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Evaluation of Al-5Ti-1B and Al-10Sr in LM6 sand castings

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ABSTRACT

Purpose: of this paper is to study the separate effects of grain refiner and modifier on the metallurgical properties of LM6 sand castings. The research aims to determine how grain refiner and modifier will influence the microstructure of LM6 sand casting and the associated mechanical properties of hardness, ultimate tensile strength and engineering strain.

Design/methodology/approach: A grain refiner consists of 0.5wt% Al-5Ti-1B and a modifier consists of 0.5wt% Al-10Sr have been introduced separately into the melt of hypoeutectic LM6 Al-Si alloy to produce slab castings by CO_2 sand casting process. The geometry of the slab casting is designed to have different section moduli to induce directional solidification. Temperature profile of cooling process is taken to correlate between the section modulus and cooling rate. This enables the effect of cooling rate on microstructure and mechanical properties to be studied for grain refined and modified LM6 sand castings.

Findings: The significant finding is that a nearly full eutectic solidification at 540°C is achieved in the Sr-modified casting with faster cooling rates than those of solely grain-refined and original LM6. The hardness and ultimate tensile strength can be improved respectively between 20~40% and 11~18% by Al-10Sr modifier. It is observed that the Al-5Ti-1B grain refiner and Al-10Sr modifier increase the strain at UTS by 11% and 22% respectively. The metallographic observations show that the eutectic phase is finer and in fibrous form in the Sr-modified LM6.

Research limitations/implications: Further research can study a wider range of inoculant percentage.

Practical implications: This eutectic solidification at 540°C achieved in Sr-modified LM6 is lower than the solidus temperature of LM6 to reduce superheat and save electrical energy consumption while ensuring complete liquid mould filling.

Originality/value: This is the original work of slab casting of LM6 and the effects of Sr modifier and TiB grain refiner on its metallurgical properties.

Keywords: Casting; Modification; Grain refinement; Eutectic solidification

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1. Introduction

LM6 alloy is essentially a hypoeutectic Al-Si alloy (typically consists of 11.5wt% Si, less than 12.6wt% Si of eutectic composition) with low copper content (<0.1 wt%) to impart it the excellent property of corrosion resistance under both ordinary atmospheric and marine conditions. The LM6 alloy possesses exceptional fluidity so that it is capable of producing intricate castings of thin sections. It is also resistant to hot tearing when cast in sand or chilled molds throughout a wide range of temperatures. LM6 is especially suited to castings that need to be welded although special care is needed when machining [1]. Carbide-tipped tools with large rake angles and relatively low cutting speeds give comparatively good machining results provided cutting lubricant and coolant are employed in the machining process. Some of the applications of LM6 alloy are marine on-deck castings, water-cooled and inlet manifolds, motor housings, doors, chemical equipment, dye and food equipment, and tools.

Most commercial hypoeutectic Al-Si alloys solidify with a large fraction of primary α-Al in their microstructures. The eutectic phase of unmodified Al-Si alloy consists of rod-angular and flake-like morphology of the silicon phase, which induces poor ductility and brittleness [2]. The inferior mechanical properties of this type of structure make modification of Al-Si based casting alloys necessary. Modification is meant to change the shape of the silicon phase from flake to fibrous. Changing the morphology of eutectic Si from its original coarse acicular structure to a finer fibrous structure will enhance the mechanical properties of Al-Si castings significantly [3]. In general, modification can be achieved by rapid solidification (quench solidification) or impurity modification (chemical modification) [4]. The ubiquitous modifier used in foundry industry is Al-Sr master alloy that contains ~10wt% of strontium.

Besides modification, grain refinement of Al-Si alloys is also a major treatment encountered in foundries. Grain refinement plays a vital role in cast and wrought aluminium alloys in terms of eliminating the associated defects caused by coarse columnar grain structure. Such defects are exemplified in reduced fabricability, yield strength and tensile elongation to fracture; hot cracking is severe in the shell zone of a continuously cast ingot as well. Proper grain refinement helps eliminate these problems to improve product quality. Grain refinement also provides several benefits in Al-Si cast alloys, such as improved mechanical properties that are uniform throughout the casting, distribution of second phase and microporosity on a finer scale, better feeding capability to eliminate shrinkage porosity, improved ability to achieve a uniform anodized surface, better fatigue life, reduced hot tearing susceptibility etc [5]. The fine equiaxed structure is achieved by inoculating the melt with aluminum-titanium alloys containing $TiAl_3$ nucleants, or preferably the more potent aluminum-titanium-boron alloys which contain both $TiAl_3$ and TiB_2 particles [6].

In the previous study about the effect of cooling rate on the mechanical properties of LM6 sand castings, it was noticed that the grain structures of the as-cast LM6 castings are coarse and columnar [7]. In the present investigation, it is intended to improve the mechanical properties by inoculating LM6 with grain refiner Al-5Ti-1B and modifier Al-10Sr separately at 0.5 wt%. A comparison will be made between the two inoculants about their effects on cooling rate, microstructure and mechanical properties of the as-cast LM6 castings. The results of investigation will shed light on how to achieve the desired quality of LM6 sand casting through proper mold design, determination of appropriate casting modulus and process parameters.

2. Experimental procedure

Two wooden patterns were made to construct the mold for slab casting and tensile test specimens. The tensile test specimens were designed according to ASTM B557-06 specification. The 3D CAD drawings of the sand mold and the tensile test mold are shown in Figures 1 and 2. It is important to highlight that the casting modulus of each section is respectively 2.25, 4.08, 6.9 and 8.96 in order to induce directional solidification with different cooling rates in each section. These are the key variables in the analysis to shed light on design criteria for casting modulus of LM6 sand casting with respect to desired mechanical properties.

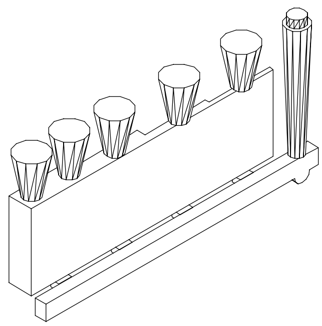


Fig. 1. Sand mold

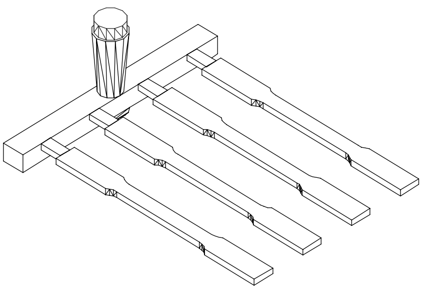


Fig. 2. Tensile test mold

The molding materials, founding technique to assemble the sand mold, melting and pouring processes were performed as per the requirements of CO_2 sand casting process. Four K-type thermocouples were connected to a data logger and inserted into the central part of each section before pouring. This enables real time temperature measurement for the whole cooling process from superheat to ambient temperature.

For each casting operation, the LM6 alloy was melted first in an induction furnace up to 720^{o}C. A K-type thermocouple was used to measure the melt temperature to ensure consistent superheat. After complete melting, 0.5wt% of Al-5Ti-1B or Al-10Sr was added to the melt in each experiment. The holding time for the additives in the melt was 15 minutes. The molten alloy was then transferred to a ladle and poured precisely into the pouring basins of the molds of slab casting and tensile test specimen. This was performed in quick pace so that the molten alloy maintained at superheat temperature throughout the entire mold filling process.

A sample of size 10 mm x 10 mm was cut from each section across the transverse plane at the central part of the casting and mounted in resin to prepare for grinding, rough polishing and finally fine polishing to the fineness of 0.3 micron. The polishing agent was Buehler alpha alumina particles of 0.3 micron. The samples were chemically treated with etchant consisting of 200 ml distilled water and 5 ml HF [8]. Microstructural studies were conducted by using an optical microscope with a maximum magnification power of 2000X. The similar resin-mounted specimens were also subjected to SEM (scanning electron microscopy) and EDS (energy dispersive spectroscopy) analyses. The SEM used is Leo 1455 Variable Pressure SEM. It is equipped with an Inca 300 EDX energy dispersive spectroscopy (EDS) facility for chemical compositional analysis.

For hardness test, the central part of each section was cut to a thickness of 10 mm on the plane as shown in Fig. 3. The sectioned part was subjected to fine 80 grit-size grinding on both sides to smoothen the coarse surface for hardness test. The hardness test was done on a Rockwell Hardness Tester. The scale of test was set to 15 T, means 15 kgf or 147.1 N. For each sample, ten hardness readings were taken randomly and averaged.

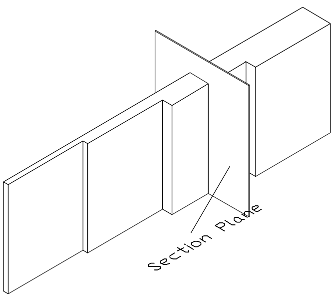


Fig. 3. Sectional plane on which hardness is tested

The samples for ultimate tensile strength test were subjected to fettling and cleaning to remove residual sands on the surfaces. The tensile test machine used is INSTRON 8500 equipped with digital control system. Differential scanning calorimetry (DSC) technique was used to study the thermal characteristics of the cast samples. The equipment used is DSC823e manufactured by METTLER TOLEDO. The sample's weight is in the range of 1~5 mg and concealed in a crucible. The heating rate is 10 oC /s. The maximum temperature can be handled by DS823e is 500oC, less than the melting point of aluminum alloy. Therefore, the thermal data can only be used to determine glass transition temperature, crystallinity and specific heat of the samples.

3. Result and discussion

The important data obtained in this investigation are the temperature profile of the cooling curve for the solidification process, the DSC thermogram, the hardness of the microsections tested by Rockwell Hardness Tester, the ultimate tensile strength (UTS) tested by Intron 8500 Tensile Strength Tester, and the micrographs captured by optical microscope and SEM

3.1. Cooling curve and solidification

The cooling curves of Al-10Sr modified, Al-5Ti-1B grain refined and original LM6 are shown in Figs.4, 5 and 6. It is noticed that an eutectic solidification at constant temperature about 540^{o}C occurs in Sr-modified casting. On the other hand, the cooling curves of the solely Al-5Ti-1B grain refined LM6 and original LM6 indicate the phase transformation occurs over a range of temperatures. The cooling rates from superheat to near-liquidus (assumed as 575°C) for the three types of casting are plotted in Figure 7. The data show that the cooling rate of Sr-modified LM6 is 3 to 5 times faster than that achieved in the original and grain refined LM6 alloys. Similar results of increasing cooling rate with strontium modification of Al alloy are also reported by differential thermal analysis in other research [9]. The phenomenon of decreasing cooling rate (due to longer freezing time) accompanied by increasing casting modulus is observed in all castings. This validates that the Chvorinov's rule still applies to the solidification process, irrespective of what additives are added to the molten metal [4,10]. The eutectic solidification time is also observed to be longer in Sr-modified LM6. The prolonged eutectic solidification time is expected to increase the proportion of solidified eutectic Si phase in the final microstructure. The addition of 0.5wt% Al-10Sr has essentially converted LM6 into an alloy close to eutectic composition. This is a desired outcome because eutectic solidification shows favorable characteristics with respect to fluidity, feeding and freedom from hot tearing. The eutectic liquid composition tends to decrease melt viscosity and surface tension so that the eutectic liquid metal will have a better ability to flow interdendritically for effective interdendritic feeding to compensate for shrinkage porosity [9, 11].

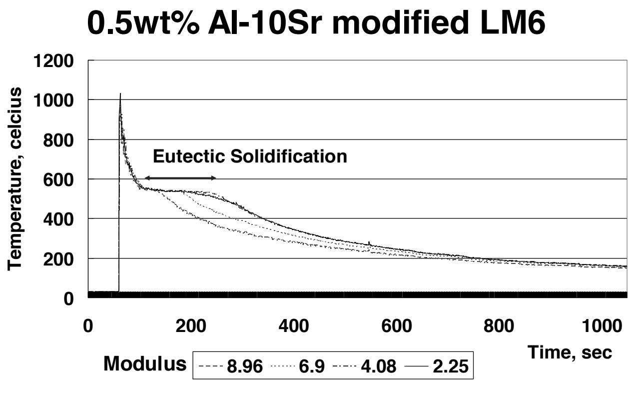


Fig. 4. Cooling curve of 0.5wt% Al-10Sr modified LM6

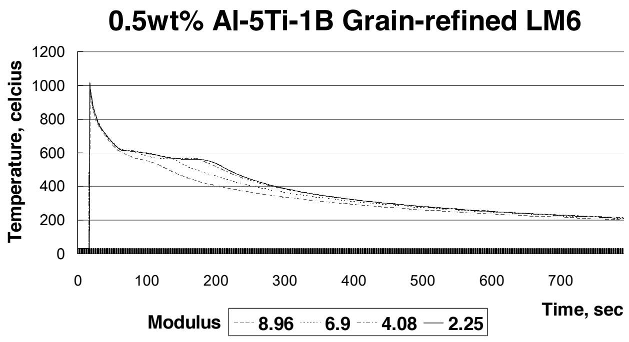


Fig. 5. Cooling curve of 0.5wt% Al-5Ti-1B grain refined LM6

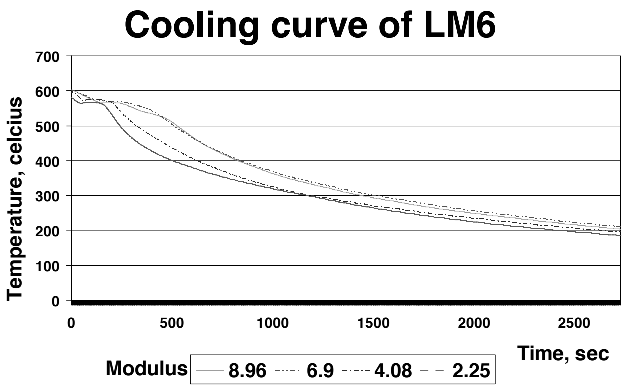


Fig. 6. Cooling curve of original LM6

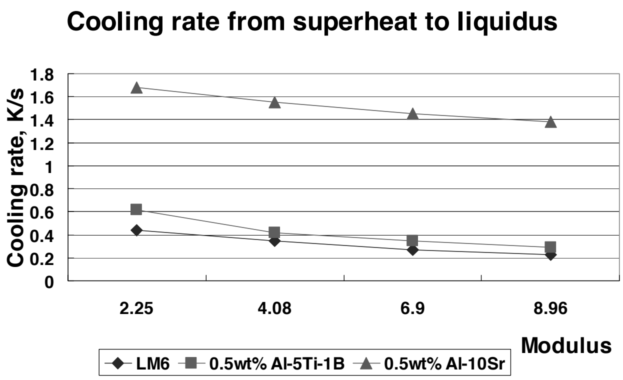


Fig. 7. Cooling rates from superheat to liquidus

3.2. Hardness and ultimate tensile strength

The hardness and UTS of the Al-10Sr modified, Al-5Ti-1B grain refined and original LM6 sand castings are plotted in Fig. 8 and Figure 9. The hardness of LM6 generally can be improved by Ti-B grain refinement and Sr modification. Compared to original LM6 hardness, Sr modification can improve hardness between 20~40%; whereas grain refinement improves between 9~25%. Hardness of LM6 casting is observed to be increasing when section modulus is reducing. This could be due to faster cooling rate in thinner section promotes nucleation of finer grains and hence improves hardness inherently. The UTS of the 0.5wt% Al-10Sr modified LM6 achieves an improvement of 18 MPa and 28 MPa compared to those of 0.5wt% Al-5Ti-1B grain refined and original LM6. This 11~18% of UTS improvement is considered significant practically. The addition of strontium modifier obviously is more effective than Ti-B refiner to enhance the tensile strength of LM6 sand castings.

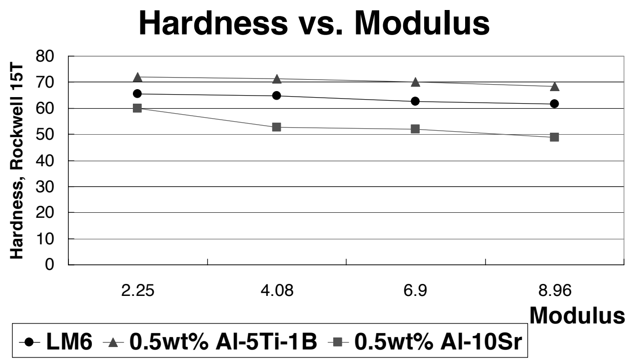


Fig. 8. Effect of grain refiner and modifier on hardness

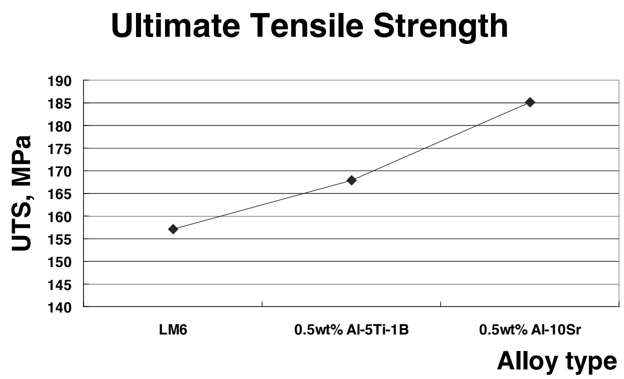


Fig. 9. Effect of grain refiner and modifier on UTS

3.3. Elongation (strain at UTS)

Figure 10 shows the effect of grain refinement and modification on ductility of LM6 sand casting. It is observed that 0.5wt% Al-5Ti-1B grain refiner and 0.5wt% Al-10Sr modifier increase the strain at UTS by 11% and 22% respectively. This improvement corresponds to the similar improvement observed in tensile strength when modifier and grain refiner are inoculated into LM6. Improvement in ductility enables the cast parts to undergo mechanical forming with less tendency of cracking. Hot tearing of casting can be reduced when ductility improves and provides better flexibility to casting design of intricate shape and varying section thicknesses.

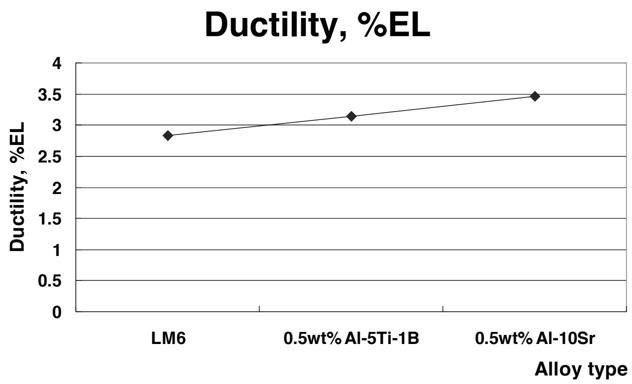
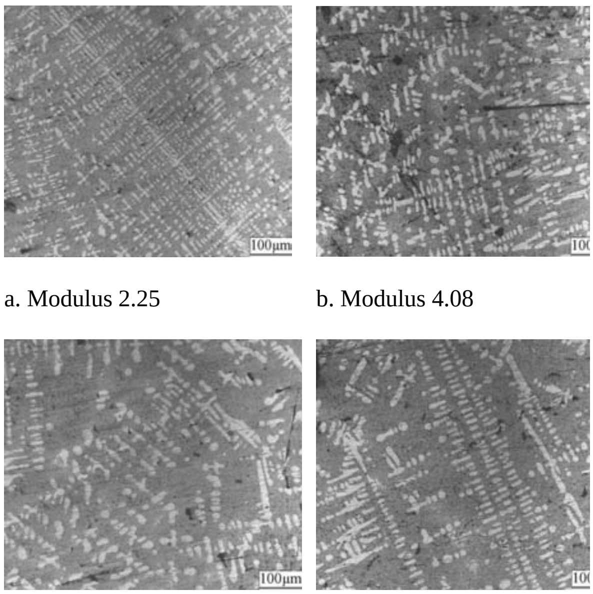


Fig. 10. Effect of grain refiner and modifier on Strain at UTS

4. Microstructural analysis of Sr-modified LM6 sand casting

The optical micrographs of the Sr-modified LM6 are shown in Figure 11 for all sections of different moduli. It is evident that the morphology of the casting microstructure has been modified by strontium that exists in the Al-10Sr modifier. According to quench solidification and crystallographic orientation studies by other researchers [12], it was shown that three different eutectic solidification modes can operate in hypoeutectic Al-Si alloys, depending upon composition and casting conditions. The three modes are: (I) nucleation on the dendrites; (II) heterogeneous nucleation of eutectic grains in the interdendritic liquid; and (III) nucleation and growth from mold wall (opposite the thermal gradient). Mode I eutectic solidification is evident in the original LM6 microstructure, as illustrated in the micrographs of Fig. 13. In the present study of Sr-modified LM6, the primary α-Al dendrites appear to be much finer than those of original and Al-5Ti-1B grain refined LM6. The primary dendrite arms of the Sr-modified LM6 alloy indicate a specific growth direction. The growth of secondary dendrite arms are noticed to be spanning laterally along the primary dendrite arm. As predicted by the prolonged eutectic solidification time of the cooling curve, a relatively higher quantity of eutectic phase is observed in the Sr-modified LM6 microstructures. This observation indicates that mode II eutectic solidification is predominant in the Sr-modified LM6. The addition of 0.5wt% Al-10Sr into the molten metal has entirely modified the morphology of the LM6 sand casting because it has effectively promoted eutectic solidification and formation of fibrous eutectic Si phase.

A number of micro-porosities are observed to be dispersed spatially in the modified microstructure, but there are scarce macro- porosities existing in the same microstructure. When the section modulus increases, the secondary dendrite arms appear to be coarser and dispersed randomly; and larger area of eutectic phase is observed too. This could be due to the longer eutectic solidification time in the section of larger modulus that provides opportunity for ripening and local remelting of the secondary dendrite arms and so results in fragmentation and subsequent transport of the fragmented dendrites by convective flow throughout the mushy zone [4,13]. It was reported that Sr actually modifies the eutectic flakes Si into fibrous form by poisoning the growth sites of primary Si, which normally grow by twin-plane re-entrant (TPRE) mechanism [2]. This transition of Si phase from eutectic flake to fibrous form can be noticed by comparing the eutectic phases between the micrographs of original LM6 and Sr-modified LM6. It was reported in literature that in the solidification of unmodified Al-Si alloys, most of the eutectic aluminium has the same crystallographic orientation as the surrounding dendrites under the observation of electron backscattering diffraction (EBSD). This suggests that the eutectic aluminium is growing epitaxially from the surrounding primary α-Al dendrites, forming a high-angle eutectic grain boundary in the center of the eutectic pocket [14,15]. In the present study, the metallographic observations show that the Al-10Sr modifier has enlarged the eutectic phase in the solidified LM6 structure by altering the mechanism of eutectic nucleation and growth mode. The presence of strontium in the melt provides extensive heterogeneous nucleation of independent eutectic grains, which apparently do not grow epitaxially from the surrounding primary α-Al dendrites. The similar effect can also be achieved by quench solidification at a high temperature gradient (~125±5 ^{o}C.cm^{-1}), but this method is not prevalent in foundries compared with strontium modification which is easier to monitor and control for consistent performance and reproducibility of the microstructures [2].



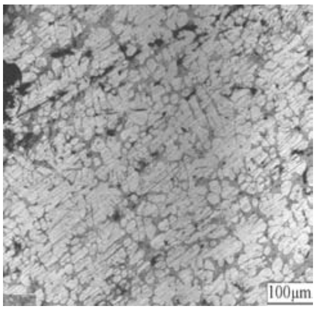
a. Modulus 2.25 b. Modulus 4.08

c. Modulus 6.9 d. Modulus 8.96

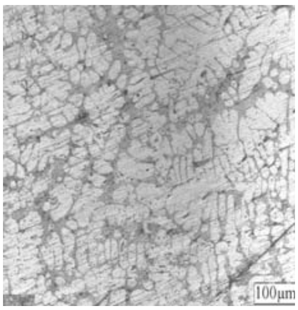
Fig. 11. Microstructures of 0.5wt% Al-10Sr-modified LM6

Based on the micrographs of 0.5wt % Al-5Ti-B grain refined LM6 in Figure 12, the metallographic observation shows that the equiaxed dendrites of grain refined LM6 have finer sizes than the original LM6. The finer grain size of grain refined LM6 conforms to the results of improvement in mechanical properties of hardness, UTS and ductility. Extensive literatures have reported the similar results that certain mechanical properties of Al-Si alloys are enhanced when their grain structures are refined [16]. When grain refiner is added, more heterogeneous nucleation sites are introduced into the melt and hence a finer grain structure will be produced [17]. It is noticed that grain size is coarser in thicker section when the cooling rate is slower. In other words, grain size is finer when cooling rate is faster in thinner section. Therefore, for better mechanical property of sand casting, the section modulus of casting design must be taken into account to achieve faster cooling rate and finer grain size.

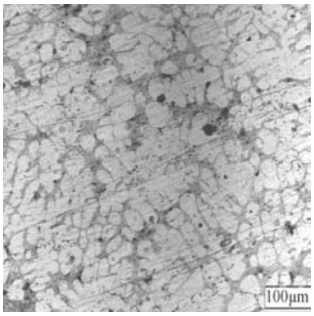
The EDS (energy dispersive spectroscopy) spectrum analyses of 0.5wt% Al-5Ti-1B grain refined, 0.5wt% Al-10Sr modified and original LM6 castings are shown in Figs. 14, 15 and 16. Their respective element analysis results are presented in Table 1. The three spectra resemble each other because the primary chemical elements contained by them are almost of similar percentage. The 0.5wt% addition of inoculants does not change the LM6 chemistry significantly. The oxygen content does not show significant variation. However, variation in Al and Si weight percentage is observed. The Sr-modified LM6 has a highest content of silicon detected by EDS on the surface. This could be due to more silicon is precipitated in the eutectic Si phase of the Sr-modified LM6 casting as a result a larger extent of eutectic solidification.



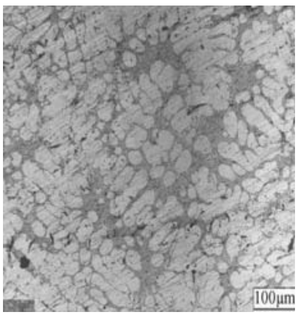
a. Modulus 2.25



b. Modulus 4.08

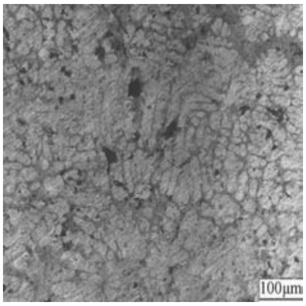


c. Modulus 6.9

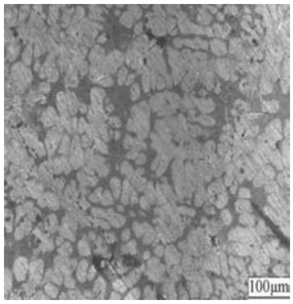


d. Modulus 8.96

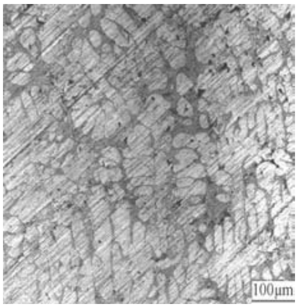
Fig. 12. Microstructures of 0.5wt% Al-5Ti-1B grain refined LM6



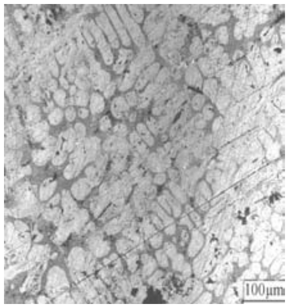
a. Modulus 2.25



b. Modulus 4.08



c. Modulus 6.9



d. Modulus 8.96

Fig. 13. Microstructures of original LM6

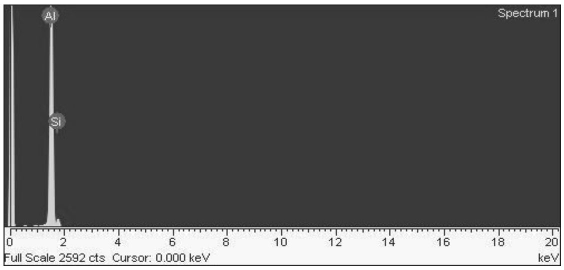


Fig. 14. EDS spectrum of 0.5wt% Al-5Ti-1B grain refined LM6

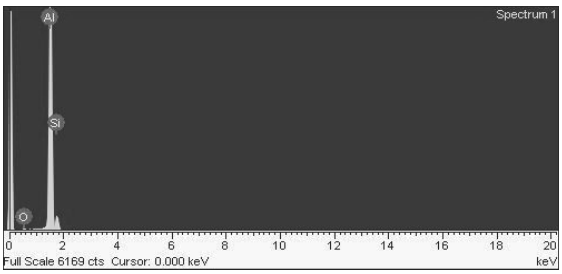


Fig. 15. EDS spectrum of 0.5wt% Al-10Sr modified LM6

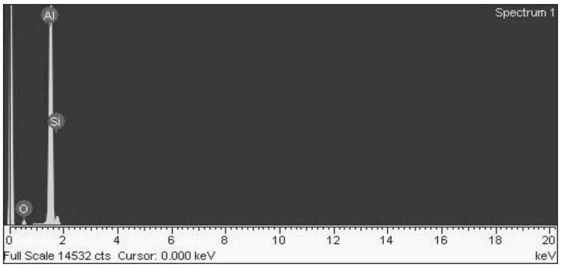


Fig. 16. EDS spectrum of original LM6

Table 1.
EDS spectrum analysis of LM6 castings

	0.5wt% Al-10Sr modified LM6		0.5wt% Al5Ti1B grain- refined LM6		Original LM6	
Element	Weight %	Atomic %	Weight %	Atomic %	Weight %	Atomic %
O	3.30	5.48	3.34	5.52	3.24	6.31
Al	83.0	81.59	88.34	86.64	86.16	84.24
Si	13.70	12.93	8.32	7.84	10.60	9.45

Figures 17 and 18 show the DSC thermograms for original LM6, 0.5wt% Al-5Ti-1B grain refined and 0.5wt% Al-10Sr modified LM6 within the temperature range from 25^{o}C to 500^{o}C. For original LM6, the onset of crystallization temperature occurs at 412.10^{o}C. For TiB grain refined LM6, the onset temperatures of crystallization occur at 443.57^{o}C; its delta c_p at glass transition is 0.747 $Jg^{-1}K^{-1}$. For Sr-modified LM6 the onset of crystallization temperature starts at 395.99^{o}C; its delta c_p at glass transition is 0.581 $Jg^{-1}K^{-1}$. The onset of solidus points (melting begins) can not be observed here evidently because the samples were not heated up to 600^{o}C or more to surpass their liquidus temperatures.

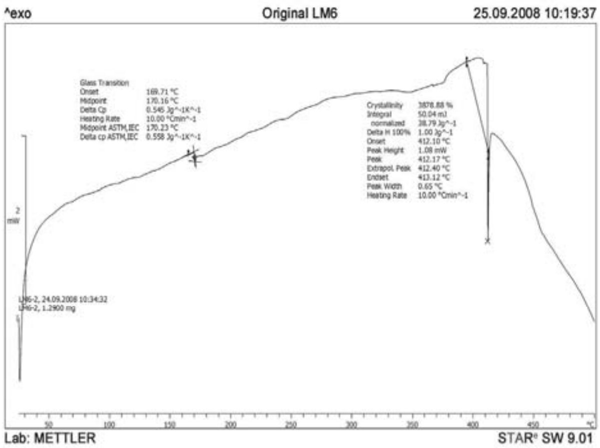


Fig. 17. DSC traces of original LM6

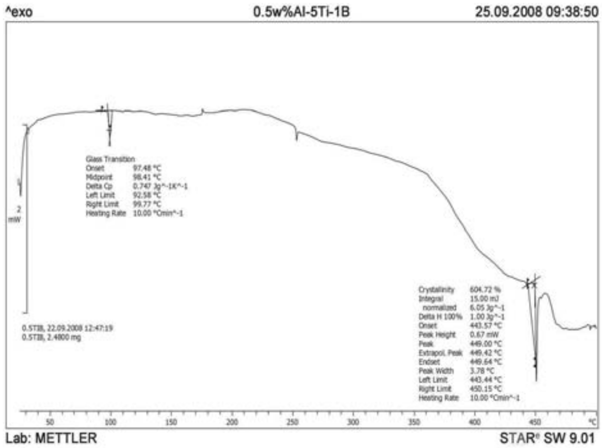


Fig. 18. DSC traces of 0.5wt% Al-5Ti-1B grain refined LM6

However, all thermograms show that endothermic process is dominating when heating temperature passes 400^{o}C. The original, grain refined and modified LM6 aluminum alloys should have been in semisolid state after the crystallization temperature.

5. Conclusions

The effects of grain refiner Al-5Ti-1B and modifier Al-10Sr at the addition level of 0.5wt% on the metallurgical properties of LM6 Al-Si alloy sand castings have been studied. Based on the thermal data, mechanical testing and metallographic examination conducted for the specimens, the following conclusions can be drawn:

- Modification with 0.5wt% Al-10Sr has transformed the LM6 solidification into a complete eutectic solidification at 540^{o}C. This eutectic temperature is lower than the solidus temperature (565^{o}C) of LM6. This implies that by adding the modifier into LM6, the superheat of the melt in the furnace can be reduced to save electrical energy consumption while ensuring complete liquid mold filling.
- The Sr-modified LM6 has a faster cooling rate than that of the original and solely grain refined LM6. The maximum cooling rate from superheat to liquidus of the Sr-modified LM6 is 1.68^{o}C/s for the section of modulus 2.25.
- The micrographs of Sr-modified LM6 show that the morphology of the casting has been modified completely to be majority fibrous eutectic phase interspersed with dendrites of α-Al.
- The Sr-modified and grain refined LM6 castings improve hardness as well as UTS. Percentage of improvement ranging from 9~40% when compared with the original LM6.
- More silicon is detected by EDS on the surface of Sr-modified LM6 castings by 5%, and the detected aluminum is inversely less by 5% too. This is in accord with the microstructure of Sr-modified LM6 castings, in which comparatively less primary α-Al dendrites are nucleated and more eutectic silicon phase is formed in the solidified structure.
- The DSC thermograms indicate lowest crystallization points in Sr-modified LM6. This result corresponds to the cooling

curve of Sr-modified LM6 in which a lower eutectic solidification point at 540°C is observed, which is much lower than the original LM6 melting range of 565 °C~575°C.

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