TECH FRONTIERS

Enhancing impact toughness of hypoeutectic Al-Si cast alloy using forging process

BASAVAKUMAR KG

Basavakumar KG is with the Department of Mechanical Engineering, RNSIT, Bangalore

The microstructures and impact toughness of hypoeutectic Al-Si cast alloys were studied before and after the forging process along with various melt treatments like grain refinement, modification, and combination of both. Results indicate that the forging process after combined grain refined and modified of hypoeutectic Al-Si cast alloys results in microstructures consisting of uniformly distributed α-Al dendrites, interdendritic network of fine eutectic silicon and fine $CuAl_2$ particles in the interdendritic region. These alloys exhibited improved impact toughness in cast condition when

ONE of the major driving forces for the development of Al-Si cast alloys is 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.[1-5] However, their low fracture compared to those treated by individual addition of grain refiner or modifier. The improved impact toughness of hypoeutectic Al-Si cast alloys is related to breakage of large aluminium dendrites and uniform distribution of eutectic silicon and fine $CuAl_2$ particles in the interdendritic region due to the forging process (50% reduction). This paper attempts in investigating the influence of forging process on microstructural changes and impact toughness of hypoeutectic Al-Si cast alloys before and after melt treatments

toughness impedes broader applications of these alloys.[6-8] The microstructure of Al-7Si alloy consists of large elongated primary ά-Al grains and the eutectic silicon (plate like) induces poor ductility to the castings. Unmodified acicular silicon structure acts as internal stress raisers in the microstructure and provides an easy path for fracture. The silicon crystals, which have three-dimensionally complex shapes that are very brittle, congregate at the grain boundaries of the ά-Al matrix. The low fracture toughness originates in the microstructure of these alloys that is influenced by ά-Al dendrite arm spacing and cell size. The improvement in impact toughness is dictated by the type, size, shape, and distribution of second phase particles in the matrix and matrix microstructures.[9-20] The production of cast Al alloys with improved quality (better structure and mechanical properties) involves:

(1) addition of alloying elements during melting and treatment of liquid alloy (refining and/or modification) and/or
(2) application of heat treatment, with the disadvantage of prolonged period of time and energy input and/or
(3) stirring during solidification and/or
(4) 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 convert large elongated ά-Al grains into fine equiaxed ά-Al grains and eutectic silicon (plate like) into fine particles respectively.[3, 9] Strengthening of Al-Si alloys is achieved by adding small amount of Cu, Mg, or Ni and the silicon provides good casting properties.[17-20] Copper improves impact toughness at the expense of ductility and corrosion resistance. Also copper results in the precipitation of $CuAl_2$ particles and depending on the cooling rate and modifier level, this phase could appear as block and/or ($Al-CuAl_2$) fine eutectic colonies in the microstructure.[13-18] The combination of alloying addition and the liquid alloy treatments is a good option to get better control of the microstructure during solidification and hence improve the impact toughness, eliminating the need of heat treatments, and resulting in reduction of production cost.

Several experimental results have been reported describing the use of grain refiners and modifiers to obtain a fine-grained microstructure of hypoeutectic Al-Si alloys.[5-11] 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 before and after the forging process have not yet been sufficiently elucidated, except for hardness, and some reports on tensile properties.[12-16] The purpose of the present study is to improve the impact toughness of Al-7Si and Al-7Si-2.5Cu cast alloys using forging process after grain refiner and/or modifier and combined addition of both and to discuss the mechanisms of improvement.

EXPERIMENTAL DETAILS

Before the forging process, hypoeutectic Al-Si alloy was prepared by melting commercially available pure aluminium (99.7%) along with Al-20%Si master alloy in clay graphite crucible in a pit type resistance furnace under a cover of 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 aluminium 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 0.02wt%Sr.[9] The melt was stirred for 30 seconds with zirconia coated iron rod after the addition of grain refiner and/or modifier. Melts were held for five minutes and poured into a cylindrical graphite mould (30 mm diameter and 150 mm height) surrounded by fireclay brick. **Table1** gives the details of the alloys and grain refinement and modification treatment. The chemical compositions of the cast alloys and master alloys, assessed using atomic emission spectroscopy, are presented in **Table2**.

The material in the form of a billet is forged at a temperature in the range of 275°C to 350°C, at which simultaneous precipitation and dynamic recovery can occur. This deformation temperature is below the normal forging temperature of 375°C-475°C, but is higher than the normal peak ageing temperature for aluminium alloys of 120°C-200°C. The processed

Table1: Test specimens of Al-7Si and Al-7Si-2.5Cu cast alloys (prepared at 720°C and 5 min holding time

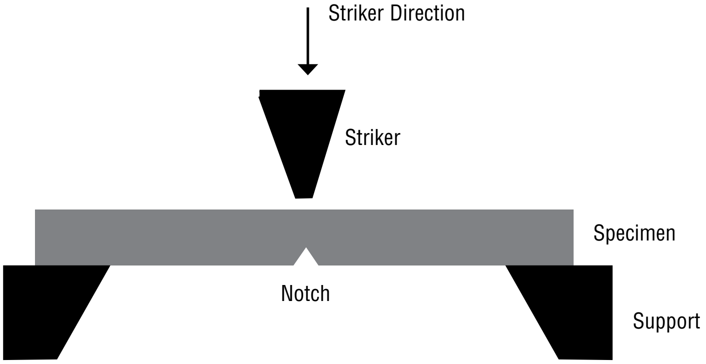
Sl no.	Alloy designation	Alloy composition	Addition level of GR (wt%)	Addition level of modifier (wt%)
1	HP-1	Al-7Si	--	--
2	HP-2	Al-7Si-2.5Cu	--	--
3	HP-3	Al-7Si-2.5Cu-0.02Sr	--	0.02
4	HP-4	Al-7Si-2.5Cu-0.02Sr-1M13	1.0	0.02

Note: GR: Grain refiner (M13=Al-1Ti-3B); Modifier (Sr-Strontium)

Table2: 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-1B	0.15	0.17	-	5.62	1.04	Balance

Figure1: Schematic of Charpy impact test



billet, which develops a fine grain size, is extremely soft at elevated temperatures and in an ideal condition well-suited for precision forging or for reduction to fine grains. Impact toughness test pieces were made from the forging processed billet by machining along the longitudinal direction. The standard Charpy specimens 10×10×55 mm with a 2.0 mm V-notch were prepared. Tests were carried out at room temperature. Before conducting the Charpy test, the samples were annealed at temperatures in the range of 325°-350°C in order to relieve the internal stresses. A Charpy impact test machine was used for measuring the absorbed energy by the samples as impact toughness during impact testing. **Figure1** shows the schematic of the Charpy impact test.

Table3 gives the average value of three test pieces made from single casting. The microstructures of the samples cut from the longitudinal section of the billets were studied. Image analyser (Lieca) was used for investigating the particle size distribution in the alloy. A few selected grain-refined and modified samples were characterised using SEM and XRD. A JEOL JSM-5800 scanning electron microscope (SEM) was employed for examining the fractured surface.

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

Figure2 illustrates the microstructures of Al-7Si and Al-7Si-2.5Cu cast alloys treated by forging process before and after modification and combined addition of both refiner and modifier.

It was observed that the forging process after modification and combined addition of both refiners and modifiers have profound influence on the microstructures of Al-7Si and Al-7Si-2.5Cu cast alloys. Alloys without any grain refiner addition have shown larger grain size measuring up to 220 µm. The present experimental results confirmed that the addition of grain refiner Al-1Ti-3B to hypoeutectic alloy significantly refines the coarse columnar primary ά-Al grains to fine equiaxed ά-Al grains (60-75 µm) due to the presence of AlB_2/TiB_2 and or $TiAl_3$ particles present in the master alloys (Al-1Ti-3B master alloys) which are nucleating agents during the solidification of ά-Al grains. The eutectic silicon particles appear to be unaffected as expected. Also the addition of modifier (Sr) to Al-7Si-2.5Cu cast alloy changes the plate like eutectic silicon to fine particles and fine $CuAl_2$ particles in the interdendritic region.[5,16] The results also suggest that forging of hypoeutectic Al-Si alloys after addition of refiner, modifier to Al-7Si-2.5Cu cast alloys along with copper shows more uniformly distributed ά-Al grains (50-55 µm), fine broken grains of silicon and fine $CuAl_2$ particles in the interdendritic region compared to the individual additions.

Impact toughness

Impact toughness of Al-7Si and Al-7Si-2.5Cu cast alloys mainly depends on the shape, size and distribution of the ά-Al

Table3: Influence of forging process before and after grain refinement and/or modification on the impact properties (energy absorbed) of Al-7Si and Al-7Si-2.5Cu cast alloys

Sl no.	Alloy designation	Energy absorbed (J/cm2)	
		Before forging	After forging
1	HP-1	1.0	4.6
3	HP-2	2.54	10.1
4	HP-3	3.0	20.3
5	HP-4	3.6	30.6

grains, eutectic silicon morphology and CuAl$_2$ blocks in the interdendritic region. **Table3** shows the relationship between the energy absorbed by the samples during impact testing and the alloy compositions. The absorbed energy of untreated Al-7Si-2.5 cu alloy is 2.54 J/cm^2. Forging process (50% reduction) after the combined addition of Al-1Ti-3B grain refiner and Sr modifier to Al-7Si-2.5Cu along with copper, the energy absorbed increases markedly with the value of over 30.6 J/cm^2. This value is almost 15 times that of the untreated hypoeutectic alloy.

Fracture surface observation

Figure3 shows the fractured surfaces of impact samples before and after the forging process as seen under SEM: HP-2 representing untreated Al-7Si-2.5Cu cast alloy and HP-4 representing being treated with grain refiner and modifier along with forging process.

The untreated 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 treated using copper (HP-2) 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 copper, modifier (Sr) and forging, (HP-2-FP), shows a fine fracture surface, including a couple of dimples and intermetallic fine CuAl$_2$ phase formed along the inter-dendritic region compared to HP-2. The sample treated by the combined addition of both grain refiner (Al-1Ti-3B) and modifier (Sr) along with forging (HP-4-FP), shows a fine and homogeneous fracture surface with many dimples indicating good toughness and intermetallic CuAl$_2$ phase formed along the inter-dendritic region.

DISCUSSION

Impact toughness of Al-Si and Al-7Si-2.5Cu as cast alloys depends mainly on the shape, size and distribution of the ά-Al grains, eutectic silicon morphology, and CuAl$_2$ blocks in the interdendritic region. [19-20] The microstructure of Al-7Si alloy consists of large elongated primary ά-Al grains and the eutectic silicon (plate-like) induces poor ductility to the casting. Unmodified acicular silicon structure acts as internal stress raiser in the microstructure and provides easy path for fracture. The addition of grain refiner (Al-1Ti-3B), modifier (Sr) and forging converts large ά-Al grains into fine equiaxed ά-Al grains, eutectic silicon (plate-like) into fine particles and fine CuAl$_2$ blocks in the interdendritic region resulting in improved impact toughness. The improvements observed in the present study are mainly due to the structural changes owing to the forging process after 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 Table3, the energy absorbed by Al-7Si and Al-7Si-2.5Cu cast alloys increase with the forging process after addition of grain refiner (Al-1Ti-3B) and modifier (Sr). As shown in Figure2, the microstructure of untreated Al-7Si and Al-7Si-2.5Cu cast alloys consists of large primary ά-Al grains, including dendrites, interdendritic networks of eutectic silicon plates, and intermetallic CuAl2 phase formed along the interdendritic region. Unmodified acicular silicon structure acts as internal stress raiser in the microstructure and provides easy path for fracture, which is the primary reason for the low impact toughness of these alloy. It is, therefore, concluded that breaking up of these microstructures and dispersing the eutectic silicon (plates) uniformly and intermetallic CuAl$_2$ blocks to fine blocks of CuAl$_2$ phase formed along the interdendritic region, would help in improving the impact toughness of the alloys. Changing the coarse columnar ά-Al grains to fine equiaxed ά-Al grains also results in improved impact toughness. As shown in Figure2 (HP-4), the microstructure of hypoeutectic Al-Si cast alloy treated with the forging process after combined addition of both grain refiner (Al-1Ti-3B) and modifier (Sr) along with copper consists of more uniformly distributed ά-Al grains, fine broken grains of silicon and intermetallic fine CuAl$_2$ phase formed along the interdendritic region, which further improves the impact toughness. The absorbed energy increases markedly with the forging process after combined addition of grain refiner and modifier along with copper, reaching the value of over 30.6 J/cm^2, which is about 15 times greater than that of the untreated alloy.

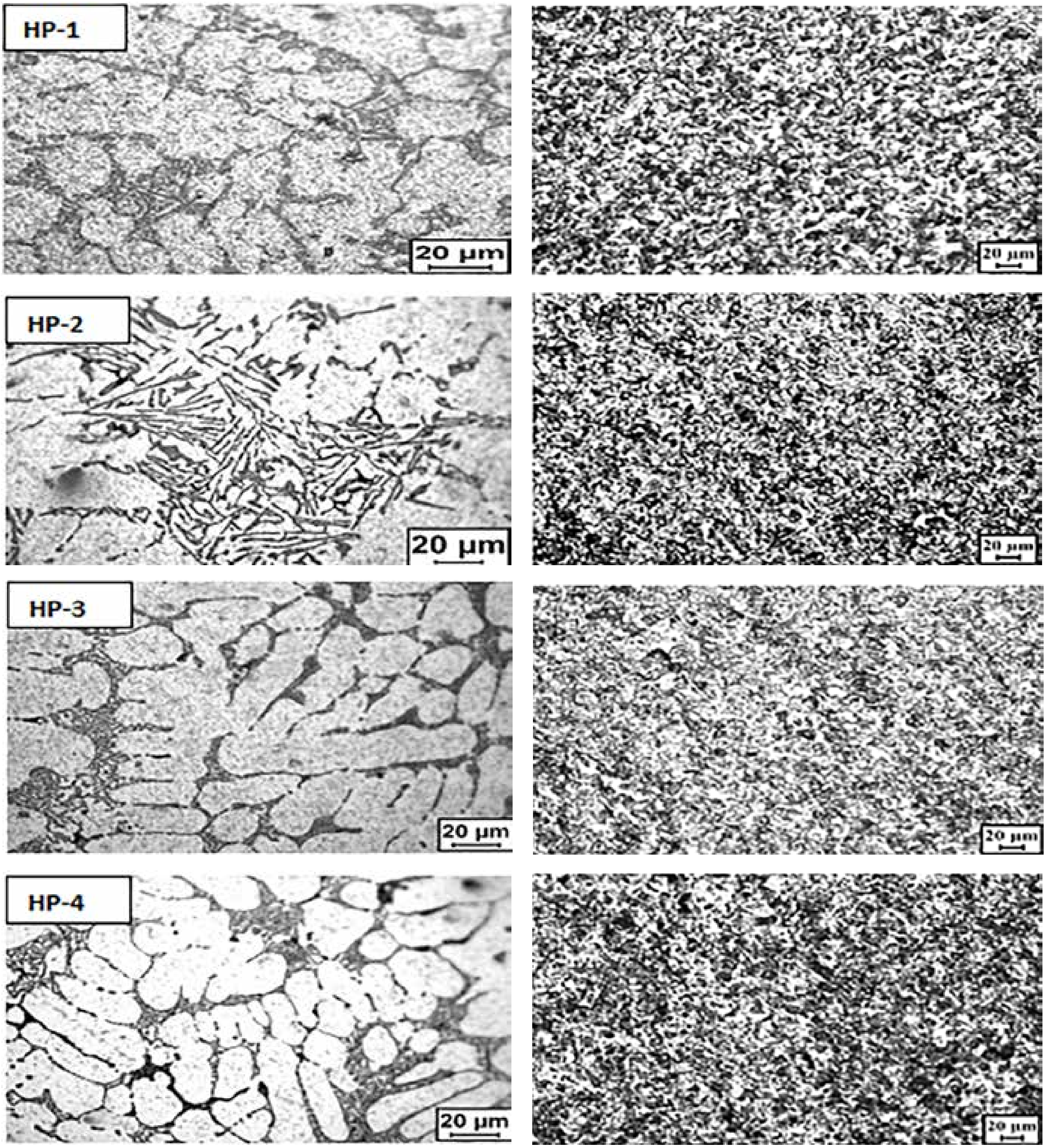
Conclusion

The effect of the forging process before and after melt treatments on the impact toughness of the Al-7Si and Al-7Si-2.5Cu cast alloys was investigated and the following conclusions were drawn:

1. Impact toughness of Al-7Si and Al-7Si-2.5Cu cast alloys depends mainly on the

RESULTS

Figure2: Optical photomicrographs of Al-7Si alloy before and after forging process

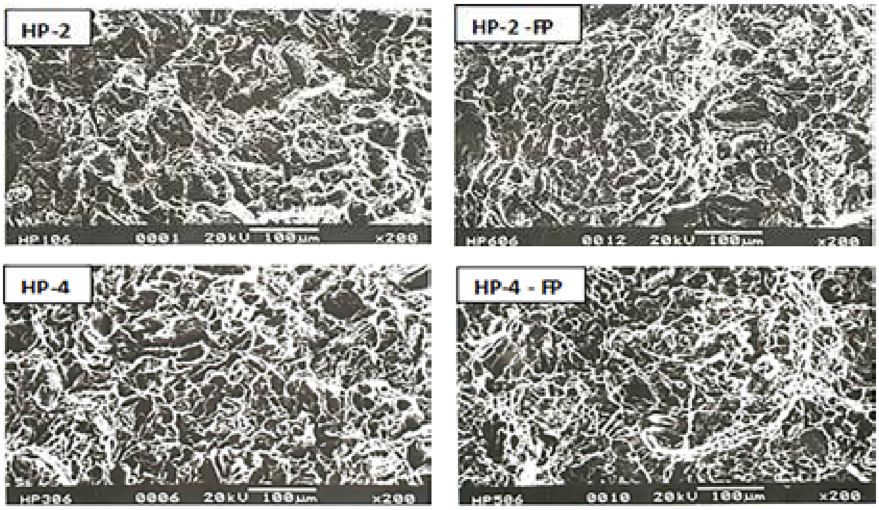


HP-1 – untreated; HP-2 – Al-7Si-2.5Cu alloy untreated; HP-3 – with modifier (0.02% Sr); and HP-4 – with grain refiner (1% of M13) and modifier (0.02% Sr) shape, type, size and distribution of ά-Al grains, silicon particles and $CuAl_2$ phases in the matrix.

2. The increase in impact toughness consists of two parts: the breakage of the elongated primary ά-Al grains into more uniformly distributed ά-Al grains owing to the forging process after refinement and the plate-like eutectic silicon to fine broken particles of silicon and massive blocks of $CuAl_2$ to fine micro constituents of $CuAl_2$ by the forging process after modification.

3. The forging process after combined addition of grain refiner and modifier (Al-1Ti-3B + Sr) to Al-7Si-2.5Cu alloy shows remarkably improved impact toughness (30.5 J/cm^2) when compared to that of un-treated Al-7Si-2.5Cu alloy (2.54 J/cm^2).

Figure3: SEM observations for the fractured surfaces of the hypoeutectic Al-Si cast alloys (HP-2 – Al-7Si-2.5Cu; and HP-4 – Al-7Si-2.5Cu-1M13) subjected to impact testing before and after forging



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