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The effects of magnesium additions on the structure and properties of Al–7 Si–10 SiC_p composites

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The additions of magnesium to an aluminium alloy matrix, which contains insufficient magnesium, was found to be essential during the synthesis of composites by the stir-casting technique. Magnesium promotes interfacial wetting between the dispersoid surface and the matrix. Dispersion of SiC_p in Al–7 Si–0.3 Mg (356) alloy matrix without agglomeration and rejection was not possible. Hence, the addition of up to 3 wt% Mg was made to the alloy matrix during the dispersion of 10 wt% SiC_p (34 μm), and the microstructure and mechanical properties of the composites were investigated with a view to optimize the magnesium content. With a magnesium content less than 1 wt% in the matrix, the SiC_p particles were essentially in agglomerated form. The highest UTS of 280–300 MPa was obtained with 1 wt% Mg content and SiC_p was uniformly distributed in the matrix. A higher magnesium content ($>$ 1.0 wt%) did not further improve the uniformity in the dispersion of SiC_p but the ultimate tensile strength properties deteriorated. This decrease in strength was attributed to the observed coarseness of the Mg_2Si phase, the precipitation of Mg_5Al_8 phase and the presence of a higher amount of porosity in the composites in the heat-treated condition. The aspect ratio (length/width) of precipitates changed from 1–3 for 1% Mg to 3–9 for 3.2% Mg in the matrix. Corresponding values for per cent porosity were 2% and 6%, respectively.

1. Introduction

Amongst the variety of manufacturing processes available for discontinuous metal-matrix composites such as Al–SiC_p (MMC) production from both the liquid state and the solid state, stir-casting or the vortex method (falling under the former) is well accepted as a promising route and is now being practiced even on a commercial scale [1–3]. This is because of its simplicity, flexibility and capability to fabricate large quantities of MMC in a batch either in the form of ingots for further processing or casting as near net-shape components. The success of this technique depends on how one improves the wetting between the discontinuous reinforcements and the matrix melt so that easy incorporation and uniform dispersion in the melt are obtained. Addition of some alloying elements, in general, and magnesium in particular, is one of the various techniques known to improve wetting [4, 5]. Such addition has also an important role in dictating the nature of the interfacial bond between the dispersoid and the matrix which, in turn, determines the mechanical properties of MMC for a given combination of matrix and dispersoid. Magnesium (being a reactive element and surfactant), on addition to aluminium, improves wetting by reducing the surface tension of the liquid melt and by promoting chemical reactions at the solid–liquid interface. Further, magnesium has a tendency to segregate to the dispersoid/matrix interface thus reducing the magnesium content in the matrix and forming chemical reaction products [2, 4–8]. The effects of magnesium in incorporating dispersoids in the aluminium melt and improving their distribution is also found to be stronger than other elements used, such as cerium [9, 10], bismuth [5], lead [5], lanthanum [10], mischmetal [10], zirconium [10], titanium [10], zinc [5], copper [5], etc. In the synthesis of Al–7 Si–0.3 Mg (356 alloy) –SiC_p composites by stir casting, 3 wt % Mg was used earlier in our laboratory [3] and similar additions have been used in synthesizing other composite systems [2]. The microstructural studies of these composites after heat treatment revealed the presence of low-melting constituents within the matrix, necessitating the need for optimizing the quantity of extra magnesium to be added during the synthesis of 356–SiC_p composites. This presentation is the outcome of the experiments carried out towards this aim in Al–7 Si–0.3 Mg–10 wt % SiC_p composite.

2. Experimental procedure

Al–7 Si–0.3 Mg (356) – 10 wt % silicon carbide particulate (SiC_p) composite (average particle size 34 μm) was prepared using the stir-casting technique, the details of which are described elsewhere [3]. The dispersoids were preheated prior to introduction into the

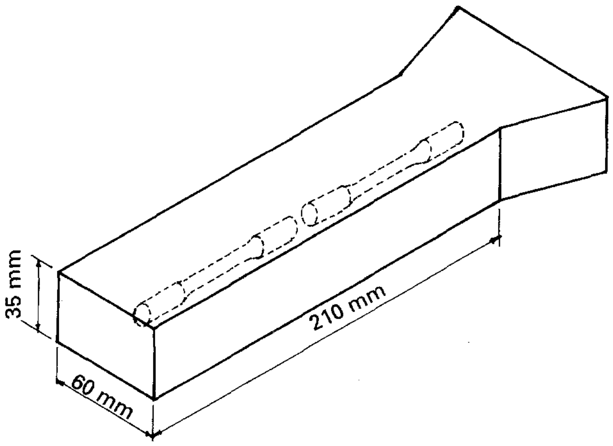

Figure 1 Isometric view of the casting and the locations of samples drawn.

TABLE I Composition (wt %) of 356–SiC_p composites

Constituent	Composite I	Composite II	Composite III
Mg	0.40	1.00	3.20
Si	6.50	7.00	7.00
Fe	0.20	0.25	0.20
SiC_p	9.20	9.40	9.40
Al	Balance	Balance	Balance

TABLE II Mechanical properties of 356–10 wt % SiC_p with varying residual magnesium contents

Additional Mg/ residual Mg (wt %/wt %)	Ultimate tensile strength (MPa)		Elongation (%)
	Range	Average	
0.0/0.4	280–300	295	0–2
1.0/1.0	280–300	297	0–2
3.0/3.2	210–260	255	0–2

melt. Composites with different additional magnesium contents, i.e. 0, 1 and 3 wt %, were prepared and cast into rectangular blocks measuring 35 mm × 60 mm × 210 mm in a permanent mould at 993 K. Fig. 1 shows the isometric view of the casting as well as the location of 12 numbers of tensile samples (ASTM) to be machined out. The composite castings were analysed for their constituents, namely magnesium, silicon, iron and aluminium by instrumental analysis (Analoy) and SiC_p by a dissolution method (digesting a composite of 15 mm size cube in 1:1 HCl for 24 h followed by decantation, washing, drying and weighing). Tensile samples were subjected to heat treatment prior to testing as per the following schedule: solution heat treatment at 808 K for 12 h, hot-water quenching, natural ageing for 12 h and artificial ageing at 438 K for 8 h. The microstructures of the composites in the heat-treated conditions were also analysed. The density of the samples was measured by Archimedes' principle and per cent porosity was computed taking the theoretical density of the composite obtained by the rule of mixtures.

3. Results

Table I lists the compositions of three 356–10 wt % SiC_p composites prepared using different additional magnesium contents. It is clear from this table that the residual magnesium contents in the composites are 0.4, 1.0 and 3.2 wt % compared with the 0, 1.0 and 3.0 wt % additional magnesium added. The mechanical properties of these composites in the fully heat-treated condition are given in Table II. With increasing residual-magnesium content in the composite, the per cent elongation of the materials remains in the same range of 0%–2%, whereas the ultimate tensile strength (UTS) does vary, i.e. the average UTS remains constant around 295 MPa and then decreases to 255 MPa for residual magnesium contents up to 1 and 3.2 wt %, respectively. The per cent porosity of 356–10 wt % SiC_p composite was also found to increase from 2% to 6% with the presence of 1 and 3.2 wt % Mg in the composite, respectively.

Photomicrographs of heat-treated Al–7 Si–Mg–10 wt % SiC_p composite with different residual magnesium contents are shown in Fig. 2. A study of these photomicrographs reveals the following points:

1. an agglomerating tendency of SiC_p, leading to non-uniform distribution without additional magnesium;
2. breaking down of dispersoid agglomerates resulting in uniform distribution of SiC_p with additional magnesium of either 1 or 3 wt %;
3. increasing trend in the size and amount of precipitates in the matrix with increasing residual/additional magnesium content. The aspect ratio (length/width) of precipitates increases from 1–3 for 1 wt % Mg to 3–9 for 3.2 wt % Mg in the matrix.

From the above observations it can be concluded that the best dispersoid distribution and UTS values of 356 – 10 wt % SiC_p composite processed under the present experimental conditions are obtained with the addition of 1 wt % extra magnesium to the matrix. The decrease in the strength of composite prepared with 3 wt % additional magnesium is due to the presence of more coarse precipitates as well as increased porosity level.

4. Discussion

The wettability of silicon carbide by molten aluminium is greatly influenced by the reactions between the surface silica on the silicon carbide particles and the melt, and magnesium aids these reactions [4, 11–15]. The major feature of this reaction-aided wetting is decoration of the dispersoid–matrix interface with spinel $MgAl_2O_4$. Details on these aspects in the presence of low or high amounts of magnesium are addressed elsewhere [4].

Similar to the observations in this investigation, i.e. addition of 1 wt % extra magnesium to 356–10 wt % SiC_p composite, the presence of additional magnesium of at least equal to or greater than 0.7 wt % is found to be essential for incorporating Al_2O_{3p} into Al–7 Si

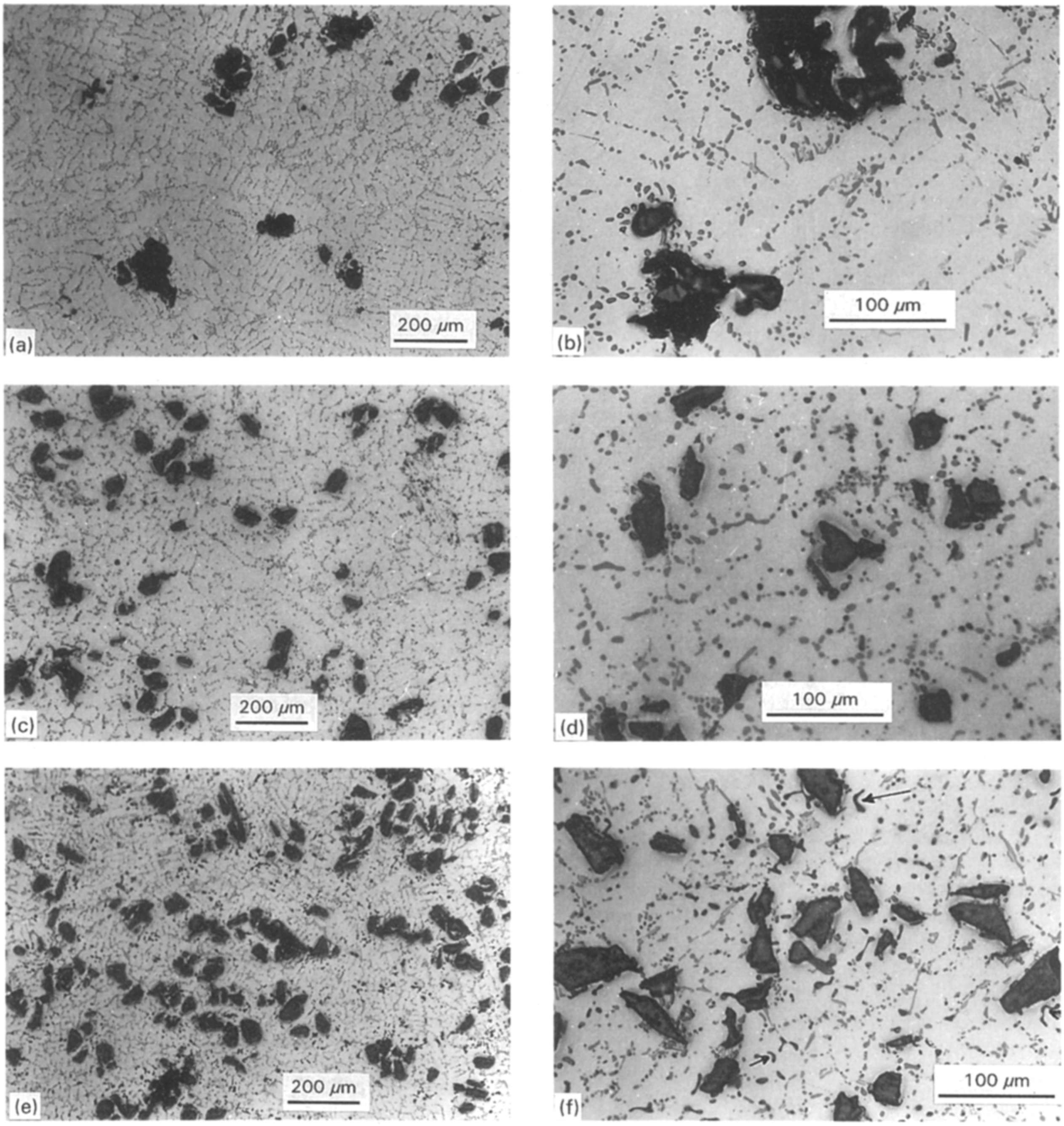

Figure 2 Photomicrographs of 356–SiC_p composites with (a, b) 0.4 wt % Mg, (c, d) 1.0 wt % Mg, and (e, f) 3.2 wt % Mg.

alloy above the liquidus temperature [14]. Further, the dispersion of Al_2O_{3p} in aluminium by stir casting is also observed to be strongly influenced by the magnesium content in the matrix aluminium alloy [15].

The presence of excess reactive elements such as magnesium in aluminium melt will alter the microstructure of the matrix alloy by forming low-melting constituents and will deteriorate the mechanical properties [16]. In the present case, the addition of 3 wt % Mg to 356 alloy leads to the formation of Mg_5Al_8 phase [16] having a low melting point of 723 K, in addition to the formation of a strengthening phase, Mg_2Si. When the composite containing the low-melting phase is solution treated at 808 K, it melts and becomes coarsened in the matrix, as seen in Fig. 2e and f. On the other hand, in the case of composite prepared with 1 wt % additional magnesium the available magnesium is sufficient to improve the wetting between SiC_p and the aluminium melt by reaction, and to form the required Mg_2Si phase on heat treatment for strengthening the alloy. In addition, the coarseness of these precipitates has been observed to increase with increasing magnesium content greater than 1 wt %. In the case of composites with 1 wt % Mg, although precipitate aspect ratios fall between 1 and 3, only a few with an aspect ratio of 3 are observed. On the other hand, more than 50% of the precipitates in the composite with 3 wt % Mg are found to have aspect ratios of more than 4. Similarly, the per cent porosity in the composite melt is also found to triple when the magnesium content is varied from 1–3.2 wt %. If the processing conditions remain the same, the enhancement in porosity with higher magnesium content may be attributed to the presence of extra magnesium available which is known to increase the solubility of hydrogen in the melt [17] as well as decreasing the fluidity of the melt [16].

The lower strength properties obtained with 3.2 wt % Mg may be attributed to the formation of coarser precipitates as well as low-melting phases and increased porosity level.

The average UTS obtained in 356–10 wt % SiC_p with 1 wt % additional magnesium, i.e. 297 MPa, is also near to the value reported for Duralcan composite F 3 A 10 S - T61 [1] i.e. 303 (Typical). Corresponding values for minimum UTS are 280 and 283, respectively. It may be noted that Duralcan composites are prepared without any additional magnesium and by proprietary treatment to SiC_p, whereas the composite reported in this paper is prepared with additional magnesium and heat-treated dispersoids without any protective atmosphere.

From the foregoing discussion, it can be summarized that an optimum amount of magnesium required for obtaining the best distribution and properties is to be arrived at while synthesizing Al-SiC_p composites by the stir-casting route.

5. Conclusions

1. Additional magnesium is necessary during synthesis of 356–SiC_p composite by the stir casting route.
2. The optimum additional magnesium essential for obtaining the best distribution and maximum mechanical properties in 356–10 wt % SiC_p composite is found to be around 1 wt %.
3. Additions of magnesium lower than the optimum value results in the formation of agglomerates of dispersoids and their non-uniform dispersion in the melt.
4. Additions of magnesium higher than the optimum value lead to the formation of coarse precipitates and low-melting constituents within the matrix, as well as enhancement of the porosity level and hence deterioration of mechanical properties of the composites.

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