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The Effect of Si Content on the Size of β-Al_5FeSi Intermetallics in Al-Si-Cu-Mg Casting Alloys

A. Lucas, C.H. Cáceres, J.A. Taylor

Co-operative Research Centre for Cast Metals Manufacturing (CAST)
Materials Engineering, School of Engineering
The University of Queensland, Brisbane QLD 4072 Australia

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Abstract

Recent experiments have shown that a high Si content increases the ductility of Al-Si-Cu-Mg alloys containing high levels of Fe. In connection with these results, it has been suggested that the β-Al_5FeSi phase is refined in the presence of high silicon hence improving the ductility. However no metallographic evidence was presented to support these claims. Therefore, a metallographic study into the effect of Si content on the morphology and distribution of the β-Al_5FeSi phase has been conducted. It is concluded that Si does indeed exert a refining effect on the β-Al_5FeSi phase. The possible refining mechanisms are discussed.

1. Introduction

In applications where ductility is not of prime importance, such as cylinder heads, Al-Si-Cu-Mg casting alloys are becoming increasingly popular due to their high strength at elevated operating temperatures. The wide latitude in the nominal chemical composition of these predominantly secondary alloys results in a correspondingly wide range of properties in both as-cast [1-3] and heat treated condition [1,4-6], and much more systematic work is still needed to fully characterise the alloy family.

An aspect that has received little attention is that of the effect of the Si content on the mechanical behaviour. In a recent publication [7] it has been shown that high levels of Si increased the ductility of the alloys with high levels of Fe. The effect is illustrated by the flow curves of Figure 1, which correspond to the alloys of Table 1. It is seen that alloy #1, with low Si and Fe content is quite ductile, while alloy #2, with increased Fe content, exhibits very limited ductility. Alloy #14, on the other hand, with increased Si content is almost as ductile as alloy #1 despite its high content of Fe. It is known that the Si content may radically change the primary aluminium grain structure from globular at Si contents below about 6% to orthogonal dendritic at higher Si levels [8]. It has recently been suggested [7] that these Si-induced morphological changes in the solidification structure may exert a refining effect on the Fe-rich phases that form during solidification, leading to the observed increase in tensile ductility. However, no metallographic studies supporting these claims were presented. The object of this paper is to present some initial metallographic evidence and to propose a microstructural mechanism.

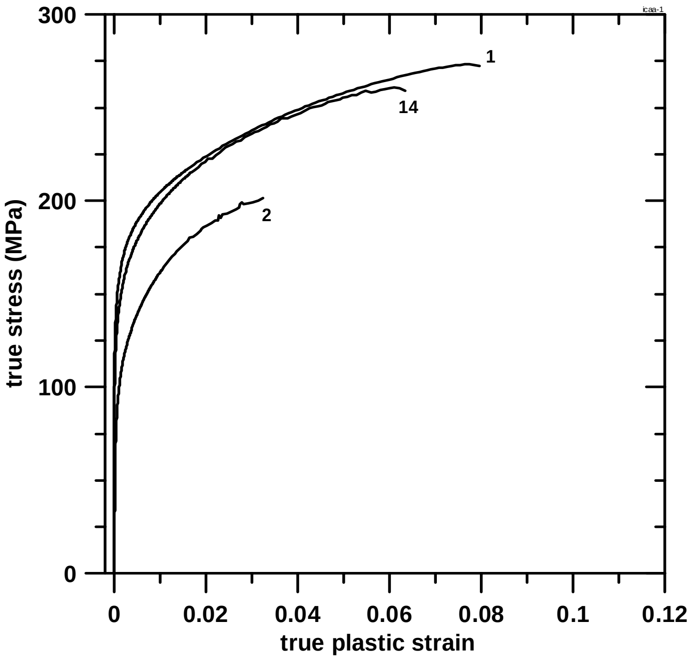

Figure 1: Stress - strain curves of experimental alloys, replotted from reference [7] (see Table 1). Comparison of alloys #1 and #2 shows that increased Fe at (constant) low Si content lowers the ductility, while increasing the Si content at high Fe content (alloy #14) restores the ductility almost to the level of the low Fe alloy #2.

Table 1: Chemical composition (in wt.%) of the experimental alloys of this study.

Alloy #	Si	Cu	Mg	Fe	Mn	Sr	Mn/Fe
1	4.57	1.02	0.10	0.20	0.01	0.020	0.05
2	4.47	0.99	0.09	0.52	0.24	0.007	0.46
14	8.50	0.96	0.09	0.48	0.46	0.018	0.96

2. Materials

The alloys of the present work are part of larger set of experimental alloys whose microstructural and mechanical property details have already been published [7,9,10]. The casting procedure and heat treatment schedule have been described in the original publications [9,10], and only brief details are given here. Binary Al-Si alloy was melted in an electric resistance furnace and metallic Si, Mg and Cu and also Fe-containing and Mn-containing master alloys were added to obtain the desired compositions. The melt was modified with a Sr-containing master alloy and commercial Ti-B grain refiner was also added. The chemical composition of the alloys of interest for this work is shown in Table 1. Iron contents of 0.2 and 0.5 wt.% represent typical primary and secondary-sourced foundry alloys, respectively. The addition of Mn to the alloys with higher Fe content was to effect the transformation of the dominant β-Al_5FeSi platelet phase in Mn-free alloys to the preferred α-$Al_{15}(Fe,Mn)_3Si_2$ script-like phase. Plates were cast for each composition in a sand mould with a heavy chill incorporated at one end. Bars were sectioned from the plates close to the chill end of the plate (corresponding to ~25 µm secondary dendrite arm spacing, SDAS) and metallographically polished to study the solidification structure. Prior to polishing, some of the bars were given a standard T6 treatment [11] comprising of solution heat treatment at 505ºC for 8 h, 60ºC water quench and subsequent ageing for 8 h at 165ºC.

3. Results

The typical microstructures of the three heat-treated alloys studied are shown in Figures 2 to 4. It can be seen that in alloy #1, the β-plates are generally small (length approx. 20-30 μm) and thin. In contrast, in alloy #2, with increased Fe content, the plates are substantially longer (typically 40-80 μm, with some platelets well over 100 μm, not shown) and are generally thicker. The increased Si content of alloy #14, together with its additional Mn, on the other hand, results in a reduction in the size of the Fe-rich β-platelets to approx. 25-50 μm. The β-plates are also fewer and there are some compact α-$Al_{15}(Fe, Mn)_3Si_2$ script-like particles present.

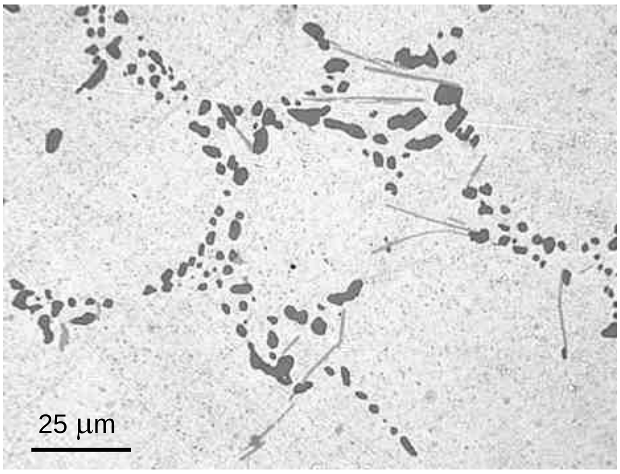

Figure 2: The microstructure of heat-treated alloy #1. The β-platelets are short (~ 20-30 μm) and thin.

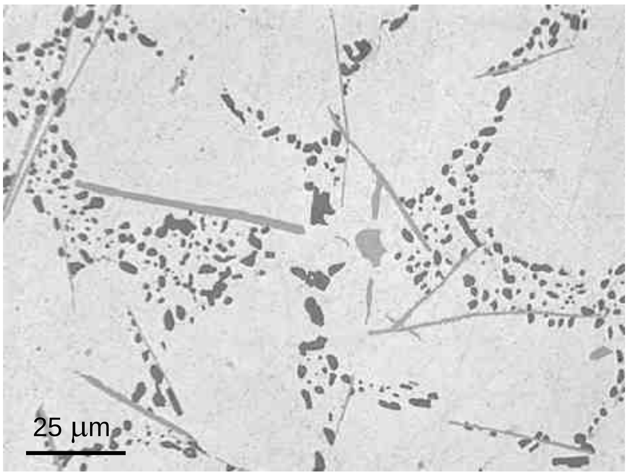

Figure 3: The microstructure of heat-treated alloy #2. The β-platelets are significantly larger (~ 40–80 μm long) and thicker compared to those of alloy #1. A small amount of α-$Al_{15}(Fe,Mn)_3Si_2$ phase is present.

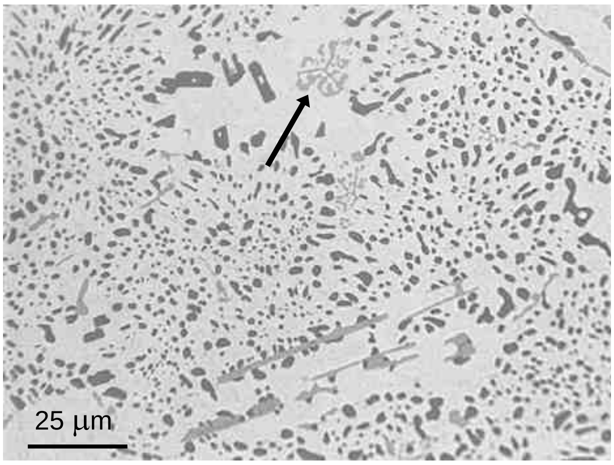

Figure 4: The microstructure of heat-treated alloy #14. The β-platelets are shorter (20~50 μm long) compared to alloy #2 and also less numerous, in part due the presence of α-$Al_{15}(Fe,Mn)_3Si_2$ script-like particles (arrowed). Note there is considerably more eutectic Si in this alloy than in either #1 or #2.

4. Discussion

The solubility of iron is very low in aluminium alloys and this leads to the formation of intermetallic phases during solidification, e.g. β-Al_5FeSi platelets. Since these phases are brittle, they tend to decrease the ductility of the as-cast material [12,13]. The β platelets do not change substantially with solution treatment [14]. The β-phase has also been shown to strongly influence porosity formation [15] in Al-Si-Cu alloys. When Mn is present with iron, there is an increased tendency for the α-$Al_{15}(Fe,Mn)_3Si_2$ phase to form [2,16]. The presence of α-phase particles rather than β-platelets improves mechanical properties, particularly ductility [2,17]. This may in part be due to the reduction in shrinkage porosity that the α phase appears to promote [18]. In general, Mn:Fe ratios of greater than ~0.5 are considered sufficient to promote complete α for β substitution during typical commercial casting conditions, however overall volume fractions of intermetallic phases are usually increased in this event. In the present work however, although the Mn:Fe ratio in alloys #2 and #14 were 0.46 and 0.96 respectively, the β-phase was still observed to form in both alloys at significant levels.

The level of Fe at which β-Al_5FeSi plates or α-$Al_{15}(Fe,Mn)_3Si_2$ particles can form prior to the Al-Si-β ternary eutectic depends on the Si content of the alloy [15,16]. To maintain consistency with prior work [7], these phases are called “pre-eutectic”. The refining effect of increased Si has been rationalised in terms of changes in the relative tendency to form pre-eutectic β-Al_5FeSi plates and/or α-$Al_{15}(Mn,Fe)_3Si_2$ particles in alloys with different Si contents [2,15,16]. The effect of increasing Si (and also Fe) on the solidification process is illustrated in Figures 5 and 6, where the Al-Si-Fe phase diagram is shown for alloys with 0 and 0.3%Mn respectively.[†] The dashed lines (a or a´) indicate the increase in Fe and Si concentration in the liquid as the primary α-Al dendritic structure develops, calculated according to the Scheil equation, for various starting compositions (indicated by the open circles). These paths eventually either intersect the Al-β or Al-Si eutectic trough. The compositions then move either along line (b) towards the ternary eutectic point, e (as in Figure 5) or follow a more complex path (b´ then c´) through the Al-α and Al-α-β phase fields before reaching ternary point e´ (as in Figure 6).

† It should be noted that the formation of intermetallics during solidification is complex and the analysis of the process illustrated in these simplified figures is only one possibility. Modelling of the alloys using solidification software packages, e.g. Thermocalc, can indicate somewhat different outcomes.

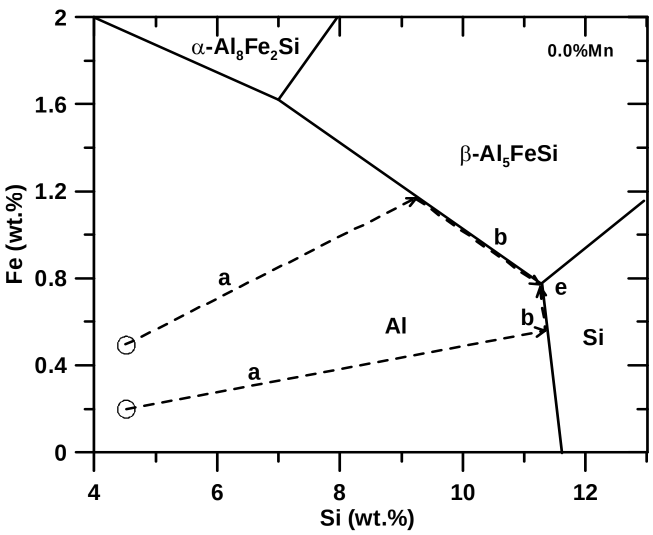

Figure 5: A simplified Al-Si-Fe phase diagram (after Backerud et al.[16]) for alloys without Mn. The sequences of arrowed dashed lines are the suggested solidification paths for the two experimental 4.5%Si alloys with 0.2 and 0.5%Fe initial concentrations, respectively.

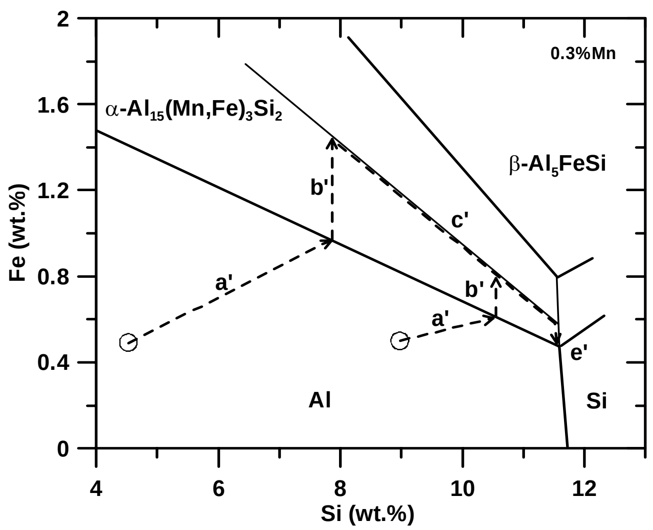

Figure 6: A simplified Al-Si-Fe phase diagram (after Backerud et al.[16]) for alloys with 0.3%Mn. The sequences of arrowed dashed lines are the suggested solidification paths for the two experimental 0.5% Fe-containing alloys with 4.5 and 9%Si initial concentrations, respectively.

Alloy #1, (4.5%Si, 0.2%Fe) solidifies without any pre-eutectic β-phase forming (Figure 5). All of the β-platelets form during the ternary eutectic reaction, and are therefore small (Figure 2), being constrained in growth within the small final liquid pools.

Alloy #2 (4.5% Si, 0.5%Fe, 0.24%Mn) solidifies according to Figure 6, rather than Figure 5, and therefore both pre-eutectic α and β intermetallic phases form prior to the ternary eutectic. This alloy has a long solidification time (see b´-c´ path for left-hand alloy in Figure 6) after the primary Al solidification is complete. This means that the Fe-rich phases, particularly β with its platelet morphology tend to grow with much less restraint than in alloy #1. The platelets are therefore larger (Figure 3) than in alloy #1 and are more detrimental to ductility (Figure 1).

Alloy #14 (9%Si, 0.5%Fe, 0.46%Mn) solidifies approximately according to right-hand path shown in Figure 6. After a much shorter primary Al solidification period than alloy #2, the b´-c´ path is also much shorter. It is possible that because of the high Si content, the primary Al grains tend to be larger and more orthogonally dendritic [8] than in either alloys #1 or #2, thus providing a multiplicity of fine dendritic channels for intermetallic phase precipitation. This, combined with the shorter growth period for the Fe-rich α and β phases (i.e. a shorter b´-c´ path) accounts for the reduction in the size range of the β-Al_5FeSi platelets (Figure 4).

5. Summary and Conclusions

Metallography shows that increased Si content in Al-Si-Cu-Mg alloy has a size refining effect on the β-Al_5FeSi platelets. This effect can be ascribed to the reduced tendency in the high Si alloys to form large pre-eutectic β-Al_5FeSi and α-$Al_{15}(Mn,Fe)_3Si_2$ particles during solidification due to a reduction in available growth time.

The refining effect of high Si contents on the β-Al_5FeSi platelets is thought to be responsible for the increased ductility of Al-Si-Cu-Mg alloy compared to the low Si alloy variants when the Fe content is high, as reported in earlier work.

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