Effect of melt treatment on microstructure and impact properties of Al–7Si and Al–7Si–2.5Cu cast alloys

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Abstract. The microstructures and impact toughness of Al–7Si and Al–7Si–2.5Cu cast alloys were studied after various melt treatments like grain refinement and modification. The results indicate that combined grain refined and modified Al–7Si–2.5Cu alloys have microstructures consisting of uniformly distributed α -Al grains, interdendritic network of fine eutectic silicon and fine CuAl₂ particles in the interdendritic region. These alloys exhibited improved impact toughness in as cast condition when compared to those treated by individual addition of grain refiner or modifier. The improved impact toughness of Al–7Si–2.5Cu alloys are related to breakage of the large aluminum grains and uniform distribution of eutectic silicon and fine CuAl₂ particles in the interdendritic region resulting from combined refinement and modification. This paper attempts to investigate the influence of microstructural changes in the Al–7Si and Al–7Si–2.5Cu cast alloys by grain refinement, modification and combined action of both on the impact toughness.

Keywords. Grain refinement; modification; impact toughness; Al–Si alloys; Al–Si–Cu alloys.

1. Introduction

One of the major driving forces for the development of Al–Si cast alloys are the superior wear resistance, low coefficient of thermal expansion (CTE), high corrosion resistance, high strength to weight ratio and excellent castability which makes them potential candidate materials for a number of tribological applications in automobiles and other engineering sectors (Mondolfo 1979). However, their low fracture toughness impedes broader applications of these alloys. The microstructure of Al–7Si alloy consists of large elongated primary α -Al grains and the eutectic silicon (plate-like) induces poor ductility to the castings. Unmodified acicular silicon structure acts as an internal stress riser in the microstructure and provides easy path for fracture. The silicon crystals, which have three-dimensionally complex shapes and are very brittle, congregate at the grain boundaries of the α -Al matrix. The low fracture toughness originates in the microstructure of these alloys, and is influenced by α -Al dendrite arm spacing and cell size. The improvement in impact toughness is dictated by the type, shape, size and distribution of second phase particles in the matrix and matrix microstructures (Basavakumar *et al* 2006). The production of cast Al alloys with improved quality (better structure and mechanical properties) involves: (i) addition of alloying elements during

melting and treatment of liquid alloy (refining and/or modification) and/or (ii) application of heat treatment, with the disadvantage of prolonged period of time and energy input and/or (iii) stirring during solidification and/or (iv) plastic deformation (extrusion, rolling and forging) with the disadvantage of time and energy input, with the first option being the most easy and efficient. The addition of grain refiner and modifiers converts large elongated α -Al grains into fine equiaxed α -Al grains and eutectic silicon (plate-like) into fine particles, respectively. Strengthening of Al–Si alloys is achieved by adding small amounts of Cu, Mg or Ni and the silicon provides good casting properties (Hafiz and Kobayashi 1994; Akamatsu 2001; Lasa and Ibabe 2002). Copper improves impact toughness at the expense of ductility and corrosion resistance (ASTM Standard E647, 2000). Also copper results in the precipitation of CuAl₂ particles and depending on cooling rate and modifier level, this phase could appear as block and/or (Al–CuAl₂) fine eutectic colonies in the microstructure (Brecht *et al* 1991; Sonsino and Ziese 1993; Nishida 2002). The combination of alloying addition and liquid alloy treatments is a good option to get better control of the microstructure during solidification and hence, improve the mechanical properties eliminating the need of heat treatments, resulting in reduction of production cost (Kori *et al* 2000; Lados and Apelian 2004; Ma *et al* 2005).

Several experimental results have been reported describing the use of grain refiners and modifiers to obtain

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Table 1. Test specimens and analysed mechanical properties of Al-7Si and Al-7Si-2.5Cu alloys.

Sl. no.	Alloy designation	Alloy composition	Addition level of GR (wt%)	Addition level of modifier (wt%)	UTS (MPa)	Hardness (HB)
1	HP-1	Al-7Si	–	–	149	60
2	HP-2	Al-7Si-1M13	1.0	–	160	66
3	HP-3	Al-7Si-0.02Sr	–	0.02	168	70
4	HP-4	Al-7Si-2.5Cu	–	–	163	73
5	HP-5	Al-7Si-2.5Cu-1M13	1.0	–	184	85
6	HP-6	Al-7Si-2.5Cu-0.02Sr	–	0.02	194	90
7	HP-7	Al-7Si-2.5Cu-0.02Sr-1M13	1.0	0.02	200	98

GR: Grain refiner (M13 = Al-1Ti-3B); modifier [(Sr-strontium)]

Table 2. Chemical analysis of cast alloys and master alloys.

Alloy	Composition (wt%)					
	Si	Fe	Sr	Ti	B	Al
Al	0.11	0.16	–	–	–	Balance
Al-7Si	6.98	0.17	–	–	–	Balance
Al-10Sr	0.12	0.17	10.0	–	–	Balance
Al-20Si	20.13	0.18	–	–	–	Balance
Al-1Ti-3B	0.16	0.17	–	1.13	2.25	Balance
Al-5Ti-3B	0.15	0.17	–	5.62	1.04	Balance

a fine-grained microstructure of hypoeutectic Al-Si alloys. The effect of grain refinement and/or modification and combined addition of both on the impact toughness of Al-7Si and Al-7Si-2.5Cu cast alloys have not yet been sufficiently elucidated, except for hardness, and some reports on tensile properties. The purpose of the present study was to improve the impact toughness, tensile properties and hardness of Al-7Si and Al-7Si-2.5Cu cast alloys using grain refiner and/or modifier and combined addition of both, and to discuss the mechanism of improvements.

2. Experimental

Al-7Si alloy was prepared by melting commercially pure aluminium (99.7%) along with Al-20% Si master alloy in clay graphite crucible in a pit type resistance furnace under a cover flux (45% NaCl + 45% KCl + 10% NaF) and the melt was held at 720°C. After degassing with 1% solid hexachloroethane, master alloy chips duly packed in aluminum foil were added to the melt for grain refinement. For modification, Al-10% Sr master alloy was used with addition level being kept constant at 0.02 wt% Sr (Kori *et al* 2000). The melt was stirred for 30 s with zirconia coated iron rod after the addition of grain refiner and/or modifier. Melts were held for 5 min and poured into a cylindrical graphite mould (25 mm diameter and 150 mm

height) surrounded by fireclay brick. The details of the alloys, grain refinement and modification treatment are given in table 1. The chemical compositions of the cast alloys and master alloys (table 2) were assessed using atomic emission spectroscopy. The microstructures of the samples that had been cut from the longitudinal section of the billets were studied. Grain size analysis was carried out by the linear intercept method after etching the polished surface with Keller's reagent (2.5% HNO₃, 1.5% HCl, 1% HF and 95% H₂O). Samples were electro polished using an electrolytic bath comprising of 80% methanol and 20% HNO₃ by volume for optical microscopic analysis. Selected grain refined and modified samples were characterized using SEM and XRD.

Impact toughness test pieces were cut from the billets. The standard charpy specimens, 10 × 10 × 55 mm, with a 2 mm V-notch were prepared. All tests were carried out at room temperature and before conducting the charpy test all samples were annealed at a temperature of about 350°C, to relieve the internal stresses. A charpy impact test machine was used for measuring the absorbed energy of the samples as impact toughness during impact testing. The impact values reported here are the average of three test pieces made from single casting. Tensile testing of the specimens was carried out using a Universal Testing Machine (AG-5000G, Shimadzu, Japan). A JEOL JSM-5800 scanning electron microscope (SEM) was employed for examination of the fractured surface.

Figure 1. Optical microphotographs of Al-7Si alloy (a) un-treated, (b) with grain refiner (1% of M13), (c) with modifier (0.02% Sr) and Al-7Si-2.5Cu alloy, (d) un-treated, (e) with grain refiner (1% of M13), (f) with modifier (0.02% Sr) and (g) with grain refiner (1% of M13) and modifier (0.02% Sr).

3. Results

3.1 Microstructures of Al-7Si and Al-7Si-2.5Cu cast alloys treated by grain refiner and modifier

The measured densities of the alloys are close to the theoretical values, which indicate that the samples are free

from porosity. The microstructures of the Al-7Si and Al-7Si-2.5Cu cast alloys before and after grain refinement, modification and combined addition of both refiner and modifier are shown in figure 1(a-g). It is observed that modification and combined addition of both refiners and modifiers have profound influence on microstructures of

the Al-7Si and Al-7Si-2.5Cu cast alloys. Alloys without any grain refiner addition have shown the maximum grain size (180–200 μm). The present experimental results confirmed that the addition of grain refiner Al-1Ti-3B to Al-7Si or Al-7Si-2.5Cu alloy significantly refines the coarse columnar primary α -Al grains to fine equiaxed α -Al grains (60–70 μm) due to the presence of $\text{AlB}_2/\text{TiB}_2$ particles present in the master alloy (Al-1Ti-3B) which are nucleating agents during the solidification of α -Al grains, while the eutectic silicon particles appear to be unaffected as expected. Also the addition of modifier (Sr) to Al-7Si or Al-7Si-2.5Cu cast alloy changes the plate-like eutectic silicon to fine particles and fine CuAl_2 particles in the interdendritic region. The results also suggest that the addition of Al-1Ti-3B master alloy along with Sr modifier to Al-7Si-2.5Cu cast alloys shows more uniformly distributed α -Al grains (55–60 μm), fine broken grains of silicon and fine CuAl_2 particles in the interdendritic region compared to the individual addition of grain refiner or modifier.

3.2 Impact toughness

Impact toughness of the Al-7Si and Al-7Si-2.5Cu cast alloys mainly depends on the shape, size and distribution of the α -Al grains, eutectic silicon morphology and CuAl_2 particles in the interdendritic region. Figure 2 shows the relationship between the energy absorbed by the sample during impact testing and the alloy compositions. The plot in figure 2 is the average value of three test pieces made from single casting. The absorbed energy of the un-treated Al-7Si alloy is 0.9 J/cm². After the combined addition of Al-1Ti-3B grain refiner and Sr modifier to Al-7Si-2.5Cu, the absorbed energy increases markedly with a value of over 4 J/cm². This value is almost 4 times that of the un-treated Al-7Si alloy.

Figure 2. Energy absorbed as a function of alloy composition.

3.3 Fracture surface observation

Figure 3(a–f) shows the fractured surfaces (low and high magnification) of impact samples under SEM, with (a) representing Al-7Si un-treated alloy, (b) representing Al-7Si alloy treated with Sr modifier, (c) representing Al-7Si-2.5Cu un-treated alloy, (d) representing Al-7Si-2.5Cu alloy treated with grain refiner, (e) representing Al-7Si-2.5Cu alloy treated with modifier and (f) representing Al-7Si-2.5Cu alloy treated with grain refiner and modifier. The un-treated sample shows a rough surface due to the large grains in the alloy and the particles of eutectic silicon and intermetallic compounds at the grain boundaries. The sample (b) treated by modifier (Sr), shows a finer fracture surface, including a couple of dimples, compared to the un-treated sample. The sample treated by copper (c), shows a rough surface due to the large grains in the alloy and the particles of eutectic silicon and intermetallic CuAl_2 phase formed along the inter dendritic region. The sample containing both copper and grain refiner, (d), shows a fracture surface, including a couple of dimples and the particles of eutectic silicon and intermetallic CuAl_2 phase formed along the inter dendritic region compared to figure (c). The sample containing both copper and modifier, (e), shows a fine fracture surface, including a couple of dimples and uniformly distributed fine eutectic silicon and fine intermetallic CuAl_2 phase formed along the inter dendritic region compared to figure (c). The sample treated by the combined addition of both grain refiner (Al-1Ti-3B) and modifier (Sr) along with copper, (e), shows a fine and homogeneous fracture surface with many dimples and uniformly distributed fine eutectic silicon and fine intermetallic CuAl_2 phase formed along the inter dendritic region.

4 Discussion

Impact toughness of Al-Si and Al-7Si-2.5Cu as cast alloys mainly depends on the shape, size and distribution of the α -Al grains, eutectic silicon morphology and CuAl_2 particles in the interdendritic region (Kori *et al* 2000; Basavakumar *et al* 2006). The microstructure of Al-7Si alloy consists of large elongated primary α -Al grains and eutectic silicon (plate-like) induces poor ductility to the casting. The addition of grain refiners (Al-1Ti-3B) and modifier (Sr) converts large α -Al grains into fine equiaxed α -Al grains, eutectic silicon (plate-like) into fine particles and fine CuAl_2 blocks in the interdendritic region resulting in the improved impact toughness. The improvements which are observed in the present studies are mainly due to structural differences between the grain refined, modified and combined effect of grain refiner and modifier in these alloys. It is important to note that the alloy has been cast in a graphite mould surrounded by fireclay brick (slow cooling) after grain refinement and

modification. Thus, further improvement in the impact toughness can be expected for fast cooled castings, as this can lead to further refinement of the microstructures.

As illustrated in figure 2 the energy absorbed by the Al-7Si and Al-7Si-2.5Cu cast alloys increases with the addition of grain refiner (Al-1Ti-3B) and modifier (Sr). As shown in figure 1(a and d), the microstructure of un-

treated Al-7Si and Al-7Si-2.5Cu alloys consists of large primary α -Al grains, including dendrites, interdendritic networks of eutectic silicon plates and intermetallic CuAl_2 phase formed along the inter dendritic region. Unmodified acicular silicon structure acts as internal stress risers in the microstructure and provides easy path for fracture, which is the primary reason for the low im-

Figure 3. For caption, see next page.

Figure 3. SEM observations of the fractured surfaces of Al-7Si and Al-7Si-2.5Cu cast alloys subject to impact testing.

pact toughness of these alloys. We, therefore, conclude that breaking up of these microstructures and dispersing the eutectic silicon (plates) uniformly and intermetallic CuAl_2 particles to fine particles of CuAl_2 phase formed along the inter dendritic region, would help in improving the impact toughness of the alloys. Changing the coarse columnar

α -Al grains to fine equiaxed α -Al grains also results in improved impact toughness. As shown in figure 1(b and e), the microstructure of Al-7Si and Al-7Si-2.5Cu alloys treated with 1 wt.% of grain refiner (Al-1Ti-3B) significantly refines the α -Al grains and converts them into fine equiaxed, while the eutectic silicon particles and CuAl_2

phase appear to be unaffected, as expected. As shown in figure 1(c and f), the microstructure of Al-7Si and Al-7Si-2.5Cu alloy treated with modifier (Sr) changes the plate-like eutectic silicon to fine particles, including homogeneous distribution of silicon particles throughout the matrix and intermetallic fine CuAl_2 phase formed along the inter dendritic region that improves the strength of the matrix and impact toughness of the alloy. Therefore, the modified grain boundaries in the microstructures are likely to be an important factor in enhancing impact toughness. As shown in figure 1(g), the microstructure of Al-7Si-2.5Cu alloy treated with the combined addition of both grain refiner (Al-1Ti-3B) and modifier (Sr) clearly reveals fine equiaxed α -Al grains together with modified silicon and intermetallic fine CuAl_2 phase formed along the inter dendritic region, which further improves the impact toughness. The absorbed energy increases markedly with a combined addition of grain refiner and modifier along with copper, reaching a value of over 4 J/cm^2 . This value is 4 times that of the un-treated Al-7Si alloy.

5. Conclusions

The effect of melt treatment on impact toughness of the Al-7Si and Al-7Si-2.5Cu cast alloys was investigated and the following conclusions could be drawn:

- (I) Impact toughness of Al-7Si and Al-7Si-2.5Cu cast alloys mainly depend on the shape, type, size and size distribution of α -Al grains, silicon particles and CuAl_2 phases in the matrix.
- (II) The increase in impact toughness consists of two parts:

- (i) The breakage of the elongated primary α -Al grains into more uniformly distributed α -Al grains by refinement and (ii) the plate-like eutectic silicon to fine broken particles of silicon and massive particles to fine micro constituents of CuAl_2 by modification.

- (III) The combined addition of grain refiner and modifier (1 wt% Al-1Ti-3B + 0.02 wt% Sr) to Al-7Si-2.5Cu alloy shows remarkably improved impact toughness (4 J/cm^2) when compared to that of un-treated Al-7Si alloy (0.9 J/cm^2).

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