

EFFECTS OF OPTIMUM AMOUNT OF Sr AND Sb MODIFIERS ON TENSILE, IMPACT AND FATIGUE PROPERTIES OF A356 ALUMINUM ALLOY *

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Abstract – In this study the effect of Sr and Sb on silicon modification were investigated. Casting properties, i.e. tendency to produce the porosity of both Sr and Sb treated alloys were evaluated. Finally, the effect of heat treatment on tensile and fatigue properties and silicon morphology was examined. Modification by Sr can convert the silicon phase from acicular to fibrous. The optimum amount of Sr content for achieving a modified fibrous structure in a sand mould is 0.013% Sr (by weight), whereas the amount for Sb is around 0.1%. Castings modified with Sr develop a significant increase in porosity, whereas little effect was observed in alloys treated with Sb. Mechanical properties of the modified A356 alloy were superior to the unmodified alloy. Solution heat treatment at 540°C for 6 hours, water quenching and aging at 150°C for 3 hours significantly enhance these properties.

Keywords – A356 aluminum alloy, Sr, Sb, modifier, fatigue, tensile

1. INTRODUCTION

The A356 aluminum alloy exhibits good castability, high strength to weight ratio and good corrosion resistance, and has been used in the automotive, machinery, and defense industries [1]. These properties can be easily achieved by modification of the eutectic silicon either by rapid solidification or by the introduction of modifiers to the melt [2]. The elements Lanthanum, Cerium, Arsenic, Antimony, Selenium and Cadmium have been reported to stimulate a silicon modification effect, but in commercial applications only Na, Sr, and Sb are used [3, 4].

The mechanical properties of the Al-Si-Mg alloy are related to the size, shape and distribution of the eutectic silicon phase in the microstructure. A well-rounded silicon phase can enhance mechanical properties, especially ductility of the alloy, and can be produced by the addition of a modifier to the melt. The addition of Sr neutralizes the effect of phosphorous (P) in forming AlP nuclei, and promotes the formation of a fibrous silicon structure by retarding the growth rate of silicon [5, 7]. The Sr recoveries are usually high (of the order of 90%), while its tendency toward fading (vanishing) is much lower than that of Na [8]. It is reported that the optimum Sr content for attaining modified morphology is in the range of 0.01% Sr, which depends on the process conditions used [6]. However, a survey of the literature shows a substantial variation in this optimum Sr content [9-11]. It is quite apparent that the rather wide variations in Sr are attributed to a number of factors, including purity of charge material, casting solidification rate, modifier addition and castings analysis method. Sr dissolution, which requires a certain incubation time along with the fading phenomenon that takes place concurrently, renders control of the optimum Sr level process dependent. It has been seen that porosity increases in the Sr treated castings [12-14]. The formation of porosity during the solidification of metals is a major concern for the casting industry since it reduces fatigue performance and total elongation [15]. In spite of recommended guidelines for process optimization during casting [16], porosity remains a costly problem for both the foundry industry and the end users.

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Therefore, special attention regarding degassing and molten metal feeding is required to produce sound castings.

The main causes of pore formation during casting are insoluble gas evolution (microporosity) and inadequate feeding, causing volumetric shrinkage (macroporosity). The classification of the observed pores is often based upon their shape, i.e. rounded pores are classified as gas pores, whereas irregular pores are classified as shrinkage pores. This classification embodies the assumption that gas pores are formed exclusively by the growth of bubbles in the liquid, whereas shrinkage pores are formed by removal of liquid from around the solidified dendrites [4, 17]. Whittenberger and Rhines [17], however, showed that the content of potential gas forming species such as hydrogen is a key factor in the formation of both types of porosity, indicating that the evolution of gas from solution also occurs during the formation of irregular pores. The amount of porosity increases by Sr modification. It has been suggested that this increase in porosity is due to the increased hydrogen content in the melt. This is either through the direct introduction of hydrogen accompanying the modifier into the melt, or results from the increased hydrogen absorbing rate of the modified melt [18]. Another report [19] shows that the tendency to absorb hydrogen gas is melt temperature dependent. Virtually no gas increase occurred when the melt temperature was below 745 °C, while the hydrogen content increased notably with temperature when the melt temperature was above 746 °C.

By using chilling and increasing the solidification rate, the percent of porosity was decreased as expected. This is due to the fact that less time is available for hydrogen diffusion into interdendritic regions to produce gas porosity, and higher temperature gradients may result, favoring interdendritic feeding [19].

The purpose of this study is to evaluate the effect of Sr and Sb on the mechanical properties of an A356 aluminum alloy, and to understand the casting characteristics of Sr and Sb treated alloys. In addition, the effects of solidification rate and heat treatment on the tensile and fatigue properties of both Sr and Sb treated alloys are examined.

2. EXPERIMENTAL PROCEDURES

The experiment procedures involved the preparation of 6.5 kg melts using SiC crucible in a gas fired furnace. The chemical composition of the alloy is shown in Table 1. Strontium was added to the melt in the form of strontium chloride salt made by the Merk company with 99% purity, using a graphite plunger. Sr was added to the melt in the range of 0.001%-0.02% wt and an optimum amount of 0.013% was found by modified morphology evaluation which was confirmed by tensile test results. All additions were made at temperatures in the range of 730 to 750 °C and the holding time was 15 minutes. All melts were degassed with pure argon. The degassing agent was bubbled into the melt at a rate of 1.5 liters per minute in a depth of 12 cm for thirty seconds.

Table 1. Chemical composition of the (A356) aluminum alloy

Si	Mg	Fe	Mn	Cu	Cr	Ni	Zn	Ti	Al
7.03	0.48	0.14	0.1	0.18	0.01	0.01	0.14	0.03	Balance

To evaluate the effect of Sb on the modification of silicon, pure Sb in the range of 0.001%-0.29% wt was incorporated into the melt in the same way as Sr was added. In this stage, the original charge materials composed of pure Al, Si, and Mg were used to avoid the contamination of other modifying agents such as Sr. After degassing, the melt was poured between 720-730 °C into silica sand molds at room temperature to produce a designed casting shape according to Fig.1. By application of local cooling (chilling) at one side of the mold and top riser at the other side, the beneficial effects of metal chill on the microstructure and mechanical properties of sand castings are evaluated. Figure 2 shows the cooling curves at the one and ten centimeter sections from the chilled end. The cooling rates before eutectic reaction at these one and ten centimeter distances from the chilled end are in sequence 2.13 and 0.95 °C/sec. The cooling rate data was joined by a network of chromel-alumel thermocouple system, which was connected to a computer.

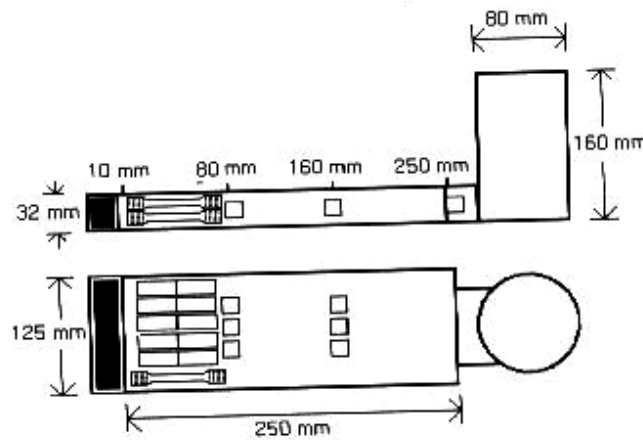


Fig.1. Schematic view of casting model with the position of chill and the tensile, impact, metallography and porosity samples

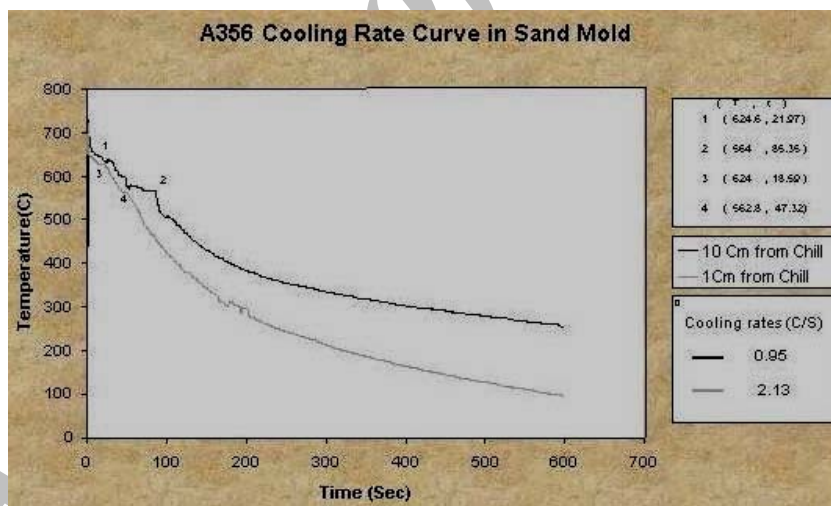


Fig. 2. Cooling curves for one and ten centimeter distance from chilled end

The modifiers content of the casting was measured by an atomic absorption method. The characteristic of the gating system height (h) and time of pouring to (t_p) are shown in Table 2. Properties of the molding sand are given in Table 3.

Table 2. Characteristics of the gating system

Sprue, Chock area (mm ²)	Sprue, Top area (mm ²)	Runner Area (mm ²)	Gate Area (mm ²)	Sprue height (mm)	Pouring Time (second)
225	435	550	1150	190	14

Table 3. Properties of the molding sand

Green compression strength (MPa)	Green shear strength (MPa)	AFS fineness	Permeability (cm ³ /min)
0.155	0.075	65	37

Porosity is calculated according to the formula [3]

$$P = \frac{\rho_t - \rho_{app}}{\rho_t} \quad , \quad \text{and} \quad \rho_{app} = \frac{W_D}{V_a} = \frac{W_D \rho_l}{W_D - W_{ss}}$$

where ρ_t = theoretical density, ρ_{app} = apparent density, ρ_l = liquid density, W_D = dry weight and W_s and W_{ss} are suspended and suspended saturated weight.

In calculations, the theoretical density of the A356 aluminum alloy which is reported as 2.685 g/cm^3 [20] was used and the apparent density was measured according to the Archimedes principle [21, 22].

The tensile test specimens were produced according to ASTM-E8 and were tested by an Instron machine with a 5 ton capacity and 0.2 cm/min cross head speed. Fatigue samples were prepared according to the ASTM-E466-82 standard from longitudinal samples cut and tested by a Wholer machine. Tests performed at ambient temperatures on smooth specimens at a stress ratio $R = -1$.

The impact test samples are prepared according to ASTM, E23-28. The samples were two types, notched and unnotched. The notched impact samples were tested by a charpy machine with the following characteristics; Hammer weight 0.917 kg, Length of hammer arm 225 mm, Impact velocity of hammer with the sample 2.93 m/s. A356 alloys are usually heat treated to develop the optimum mechanical properties. In this work the following heat treatment was used [1, 9]: Solution treatment at $540^\circ\text{C} \pm 5$ for 6 hours. Water quenched to 60°C . Precipitation hardening at $150 \pm 5^\circ\text{C}$ for 3 hours.

3. RESULTS AND DISCUSSION

The microstructure of the test samples was examined by optical and scanning electron microscopes. Typical microstructures in the as-cast condition are shown in Figs. 3-5. Unmodified sand castings contain large flakes of Si (Fig.3). A fibrous Si is obtained upon modification with 0.013% Sr (Fig.4).

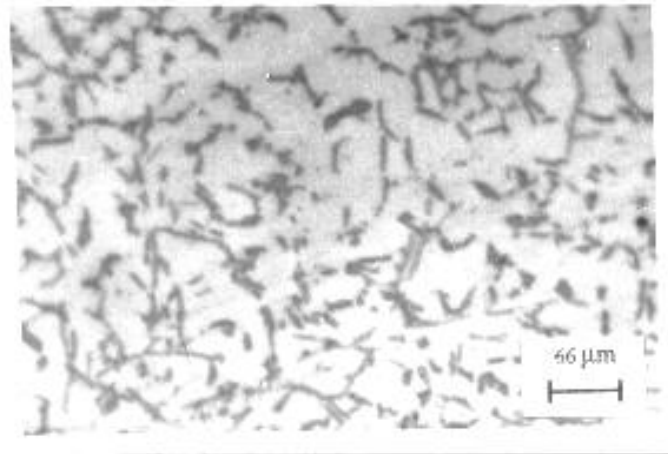


Fig. 3. Optical microstructure of "as received" A356 aluminum alloy (flakes = silicon phase)

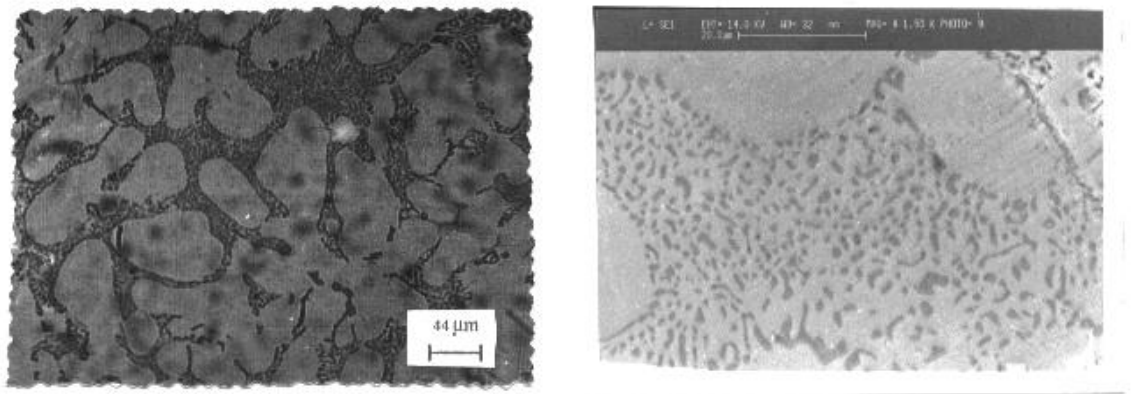


Fig. 4. (a) Optical and (b) SEM, microstructure of Al-Si alloy modified with 0.013% Sr

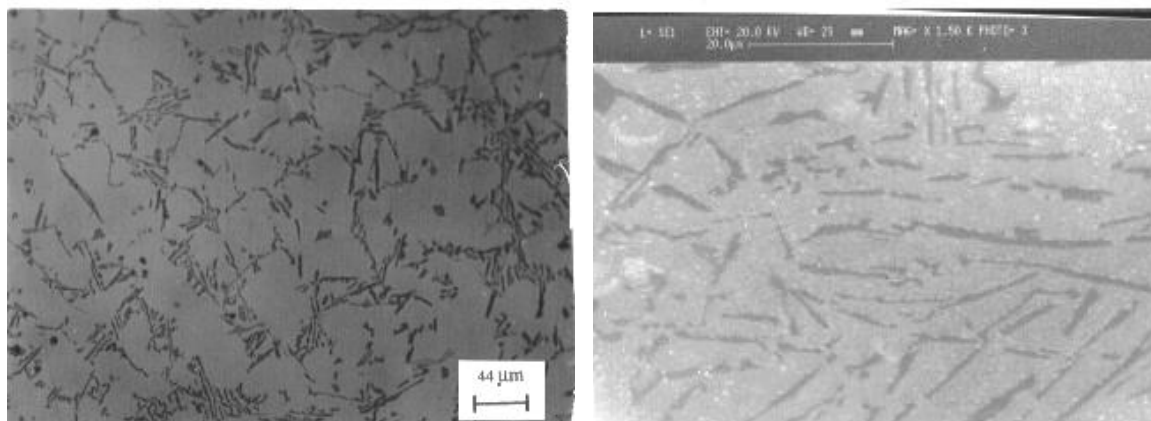


Fig. 5. (a) Optical and (b) SEM, microstructure of Al-Si alloy modified with 0.1% Sb

By increasing the wt% of Sb of the melt from 0 to the 0.1 % Sb, a general trend can be seen; that is, the morphology of the eutectic silicon changes progressively from unmodified acicular (Fig.3) to lamellar as (Fig.5). In order to attain a lamellar or a modified structure, optimum Sb concentration of 0.1% is required.

The Sr modified samples contain a significant number of pores compared to the unmodified castings. The results of the porosity measurements are shown in Table 4. As can be seen, the chill reduced the porosity in both the modified and unmodified castings. Comparison of modified and unmodified casting shows the Sr modified samples contain higher porosity than the unmodified. The porosity of Sb modified castings decreased a little with respect to the unmodified castings.

Table 4. Percent of porosity of A356 aluminum alloy castings with different distances from the chill zone

Casting Series	Distance from the chill zone			
	1 cm	8 cm	16 cm	25 cm
Unmodified, no chill	1.35	1.42	1.45	1.34
Unmodified, with chill	0.14	0.22	0.47	0.91
0.013% Sr modified, with chill	0.24	0.46	1.02	1.97
0.1% Sb modified, with chill	0.13	0.21	0.43	0.82

Mechanical properties of Al-Si casting alloys, especially elongation, depend on the alloy structure and on the eutectic silicon, which may have an acicular or lamellar shape. It is known that elongation is improved by modifying the alloy by Sr to form a fibrous eutectic structure [9].

The result of tensile properties of 0.013% Sr modified and unmodified sand mold castings is shown in Table 5. Tensile strength and percent elongation increased respectively from 111 Mpa to 165 Mpa and 2.4% to 5.9% for Sr modified.

Table 5. Tensile properties of modified and unmodified A356 alloy

Condition	YS (MPa)	UTS (MPa)	%Elongation (25.0mm gage length)
unmodified	82	111	2.4
0.013%Sr modified	87.5	165	5.9
0.1%Sb modified	88	162	5.7

Charpy impact test samples were tested at different temperatures. The results of the impact tests are shown in the Table 6.

Impact test results show the modifier element enhanced the impact resistance of the alloy, especially the role of Sr. In this respect, Sr is superior to Sb at all test temperatures.

In 0.013% Sr modified specimens the ambient impact resistance of the unnotched samples at position A (1-8 cm from the chilled end) is 10.4 joule, which is 35% higher than the samples from position B(7.7 joule,

8-16 cm from the chilled end), due to the higher cooling rate at position A. Therefore a higher cooling rate can alleviate the deteriorating effect of Sr in the increase of porosity.

Table 6. Impact test results of A 356 Aluminum alloy

Conditions	Notched impact Energy, J at -50 °C A	Notched impact Energy, J at -10 °C A	Notched impact Energy, J at 25 °C A	Notched impact Energy, J at 90 °C A	Unnotched impact Energy, J at 25 °C for section A	Unnotched impact Energy, J at 25 °C for section B
unmodified	1.11	1.16	1.22	1.30	6.2	5.7
0.013% Sr modified	2.15	2.25	2.45	2.58	10.4	7.7
0.1% Sb modified	1.62	1.71	1.86	1.97	7.5	7.1

Section A is 1-8 cm from chilled end and section B 8-16 cm.

The rotating-bending stress fatigue behavior of the Al-Si (A356) alloy was measured with and without homogenization treatment at 540°C for 6 hr. An unmodified Al-Si (A356) alloy was used for comparison. Results of the fatigue tests are shown as S-N curves in Figs. 6 and 7. These curves show that the fatigue properties of the modified alloy are clearly superior to the reference alloy. A stress greater than 37 MPa can be sustained at a cycle level of $N = 10^6$ for near riser (NR), 0.013%Sr modified alloy; this is, when compared with the unmodified alloy (25MPa), an advantage of at least 48 percent.

The corresponding values for near chill (NC) samples are 58.5 MPa and 58 MPa, which show the beneficial effect of a higher cooling rate on the refinement of the microstructural constituents. Although the samples were all prepared from part A (1-8 cm from chilled end), the Sr modifier does not show any effects. This is due to the increase in porosity due to the Sr addition.

At a low number of cycles ($N=10^4$) the Sr modified alloy withstands stress values greater by more than 14 MPa for the A section samples and 35MPa for the B section samples relative to the unmodified specimens.

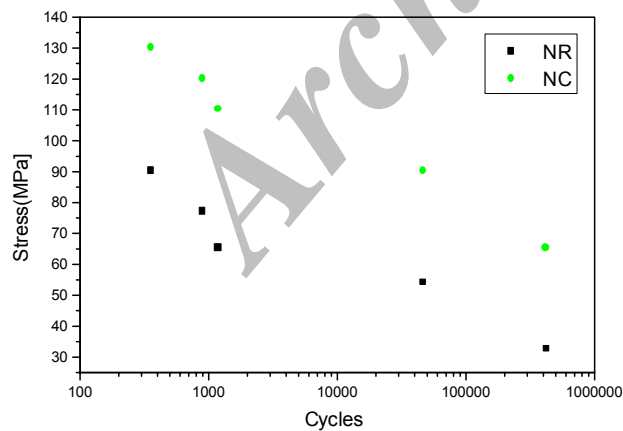


Fig. 6. Fatigue stress versus cycles curves for unmodified A356 aluminum alloy for near riser (NR, 8-16 cm from end quenched) and near chill (NC, 1-8 cm from quenched end) samples

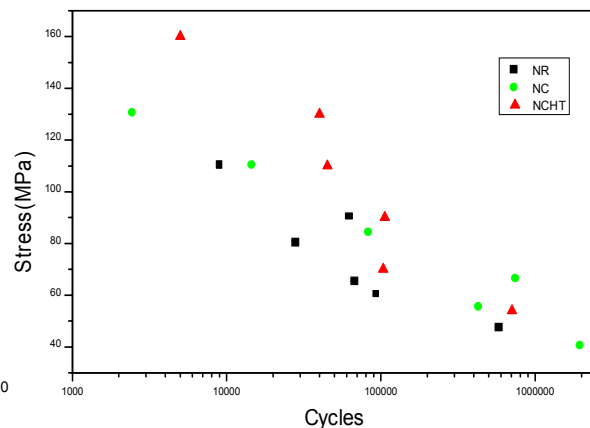


Fig. 7. Fatigue stress versus cycles curves for Sr modified A356 aluminum alloy for near riser (NR, 8-16 cm from end quenched), near chill (NC, 1-8 cm from quenched end), and near chill heat treated (NCHT) samples

4. CONCLUSIONS

1. Tensile strength of the 0.1% Sb and 0.013% Sr modified aluminum A356 alloy in sequence increased 31% and 33%, yield strength around 6% and strain to fracture 84% and 88% relative to the unmodified alloy. Therefore, the most profound effect of the modifier is on the ductility.

2. Sr increases the porosity. Raising the cooling rate decreases this effect. Therefore, higher cooling rates can alleviate this negative effect of Sr modifier addition. Not only does Sb not increase porosity, it also decreases it slightly.
3. Unnotched impact energy of unmodified, 0.013% Sr modified and 0.1% Sb modified samples are in the sequence 6.2, 10.4, and 7.5 Joule. Therefore, strontium increases the impact resistance of the alloy more than three times (10.4/6.2) relative to antimony (7.5/6.2). This ratio is less than 2 for notched samples at the same ambient temperature of (25°C).
4. The fatigue strength of near riser (NR) 0.013% Sr modified A356 aluminum alloy samples at 10^6 cycles is more than 48% greater than for the unmodified alloy. This is because Sr modification of the silicon phase increases the fatigue strength much more than the decrease due to porosity formation.
5. Near chill (NC) unmodified and Sr modified samples do not show any remarkable difference in fatigue strength at a cycle level of $N = 10^6$; this is due to the chill effect on the prevention of porosity formation caused by the Sr addition.

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