Solidification characteristics and mechanical properties of hypoeutectic aluminum-silicon alloy containing sulfur

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The present study reports experimental findings concerning the effect of sulfur on A356 alloy. Although it is found that sulfur can affect eutectic reaction of aluminum-silicon alloys, limited work pertaining thereto is published and no detailed study is available. It is of metallurgical interest to have a better understanding regarding the influence of sulfur on solidification as well as mechanical properties of the alloy. In this study casting experiments were conducted on a hypoeutectic grade aluminum-silicon alloy, A356, with sulfur addition. Thermal analysis shows that the eutectic reaction temperature of the A356 alloy containing sulfur is higher than that of the normal alloy and that the time interval of the eutectic reaction of the sulfurized alloy is longer. Series of microscopic examination of as-cast samples suggest some interesting findings. In contrast to the normal case, eutectic silicon phase of the alloy containing sulfur tends to appear in form of cluster comprising of broken acicular-like silicon phase. Although there seems to be no differences in ultimate tensile strength as well as bulk hardness between the sulfurized alloy and the normal A356, it is evident that yield strength and ductility of the A356 alloy are reasonably altered with the presence of sulfur. The A356 alloy containing sulfur exhibits greater ductility and lower yield strength in comparison with the normal A356 alloy.

Keywords: aluminum casting, sulfur, A356, hypoeutectic aluminum-silicon alloy, solidification characteristics

INTRODUCTION

Evidently, aluminum-silicon foundry alloys have gained increasingly uses, particularly in engineering applications such as automotive parts and structural components, in the past decades. Liquid treatment of aluminum-silicon alloys, including fluxing, is one of the most important operations toward successful casting of these foundry alloys. It is found that several commercial fluxes used in liquid aluminum treatment contain fair amounts of sulfur. It is reported that only a small amount of sulfur could affect eutectic reaction temperature of aluminum-silicon alloys [1-2]. This is seemingly similar to the modification effect by sodium or strontium. Nevertheless, rather limited work pertaining thereto is published and no detailed study is available. It is of metallurgical interest to gain a better understanding concerning the influence of sulfur on solidification as well as mechanical properties of aluminum-silicon alloys.
The purpose of the present study is to explore the effect of the presence of sulfur on the solidification characteristics, microstructures, and mechanical properties associated with a hypoeutectic aluminumsilicon.
The alloy of concern in this study is A356 which is used widely, particularly in aluminum casting industry making automotive parts.

EXPERIMENTAL PROCEDURE

In this study an A356 alloy with a nominal composition as tabulated in Table 1 was cast into specimens for thermal analysis and mechanical testing. For our reference case, i.e. A356 alloy with no sulfur addition, charge ingots were melted in silicon carbide crucibles using a heat-resisting furnace. The melt was further heated up to 900°C. Prior to pouring the liquid alloy was degassed with dry argon to ensure minimized level of dissolved hydrogen and dross was carefully removed. Subsequently, the melt was poured at a temperature of 700°C into preheated molds prepared for thermal analysis and standard mechanical testing.
Regarding the alloy with sulfur addition, meting and pouring practices were carried out similarly to those for the normal alloy. Except that during degassing sulfur was added into the liquid alloy before pouring. Thermal analysis cups in form of cylindrical stainless steel mold, whose diameter and height, respectively, are 30 mm and 50 mm, were used in the casting experiment for thermal analysis of both test alloys. During solidification cooling curves of the test alloys were measured, using thermocouples located at the center of the mold, and thermal data was logged on a computer through a data acquisition system with a commercial interface. Prior to casting the molds were preheated up to 200°C in order to

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Alloy	Si	Fe	Cu	Mn	Mg	Ti	Zn	Sn	Ni	Cr	Al
Actual	7.32	0.147	<0.002	0.006	0.30	0.127	<0.001	<0.003	0.005	-	Bal.
Spec.	6.5-7.5	0.20	0.20	0.10	0.25-0.45	0.20	0.10	-	-	-	Bal.

Table 1 – Chemical composition of A356 (wt. %).

Tabella 1 – Composizione chimica della lega A356 (peso %).

Specimen	Temperature °C		Mold	
	Melting	Pouring	Preheat °C	Material
For microstructural & thermal analysis	900	700	200	Stainless steel
For tensile test	900	700	200	Brass

Table 2 – Summary of the casting conditions.

Tabella 2 – Riepilogo delle condizioni di colata.

Fig. 1 – Samples of the cast specimens, after machining, for tensile test.

Fig. 1 – Alcuni campioni ricavati da campioni colati utilizzati per la prova di trazione.

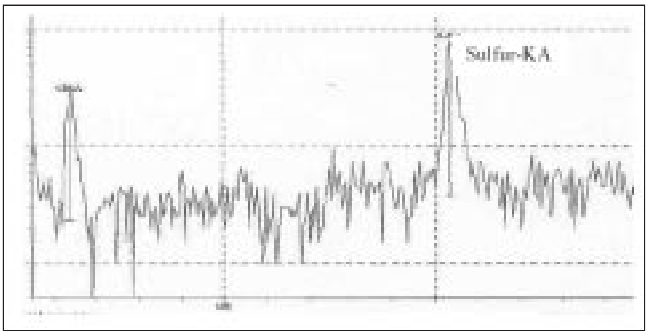

Fig. 2 – A sample of XRF spectra of the A356 containing 0.03 wt. % sulfur.

Fig. 2 – Esempio di spettro XRF della lega A356 contenente zolfo in percentuale del 0,03% del peso.

attain slow cooling rates which, in turn, resulted in well-defined cooling curves suitable for thermal analysis. Table 2 summarizes the casting conditions used in this study.
The specimens for tension test were cast and subsequently machined in accordance with ASTM B557M-94. The tensile specimens were 62.5 mm in gauge length and 12.5 mm in gauge diameter as illustrated in Fig.1. A series of tensile test was conducted at a crosshead speed of 5 mm·min^{-1} at room temperature employing a Universal Testing Machine. Values of ultimate tensile strength, yield stress, i.e. 0.2% proof stress, and elongation of each specimen were then measured. It should be noted that, prior to testing, all tensile specimens were subjected to x-ray radiograph test to examine porosity defects. The specimens appeared to be perfectly sound.
The specimens cast in the thermal analysis cups were subjected to microstructural examination and composition analysis. Samples for microstructural examination were cut from the central part of each specimen cast from both test alloys, i.e. with and without sulfur. The chemical analysis was carried out employing x-ray fluorescence technique, XRF, in order to measure sulfur content.

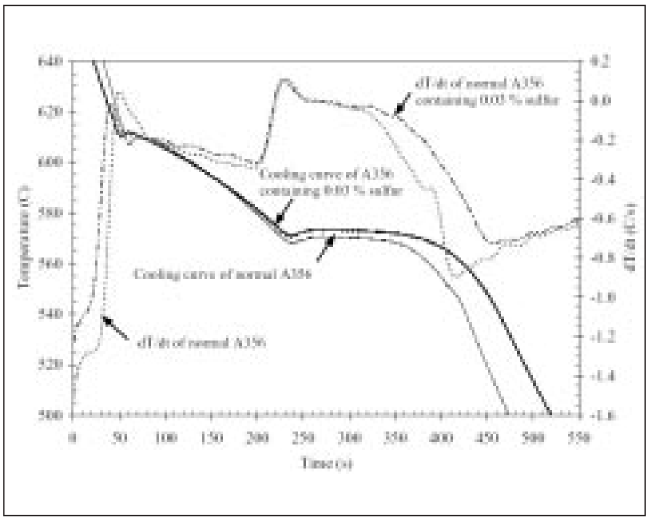

Fig. 3 – Cooling curves and first derivatives of the test alloys: the normal A356 and the A356 with 0.03 wt. % sulfur.

Fig. 3 – Curve di raffreddamento e loro derivate prime per le leghe sottoposte a prova (lega A356 e lega A356 con 0,03% di zolfo).

RESULTS AND DISCUSSION

A series of XRF analysis indicates that the sulfur content of the cast samples with sulfur addition is within 0.03 wt. %. Fig.2 shows a sample of XRF spectra of a cast sample of the A356 alloy containing sulfur. Fig.3 depicts cooling curves of the test alloys measured from the central section of each specimen cast in the thermal analysis cup. Also Presented in Fig.3 are the first derivatives. The cooling rates, defined as the rate over the range of the nucleation of primary alpha aluminum through the eutectic start [3-4], of both normal A356 and the alloy containing 0.03 wt. % sulfur are fairly comparable at the average rates of, respectively, 0.27 and 0.24°C·s^{-1}.
It is fairly seen from Fig.3 that the cooling curve of the alloy containing sulfur exhibits relatively higher nucleation temperature of primary alpha phase and higher eutectic temperature than those of the normal A356. In addition it is found that the duration of the eutectic transformation of the A356 with sulfur addition is longer than that of the normal A356.
In regard to the thermal analysis of the cooling curves, important temperatures and time intervals concerning the eutectic reaction during the solidification of the test alloys are summarized in Table 3.
The definitions [3] of such temperatures and times presented in Table 3 are as follows: T_{nucl} – the eutectic nucleation temperature; T_e – the eutectic growth temperature; T_{min} – the temperature at the minimum before the eutectic plateau; $\Delta\theta$ – undercooling (T_e - T_{min}); ΔT – the change in eutectic growth temperature ($T_{e(normal\ A356)} - T_{e(A356\ with\ S)}$; t_e and t_{fin} are the times, respectively, corresponding to the beginning and the end of the eutectic plateau; t_{nucl} – the time of eutectic nucleation; and t_{min} – the time at the minimum of the cooling curve.
Figs. 4(a) through 4(d) are micrographs of the metallographic samples prepared from the central sections of the thermal analysis samples. The microscopic examination reveals that the A356 alloy containing sulfur exhibits fairly different di-

Table 3 – Data related to eutectic reaction the test alloys.

Tabella 3 – Dati relativi alla reazione eutettica delle leghe in esame.

Alloy	Cooling rate, °C	Temperature, °C				Time duration, sec		
		T_{nucl}	T_e	$\Delta\theta$	ΔT	t_e-t_{min}	t_{fin}-t_{min}	t_{fin}-t_{nucl}
A356 (normal)	0.27	579.9	570.7	2.8	2.6	23	179	218
A356 0.03 wt.%	0.24	580.8	573.3	2.8		23	220	256

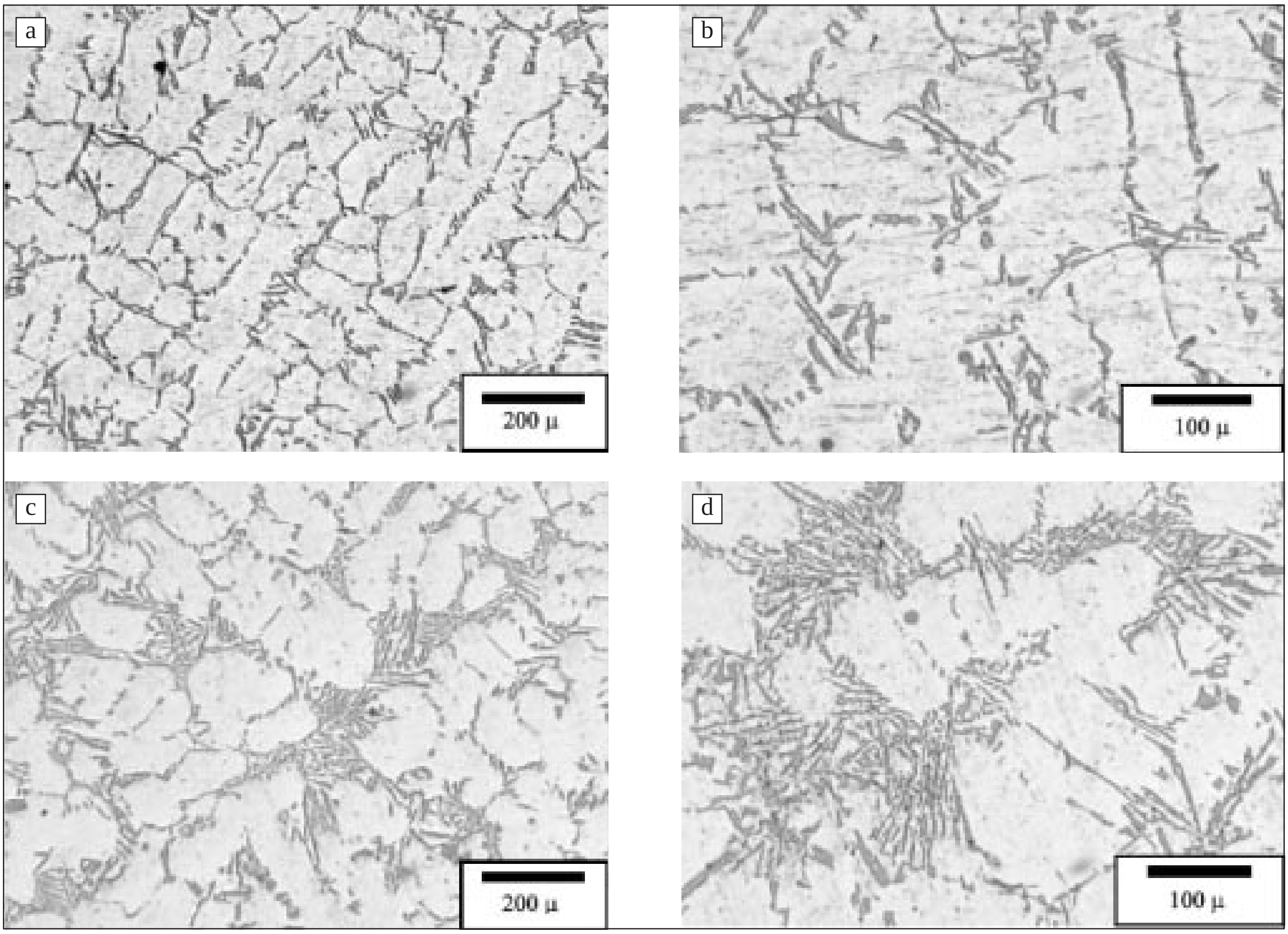

Fig. 4 – Micrographs of the samples of the test alloys: (a) and (b) normal A356 sample; (c) and (d) A356 sample containing 0.03 wt. % sulfur.

Fig. 4 – Micrografie dei campioni delle leghe esaminate: (a) e (b) campioni nella normale lega A356; (c) e (d) campioni nella lega A356 con 0,03% di zolfo.

stribution characteristics of the eutectic silicon phase.
Unlike the eutectic silicon phase typically found in a normal A356 alloy, instead of uniform distribution along dendrite boundaries of the aluminum alpha phase, most of the silicon phase in the A356 containing sulfur appears to coalesce in a cluster-like form as seen in Figs.4(c) and (d). Such clusters comprise of somewhat broken acicular-like silicon phase. The Degree of the clustering in the A356 containing sulfur samples is greater than that in the normal A356 samples. In addition, it can also be observed from these micrographs that the dendrites of the A356 containing sulfur appear somewhat coarser than those of the normal A356 alloy despite the fact that the cooling rates of these samples were of the same order. Based on the preliminary microscopic examination using scanning electron microscope, the intermetallics phase found in both test alloys appear to be alike. Detailed observation of this is yet to be carried out in order to have a conclusive finding. It should be noted that additional chemical analysis with the aid of energy dispersive spectroscopy technique was also conducted in an attempt to find out that where the sulfur is. Due to the small amount of sulfur content, the EDS analysis was not useful.

The result obtained from series of tension test showed that an average value of the ultimate tensile strength of the test-pieces cast from the alloy containing sulfur appears to be comparable with that of the samples cast from the normal A356 alloy. This average value of ultimate tensile strength is of the order of 195 MPa. Nonetheless, it is found that yield strength, i.e. 0.2% proof stress, of the specimens cast from the alloy containing sulfur is approximately 13 % lower than that of the normal A356 specimens. While; on the other hand, an average percentage of elongation of the formers is about 21 % greater than that of the latter. Table 4 summarizes the mechanical properties of the specimens. In addition, series of hardness test were also carried out. The samples representing both test alloys exhibit hardness values of a reasonably same order of 42 HB.

CONCLUDING REMARKS

Thermal analysis shows that primary nucleation and eutectic reaction temperatures of the A356 alloy containing sulfur is higher than those of the normal alloy and that duration of the

Alloy	UTS, MPa	0.2% Proof stress, MPa	Elongation, %	Hardness, HB
A356 (normal)	194.6 ± 2.1	94.9 ± 2.5	6.2 ± 0.2	42.2 ± 0.9
A356 0.03 wt.%	194.2 ± 1.6	83.9 ± 3.7	7.5 ± 0.5	40.9 ± 0.6

Table 4 – Mechanical properties of the normal A356 vs. the A356 containing sulfur.
Tabella 4 – Proprietà meccaniche della lega A356 e della lega A356 contenente zolfo.

eutectic reaction of the sulfurized alloy is longer. Series of microscopic examination of as-cast testpieces suggest some interesting findings. In contrast to the normal case, eutectic silicon phase of the alloy containing sulfur tends to appear in form of cluster comprising of broken acicular-like silicon phase. In fact, this altered silicon phase appears to be similar to the sodium or strontium modified eutectic silicon. Typical modified eutectic silicon phase is, however, finer than the silicon phase in the sulfurized alloy.

Although there seems to be no differences in ultimate tensile strength as well as bulk hardness between the sulfurized alloy and the normal A356, it is evident that yield strength and ductility of the A356 alloy are reasonably changed with the presence of sulfur. The A356 alloy containing sulfur exhibits greater ductility and lower yield strength compared to the normal A356 alloy.

Further micro-composition analysis, i.e. electron probe micro analysis technique or EPMA together with micro-hardness test, in each phase regions, i.e. the alpha aluminum, eutectic silicon, and intermetallics has yet to be conducted in order to have a better understanding in terms of the presence of sulfur in the Al-Si alloy.

Finally, thermodynamic and kinetic aspects of the solidification of the sulfurized A356 alloy should be further addressed in conjunction with a series of comprehensive microstructural examination as well as fractographic investigation. This will be likely to gain insights with respect to the influence of sulfur on nucleation and growth mechanisms, which may in turn, elucidate microstructure evolution of the alloy.

ACKNOWLEDGMENTS

The authors would like to acknowledge the staff, S. Petcrie, A. Rengsomboon, and S. Luankosolchai, of the Casting Technology Program of the Manufacturing and Design Technology R&D Group of the National Metal and Materials Technology Center (MTEC) for their valuable technical assistance.

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ABSTRACT

CARATTERISTICHE DI SOLIDIFICAZIONE E PROPRIETÀ MECCANICHE DI UNA LEGA ALLUMINIO-SILICIO IPOEUTETTICA CONTENENTE ZOLFO

Parole chiave:
alluminio e leghe, solidificazione

Il presente studio riporta i risultati sperimentali relativi agli effetti dello zolfo sulla lega A356.

Sebbene sia risaputo che lo zolfo può avere effetti sulla reazione eutettica delle leghe alluminio-silicio, in letteratura vi sono pochissimi lavori in proposito e non sono disponibili studi dettagliati. Si ritiene sia interessante a livello metallurgico ottenere una migliore comprensione dell'influenza dello zolfo sulla solidificazione e sulle proprietà meccaniche della lega. Nel presente studio sono stati condotti esperimenti di fusione su una lega ipoeutettica di alluminio-silicio, la lega A356, con aggiunta di zolfo.

L'analisi termica dimostra che la temperatura di reazione eutettica della lega di alluminio A356 contenente zolfo è più alta di quella della lega normale e che l'intervallo di tempo della reazione eutettica della lega con aggiunta di zolfo è più lungo. Una serie di esami al microscopio dei campioni as-cast rivelano risultati interessanti. Contrariamente al caso della lega normale, la fase eutettica ricca in silicio, nella lega contenente zolfo, tende a presentarsi sotto forma di cluster comprendenti una fase aciculare spezzetata. Sebbene non sembrino esservi differenze in termini di carico di rottura né di macrodurezza fra la lega con aggiunta di zolfo e la normale lega A356, si è evidenziato che carico di snervamento e duttilità della lega A356 risultano modificati dalla presenza di zolfo. La lega A356 contenente zolfo mostra una maggiore duttilità e un più basso carico di snervamento rispetto alla normale lega A356.