Effect of cooling rates of production process of Al-3%B-3%Sr master alloy on grain refinement and eutectic modification efficiency in cast A356 alloy

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Abstract. In this paper, size and morphology of the grain refiner and modifier particles in the Al-3%B-3%Sr master alloy production by using different cooling rates were investigated. Two Al-3%B-3%Sr master alloys were produced with 0.2 and 10°C/s, respectively. The grain refinement and eutectic modification efficiency of the Al-3%B-3%Sr master alloy were tested in casting process of A356 alloy by addition of 4wt.% and holding times for 10-120 min. The experimental result showed that microstructure of the M1 alloy (Slow cooling) consisted of larger solidified particles of AlB₂, SrB₆ and Al₄Sr in the matrix of α -Al compared to the M2 alloy (Rapid cooling). The addition of the M1 alloy in cast A356 alloy, it was found that small grain size and fully modify eutectic silicon were obtained from the holding time in a range of 10-60 min. While the addition of M2 alloy, a small grain size was achieved in shorter holding time in a range of 10-30 min but the eutectic silicon was partly modify. From the thermal analyzed result, solidification of un-modified A356 alloy was changed after addition of Al-3%B-3%Sr master alloy. It was clearly observed that both the undercooling of nucleation and eutectic reaction was reduced and the solidification time was shifted to longer.

1 Introduction

Al-Si-Mg/Al-Si-Cu based alloys are widely used for cast complex part because of an excellent castability, resistance to hot tearing in casting, enhance mechanical properties by using the precipitation strengthening by controlling the precipitated particle of Mg₂Si or Al₂Cu [1]. There are two melt treatment processes in casting of hypoeutectic Al-Si based alloy. One is the grain refinement process by the addition of grain refiner such as Al-Ti, Al-Ti-C, Al-Ti-B, Al-B master alloys [2-4]. A fine α -Al grain is achieved by producing of heterogeneous nucleation site in the melt during it solidified in the mold [5-6]. Second, the eutectic modification process by addition of modifier such as Al-Sr alloy [7]. The eutectic modification process can be improvement mechanical properties, the die filling, controlling the porosity distribution [7-8] and reducing the solution heat treatment in the age hardening process [9]. Moreover, other elements such as Cr can refine the eutectic silicon however the sludge phase can easily form with high Cr content and slow cooling rate [10]. Upon addition with Al-Sr alloy, it was dissolve into the melt and form the SrAl₂Si₂ compound [11] which increases the impurity twinning for changed eutectic Si from acicular into a fibrous morphology.

The combination between the grain refiner and modifier of master alloys can enhance quality and mechanical properties of casting part [12]. Recently, there are many grain refiner and modifier were developed such Al-Ti-B-Sr and Al-B-Sr master alloys by producing various types of particles such as TiB₂, TiAl₃, AlB₂ and SrB₆ as the heterogeneous nucleation site and modification in the melt treatment process,

simultaneously. The Al₄Sr particle is found in the Al-Sr or Al-B-Sr master alloys was dissolved when it was added into the melt during casting [13]. Then, Sr will affect to the eutectic reaction temperature (ERT) and modify microstructure of eutectic phase will be obtained [14].

Form many research papers, the size and morphology of various phases in the master alloy production depend on the melting temperature, cooling rate, chemical compositions and casting method. Ding reported that the blocky TiAl₃ phase was fully refined grain size compared to combined the needle-like TiAl₃ phase [15]. Liao reported that the size and morphology of Al₄Sr phase from different processes affects to the modification efficiency [13]. Wang found that the morphologies of TiAl₃, TiB₂, AlB₂ and AlB₁₂ phases form different synthesis temperature of the Al-3%Ti-3%B master alloy were effect to reduce the α -Al phase in Al-Si alloys [16]. Cui, reported SrB₆ phase of Al-3B-5Sr master alloy can refine the α -Al of A356 alloy but have not investigated the size and morphology on grain refinement and eutectic modification efficiencies [17].

This paper studied the effect of cooling rates on size and morphology of AlB₂ and SrB₆ particles in production of Al-3%B-3%Sr master alloy. The comparison of grain refinement and eutectic modification efficiency in cast A356 alloy were discussed.

2 Experimental procedures

In order to develop and produce the Al-3%B-3%Sr master alloy, the Al-6%B alloy was melted by using a low frequency induction furnace at 900°C. Then, the

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melt was added of the Al-10%Sr master alloy and held for 30min. After that the melt was poured into a molds. There were two different cooling rates of casting for 0.2 and 10°C/s, respectively. The difference wall thickness of the molds between a stainless-steel cup and cylinder steel molds were used to control the cooling rate. The solidification curve of casting was detected by chromel-alumel thermocouple with 0.5°C/s in a stainless-steel cup by using the thermal analysis technique. The specimens were polished and etched by the Keller's reagent. The microstructure was analyzed by optical microscope. The grain refiner and modifier phase were identified by the scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS) technique. The phase fraction of each phase was analyzed by the image analyzer as shown in table 1.

Table 1. Cooling and phase fraction of master alloys

Master alloys	Cooling rate	Phase fraction (%)		
		AlB ₂	SrB ₆	Al ₄ Sr
Al-3%B-3%Sr (M1 alloy)	0.2°C/s (Slow cooling)	0.34	3.88	0.38
Al-3%B-3%Sr (M2 alloy)	10°C/s (Rapid cooling)	0.32	3.43	0.27

In the grain refinement and eutectic silicon modification efficiency tests, the Al-7%Si-0.3%Mg alloy was melted at 900°C by using the low frequency induction furnace. The Al-3%B-3%Sr master alloy was added into the melt with 4wt.% and holding for 10-120 min. The covering flux was used to prevent the hydrogen gas diffuse into the melt during casting. The Ar gas was used to remove hydrogen gas and various inclusions with flow rate 10L/min. The melt was poured at 720°C into a stainless-steel cup with control cooling rate for 0.2°C/s. The specimen preparations of macrostructure and microstructure were grinded, polished and etched by the Keller's and Tucker's reagents, respectively. The grain size was measured by the linear intercept method according to ASTM E112.

3 Result and discussion

3.1 Microstructure of Al-3%B-3%Sr master alloy

Microstructures of Al-3%B-3%Sr master alloy with resulted from different cooling rates of the production were shown in Fig.1 and Fig.2.

Fig. 1. Microstructure of Al-3%B-3%Sr master alloy with cooling rate of 0.2°C/s

Each phase in the microstructures were identified by the SEM-EDS in order to clarify the composition. The microstructure of the M1 alloy (Slow cooling) consisted of solidified phase of AlB₂, SrB₆ and Al₄Sr in the matrix of α-Al as shown in Fig. 1 It can be seen that the SrB₆ (gray-black) was blocky morphology. The AlB₂ was surrounded by the SrB₆ particle while Al₄Sr was the plate-like morphology.

Microstructure of the M2 alloy (Rapid cooling) consisted of the smaller particles of AlB₂, blocky SrB₆ and Al₄Sr. It can be seen that the SrB₆ was found in cluster, while AlB₂ was uniform distribution as shown in Fig. 2. From phase fraction analyzed as shown in Table.1, it was found that the M1 alloy have higher amount of phase fraction than the M2 alloy.

Fig. 2. Microstructure of Al-3%B-3%Sr master alloy with cooling rate of 10°C/s.

3.2 Microstructure of un-modified A356 alloy

Fig. 3 (a-b) show the macrostructure and microstructure of un-modified A356 alloy which consisted of coarse grain size (Fig.3 (a)) and acicular eutectic Si (Fig.3(b)).

Fig. 3. Showed (a) macrostructure (b) microstructure of un-modified A356 alloy.

3.3 Solidification and microstructure of modified A356 with M1 alloy

Fig. 4 shows comparison of cooling curves of modified A356 by addition of M1 alloy with various holding times. The solidification behavior as observed from cooling curve, it was found smaller peaks of undercooling of α-Al in comparison to cooling curve of un-modified A356. This is because AlB₂ and SrB₆ particles in master alloy act as the heterogeneous nucleation site. When comparison effect of holding time in furnace, it found that holding time in a range of 10-60min specimens have smaller grain size compared to 120min specimen as shown in Fig.5.

The eutectic reaction temperature (ERT) of un-modified A356 is 578°C after cooling time in the mold

for 110s. When addition of M1 alloy after holding in furnace for 10-30min, it was found that the ERT occurred at lower temperature of 572°C and increase cooling time to longer for 140s and 153s, respectively. When holding in furnace for prolong time for 120min, the ERT occurred at 576°C with cooling time for 120s. These solidification behaviors can be explained by the Sr in master alloy affect to ETR and solidification time as shown Fig. 6.

Fig. 4. Comparison of cooling curves at α -Al formation with various holding time for 10 to 120 min.

Fig. 5. Macrostructures of modified A356 by added M1 alloy (a) 10 (b) 30 (c) 60 (d) 120 min, respectively.

Fig. 6. Comparison of cooling curves at ERT with various holding time for 10-120 min.

Fig. 7. Microstructure of modified A356 by addition of M1 alloy (a) 10 (b) 30 (c) 60 (d) 120 min, respectively.

Fig. 7 (a-d) show microstructure of various holding times. It is clearly seen that the 10min specimen (Fig. 7 (a)) has finer fibrous Si compared to other specimens (Fig. 7 (b-e)). Thus, when prolong holding time the modification efficiency was reduced.

3.4 Solidification and microstructure of modified A356 with M2 alloy

Fig. 8 shows comparison of cooling curves of modified A356 by added M2 alloy with various holding times. The solidification behavior, it was found smaller peaks of undercooling when the melt was added M2 alloy compared to un-modified A356. When comparison effect of holding time, it was found that holding time in a range 10-30min specimens have smaller grain size compared to 60-120min specimen as shown in Fig. 9.

Fig. 8. Comparison of cooling curve at α -Al formation with various holding time for 10 to 120 min.

Fig. 9. Macrostructures of modified A356 by added M2 alloy (a) 10, (b) 30, (c) 60, (d) 120 min, respectively.

When addition of M2 alloy after holding in furnace for 10-30min, it was found that the ERT occurred at lower temperature of 573°C and longer cooling time for 140s and 145s, respectively. When holding in furnace for prolong time for 120min, the ERT occurred at 575.8°C and cooling time for 130s as shown Fig. 10.

Fig. 10. Comparison of cooling curves at ERT with various holding time for 10-120 min.

Fig. 11 (a-d) show microstructures of various holding times. It is clearly seen that the 60min specimen has finer fibrous Si compared to 10-30min specimens (Fig. 11 (a-b)). When holding for prolong time the modification efficiency was reduced (Fig. 11 (d)).

Fig. 11. Microstructure of alloy with M1 alloy (a) 10 (b) 30 (c) 60 (d) 120 min, respectively.

4.4 Effect of size and morphology of AlB_2 and SrB_6

Form these experimental results, it can be discussed that addition of the M1 alloy with higher amount of AlB_2 and SrB_6 particles has higher grain refining efficiency than the M2 alloy as shown in Fig. 12. The M2 alloy has shorter efficiency time with in 30min because a fine particles is easy dissolved into the melt when prolong holding time.

Fig. 12. Comparison of grain size with various holding time.

Moreover, the M1 alloy has higher modification efficiency than the M2 alloy in all period holding times, especially for 10min specimen (Fig. 7 (a-b)). This is because the ERT of the modified A356 is become lower 5-6°C compared to the un-modified A356. It also found that the solidification time (ST) of the modified A356 was expended to 110s to 140s, simultaneously. Thus, when the ERT reduced and ST shifted to longer (shift to right of Al-Si phase diagram) it should be achieved fine microstructure. Therefore, from these experimental results, the cooling rate of production of Al-3%B-3%Sr master alloys is very important parameter in order to achieve high efficiency of grain refinement and modification.

5 Conclusions

1. The cooling rate of master alloy production affected to the size and morphology. The slow cooling have larger particle than rapid cooling.
2. The larger particle of AlB_2 and SrB_6 was higher efficiency than smaller particles.
3. The plate-like Al_4Sr particle was better modifying the eutectic silicon compared to smaller particle.
4. The addition of M1 and M2 alloys were reduced of ERT and shifted ST to longer.

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