An addition of 0.5%Mn to the copper-containing alloy results in reduced variability, with porosity levels in the upper range of the 1%Fe alloy. The β-Al_5FeSi phase was still present in the microstructure after the addition of 0.5%Mn, at both copper-levels. The porosity levels of the copper-containing alloys are, in general, higher than the corresponding copper-free alloys.

Porosity is controlled by the permeability of the mushy zone, which is influenced by the distribution of phases [10]. The effect of iron and manganese has traditionally been considered in terms of the role of intermetallics [5, 6]. However, the inconsistent effect of manganese observed here suggests that this focus may be oversimplified. Attention has turned to the role of the Al-Si eutectic in porosity formation [2]. However, rather than acting as a nucleant for the Al-Si eutectic, as suggested by Taylor [2] and Otte [3], β-Al_5FeSi reduces the number of eutectic nucleation events.

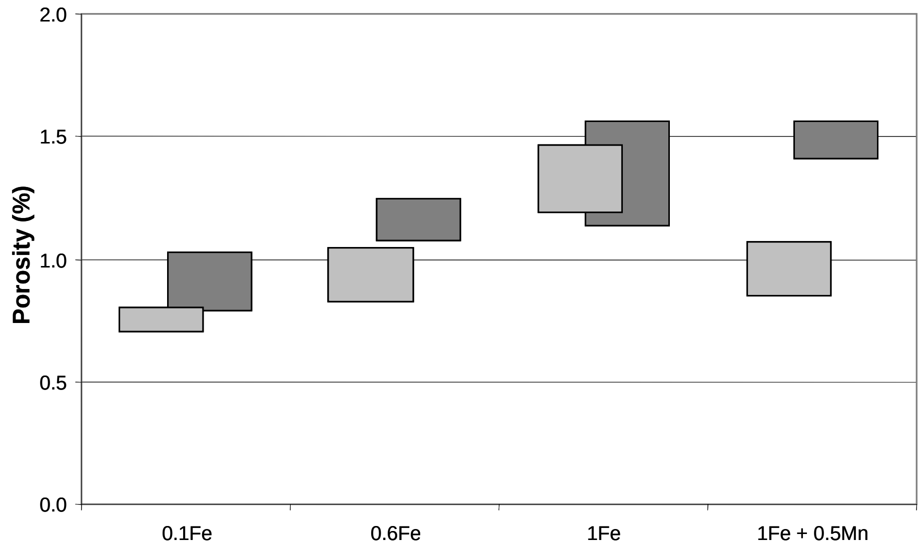

Figure 4: Porosity levels in plate castings made from Al-9%Si-0.5%Mg (light grey) and Al-9Si-0.5Mg-3Cu (dark grey) with varying iron and manganese levels. The bands represent 90% confidence intervals and have been offset horizontally for clarity.

The porosity levels of copper-free alloys appear well correlated with the number of eutectic nucleation events. The eutectic grain size will vary inversely with the number of nucleation events. Therefore, increasing the eutectic grain size decreases permeability. In alloys with 0.1%Fe, the eutectic grain size is small and therefore, feeding channels are not blocked by eutectic grains or intermetallic particles until late in solidification. Porosity slightly increases with 0.6%Fe because the eutectic grain size slightly increases and β-Al_5FeSi platelets form at the same time as the eutectic reaction. Porosity is increased at 1%Fe because of obstructions to feeding by larger eutectic grains and large β-Al_5FeSi platelets. In the manganese-containing alloy, the iron is partially consumed prior to the Al-Si eutectic by the formation of α-$Al_{15}(Fe,Mn)_3Si_2$, instead of β-Al_5FeSi, resulting in a similar number of eutectic grains to that in the 0.6%Fe alloy and, therefore, similar porosity levels.

The porosity levels in the copper-containing alloys are not as well correlated with the number of eutectic nucleation events. Differences in the number of nucleation events due to iron and manganese concentrations are not as large as in the copper-free alloys, hence, the changes in eutectic grain size are much less. Further, the increase in the number of eutectic grains upon addition of manganese is not matched by a decrease in porosity. The trend of increasing porosity with increasing iron from 0.1 to 0.6 to 1% can be explained in a similar manner to the copper-free alloys.

An additional mechanism that may influence porosity levels in the copper-containing alloys involves the formation of Al_2Cu. The presence of Al_2Cu is a major difference between the copper-containing and copper-free alloys. Al_2Cu solidifies at high solid fractions after the Al-Si eutectic and is likely to be unfed. Similar numbers of eutectic nucleation events were measured in the copper-containing and copper-free 0.1%Fe alloy equivalents, therefore, porosity may be higher in the former due to the unfed solidification of Al_2Cu. Al_2Cu is believed to nucleate on β-Al_5FeSi platelets because regions of Al_2Cu become smaller and more numerous as the iron content increases [11]. Hence, Al_2Cu may affect porosity less at high iron contents because of the smaller regions induce lower shrinkage stresses [12]. Manganese may have no beneficial effect in the copper-containing alloys because the eutectic grain size does not change substantially and the refinement of Al_2Cu is reversed.

4. Conclusions

This investigation has shown that iron additions to Al-Si foundry alloys reduce the number of nucleation events of the Al-Si eutectic. Manganese additions were found to increase the number of nucleation events in iron-containing alloys. The strength of these effects was reduced in the copper-containing Al-Si alloys. The number of eutectic nucleation events determines the eutectic grain size. The size and spatial distribution of eutectic grains and intermetallic phases was proposed to determine the permeability of the solidifying structure and, therefore, the level of porosity.

Porosity was found to increase with increasing iron concentration, regardless of the copper concentration. Copper was observed to increase porosity in the alloys with 0.1 and 0.6%Fe but have no effect on the alloy with 1%Fe. Therefore, the effect of iron was less pronounced in the copper-containing alloy. The effect of manganese on porosity was found to be dependent on the copper concentration of the alloy. In the copper-free alloys, manganese additions reduced porosity whereas manganese additions to the copper-containing alloys increased porosity. The difference in the effect of manganese in the copper-containing and copper-free alloys suggests that manganese reduces porosity only if it is accompanied by a significant increase in the number of eutectic nucleation events.

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