JOURNAL OF MATERIALS SCIENCE 39 (2004) 2023–2032

Influence of modification, solidification conditions and heat treatment on the microstructure and mechanical properties of A356 aluminum alloy

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The effects of casting thickness, modification and heat treatment on the microstructure and mechanical properties of A356.2 alloy have been investigated. Experiments were conducted with unmodified, Sr-modified (0.02% Sr) and Sb-modified (0.2% Sb) on both sand cast test bars with various thicknesses (from 3 to 9 mm) and permanent mold cast test bars.

The microstructural changes associated with these treatments have been studied by optical metallography, scanning electron microscopy (SEM) and image analysis.

The tensile properties of all samples were determined and the relationship between cooling rate, modification and heat treatment has been investigated.

The results show that modification has a beneficial effect on microstructure and improves the mechanical properties of the alloy. Modification has a major role in controlling the kinetics of the spheroidisation of silicon particles during heat treatment. Tensile properties improved more with heat treatment than with modification or cooling rate.

Antimony is effective on mechanical properties at higher solidification rates, while Strontium is more effective at lower solidification rates.

1. Introduction
Mechanical properties of Al-Si alloys are related to the morphology of silicon particles (size, shape and distribution), Al grain size, shape and dendrite parameters [1–4].

Modification changes silicon morphology and is achieved by rapid solidification, chemical modification and thermal modification in the solid state [3–9].

Na, Sr and Sb are commonly used for chemical modification and addition of small amounts of these elements to the melt changes the coarse and large needles of silicon into a fine and well-rounded form [3–10].

Heat treatment changes silicon morphology and the kinetics of spheroidisation are affected by the as-cast microstructure [11–13].

Three factors, cooling rate, modification and heat treatment can alter the silicon morphology separately or in conjunction with each other, to develop desired and optimum properties in the casting.

The effects of cooling rate, Strontium and Antimony addition, heat treatment and their relationship with microstructure and mechanical properties of A356 alloy are investigated in the present work.

2. Experimental work
2.1. Melt preparation and casting procedure
Melting was carried out in an induction furnace using a clay-graphite crucible. The chemical composition of the alloy used in the experiments is shown in Table I. The melt was thoroughly degassed with nitrogen and the temperature of the melt was 730 ± 5°C.

Elemental Sb and 10% Sr-90% Al master alloy was added to the melt to achieve the Sb level of 0.2% and Sr level of 0.02%. Impeller stirring was used for five minutes to homogenize the melt. To obtain various cooling rates, castings were made in a sand mold with various thicknesses (from 3 to 9 mm) with dypure system (Fig. 1) [14] and a standard ASTM-B-108-85a gravity die [15].

2.2. Heat treatment
Heat treatment of the castings was carried out in a muffle furnace. Solution heat treatment was carried out at

TABLE I Chemical composition of A356 alloy

Si	Mg	Fe	Cu	Zn	Mn	Ti	Al
7.3	0.43	0.11	0.03	0.02	0.09	0.11	Balance

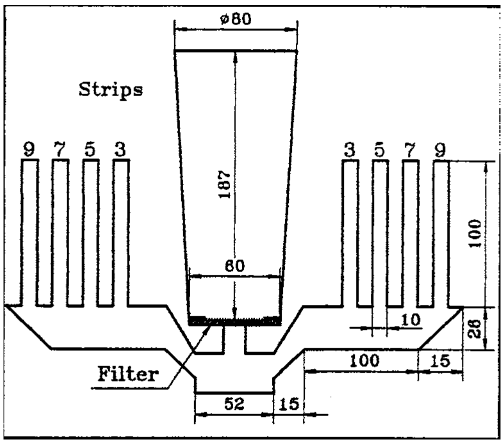

Figure 1 Schematic of sand cast tensile test bars.

540°C for 6 h. All of the samples were quenched in water at a temperature of 60°C and then aged at 155°C for 4 h (T6 condition).

Six tensile test specimens were machined according to ASTM-B577 [16] for each condition (sand or permanent mold casting). The tensile tests were carried out on a computer controlled testing machine (Instron) at a constant cross head speed of 2.5 mm/min. A strain gauge extensometer (gauge length of 25 mm) was used to measure the 0.2% proof stress, ultimate tensile strength and the elongation up to fracture.

The metallograghic samples were obtained by sectioning the gauge length portion of the test bars. The microstructure changes were studied by optical and scanning electron microscopy. In order to develop a more consistent and less subjective evaluation of the microstructure, quantitative metallograghy was employed using an image analyzer interfaced with an optical microscope. A total of 20 fields were evaluated on each sample. The dendrite arm spacing (DAS) was determined through image analysis. The following parameters were also determined to quantify the Si particles:

Average particles area (μm^2)
Average particle diameter (μm)
Average particle perimeter (μm)
The number of particles per unit area
Aspect ratio
Shape factor

The shape factor is defined as:

$$SF = P^2/4\pi A$$

where P is the particle perimeter and A is the particle area.

3. Results and discussions

3.1. Effect of cooling rate and modification

Typical microstructures in the as-cast condition for both sand and permanent mold test bars are shown in Figs 2 and 3. These figures indicate a general coarsening

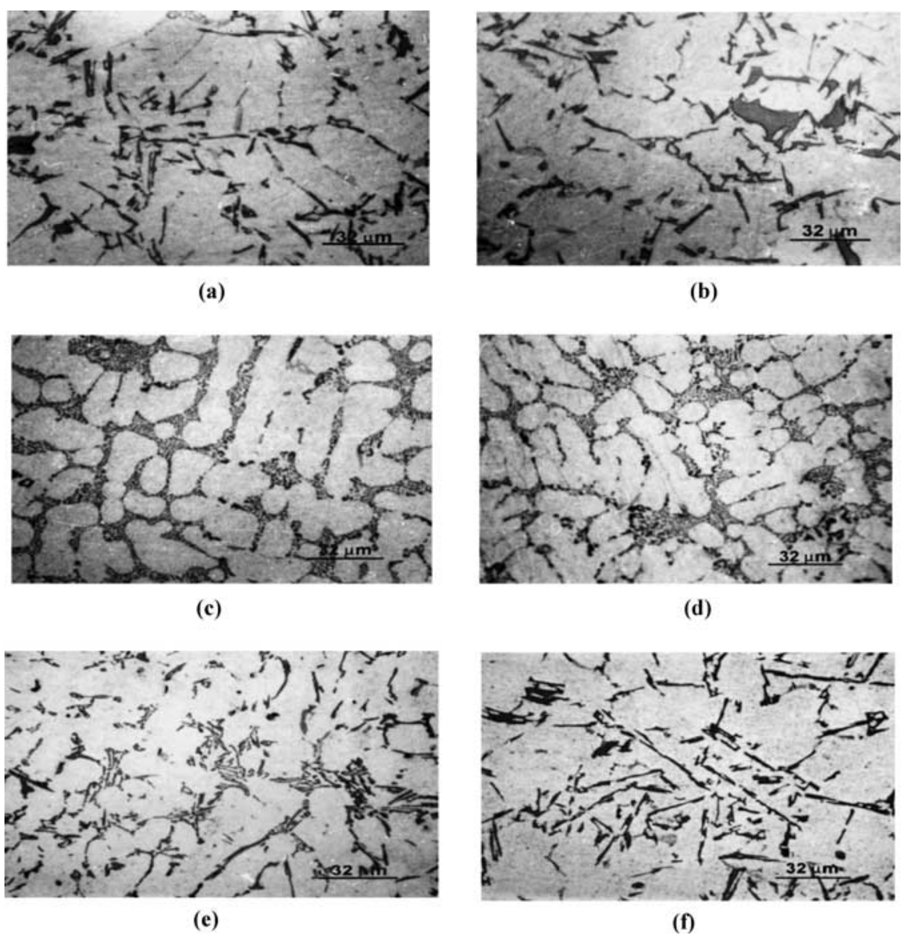

Figure 2 Effect of casting thickness and modification on microstructure of sand cast specimens (As-cast condition): (a) 3 mm, unmodified, (b) 9 mm, unmodified, (c) 3 mm, Sr modified, (d) 9 mm, Sr modified, (e) 3 mm, Sb modified and (f) 9 mm, Sb modified.

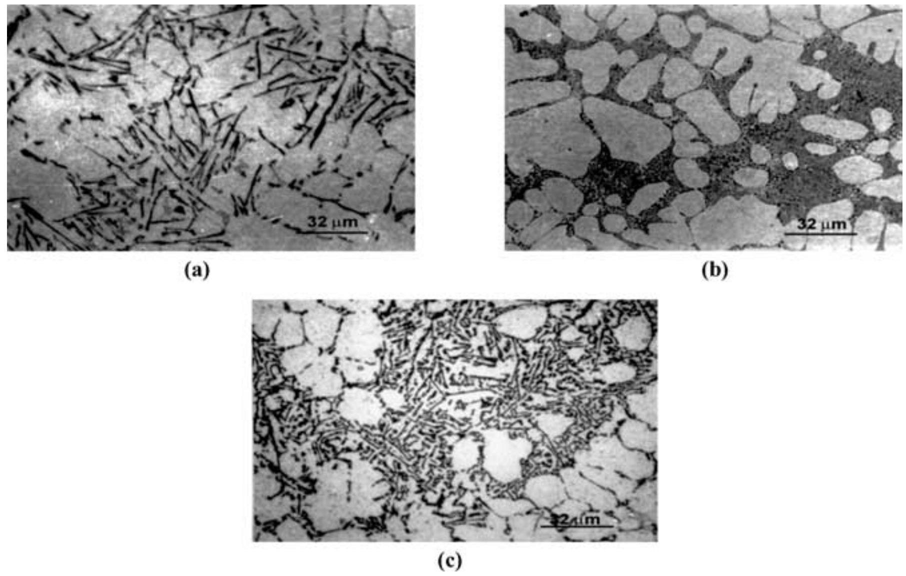

Figure 3 Typical microstructure of permanent mold cast specimens (As-cast condition): (a) Unmodified, (b) Sr modified and (c) Sb modified.

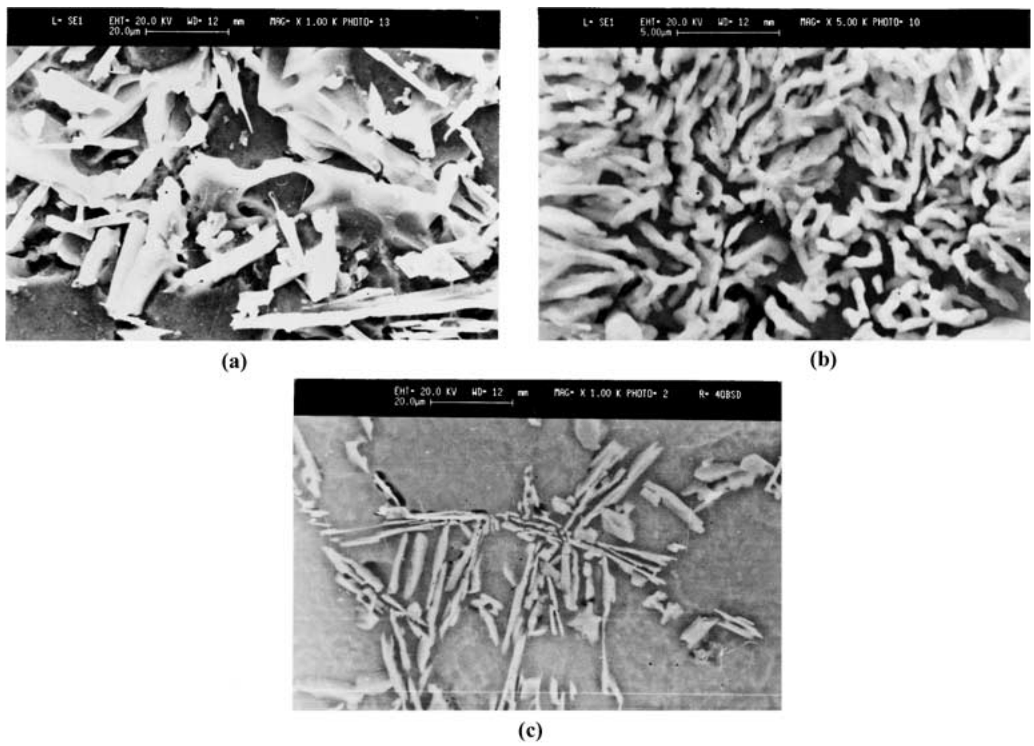

Figure 4 SEM micrograph of sand-cast specimens (As-cast condition): (a) Unmodified, (b) Sr-modified and (c) Sb-modified.

of eutectic silicon in unmodified and thicker samples (2a,b–3a).

This observation follows a well-established physical explanation of the effect of cooling rate on as-cast microstructure of the alloy. Faster cooling rate in the thin wall castings or permanent mold castings promotes a faster nucleation and growth rate and results to a finer microstructure (Figs 2 and 3) that is associated with higher mechanical properties.

Fig. 4 shows the SEM micrograph of sand cast specimens. Modification affects the size and shape of silicon particles. With a higher solidification rate, modification of microstructure is more evident and for Sr-modified samples a fully modified structure can be achieved.

Paray and Gruzleski [19] have reported that the amount of modifier required for a given alloy is lower for a permanent mold casting than for sand casting.

The variation in Si particle morphology with dendrite arm spacing (DAS) in Sr and Sb modified alloys for sand cast test bars is shown in Fig. 5a–c for the as-cast conditions. Fig. 5a shows the variation of average diameter of Si particles as a function of the dendrite arm spacing and modification. The average diameter decreases significantly with decreasing dendrite arm spacing in both modified and unmodified specimens. Results show that Sr is more effective than Sb for all cooling rates.

For Sb-modified alloys the decreases in average Si particles size is strongly affected by cooling rate.

Fig. 5b shows the Si particle count per unit area varies as a function of modification and dendrite arm spacing.

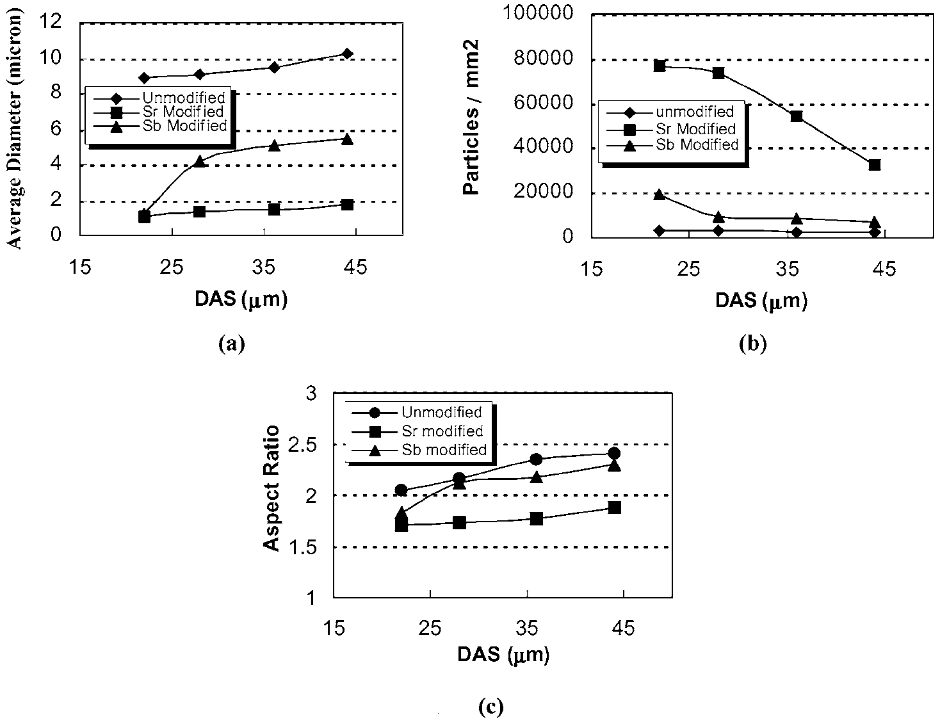

Figure 5 Particles shape as a function of the dendrite arm spacing in the as-cast condition: (a) Average diameter, (b) particles density and (c) Aspect ratio.

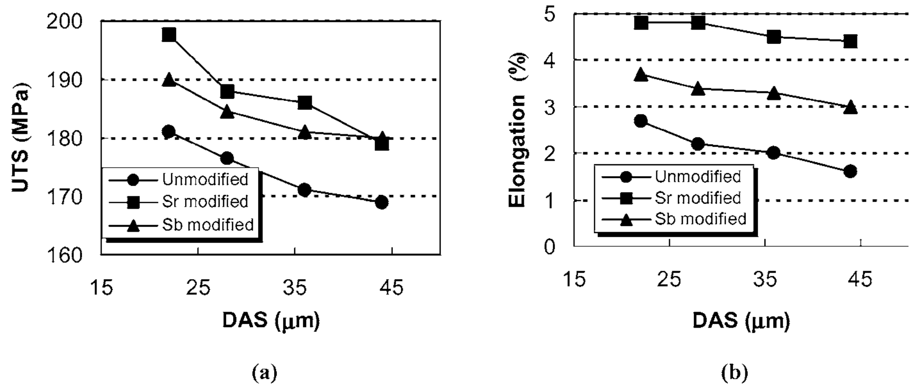

Figure 6 Mechanical properties as a function of dendrite arm spacing (DAS) in the as-cast condition: (a) Ultimate tensile strength and (b) tensile ductility.

The number of particles per unit area significantly increases with Sr modification and higher cooling rate. Strontium strongly increases the particle number particularly at faster cooling rates. The particle count per unit area in Sb-modified samples is strongly affected by cooling rate.

The aspect ratio of Si particles is plotted in Fig. 5c as a function of modification and dendrite arm spacing. Aspect ratio of Silicon particles in Sr-modified samples is low for all cooling rates.

In Sb-modified alloys the aspect ratio decreased significantly in thin sections. Also, because of the higher solidification rate, the size, shape and particle count of silicon are more affected in permanent mold than in sand cast condition for both modified and unmodified samples (Table II).

The mechanical properties of as-sand cast specimens (ultimate tensile strength and percent elongation) are plotted in Fig. 6a–b as a function of dendrite arm spacing and modification for as-cast samples.

The ultimate tensile strength and yield strength increased with Sr and Sb modification and increasing cooling rate. For example in-unmodified samples with decreasing casting thickness (from 9 to 3 mm), the ultimate tensile strength increased 7%. With modification for the same casting thickness (for example 9 mm) the ultimate tensile strength increased by 1.7% in

TABLE II Silicon particles size analysis at permanent mold cast condition (As-cast)

Parameter	Unmodified	0.02% Sr	0.2% Sb
Perimeter (μm)	29.12 ± 21.32	3.94 ± 2.89	14.5 ± 12
Area (μm^2)	7.4 ± 7.16	1.21 ± 1.09	5.78 ± 4.45
Average diameter (μm)	7.85 ± 6.23	1.31 ± 1.21	2.88 ± 2.3
Particles/mm^2	10303 ± 1079	102415 ± 28163	27551 ± 2564
Shape factor	9.11 ± 5.05	1.02 ± 0.56	2.89 ± 1.76
Aspect ratio	2.14 ± 0.96	1.74 ± 0.63	1.92 ± 0.84

TABLE III Tensile properties of permanent mold cast samples (as-cast)

Parameter	Unmodified	0.02% Sr	0.2% Sb
UTS (Mpa)	195 ± 14	209 ± 7	204 ± 3
Y.S. (Mpa)	151 ± 11	147 ± 8	145 ± 84
El.%	6 ± 1.3	7 ± 2.4	6.3 ± 1.4

unmodified samples to 4.4 and 3% for Sr and Sb modified samples respectively. An improvement of about 78 and 37% was observed in the percent of elongation in 3 mm thickness for Sr and Sb modified test bars, while for 9 mm thickness an improvement of 175 and 78% was observed for Sr and Sb modified test bars respectively.

In permanent mold casting the mechanical properties are higher than those obtained in the sand cast condition (Table III). It was observed that the percent elongation was increased about 16% in Sr modified and 5% in Sb modified test bars.

There is evidence from the present study and elsewhere that the greatest improvement in tensile properties of modified alloys is observed at slow solidification rate i.e., thick casting sections.

3.2. Effect of cooling rate, modification and heat treatment

Typical heat-treated microstructures for unmodified, Sr modified and Sb modified samples are shown in Figs 7a–f and 8a–c. A comparison shows that the microstructures of castings produced with thinner walls or in a permanent mold are generally finer than those produced in thicker sand molds even after heat treatment. The particles undergo changes in shape and size during heat treatment.

In thinner sand castings and permanent mold castings (faster solidification rates) a fully spheroidized structure is observed for Sr modified samples (Figs 7c and 8b), while in Sb modified samples some elongated Si particles, especially in slower solidification rates, are still present (Fig. 7f).

The result of quantitative analysis for sand casting in DAS and permanent mold castings are presented in Tables IV–VII for heat-treated samples.

Fig. 9a shows the effects of modification on the average size of silicon particles in heat-treated sand cast test bars. The size of the silicon particles in 3 and 9 mm thicknesses of unmodified samples is 7.74 and 8.85 μm respectively. While the size of particles is 1.54 and 3.75 μm in Sr

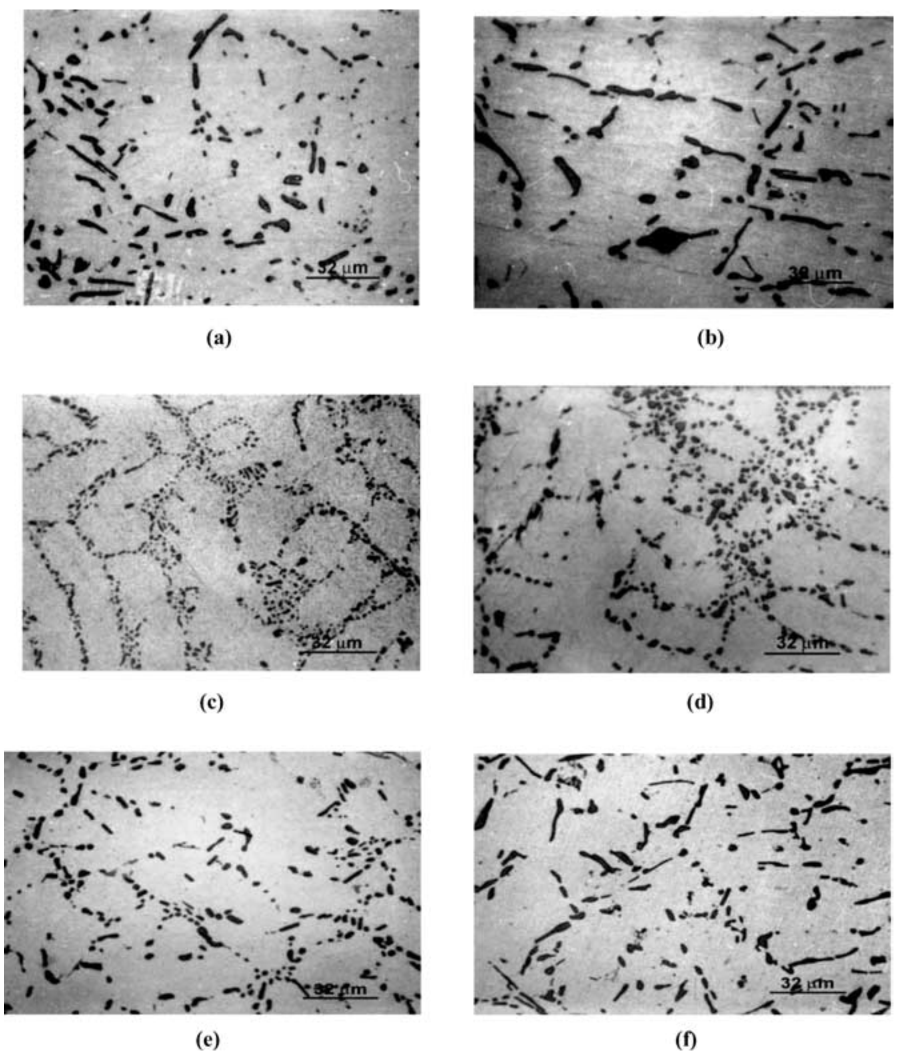

Figure 7 Typical microstructures of heat-treated sand-cast test bars: (a) 3 mm, unmodified, (b) 9 mm, unmodified, (c) 3 mm, Sr modified, (d) 9 mm, Sr modified, (e) 3 mm, Sb modified and (f) 9 mm, Sb modified.

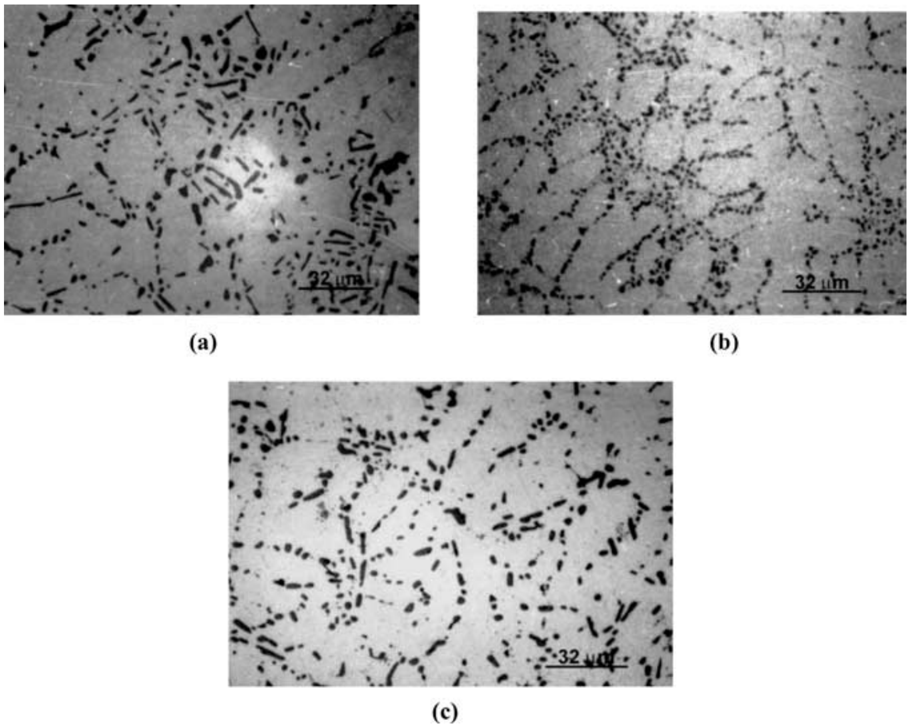

Figure 8 Typical microstructures of heat-treated permanent cast test bars: (a) Unmodified, (b) Sr modified and (c) Sb modified.

modified and 3.56 and 7.6 μm in Sb modified samples.

The influence of dendrite arm spacing and modification on the number of particles formed per mm^2 for heat-treated samples is shown in Fig. 9b. The number of particles decreased significantly with increasing DAS. The results of image analysis indicate that the number of particles decreased from 3677 to 2730 by increasing casting thickness from 3 to 9 mm in unmodified specimens (Table IV). In Sr and Sb modified specimens this parameter decreased from 23103 to 8665 (Table V) and 8679 to 4112 respectively (Table VI). Thus there was a reduction of 26, 62 and 52% for unmodified, Sr and Sb modified specimens in the number of particles per unit area by increasing casting thickness respectively.

Fig. 9c shows the aspect ratio of Si particles as a function of DAS and modification for heat-treated specimens. Unmodified specimens and higher DAS exhibit a higher aspect ratio than modified specimens. As expected the differences between unmodified and modified Si particles for various thicknesses diminish during heat-treatment.

The average diameter of Si particles for unmodified and Sr modified specimens are compared in Fig. 10. For example, in Sr modified specimens the size of particles

TABLE IV Image analysis measurement of unmodified heat-treated sand-cast test bars

	Thickness (mm)			
Parameter	3	5	7	9
Perimeter (μm)	25.75 ± 22.37	29.17 ± 27.36	30.16 ± 29.03	32.39 ± 32.05
Area (μm^2)	23.73 ± 20.01	29.36 ± 26.65	31.47 ± 28.41	31.96 ± 30.72
Av. diameter (μm)	7.74 ± 6.52	7.89 ± 7.33	8.78 ± 7.91	8.85 ± 8.03
Particles/mm^2	3677 ± 153	2979 ± 247	2894 ± 301	2730 ± 725
Shape factor	2.22 ± 2.17	2.31 ± 1.78	2.3 ± 1.95	2.61 ± 2.44
Aspect ratio	1.86 ± 0.75	1.93 ± 0.91	1.97 ± 1.08	2.1 ± 1.17

TABLE V Image analysis measurement of Sr modified heat-treated sand-cast test bars

	Thickness (mm)			
Parameter	3	5	7	9
Perimeter (μm)	6.51 ± 6.33	8.65 ± 7.93	10.6 ± 9.88	12.95 ± 11.5
Area (μm^2)	4.85 ± 4.09	5.25 ± 5.08	7.72 ± 7.94	9.02 ± 8.38
Av. diameter (μm)	1.54 ± 1.48	2.4 ± 1.81	3.03 ± 2.36	3.75 ± 2.96
Particles/mm^2	23103 ± 5107	14067 ± 3412	12181 ± 1936	8865 ± 1912
Shape factor	1.14 ± 0.62	1.14 ± 1.1	1.18 ± 0.99	1.47 ± 0.92
Aspect ratio	1.62 ± 0.58	1.63 ± 0.65	1.65 ± 0.7	1.75 ± 0.7

TABLE VI Image analysis measurement of Sb modified heat-treated sand cast test bars

	Thickness (mm)			
Parameter	3	5	7	9
Perimeter (μm)	12.34 ± 10.36	12.78 ± 11.86	16.34 ± 12.45	26.91 ± 23.86
Area (μm^2)	10.96 ± 10.42	11.92 ± 11.55	16.71 ± 15.91	16.74 ± 11.8
Av. diameter (μm)	3.56 ± 2.77	3.72 ± 3.11	4.77 ± 3.38	7.6 ± 5.82
Particles/mm^2	8679 ± 1987	7308 ± 1476	5356 ± 1213	4112 ± 536
Shape factor	1.1 ± 0.78	1.16 ± 0.73	1.27 ± 0.62	3.44 ± 1.9
Aspect ratio	1.75 ± 0.85	1.85 ± 0.85	1.88 ± 0.79	2.01 ± 1.04

TABLE VII Image analysis measurement of heat-treated permanent mold test bars

Parameter	Unmodified	0.02% Sr	0.2% Sb
Perimeter (μm)	21.65 ± 18.92	7.11 ± 6.17	12.96 ± 9.26
Area (μm^2)	16.98 ± 14.37	3.27 ± 3.22	8.4 ± 7.38
Av. diameter (μm)	6.06 ± 4.4	2.34 ± 1.59	3.81 ± 2.49
Particles/mm^2	6773 ± 651	21427 ± 2695	9361 ± 1084
Shape factor	2.19 ± 1.39	1.23 ± 1.17	1.59 ± 0.93
Aspect ratio	1.82 ± 0.63	1.62 ± 0.57	1.75 ± 0.87

increased from 1.12 to 1.54 μm for as-cast samples with 3 mm thickness and from 1.75 to 3.75 μm for 9 mm thickness after heat treatment. While in unmodified samples a decrease of 8.92 to 7.74 μm for 3 mm thickness and 10.25 to 8.85 μm for 9 mm thickness was observed after heat treatment.

The comparison of particle count per unit area between as-cast and heat-treated unmodified and Sr-modified specimens is shown in Fig. 11. The number of particles for unmodified specimens increased after heat treatment. For example, for 3 mm thickness the number of particles increased from 3256 to 3677 and for 9 mm thickness from 2553 to 2730. While for Sr-modified samples the number of particles for 3 mm thickness decreased from 77106 to 23103 and for 9 mm thickness from 32873 to 8865 after heat treatment.

It was also observed that at low cooling rates (thick sections) variation of particles per unit area and average diameter for both modified and unmodified specimens was more affected after heat-treatment. The image analysis results of permanent mold cast samples after heat treatment (Table VII) indicate that there is not too much variation in size and shape of silicon particles in both modified and unmodified specimens, because of the high cooling rate of the permanent mold casting.

The tensile properties of heat-treated (T6) specimens and their quality index (Q) values, defined as:

$Q = \text{UTS} + 150 \log (\% \text{ elongation})$ [18] are given in Tables VIII–XI.

The percent elongation and quality index for sand cast specimens are plotted as a function of dendrite arm spacing in Figs 12 and 13.

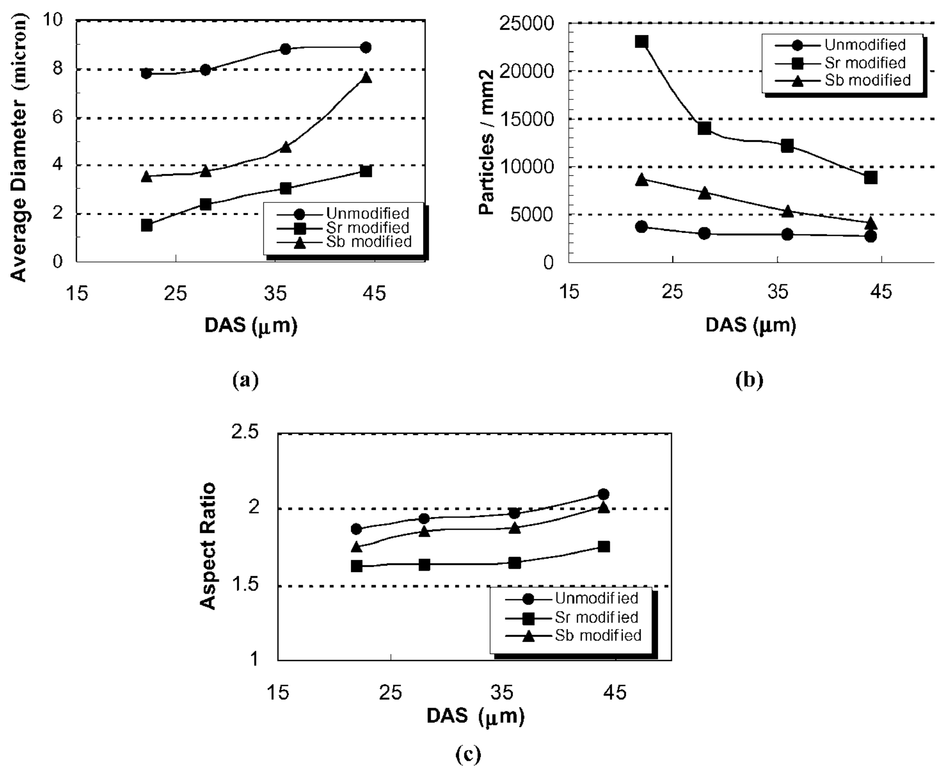

Figure 9 Particles shape as a function of dendrite arm spacing for sand-cast heat treated specimens: (a) Average diameter, (b) particles density and (c) aspect ratio.

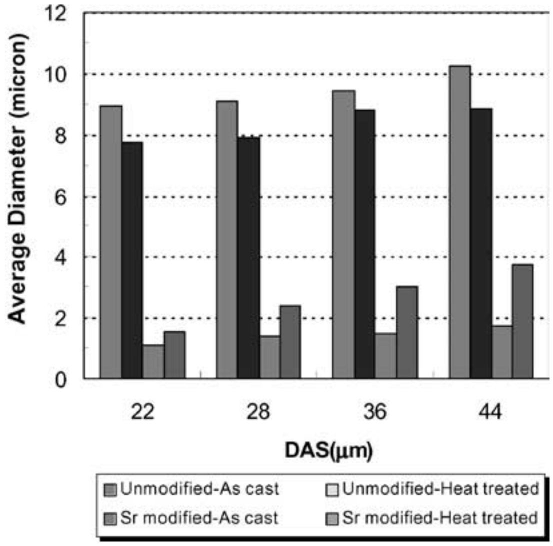

Figure 10 Effect of heat treatment on the size of particles in unmodified and Sr-modified sand-cast specimens.

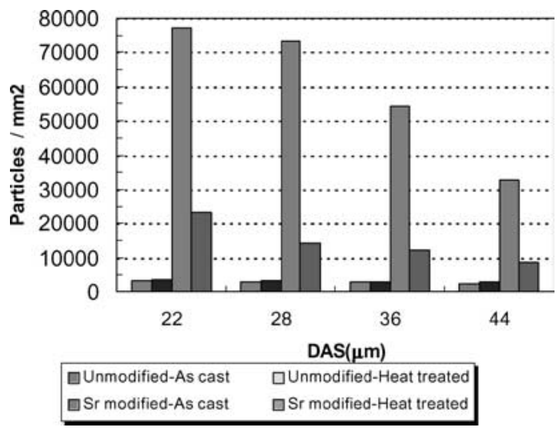

Figure 11 Effect of heat treatment on the particles density of unmodified and Sr modified sand-cast specimens.

The % elongation of test bars decreased for all specimens with increasing DAS (Fig. 12). However, in most cases the presence of Sr in sand or permanent mold cast samples results in higher % elongation values. For example, the % elongation of 3 mm thickness sand cast unmodified specimens is 2.2%, while for Sr and Sb modified specimens an increase of 208 and 186% was observed and for 9 mm thickness an increase of 238 and 178% for Sr and Sb modified specimens was observed respectively.

Fig. 13 shows the *Q* values of sand-cast specimens as a function of dendrite arm spacing and Table XI shows this parameter for permanent mold specimens. As can be expected, the Sr-modified specimens have higher values of *Q* due to the higher % elongation.

TABLE VIII Tensile properties of unmodified sand-cast specimens in T6 condition

Thickness (mm)	YS (Mpa)	UTS (Mpa)	El. (%)	Q (Mpa)
3	238 ± 12	274 ± 4	2.3 ± 0.8	328
5	226 ± 13	266 ± 3	2.2 ± 0.8	317
7	223 ± 8	263 ± 11	1.9 ± 0.9	305
9	215 ± 5	254 ± 9	1.8 ± 1.1	292

TABLE IX Tensile properties of Sr-modified sand-cast test specimens in T6 condition

Thickness (mm)	YS (Mpa)	UTS (Mpa)	El. (%)	Q (Mpa)
3	253 ± 1.5	288 ± 4	4.8 ± 0.5	390
5	249 ± 8	282 ± 6	4.4 ± 0.7	373
7	246 ± 7	275 ± 5	4.3 ± 0.8	370
9	241 ± 5	271 ± 7	4.3 ± 0.9	366

TABLE X Tensile properties of Sb-modified sand-cast test specimens in T6 condition

Thickness (mm)	YS (Mpa)	UTS (Mpa)	El. (%)	Q (Mpa)
3	257 ± 11	291 ± 7	4.1 ± 1.3	383
5	254 ± 5	273 ± 7.5	4 ± 0.9	363
7	232 ± 3	272 ± 4	3.6 ± 0.9	355
9	230 ± 4	268 ± 3	3.2 ± 1.1	344

TABLE XI Tensile properties of permanent mold test specimens in T6 condition

Parameter	Unmodified	0.02% Sr	0.2% Sb
YS (Mpa)	218 ± 0	212 ± 5	219 ± 3.5
UTS (Mpa)	272 ± 5	265 ± 16	283 ± 8
El. (%)	8.3 ± 1	8.7 ± 1.4	8.2 ± 0.8
Q (Mpa)	410 ± 5	406 ± 38	411 ± 22

3.3. The relationship between microstructure and mechanical properties

For as-cast specimens the correlation and relationship between the ultimate tensile strength, % elongation,

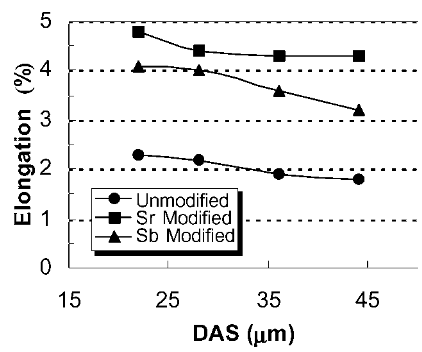

Figure 12 Elongation to fracture as a function of dendrite arm spacing (DAS) for sand-cast heat-treated.

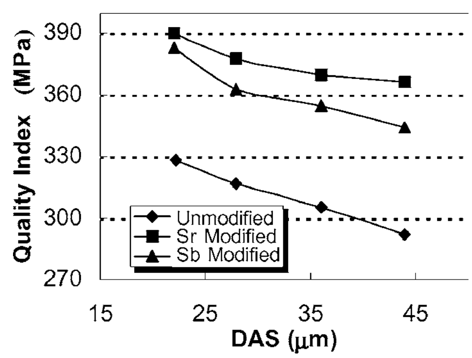

Figure 13 Quality index as a function of the dendrite arm spacing (DAS) for sand-cast heat-treated.

TABLE XII Relationships between microstructure and mechanical properties for as-cast conditions

Condition	Number of data	Relationships	Equations	Degree of confidence, X
Sand + Permanent	15	UTS=F (D)	196.05 − 2.09 D	$X > 90\%$
	15	UTS=F (N)	$179.33 - 210^{-4}$ N	$X > 75\%$
	15	UTS=F (AR)	253.89 − 33.56 AR	$X > 90\%$
	15	El=F (D)	5.44 − 0.3 D	$X > 50\%$
	15	El=F (N)	$3 + 3.410^{-5}$ N	$X > 60\%$
	15	El=F (AR)	13.54 − 4.7 AR	$95\% > X > 60\%$
Sand	12	UTS=F (D)	190.89 − 1.8 D	$X > 95\%$
	12	UTS=F (N)	$176.87 - 210^{-4}$ N	$X > 80\%$
	12	UTS=F (AR)	237.01 − 26.97 AR	$X > 95\%$
	12	El=F (D)	4.8 − 0.29 D	$X > .85\%$
	12	El=F (N)	$2.53 + 3.410^{-5}$ N	$X > 60\%$
	12	El=F (AR)	11.62 − 4.04 AR	$X > 70\%$
Permanent	3	UTS=F (D)	210.93 − 2.06 D	$X > 99\%$
	3	UTS=F (N)	$197.1 - 10^{-4}$ N	$X > 85\%$
	3	UTS=F (AR)	270.75 − 35.22 AR	$X > 99\%$
	3	El=F (D)	6.96 − 0.13 D	$X > 95\%$
	3	El=F (N)	$5.96 + 10^{-5}$ N	$X > 95\%$
	3	El=F (AR)	11.17 − 2.46 AR	$X > 95\%$

UTS = Ultimate tensile strength (MPa), El = Elongation (%), D = Diameter average (μm), N = Particles density, AR = Aspect ratio.

TABLE XIII Relationships between microstructure and mechanical properties for T6 conditions

Condition	Number of data	Relationships	Equations	Degree of confidence, X
Sand + Permanent	15	Q=F (D)	421.7 − 11.97 D	$X > 90\%$
	15	Q=F (N)	$325.6 + 0.410^{-2}$ N	$X > 90\%$
	15	Q=F (AR)	720.96 − 198.47 AR	$X > 85\%$
Sand	12	Q=F (D)	409.84 − 11.43 D	$X > 95\%$
	12	Q=F (N)	$315.77 + 0.410^{-2}$ D	$X > 95\%$
	12	Q=F (AR)	677.63 − 179.12 AR	$X > 85\%$
Permanent	3	Q=F (D)	405.14 + 0.95 D	$X > 99\%$
	3	Q=F (N)	$412.97 - 0.310^{-3}$ N	$X > 95\%$
	3	Q=F (AR)	370.37 + 22.33 AR	$X > 95\%$

Q = Quality index (MPa), D = Diameter average (μm), N = Particles density, AR = Aspect ratio.

particles count per unit area and particle shape are given in Tables XII and XIII. The best results that predict the tensile properties are the particles density and the size of them. In the other hand, due to various parameters such as porosity, casting solidification rate, the type and shape of Si particles (kind of modifier), the relationship between % elongation and these parameters doesn't have a good degree of confidence.

The quality index has been used to develop a relationship for heat-treated specimens in the T6 condition

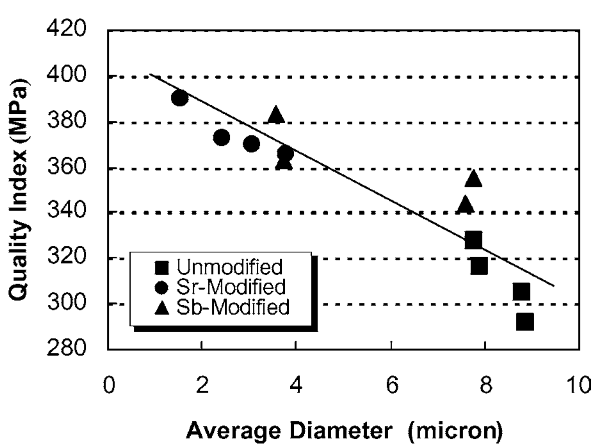

Figure 14 Relationship between quality index and particle diameter in heat-treated sand-cast specimens.

(Table XIII). For the heat-treated sand cast specimens, the size of particles gives the best prediction of tensile properties (Fig. 14). Also For permanent mold test specimens, particles size and density give the best prediction of tensile properties. These results of the relationship between microstructure and mechanical properties are in good agreement with other researchers [17–20].

4. Conclusions

The conclusions drawn from this study are summarized as follows:

1. At higher solidification rates, the effects of modification on microstructure are more evident.
2. For Sb-modified specimens decreasing of Si particles size and increasing particles density are strongly affected by casting solidification rate.
3. Modification has a major role in controlling the kinetics of the spheroidisation of Si particles. In unmodified specimens, the average size of particles decreases and their number of them increases, while in modified specimens the number of particles decreases and their average size increase.
4. The ultimate tensile strength and yield strength increased with Sr and Sb modification and cooling rate.
5. The greatest improvement of mechanical properties obtained with modification is observed for percent

of elongation at slow solidification rates i.e., thick sand casting.

6. Heat treatment is more effective on tensile properties than do solidification rate and modification.

7. At higher solidification rates, the mechanical properties improvement is more affected by Sb-modification, while at lower solidification rates strontium is more effective.

8. The best prediction of tensile properties, according to the microstructure-mechanical property relationship is governed by the size and the number of silicon particles per unit area.

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Received 2 May and accepted 11 November 2003