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Microstructure and mechanical properties of modified and non-modified stir-cast Al–Si hypoeutectic alloys

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The microstructure and mechanical properties of modified and non-modified stir-cast commercial aluminium alloys A-S7G03 and A-S4G have been investigated. Stir casting of these alloys resulted in spherical and/or rosette shape primary α-phase, and the eutectic silicon was broken into miniature needle morphology. This stir-cast structure slightly improved the mechanical properties in comparison to those of conventionally cast alloys, however the fracture of the stir-cast alloys revealed intergranular brittle fracture. The addition of 0.02% strontium, in the form of Al-5 mass% Sr master alloy, during stir casting modified the eutectic silicon into a very fine spheroidal morphology, while the α-phase particle showed the same morphology as the stir-cast alloys. This novel structure resulted in significant improvement of mechanical properties. The elongation of the modified stir-cast alloys was five times greater than that of the non-modified one. A transgranular mode of fracture was observed for the modified stir-cast alloys, moreover smooth ripple and dimple patterns were observed reflecting the high ductility of the modified stir-cast alloys.

1. Introduction

During the last two decades Flemings and his colleagues have described, in a series of publications, the process of stir casting [1–8]. They showed that the effect of stirring in the liquid–solid region was to transform the normal dendritic structure to one consisting of spherical or rosette shaped particles of primary phase owing to the fragmentation of the dendrites. Other researchers have been attracted to the subject since this new novel structure was found to improve the mechanical properties [9–13]. Most of the experiments on stir casting have been carried out on aluminium alloys since their phase diagrams reveal a large range of temperatures in the liquid–solid region. The Al–Cu alloys have received a considerable attention concerning the subject of stir casting [9, 11–15]. However, there is very little in the literature concerning the stir casting of Al–Si alloys [16–18]. Additionally, most of the previous work was focused on the morphology and mechanisms of formation of the stir-cast structure. Therefore, it is one of the aims of the present investigation to study the microstructure and mechanical properties of stir-cast Al–Si alloys in the hypoeutectic region.

Since Pacz [19] discovered in 1920 that small additions of sodium (~0.01 mass%) can modify the Al–Si alloys, with a spectacular refinement in the scale and distribution of the phases which is accompanied by a great improvement in the mechanical properties, many investigators [20–29] have developed the modification technique and furthermore introduced new modifiers. Through these earlier researches it was completely clarified that not only the morphology and size of the primary α-phase but also the fineness and morphology of the eutectic silicon affect the mechanical properties of Al–Si alloys. The stir-cast process is known to control the morphology and size of the primary α-phase, and the modification process is known to alter the morphology and fineness of the eutectic silicon. Therefore, it is the main goal of the present investigation to study the microstructure and mechanical properties of some modified and non-modified stir-cast Al–Si hypoeutectic alloys using Al-5 mass% strontium master alloy as a modifier.

2. Experimental procedure

Two commercial hypoeutectic aluminium alloys have been used in the present study, being A-S7G03 and A-S4G. The composition of A-S7G03 alloy is Fe 0.12%, Si 7.1%, Cu 0.07%, Mg 0.29%, Mn 0.08%, Ni <0.05%, Zn 0.08%, Ti 0.13%, Pb <0.05%, P 11 ppm, and that of A-S4G alloy is Fe 0.4%, Si 4.2%, Cu 0.08%, Mg 0.1%, Mn 0.4%, Ni <0.05%, Zn 0.9%, Ti 0.15%, Co 0.13%, Pb 0.06%, Sn <0.05%.

All experiments on stir casting were performed using a graphite crucible surrounded by an induction heater, and a stirrer rotating at a constant speed of 500 r.p.m. The temperature was monitored through an alumel–chromel thermocouple connected to a digital

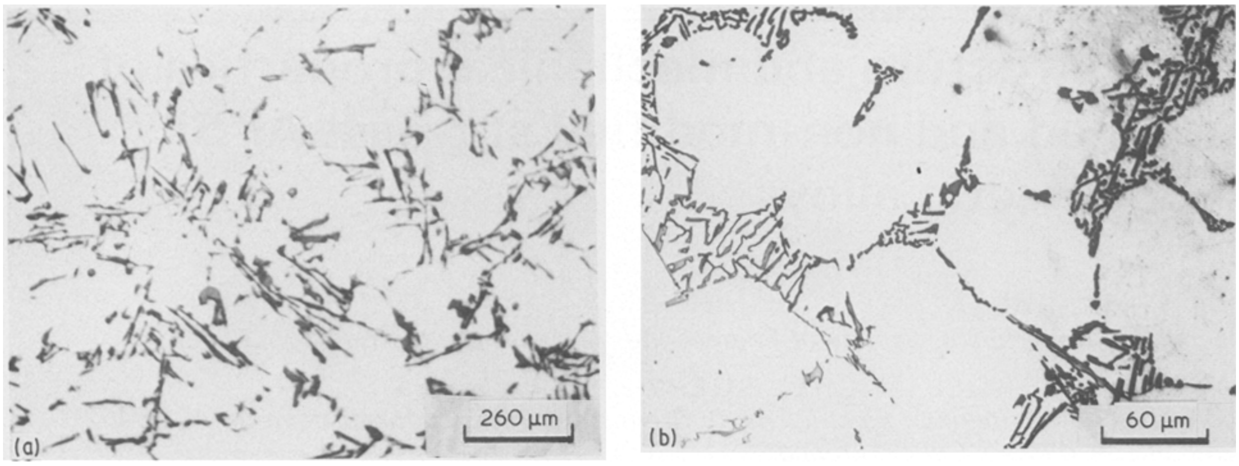


Figure 1 Alloy A-S7G03 (a) conventionally cast, and (b) stir cast.

counter and attached to a x–t recorder. The temperature of each ingot was first raised to 973 K (i.e. above the melting temperature) and then started cooling. Stirring was performed isothermally at 873 K for A-S7G03 alloy. For the A-S4G alloy it was stirred at 893 K. Time of stirring ranged from 120 to 180 sec for both alloys. The stirrer was then taken out of the crucible and the electric current was cut. The ingots were then left to cool in air. For experiments on modified stir-cast alloys, a calculated quantity of Al-5 mass% Sr master alloy was added to each ingot in the liquid state at about 973 K, just prior to cooling. The total time taken from the moment of addition of the modifier to the solidification at the eutectic temperature did not exceed 300 to 360 sec.

Tensile tests were conducted on cylindrical specimens with threaded shoulders having gauge dimensions of 4 mm diameter and 7 mm length. These tests were carried out on a Zwick machine at a constant cross-head speed of 7×10^{-3} mm sec^{-1}, i.e. a strain rate of 10^{-3} sec^{-1}, at room temperature. Specimens for optical metallography were sectioned by a cut-off wheel, ground on emery papers up to 1000 grit and were finally polished using 3 μm diamond paste [30–33]. The microstructure was revealed using a dilute solution of sodium hydroxide as a chemical etchant. Fracture surfaces were observed using a JEOL scanning electron microscope.

3. Results and discussion

Fig. 1a shows the microstructure of the conventionally cast A-S7G03 alloy. It reveals primary α-dendrites (bright phase) embedded in a eutectic matrix. As can be seen, the eutectic silicon (dark phase) is needle-like and has relatively large size. This structure is known to result in poor mechanical properties regardless of the grain size [33, 34]. The effect of stirring on the same alloy can be seen in Fig. 1b. Not only the α-particles took the rosette or spherical shape but also the eutectic silicon is broken into much smaller sizes (cf. Figs 1a and b), although it kept its needle-like shape. However, the eutectic silicon in the former (Fig. 1a) possess much more angular morphology. The microstructure of the A-S4G alloy showed strong resemblance to those of Figs 1a and b. It only differs in the volume fraction of the constituent phases. Recent research on the effect of stir casting on hypoeutectic Al–Si alloys showed a similar α-particle morphology [17], and moreover, revealed a fine acicular eutectic silicon due to stirring.

Figs 2a and b illustrate the microstructure of sample specimens stir cast A-S7G03 alloy modified with 0.02% and 0.04% strontium respectively. The photographs show the following details:

(1) rosette and spherical α-particles (cf. Fig. 2a and b),

(2) very fine eutectic-silicon of spherical morphology (cf. area marked "A" in Fig. 2a),

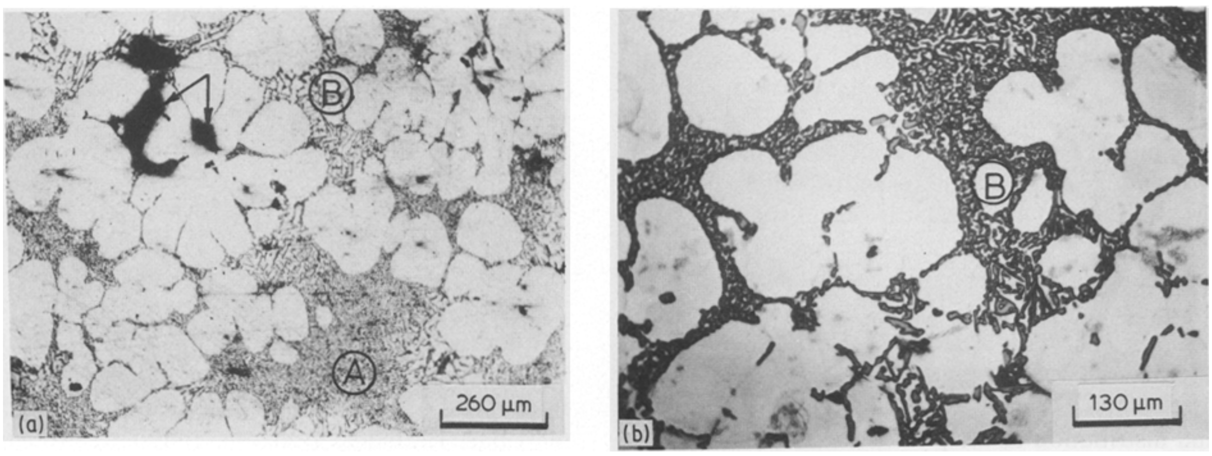


Figure 2 Microstructure of stir-cast A-S7G03 alloy (a) 0.02% strontium, (b) 0.04% strontium.

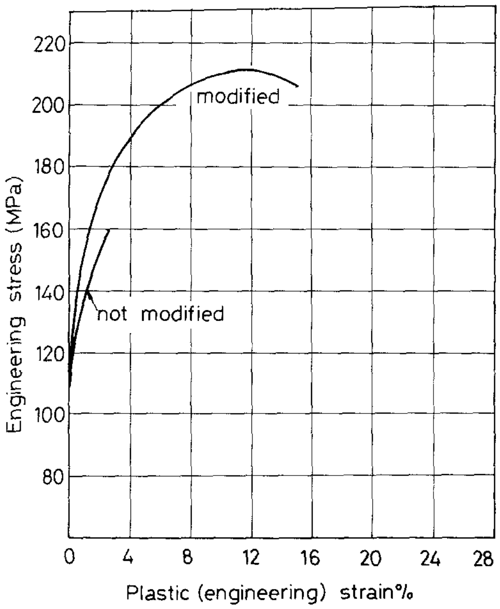


Figure 3 Engineering stress–strain diagram for stir-cast, modified and non-modified A-S7G03 alloy.

(3) black holes, formed by trapping air in the liquid during stirring (indicated by arrow in Fig. 2a),

(4) small α-dendrites among large α-rosettes (cf. area marked "B" in Fig. 2b).

The addition of 0.04% Sr to the stir cast alloy A-S7G03 resulted in the microstructure shown in Fig. 2b. It is clear that overmodification has occurred and that the silicon particles grew. This eutectic silicon morphology is known to deteriorate the mechanical properties obtained by optimum modification [20–28]. Again, similar results were obtained for the A-S4G alloy regardless of the volume fraction of the constituent phases.

Fig. 3 shows engineering stress–strain curves for the non-modified and modified stir cast A-S7G03 alloy. The yield strength has almost the same value of 110 MPa for both cases. The ultimate tensile strength (UTS) has significantly increased from 160 MPa for the former to 210 MPa for the latter. Moreover,

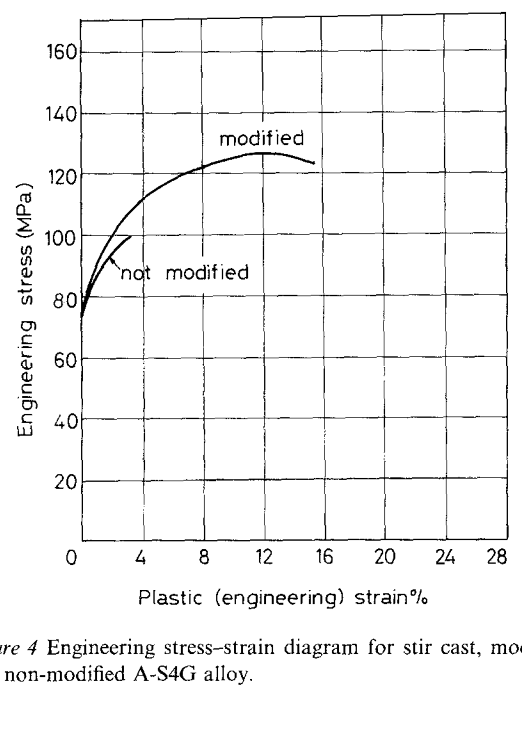


Figure 4 Engineering stress–strain diagram for stir cast, modified and non-modified A-S4G alloy.

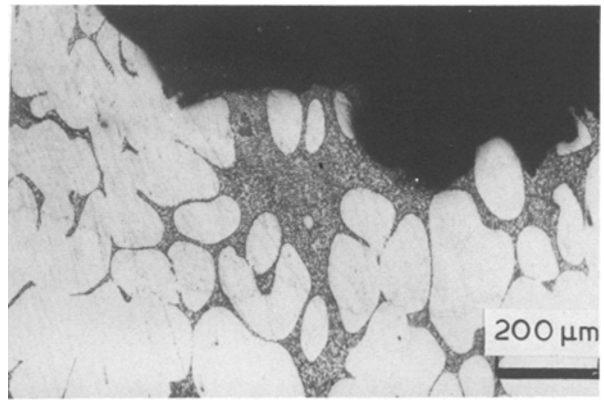


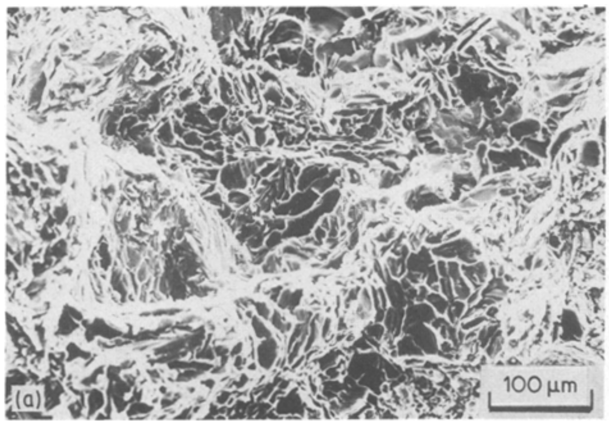
Figure 5 Optical fractography on longitudinal sections of stir-cast A-S7G03 modified alloy.

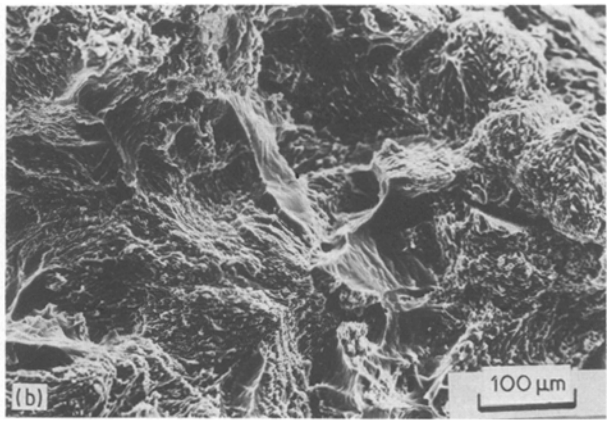
elongation and therefore toughness was remarkably increased from 2.75% for the non-modified alloy to 15% for the modified one. It is worth mentioning that the stress–strain diagram for the modified alloy exhibited necking. The available information in the literature about the mechanical properties of stir-cast Al–Si alloys are those published recently [16]. Their experimental procedure was not the same as that of the present study. However, for the sake of comparison they will be given here. For Al-8% Si alloy the UTS was 150–170 MPa and the elongation was 5%. These values are in agreement with those obtained in the present investigation, taking into consideration the different silicon contents and the experimental procedures. The slight improvement of elongation due to stirring in the present study (2.75%), rather than (1.8%) [28] obtained for the same A-S7G03 alloy as conventionally cast under the same conditions, is believed to stem mainly from the breaking of the eutectic silicon into small particles (cf. Fig. 1b). On the other hand, the dramatic improvement in the mechanical properties of the modified stir-cast A-S7G03 alloy refers mainly to the modification of the eutectic silicon.

As can be seen from Fig. 4, for the stir-cast A-S4G alloy, the UTS has increased from 100 MPa for the non-modified alloy to 126 MPa for the modified one. Additionally, the elongation has improved from ~3% for the former to a value of 15.5% for the latter. Again, necking was observed in these specimens prior to fracture as was observed in the modified stir-cast A-S7G03 alloy.

Fig. 5 shows the optical fractography on longitudinal section of the modified stir-cast A-S7G03 alloy. The fractograph illustrates some indications of transgranular fracture across the α-phase particles. The very fine (spherical) eutectic silicon shown in Fig. 5 possesses high ductility [33] and therefore resulted in such transgranular fracture.

Fig. 6a shows a view of the fracture surface of stir-cast A-S7G03 alloy as observed by SEM. It contains cellular structure. There is little evidence of surface flow indicating a brittle fracture. These patterns of fracture agree with those reported recently [28] except that the present pattern showed very little cavities (shrinkage porosity) and therefore exhibited very





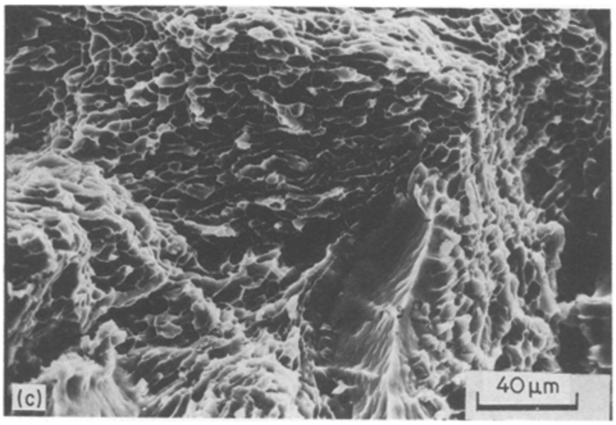


Figure 6 (a) Fracture surface of stir-cast A-S7G03 alloy as revealed by SEM, (b) Features observed on the fracture surface of stir-cast modified A-S7G03 alloy, (c) Ductile rupture observed on the fracture surface of stir-cast modified A-S7G03 alloy as revealed by SEM at high magnification.

little dendrite lobes (free surfaces). Fig. 6b shows the general features observed on the fracture surface of the modified stir-cast A-S7G03 alloy. Some evidence of surface flow can be seen in Fig. 6b specially in the bright areas (these areas are believed to be α-phase regions), which exhibits a smooth ripple pattern (this pattern appears as a result of the interaction of slip with the fracture surface [32]). Fig. 6c shows the fracture surface of the same alloy at high magnification. It shows a dimple-like pattern on the eutectic regions and smooth ripple pattern on the α-phase region. Thus, from Fig. 6b and c this fracture of modified stir-cast A-S7G03 alloy may be rated as ductile.

Fig. 7 shows that an intergranular mode of fracture has occurred passing along a eutectic ribbon around α-particles of the A-S4G alloy as revealed by optical microscopy. The fracture surface propagates along eutectic regions circumventing the α-particles. This optical fractography on longitudinal sections explains the relatively low ductility of the stir-cast alloy (3%).

Fig. 8a shows the fracture surface of the stir-cast A-S4G alloy. It indicates lack of plastic deformation. No shrinkage porosity could be observed in these specimens. Although a small area indicated a dimple-like pattern (marked by arrow) the fracture was in general brittle in nature. Fig. 8b exhibits the general features of the modified stir-cast A-S4G alloy. It shows dimple-like pattern on the eutectic regions and smooth ripple pattern on the α-phase region. Fig. 8b, in general, indicates a ductile rupture consistent with the results obtained in the present study on the mechanical properties (cf. Fig. 4).

4. Conclusions

For the commercial aluminium alloys A-S7G03 and A-S4G, the following conclusions can be drawn:

(1) The microstructure of stir-cast alloys revealed spherical and/or rosette shape of α-particles and broken (small) needle-like eutectic silicon.

(2) The modification of the alloys by Al-5 Sr master alloy resulted in fine and spheroidal eutectic silicon.

(3) Optimum modification of stir-cast alloys occurred at a modifier per cent of 0.02. Using higher percentages of strontium resulted in over-modification and deterioration of mechanical properties.

(4) The modified stir-cast alloys showed superior mechanical properties in comparison to those of conventionally cast alloys. In particular elongation increased from about 3 to 15%.

(5) The stir-cast modified alloys showed indications of transgranular mode of fracture.

(6) The fracture surfaces as revealed by SEM showed dimple and smooth ripple patterns, for the modified stir-cast alloys, reflecting the high ductility.

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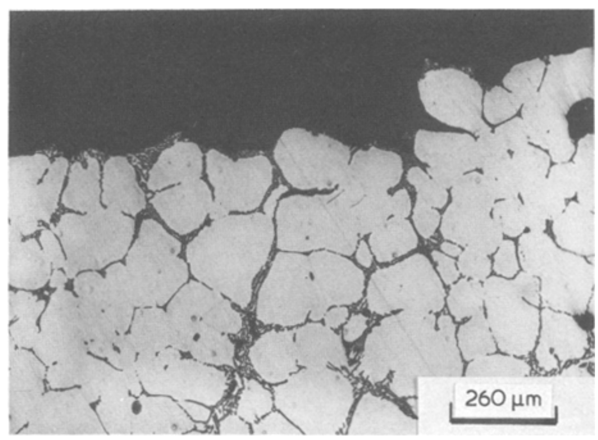

Figure 7 Optical fractography of longitudinal sections for stir-cast A-S4G alloy.

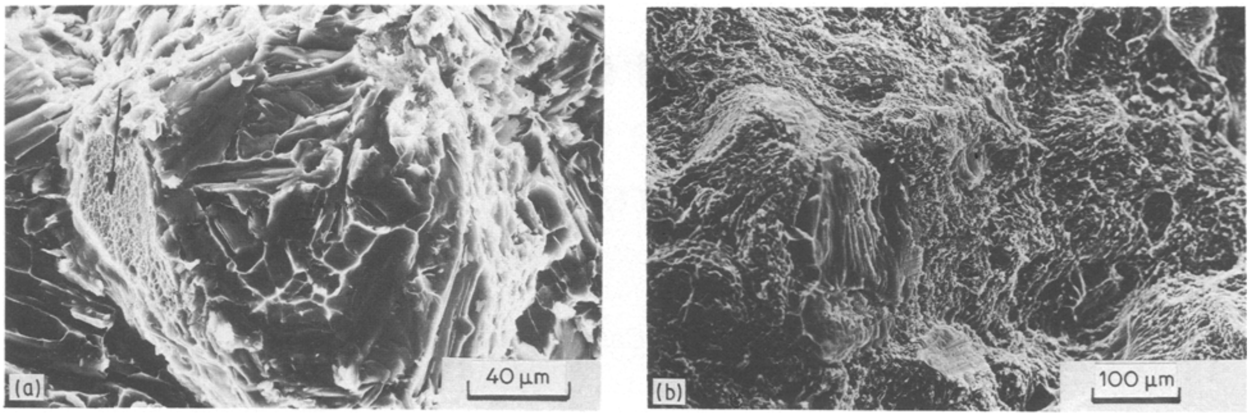

Figure 8 (a) The fracture surface of stir-cast A-S4G alloy. (b) Stir-cast modified A-S4G alloy as revealed by SEM.

the supply of the raw materials and for laboratory facilities.

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