Strengthening of the ASTM-356 Alloy with Silicon Carbide Particles

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Abstract

Extensive research has been done in recent years in composites of metallic matrix in order to get better melting practices, mechanical properties and structure. In this work, steel metal mould was previously preheated to three different temperatures. The ASTM-356 alloy was melted and heated to 993 K. For the purpose of reinforcing, silicon carbide particles (mesh: 325, 400) were introduced into the melted alloy then stirred. For each obtained solid its solidification time was recorded. Cylindrical specimens were tested in a tension test machine in order to obtain the ultimate tensile strength (UTS) and fracture toughness (K_{Ic}) values. Hardness measurements were carried out in the sections of the specimens. Metallurgical structure was observed with the aid of the optical microscope. Finally, it was found that the presence of SiC in the melted alloy alters the shape of the cooling curve. In general, the composite of ASTM-356 with SiC inclusions shows an improvement of the mechanical properties as hardness and tensile strength when the cooling rates are high.

Keywords: Reinforced alloy; Oxidized SiC particles; Ultimate tensile stress; Fracture toughness; Metallurgical structure.

Introduction

The growing demand of technological materials has required of the investigation and development of new composite materials, with object of satisfying the requirements for the different applications.[1-6] The aluminium-based composite materials play an important role, given its low cost of manufacture and light weight. The ASTM-356 alloy has been selected to improve its hardness, tensile strength (UTS) and the plane-strain fracture toughness (K_{Ic}), by means of the insertion of oxidized silicon carbide (SiC) particles into the metallic base. The finality of this is to introduce inclusions, finely dispersed, to increase its mechanical resistance.

They have been observed around of 250 different forms of the SiC, a part is conformed by amorphous solids and the rest is found structured in crystalline way (poly-types).[7] In this work, 6H (α-SiC) poly type was aggregated to the alloy in liquid state in order to observe the mechanical behaviour after solidification. The aim of this research is to present the results attained as for as the mentioned properties as well as to give the explanations that allow to understand the phenomenon in study.

Materials and Experimental Procedures

Materials

Particles of silicon carbide (SiC; 37 and 44 µm in sizes) were employed to reinforce the metallic base. Such particles were previously subjected to the oxidation process in order to avoid its decomposition at the contact with molten aluminium. The oxidation process was performed by placing the SiC particles on a SiO_2 substratum, followed of a heating to 1273 K during 2 h.

To fill the mould completely, it was necessary to improve the fluidity of the melted alloy; for this purpose, it was necessary to increase the content of magnesium in the melted mass in a proportion of 2% weight. Immediately, oxidized SiC particles were added (12% weight) and, to obtain homogeneity, the mix was stirred then cast.

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A mould with shape of tension test specimen was used to obtain the solid. Before cast, the mould was preheated to 333, 473 and 623 K

After cast, a standard 12.5 mm round tension test specimen (ASTM E 8/E 8M-08 Standard) of ASTM-356 alloy containing oxidized SiC particles was machined.

Equipment for characterization

A Kintel temperature-controlled furnace was used to carry out the melt; the electronic circuit of the furnace is able to control variations in the temperature of ± 5 K.

An electric stove that is able to reach a maximum temperature of 650 K was used to preheat the mould.

A Wilson Tukon-1102 hardness tester was utilized employing a 100 g load.

The tests of tension and fracture toughness were performed with the aid of an Instron 600DX. A strain rate of 0.254 mm/min was established.

Results

Hardness

The indentations were carried out in different areas, to know, around and close to the SiC particles and in areas free of particles. The obtained hardness measures were averaged and graphically logged (Figure 1). As can be seen in the graph, the best value that is attained with this process is by means of the insertion of particles of 44 μm with a mould temperature of 333 K. The average value reached to the end of the process was 110 HV0.1; however, when the melt was cast in the mould preheated to 473 K a reduction in the hardness of around 26% was obtained. From the same Figure 1, the metallic base as well as the reinforced alloy with particles of 37 um, they showed reductions in hardness in the same proportion when the moulding temperatures were 473 and 623 K.
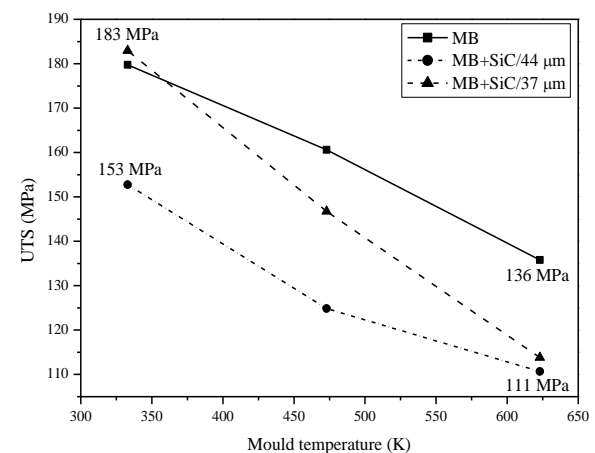
Tensile strength

Figure 2 shows the results of the tension tests. On the graph, the ultimate tensile stress versus mould temperature can be viewed. As in the before-mentioned case, tensile strength was improved (183 MPa) when SiC particles of 37 μm are added to the melt and the mould temperature was low (333 K). At the same time,

it is noticeable that this parameter is extremely sensitive to the thermal gradient in the alloy-mould interface, because in all the shown cases a clear reduction of this property is observed when increasing the mould temperature
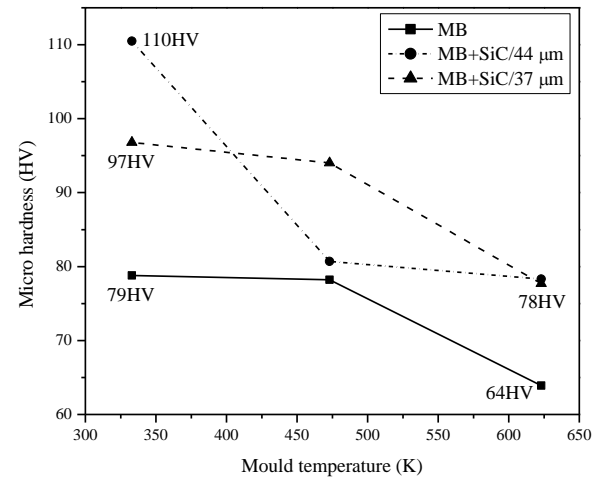
Figure 1. Graph that shows the effect that produces the temperature of the mould in the hardness of the solidified material. The measures were taken close to inclusions and far from these.


Figure 2. Ultimate tensile stress (UTS) value versus the mould temperature. MB values correspond to the ASTM-356 alloy free of SiC inclusions. Note the lineal relation that exists between the UTS and the mould temperature for the metallic base.

K_{Ic} plane-strain fracture toughness

In order to define the conditions for brittle fracture, the critical value of K (stress intensity factor) was determined by using tension specimens with V-notch. The most common specimen design was considered for this purpose (3 mm, notch length; 0.11 mm, radius of curvature of the crack-tip). Then, under the experimental conditions before

established the results are: In the cases with SiC inclusions, the K_{Ic} value was always lower (~ 4.2 MPa$\sqrt{m}$) than the corresponding one for the alloy without particles (6.2 MPa$\sqrt{m}$) at the mould temperature of 333 K; likewise, to the mould temperatures of 473 and 623 K, the same observation it remains (Figure 3).
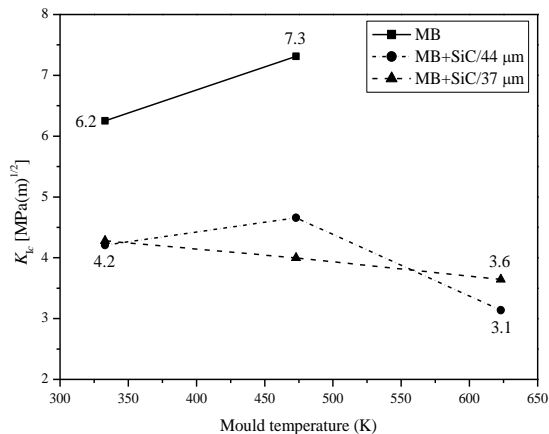

Figure 3. Plane-strain fracture toughness (K_{Ic}) versus the mould temperature (K). From graph it can be observed an increase in ductility when reducing the difference of temperatures between the liquid and the mould for the metallic base (MB).

Discussion

Based on the hardness measures, it is clear that the addition of SiC particles to the ASTM-356 alloy increased the mentioned property with the particle sizes utilized; however, depending on the cooling rate the hardness states resulted different. The fact that at 333 K the particles of 44 um are showing a strong increase of the hardness in the solid, it can be explained as consequence of the higher content of residual stresses around these particles than the corresponding ones to the small particles (37 µm). These residual stresses are the result of differences in the thermal expansion among the SiC inclusions and the metallic matrix.[8] It is important to point out that for a mould temperature of 623 K the hardness measures in the solids are similar for both sizes of SiC particle, which indicates that a more stable mechanical state in between the micro constituents and the matrix is attained under this solidification condition.

As it is known, the grain size in a metallic solid is a factor that determines the mechanical characteristic of itself. In this manner, the metallurgical structure of strong metallic materials is always conformed by fine grains.[9] Experimentally, the fine structures are obtained as consequence of high cooling rates, principally. Therefore, in this work, the thermal gradient in between the melt and the mould it propitiated the formation of fine grains (Figure 4). In addition, as in the above paragraph, the decrease of the thermal gradients between the melted alloy and the mould causes the relaxation of the stresses around the inclusions what gives place to an increase in the ductility. The UTS behaviour in the graph of Figure 2 reflects said tendency as for the mould temperature, the higher mould temperature the lower ultimate tensile strength. A light improvement in the tensile strength with the addition of SiC of 37 µm at 333 K (mould temperature) with respect to the metallic base was obtained; this result can be explained as a combination of small grains with small SiC particles and a low formation of porosity
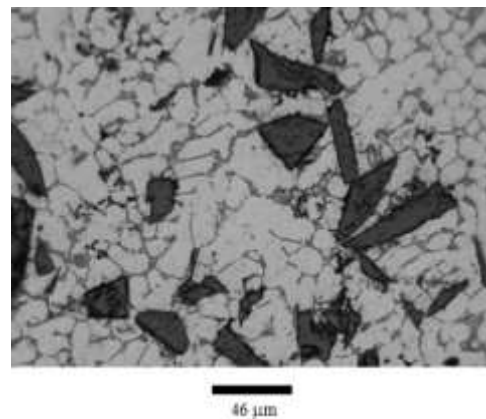
Figure 4. Image showing the micro structure of the ASTM-356 alloy containing SiC inclusions (dark particles). Metallic base is conformed by equiaxed grains and dendrites (clear grains).

Finally, as it is known, K_{Ic} is strongly dependent on metallurgical variables as melting practice, impurities, inclusions, and, it changes with important variables as temperature and strain rate.[10] Regarding the inclusions, the shape and size of the inclusions affect the fracture toughness. In this work, most of the inclusions presented a polyhedral shape while the rest of the same ones had the needle form. By considering the elongated particles, it is possible that those ones that are located in cross direction to the load and near to the notch tip they are propitiating the propagation of the flaw, meanwhile, the particles of polyhedral shape could act as a dispersion centre that prevent the fissures progress. It is clear that, in the case in

study, the SiC inclusions originated the observed behaviour, principally; given that, the presence of inclusions close to the tip of the V-notch gave place to the initiation and propagation of fissures that culminated with the catastrophic fracture. More, in pieces that were cast in moulds preheated at more high temperatures, additional factors as inclusions segregation and an increase of porosity was observed; therefore, together with the coarsening of dendrites at low cooling rates, the form of the graph in the Figure 3 is understandable. The improvement in the K_{Ic} value (7.3 MPa$\sqrt{m}$) that was observed in the metallic base that was cast in the preheated mould at 443 K was due to the action of the micro constituents of the alloy itself, this effect is observed too when SiC particles of 44 μm are added to the alloy to such temperature

Conclusions

1. An increase of 2 % weight of the content of magnesium in the ASTM-356 alloy it improves the wet between the liquid mass and the solid inclusion.
2. The previous process of oxidation of the SiC particles reduced the number of possible reactions in between the aluminium and such particles in the liquid mass.
3. The wide solidification interval of the ASTM-356 alloy allows the heterogeneous nucleation of α-Al crystals around the SiC inclusions at early solidification stages, with that which makes sure the retention of such particles.
4. The inclusion of SiC particles into the alloy in liquid state, improves the hardness of the obtained solid when the cast is carried out in the condition of high thermal gradient. On the contrary, more long cooling times they cause that this property of the composite to diminish.
5. Ultimate tensile stress is little improved with the more small inclusions of SiC when the solidification is carried out in the preheated mould to 333 K (i.e. high thermal gradient). This property is drastically reduced for long cooling.
6. The insertion of oxidized SiC particles produce an increase in the brittleness of the composite when the ASTM-356 alloy is utilized as metallic base

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