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GRAIN REFINER FOR ALUMINIUM-SILICON SAND CASTING ALOYS

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Grain refinement, Nucleation, Casting alloys

Abstract

Al-Si alloys exhibit large grain structure when Al-Si alloy melt is solidified in sand moulds due to low cooling rate provided by the mould. Ti-based grain refiner (Al-Ti-B) is known to be less-effective to refine grain structure of Al-Si alloys due to formation of Ti-Si phase. Recently, we have developed an effective novel grain refiner (NGR) for aluminium-silicon sand casting alloys. Effectiveness of grain size under slow cooling conditions has been investigated. For comparative purposes, a range of sand casting alloys with NGR addition have been produced. The results show that the addition of novel grain refiner reduces the grain and eutectic size significantly for all these alloys at lower cooling rate <0.5 °C/s. As a result of fine primary Al grains, the porosity and elongation in the solidified alloys is notably improved.

Introduction

The Al-Si alloy automotive parts like engine blocks and brackets are usually formed by shape casting. A good casting is supposed to fill the mould cavity without defects. Thus, the gating system design, cooling rate and casting pressure can all affect the cast structure. The refinements of structure can often be achieved by controlling casting process parameters. Cooling rate is important in formation of microporosity. Higher cooling rate reduces solidification time and grain size of casting. With a higher cooling rate, the grain density increases, dendrite arm spacing and the average pore size decrease. With a lower cooling rate, more gas can precipitate from the melt and thus produce higher porosity. [1]. Low cooling rates with usage of sufficient grain refinement can be a good practice for the industry to produce more complicated shaped parts with thinner walls. Therefore, our objective is to develop a grain refiner that can be effectively used for Al-Si casting alloys. By investigating the analogy between Al-Ti and other Al-X equilibrium phase diagrams, we have developed novel grain refiner (NGR) which also exhibit a peritectic reaction (Liquid + $Al_3Ti \rightarrow$ solid solution) between liquid aluminium and Al_3X solid phase [2]. Series of experiments were conducted to investigate the influence of novel grain refiner under different cooling rates. We present here the microstructures and mechanical properties of grain refined range of Al-Si binary and commercial casting alloys.

Experimental

The binary alloys were prepared from pure commercial aluminium with addition of silicon. The addition of new grain refiner to commercial silicon alloys like LM6 (A413) and LM25 (A356) was investigated. The alloys were melted at 800 °C, without and with new grain refiner addition, cast into different moulds to achieve diverse cooling rates. Chemical electro-polishing ($HClO_4$+CH_3COOH) and Baker's anodizing have been used to reveal grain boundaries. A Zeiss polarized optical microscope with an Axio 4.3 image analysis system was used to measure the grain size using the linear intercept method. The mean intercept length, $\bar{l}$, is then calculated from using equation: $\bar{l} = L_T / N_i$, where L_T is the total length of the test lines and N_i the total number of grain boundary intersections on line L_T. The macro-etching was performed with Keller's solution to have a visual comparison of the grain size. The cooling curves were measured with data logger and a thermocouple.

Results and Discussion

Grain Refining of α-Al

It is known that the Al-Si casting alloys can be refined to a certain extent using the Al-B master alloys, primary Si size can be refined with the addition of P and eutectic can be modified by using Sr. However it is very difficult to refine the α-Al grain size when the Si content is high. As shown in Figure 1, Jhonsson [3] showed that the Al-5Ti-1B master alloy poison the Al-Si alloys when they contain > 3 wt.% of Si. The reason for poisoning is suggested to be the consumption of Ti by Si to form the $TiSi_2$ phase.

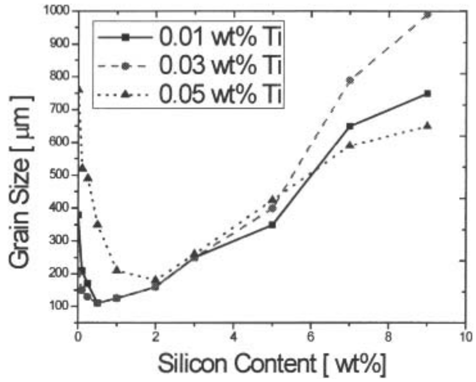

Figure 1 Grain size as a function of Si content [3]. When Al-5Ti-B grain refiner is added, grain refinement is not observed for higher Si alloys. Higher amount of Ti is observed to increase the grain size further.

Thermal analyses were interpreted for Al-5Si to see if the heterogeneous nucleation was taking place without and with addition of novel grain refiner, based on terminologies developed by Backerud et al.[4]. Furthermore the morphology of the grains of solidified ingots was analyzed after recording the temperature as a function of time during solidification. By analyzing the cooling curves shown in Figure 2 we determine the nucleation temperature and undercoooling. Lowering the undercooling has a great influence on growth of primary α-Al particles. In untreated alloys, the existence of undercooling means that heat generated with the commencement of solidification could not be transferred out of the mould completely and therefore the heat balance leads to the appearance of undercooling. However this is not a case for the grain refined alloy. In the refined alloy, shown in Fig.2 b, the nucleation temperature is increasing. The points for thermal analysis are:

- T_{nucl}: Start of primary α-Al dendrites nucleation temperature
- T_{minAl}: Unsteady state growth temperature, the temperature beyond which the newly nucleated crystal grow to such extent that the latent heat liberated surpasses the heat extracted from the sample
- T_{gAl}: Recalescence of steady growth due to release of latent heat of primary α-Al dendrites
- *ΔT:* the undercooling. Temperature difference between unsteady *(T_{minAl})* and steady *(T_{gAl})* state growth temperatures of primary α-Al particles

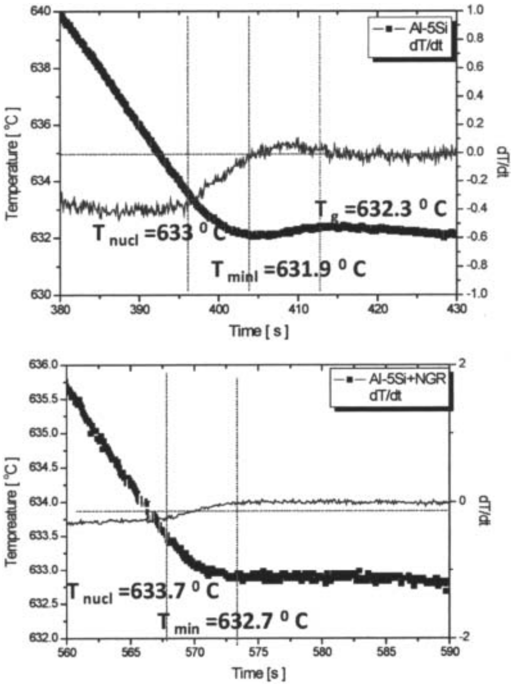

Figure 2. The thermal analysis of Al- 5Si was done to investigate the undercooling and nucleation temperature. The cooling curves of a) Al-5Si with undercooling of 0.4 °C, nucleation temperature of 633 °C and cooling rate of 0.04 °C/s b) Al-5Si with novel grain refiner addition with undercooling of ~0.1 °C, nucleation temperature of 633.7 °C and a cooling rate of 0.03 °C/s.

The macro-etched surfaces of ingots that are produced as a result of cooling curve measurements are shown in Figure 3. A big difference in grain size is achieved with the usage of NGR addition for very slow cooling rates of 0.04°C/s, similar to the sand casting process that is commonly used by industries to produce large cast structures for automotive applications.

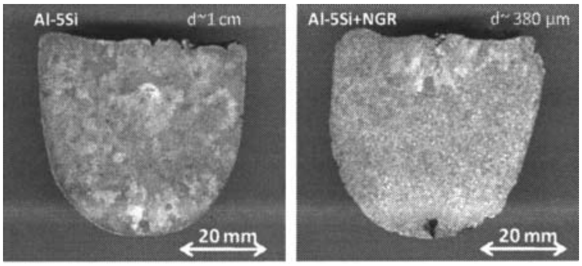

Figure 3. The samples of Al-5Si without addition and with novel grain refiner. A slow cooling rate of ~0.04 °C/s was imposed during solidification. The grain size of Al-5Si is about 0.8 cm and when grain refiner is added it is decreased to 380μm.

The further experiments were carried on to investigate the influence of novel grain refiner under different cooling rates. The commercial alloys LM6 (A413) and LM25 (A356) were melted at 800 °C, without and with grain refiner addition, cast into different moulds to achieve diverse cooling rates. Figure 4 shows the grain sizes as a function of cooling rate. It can be seen that the grain refiner is less sensitive to cooling rate. Even with cooling rate as low as 0.03 °C/s the grain sizes are still smaller.

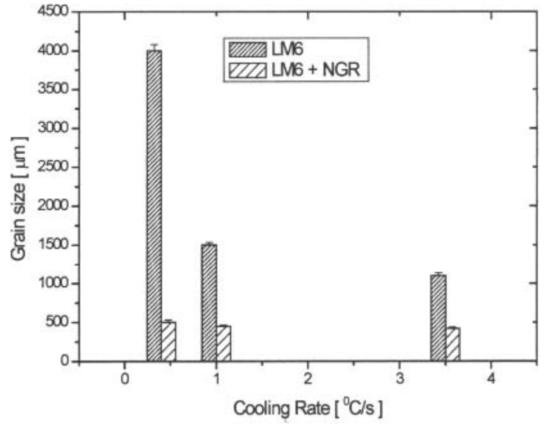

Figure 4. The grain sizes as a function of cooling rate for LM6 and LM6 with NGR. The samples were all melt at 800 °C and cast into the moulds that provide different cooling rates 0.03 °C/s, 1 °C/s and 3.5 °C/s. The novel grain refiner added samples are less sensitive to cooling rate.

The literature suggested that with lower cooling rate the porosity is higher [1], it is true only for the aluminium-silicon alloys without any grain refiner. However as the Figure 4 present the NGR has a huge influence on the grain sizes and the porosity of the LM6. The grain sizes decreased from 4-6 mm to 450 μm and the porosity is noticeably reduced.

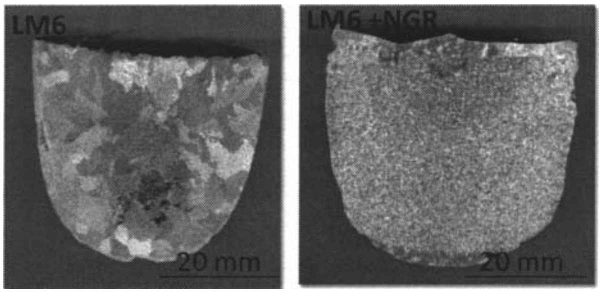

Figure 5. The LM6 macro-etched samples without any addition and with NGR. The cooling rate is 0.03 °C/s. The grain sizes decreased from 4-6 mm to 450 μm and the porosity is significantly reduced.

The LM25 results presented in Fig.6 confirm that NGR is less sensitive to cooling rate and it can refine the alloys even in very low cooling rates. The very low cooling rate used in this example was about 0.003 °C/s.

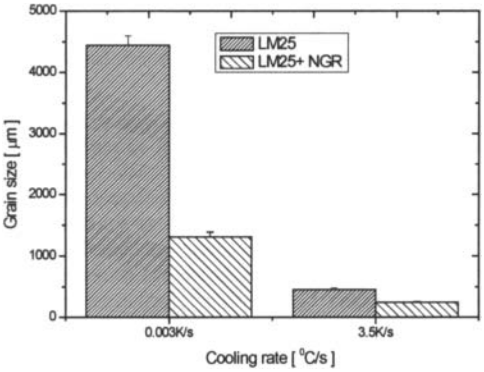

Figure 6 Grain size as a function of cooling rate for LM25 without any addition and with NGR. The cooling rates used are 0.003 °C/s and 3.5 °C/s. NGR addition has significantly reduced grain size at very slow cooling rate.

Al-Si Eutectic Refinement

The research was continued to investigate the influence of NGR addition on eutectic grain structure. A previous study on the eutectic solidification mechanism in hypoeutectic Al-Si alloys has identified large difference in the nucleation and growth modes of unmodified and impure alloys [5,6]. Eutectic nucleation in unmodified alloys occurs by the nucleation of a large number of α-Al eutectic phases, at or near the primary aluminium dendrite-liquid interface. Relatively, in modified alloys with strontium addition, α-Al eutectic phase nucleate is independent of the surrounding dendrites. Analyses of the eutectic structure with the addition of NGR were investigated. The results shown in the Figure 6 suggest that the eutectic Si size is refined. To achieve the fibrous like eutectic structure, the addition of Strontium is used in industry. However with the addition of NGR the structure is still plate like, the density of α-Al eutectic phase is significantly increased; the addition of NGR to Al-Si alloys enhances a large amount of nucleation sites for primary α-Al phase, remarkably refining the dendrite grains. The lattice constants of eutectic α-Al phase are very close to those of the primary α-Al phase, so it is rational to think that addition of NGR also enhances a grain refining of α-Al phase in eutectic.

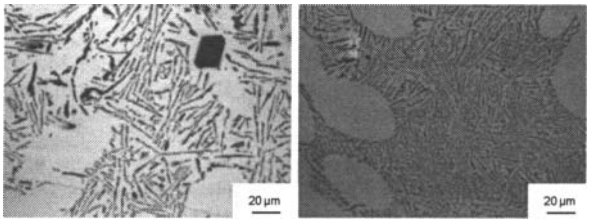

Figure 7.The microstructure of Al-10 Si without and with NGR addition. The samples were cast at 700 °C into the TP-1 mould that provides the cooling rate of 3.5 °C/s. The NGR addition refines the α-Al and the eutectic phases.

Microstructural analyses were made to investigate the cooling rate influence on eutectic structure for commercial alloy. In Figure 7, eutectic Si size is shown for LM6 without addition and with NGR under different cooling rates.

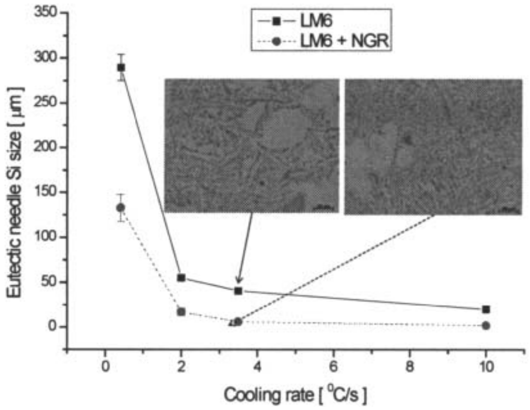

Figure 8 The eutectic size as a function of cooling rate for LM6 without addition and with NGR addition. The eutectic size is observed to reduce with usage of NGR.

It is well known that eutectic modification with strontium addition is very difficult under slow cooling conditions. The LM6 with NGR addition and without any addition had a cooling rate of 0.03°C/s. Under such low cooling rate, we still can observe the grain refinement not only in α-Al but also in eutectic Al-Si.

Mechanical Properties

Most aluminium castings are used in the 'as cast' condition, but there are certain applications that require higher mechanical properties, or different properties from the as cast material.

The macrostructure analyses of dendrites in Al-Si alloys were done to investigate the influence of NGR on secondary dendrite arm spacing. It is known [7] that the mechanical properties of these alloys may be improved by controlling their microstructure. Decreasing the secondary dendrite arm spacing can result in an increase in tensile strength and elongation. Cooling rate found to be one of the effective parameters to control the microstructure of as cast alloys. By increasing the cooling rate the secondary arm spacing of the alloys decrease. In general the dendrite arm spacing can be related to cooling rate as:

$$\lambda = (R^{-n}) \tag{1}$$

Where λ is SDAS and *n* is in the range of 1/3 to 1/2 for secondary spacing [8]

However the slow cooling rates used in sand casting are resulting in lower tensile strength of materials. By reducing the grain size and SDAS, one can improve the mechanical properties of alloys.

The analyses were made to compare the SDAS with cooling rate. It is well known that with increasing the cooling rate the SDAS will be smaller. Figure 9 presents dependency between the cooling rate, the secondary arms spacing and grain size.

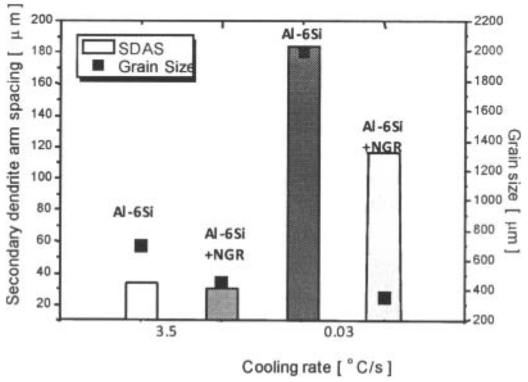

Figure 9. The secondary arms spacing and grain size as a function of cooling rate for Al-6Si without any addition and with NGR. The secondary arm spacing is decreased with increasing of cooling rate. The grain sizes have some influence on the SDAS.

The secondary arms spacing size in Al-6Si without and with NGR addition shows that the arms spacing is sensitive to the cooling rate. With low cooling rates the SDAS is higher when compared to higher cooling rates.

The heat treatment of aluminium castings is carried out to change the properties of the as cast alloys by subjecting the casting to a thermal cycle or series of thermal cycles. For sand castings and gravity die castings all heat treatments are possible, though not all are standardised. Pressure die castings however, cannot generally be heat treated.

The experiments were done to compare the tensile properties of LM25 without any addition and with NGR. Also the heat treatment was performed on the tensile bars to analyse the heat treatment influence on the castings. The LM25 alloys with and without addition of NGR are heat treated with TB7: solution treated and stabilized for 5h at 532 °C and then quenched in hot water followed by stabilizing treatment at 250 °C for 3h. The diagram shown at the Figure 10 presents the maximum value of measured samples elongation as a function of tensile stress for LM25 without addition and with NGR, heat treated and not heat treated.

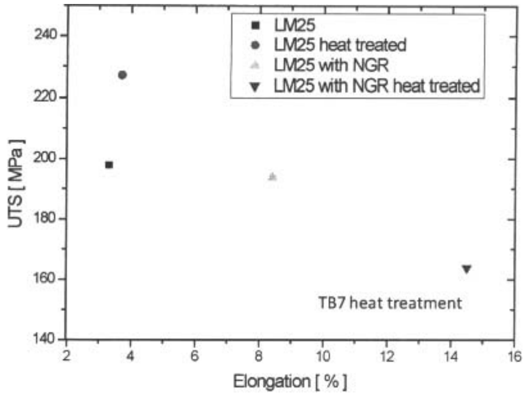

Figure 10 The ultimate tensile strength (UTS) and elongation for LM25 without and with NGR addition; with heat treatment and without.

The elongation is significantly improved for LM25 with addition of novel grain refiner. It is well known that if two materials have the same strength and hardness, the one which has higher ductility is more desirable.

The experiments were carried out to investigate the cooling rate influence on mechanical properties such as tensile strength and elongation for another commercial alloy LM6. Figure 11 presents the tensile properties of LM6 cast bars with and without addition of NGR. The measured cooling rate during solidification was ~1 °C/s. In this case the elongation and tensile strength are significantly improved. The conclusion can be made that addition of novel grain refiner has positive influence on ductility of the samples.

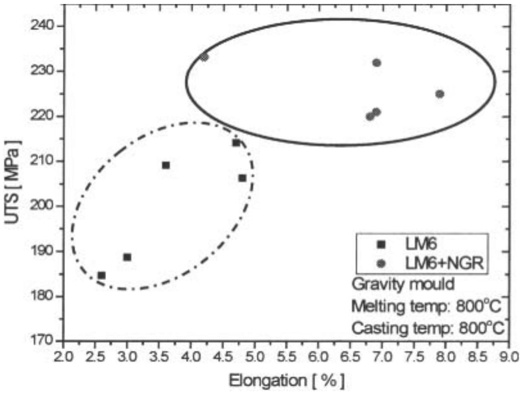

Figure 11. The Ultimate tensile strength as a function of elongation for LM6 without and with novel grain refiner. The LM6 with grain refiner has better strength and elongation than without any addition.

The hardness of the material plays significant role in the assessment of materials for applications. The Vickers hardness measurements were performed on LM6 with different cooling rates from 0.03 °C/s for the slow cooling rate to 1000 °C/s for the

HPDC samples. Figure 12 shows the measurement of average hardness for 5 different positions in each sample.

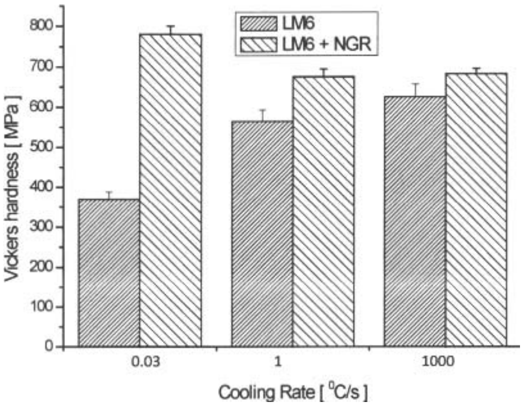

Figure 12. The Vickers hardness as a function of cooling rate for LM6 without and with NGR addition.

The Vickers hardness test shows that the addition of NGR has a positive influence on hardness test especially in slow cooling samples. Figure 12 suggest that small grain sizes improve micro-hardness of the material. The mechanical property data provided in this paper suggests that with the use of NGR, the sand cast commercial alloys can have higher hardness, strength and ductility. Therefore, NGR can play a key role in producing lightweight Al-Si automotive parts.

Conclusion

This research show that for the first time we can chemically refine the α-Al grains of high silicon containing Al alloys under cooling conditions provided by sand casting process. The novel grain refiner is very effective under wide range of cooling rates (0.03 - 100 °C/s). The grain sizes are less sensitive to the cooling rates. This technical development is very significant for industry specially in casting the Al-Si engine blocks or large complex shaped structures with variable thicknesses.

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