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Influence of Ti, B and Sr on the microstructure and mechanical properties of A356 alloy

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Abstract In the present investigation, the microstructural and mechanical properties study of A356 alloy have been discussed. The microstructural aspect of cast A356 alloy employed in the present study is strongly dependent on the grain refinement (Ti and B) and modification (Sr). The mechanical properties such as PS, UTS, %E, %R, YM and VHN have been investigated. This paper deals with the combined effect of grain refinement and modification, which improves the overall mechanical properties of the alloy. It is also a well-known fact that the mechanical properties of cast A356 alloy were improved by subjecting suitable melt treatment such as grain refinement, modification and mould vibration, etc. The quality of castings and their properties can be achieved by refining of α-Al dendrites in A356 alloy by means of the addition of elements such as Ti and B which reduces the size of α-Al dendrites, which otherwise solidifies with coarse columnar α-Al dendritic structure. In addition, modification is normally adopted to achieve improved mechanical properties. Metallographic studies reveal that the structure changes from coarse columnar dendrites to fine equiaxed ones on the addition of grain refiner and further, plate like eutectic silicon to fine particles on addition of 0.20% of Al–10Sr modifier. The present result shows that a reduction in the size of α-Al dendrites, modification of eutectic Si and improvement in the mechanical properties were observed with the addition of grain refiner Al–3Ti, Al–3B and modifier Al–10Sr either individual addition or in combination. The change in the microstructure from coarse columnar α-Al dendrites to fine equiaxed dendrites and plate like eutectic silicon to rounded particles leads to improved mechanical properties.

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Introduction

Aluminium silicon casting alloys are essential to the automotive, aerospace and engineering sectors. Al–Si alloys allow complex shapes to be cast; however the silicon forms brittle needle-like particles that reduce impact strength in cast structures. As an additive to Al–Si casting alloys, strontium improves strength, enhances mechanical properties and disperses porosity as it modifies the eutectic structure. The modified alloy displays a finer, less needle-like microstructure. Al–Si alloys, which comprise 85–90% of the total aluminium-cast parts produced, exhibit excellent castability, mechanical and physical properties [1]. The microstructure and alloy constituents are necessitated to achieve optimum mechanical properties. A356 aluminium alloys are mostly used for cast hypoeutectic Al–Si alloys to improve flowability of the melt and interfacial properties [2, 3]. However, eutectic Si particles present along solidification cells of the A356 aluminium alloy deteriorate strength, ductility and fracture toughness, and thus researches to develop processes for enhanced distribution of eutectic Si particles have been actively pursued [4, 5]. A356 alloy belongs to group of hypoeutectic Al–Si alloys and has a wide field of application in the automotive and avionics industries. It is used in the heat-treated condition in which an optimal ratio of physical and mechanical properties is obtained [6]. The alloy solidifies in a broad temperature interval (43 °C) and is amenable to treatment in semi-solid state as well as castings [7]. For this reason it is the subject of rheological investigations [8], as well as methods of treatment in the semi solid state [7, 9]. By these methods it is possible to obtain castings with reduced porosity of a non-dendritic structure and with good mechanical properties. Besides this the A356 alloy is used as a matrix for obtaining composites [10], which have an enhanced wear resistance, favourable mechanical properties at room temperature and enhanced mechanical properties at elevated temperatures. Cast aluminium-A356 alloy is one of the most well-developed aluminium alloys due to its outstanding properties. It is widely employed in numerous automotive and industrial weight sensitive applications, such as aeronautics and space flight, because of its low density and excellent castability. The A356 alloy contains about 50 vol% eutectic phases. A356 alloy finds wide application in the marine, electrical, automobile and aircraft industries. It is well known that on solidification of hypoeutectic Al–Si alloys the primary α-Al solidifies with coarse columnar or twinned columnar [11]. Actually, in most cases high-level mechanical properties are needed for industrial applications, so the performance of this alloy has been the subject of many micromechanical investigations [5, 12–14]. Since the strength and hardness of alloys mainly depend on their microstructure, a lot of efforts have been made to refine the microstructure of the castings in order to enhance the mechanical properties of aluminium-A356 alloy. Adding modifier and refiner [15, 16] to the melt is a common way of doing this, and has been adopted by many researchers. The microstructure of alloy A356 comprises of an aluminium matrix, which is strengthened by MgSi precipitates and, to a far lesser extent, by Si precipitates, and a dispersion of eutectic silicon particles and Fe-rich intermetallics. The variables affecting the microstructure mainly include composition, solidification conditions and heat treatment. The physics governing the formation of aluminium dendrites and the eutectic structure are reasonably well understood [17, 18]. Mechanical properties of Al–Si alloys are related to the morphology of silicon particles (size, shape and distribution), grain size, shape and dendrite parameters [19–22]. Modification changes silicon morphology and is achieved by rapid solidification, chemical modification and thermal modification in the solid state. The refinement of grain structure is achieved by controlling casting process parameters and/or melt chemistry (i.e. grain refinement, eutectic modification). Each control methodology refines a certain aspect of the microstructure. Thus, keeping in view, an attempt has been made to study the effect of minor additions of Ti, B and Sr in the form of master alloys on the microstructure and mechanical properties of A356 alloy either individually or in combinations.

Experimental details

The basic raw materials used in the present work are aluminium, potassium titanium fluoride (K_2TiF_6) and potassium borofluoride (KBF_4) for the preparation of Al–3Ti and Al–3B master alloys as shown in Table 1. In the present study, the master alloys (Al–3Ti and Al–3B) have been produced by the reaction of fluoride salts potassium titanium fluoride (K_2TiF_6) and potassium borofluoride (KBF_4) of Madras Fluorine Pvt. Ltd. in the powder form ($\leq$74 μm) with molten Al, which is an established practice [23] using induction furnace (2 kg, 4.5 kW, 50 cycles/s medium frequency induction furnace) with neutral refractory lining [24]. Al–10Sr master alloy procured from M/s Fenfe Metallurgicals, Bangalore was used as modifier throughout the present work for modification of eutectic silicon present in A 356 alloy. Specimens for microstructure and mechanical properties were prepared by melting A356 alloy in a resistance furnace (Kanthal heating elements, M/s Cera Therm International, India) under a cover flux (45%NaCl + 45%KCl + 10%NaF) and the melt was held at 720 °C. After degassing with solid hexachloroethane (C_2Cl_6), the melt was poured into a cylindrical graphite mould (25 mm diameter and 100 mm height) surrounded by fire clay brick with it's top open for pouring (for macro and micro structural studies) and also the melt was poured into split type graphite mould (12.5 mm diameter and 125 mm height) for preparing as-cast ('0' min) tensile specimens. Similarly, for preparing grain refined or modified samples, master alloy chips (Al–Ti and Al–B and or Al–Sr) were added to A356 alloy after degassing. The melt was stirred for 30 s with zirconia coated steel rod after the addition of master alloy, after which no further stirring was carried out. After 5 min of holding, the melt was poured into the graphite moulds. The '0' min refers to the melt without the addition of grain refiner and or modifier.

Figure 1a, b shows the cylindrical graphite mould [23] and Fig. 2a, b shows split type graphite mould used for tensile specimen castings [25]. The chemical compositions of the commercial purity Al (99.8%) and commercial A356

Table 1 Preparation of master alloys

Alloy no.	Composition	Salts used	Processing conditions
1	Al–3Ti	K_2TiF_6	800 °C and 60 min
2	Al–3B	KBF_4	800 °C and 60 min

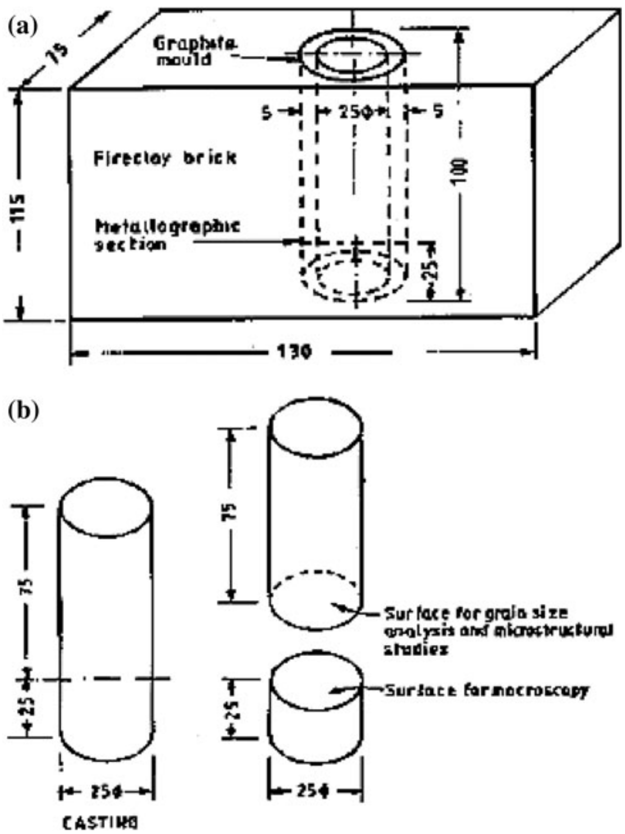

Fig. 1 **a** Cylindrical graphite mould surrounded by fireclay bricks. **b** Castings obtained from cylindrical graphite mould showing the sections selected for characterization (All dimensions are in mm)

alloy used in the present study were assessed using Atomic Absorption Spectrometer (Model AA 240: VARIAN, The Netherlands). Table 2 shows the chemical composition of the commercial purity Al (99.8%) and commercial A356 alloy. Also, Tables 3 and 4 clearly indicate the percentage of grain refiner and modifier and chemical composition of various master alloys.

Specimen preparation for microstructure studies

A specimen of 5 mm height was cut from the section, which was left after macroscopic study. One surface of the specimen was initially polished using belt grinder and then a series of waterproof emery papers with increasing fineness to remove any of the scratches present. Final polishing was carried out on a disc polisher using 400-mesh alumina powder until the mirror finish and scratch free surface was obtained. Final polishing was carried out using electropolishing machine (Model: Electropol, METATECH, Pune) with electrolyte having composition of 72.4% methanol, 7.8% perchloric acid, 9.8% Butylcellosolve and 10% distilled water by volume. Polished samples were cleaned with soap solution, distilled water and ethyl alcohol followed with drying. The polished samples were etched using Keller's reagent (2.5%HNO_3 + 1.5%HCl + 1%HF + 95%H_2O by volume) for about 75–90 s in order to develop microstructure with grain boundaries and then the polished specimens were taken for optical microscopy, SEM/EDX analysis.

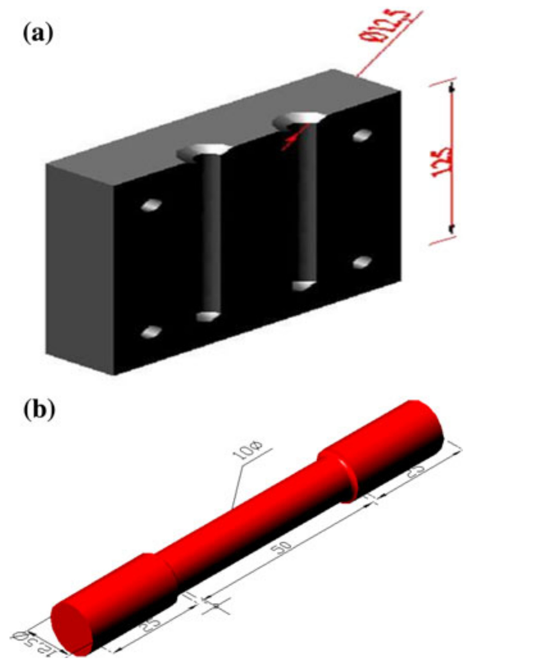

Fig. 2 Details of the preparation of tensile test specimens; **a** part of split type graphite mould and **b** tensile test specimen

Mechanical properties study

A computerized universal testing machine shown in Fig. 3 and microhardness tester shown in Fig. 4 were used for mechanical properties (0.2%PS, UTS, %E, %R and YM) and microhardness study (VHN) on A356 alloy before and after grain refinement and modification. Tensile tests on the prepared tensile specimens (10 mm dia × 50 mm length) were carried out to determine the mechanical properties like, 0.2% proof stress, ultimate tensile strength, percentage elongation, percentage reduction and YM The microhardness of the prepared specimen to determine VHN was tested using microhardness tester on A356 alloy before and after grain refinement and modification. Micro hardness tests were carried out on the polished specimens by applying a 500 g load for 20 s using a diamond indenter. The hardness was measured at different locations of each specimen and the mean values of readings were taken as hardness number.

Table 2 Chemical composition of the commercial purity Al and A356 alloy

Alloy composition	Composition (wt%)									
	Si	Cu	Mg	Fe	Mn	Zn	Pb	Sn	Ti	Al
Al	0.11	–	–	0.18	–	–	–	–	–	Bal
A356	6.96	0.10	0.30	0.50	0.30	0.10	0.10	0.05	0.20	Bal

Table 3 Percentage of the grain refiners and modifier

Alloy no.	Alloy composition	% of element
1	A356	–
2	A356 + 0.65% of Al–3Ti	0.02Ti (GR)
3	A356 + 0.60% of Al–3B	0.018B (GR)
4	A356 + 0.20% of Al–10Sr	0.02Sr (Modifier)
5	A356 + 0.65% of Al–3Ti + 0.60% of Al–3B + 0.20% of Al–10Sr	0.02 Ti, 0.018B and 0.02Sr

Table 4 Chemical composition of various master alloys

Master alloy composition	Composition (wt%)							
	Si	Cu	Mg	Fe	Sr	Ti	B	Al
Al–3Ti	0.13	–	–	0.20	–	2.98		Bal
Al–3B	0.14	–	–	0.16	–		2.83	Bal
Al–10Sr	0.10	–	–	0.16	10.0	–	–	Bal

Fig. 3 Computerized universal testing machine

Fig. 4 Microhardness tester

Results and discussion

Figure 5 shows the SEM photomicrograph of A356 alloy in the absence of grain refiner. From figure it is clear that in the absence of Al–3Ti master alloy, A356 alloy shows coarse columnar α-Al dendritic structure and unmodified needle/plate-like eutectic silicon. With the addition of 0.65% of Al–3Ti master alloy, A356 alloy shows response towards grain refinement with structural transition from coarse columnar dendritic structure to fine equiaxed structure as shown in Fig. 5b. With the addition of 0.60% of Al–3B master alloy, the structure of A356 alloy changes from columnar to finer equiaxed α-Al dendrites compared to the addition of Al–3Ti grain refiner as clearly observed in Fig. 5c, while eutectic silicon remains unmodified as expected. This could be due to the presence of AlB_2 particles present in the Al–3B master alloy and these particles act as heterogeneous nucleating sites during solidification of α-Al. While addition of A356 alloy to 0.20% of Al–10Sr master alloy, the plate-like eutectic Si is converted into fine particles and α-Al dendrites remain as columnar dendritic structure only as clearly seen in Fig. 5d. However, Fig. 5e shows the simultaneous refinement (α-Al dendrites) and modification (eutectic Si) of Al356 alloy due to the

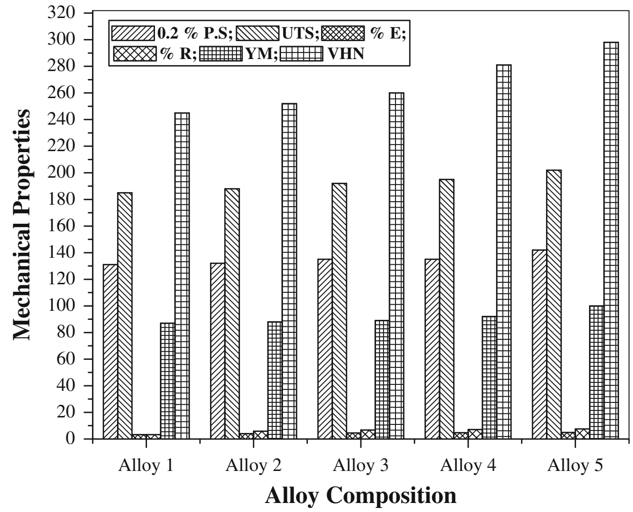

Fig. 6 Mechanical property study of A356 alloy before and after the addition of grain refiner and or modifier

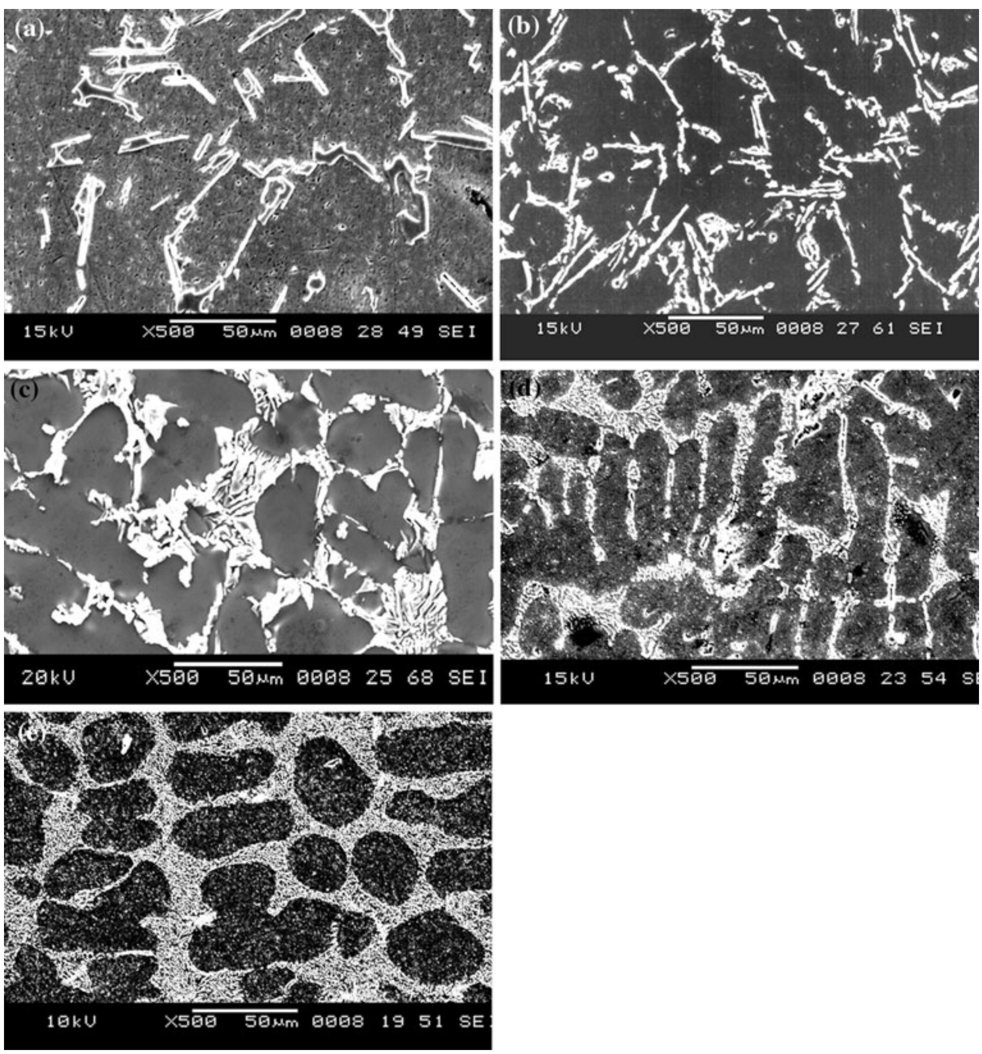

Fig. 5 SEM photomicrographs of A356 alloy **a** as cast alloy; **b** with 0.65% of Al–3Ti grain refiner; **c** with 0.60% of Al–3B grain refiner and **d** with 0.20% of Al–10Sr modifier, and **e** with combined addition of 0.60% of Al–3B grain refiner and 0.20% of Al–10Sr

Table 5 Mechanical property study on A356 alloy

Alloy no.	Alloy composition	0.2% PS (MPa)	UTS (MPa)	%E	%R	YM	VHN
1	A356	131	185	3.25	3.32	87	245
2	A356 + 0.65% of Al–3Ti	132	188	4.05	5.85	88	252
3	A356 + 0.60% of Al–3B	135	192	4.52	6.74	89	260
4	A356 + 0.20% of Al–10Sr	139	195	4.78	7.15	92	281
5	A356 + 0.65% of Al–3Ti + 0.60% of Al–3B + 0.20% of Al–10Sr	142	202	4.92	7.55	100	298

combined action of AlB_2 and Al_4Sr particles present in Al–3B grain refiner and Al–10Sr modifier, respectively.

Figure 6 shows the influence of the Ti, B and Sr on the mechanical properties of A356 alloy. From the figure, it is clearly observed that the improvement in the mechanical properties such as PS, UTS), %E, %R, YM and VHN increases with the addition of master alloys containing Ti, B and Sr due to change in the microstructure. It is also clear that the combined addition of grain refiner and modifier to A356 alloy has resulted in maximum improvement in mechanical properties as compared to the individual addition of grain refiners, modifier and in an untreated as cast condition. Addition of the grain refiners to A356 alloy predominantly converts columnar grain/dendritic structure to fine equiaxed grain/dendritic structure thereby by enhances the mechanical properties. The effect of silicon on the mechanical properties of Al–Si alloys is a well-known fact. The mechanical properties depend on the shape, size and distribution of eutectic silicon and α-Al grains/dendrites in case of Al–Si alloys. It is also clear from the experimental results that the combined addition of 0.65% Al–3Ti, 0.60% of Al–3B grain refiner and 0.20% of Al–10Sr modifier to A356 alloy resulted in maximum UTS, when compared to the individual addition of grain refiner and modifier in an untreated conditions. The effect of grain refinement and modification on the mechanical properties is shown in Table 5. Further an improvement in the mechanical properties with the addition of grain refiners and modifier is clearly indicated in Table 5 and Fig. 6. In the absence of grain refiner and modifier, A356 alloy shows 131 MPa 0.2% PS, 185 MPa UTS, 3.25%E, 3.32%R, 87YM and 245VHN, while with the combined addition of grain refiner and modifier, 142 MPa 0.2% PS, 202 MPa UTS, 4.92%E, 7.55%R, 100YM and 298VHN were obtained.

Conclusions

1. Addition of grain refiner (Al–3Ti and Al–3B) and modifier Al–10Sr master alloys to A356 alloys leads to change in microstructure.
2. Improved mechanical properties were obtained due to the change in the microstructure of A356 alloy due to the addition of grain refiner/modifier.
3. Improvements in mechanical properties were observed with the minor additions of grain refiner and or modifier to A356 alloy.

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