Effect of Electromagnetic Stirring on Microstructure Evolution in Solidification of a Near-Eutectic Al-Si Alloy

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초 록 : 본 논문에서는 공정조건 부근의 Al-Si 합금의 미세구조에 미치는 전자기교반 (EMS)의 영향에 대하여 연구하였다. 초정 α상의 형상에 미치는 전자기교반의 세기의 영향을 조사하기 위하여 각각 교반장치에 60, 80, 및 120V의 전압을 가하여 미세조직을 관찰하였다. 60V이하의 전압이 인가되었을 때 전자기교반의 효과가 나타나지 않은 반면에, 80V이상의 전압으로 5초 이상 인가되었을 때 구상화된 초정 α상은 얻을 수 있었다. 인가된 전압이 120V일 때 초정 α상은 보다 균일한 분포를 가지며 구상화 되었다. 전자기교반의 세기와 함께 교반시간의 영향을 확인하기 위하여 교반시간을 증가시키면서 미세조직을 관찰하였다. 또한 초정 α상의 형상에 미치는 주조변수의 영향에 대해서도 실험하였다.

Key words : EMS, Primary α-phase, Near-eutectic alloy.

1. Introduction

Al-Si alloys have the potential for excellent castability, good weldability, good thermal conductivity, high strength at elevated temperatures and excellent corrosion resistance [1]. These properties led to the application of Al-Si alloys in automobile industry, especially for cylinder heads, pistons and valve lifters [2,3]. The low expansion group of Al-Si eutectic or near-eutectic alloys provides the best overall balance of properties.

Semi-solid metal (SSM) processing has been a promising technology for forming alloys and composites to near-net shaped products with better mechanical properties, less energy-consuming and longer die-life [4]. There are several reports on the fabrication of semi-solid slurries of hypo- and hyper-eutectic Al-Si alloys for rheo-casting [5-8]. But until now there are few reports on the formation of semi-solid slurries for rheo-casting of near-eutectic piston alloys due to the narrow range between the liquidus and solidus temperatures.

In this paper, the fabrication of high quality of semi-solid slurry in a near-eutectic piston alloy was investigated experimentally. In the process, the various stirring powers and stirring times were applied to churn up the alloy melt during solidification. The main theme of the present investigation was to evaluate the effects of EMS intensity and stirring time on the morphology of primary α-phase of the alloy. The appropriate casting parameters for the fabrication of semi-solid slurry were also examined.

2. Experimentals

The composition of an alloy used in the present study is shown in Table 1.

The melting operation was carried out in an electric resistance furnace. The temperature was measured using a K-type thermocouple and the temperature-time curves were recorded using the Midi Date Recorder. The cup diameter for slurry making was 90 mm and the wall thickness of the cup was 1 mm. The EMS was made up of a two-phase two-pole coil and the frequency was 60 Hz. Fig. 1 shows a schematic diagram of the equipment used in the present study. The specimens were polished and etched in Keller liquor for 20 sec to reveal the microstructure under a light optical microscope.

3. Results and discussion

3.1 Effect of EMS intensity

The melt was superheated at 700 °C for more than 20 minutes. In the experiment, the pouring temperature, the quenching temperature and the mold temperature were 567°C, 555°C, and 300°C, respectively. The microstructure of an as-cast alloy without EMS is shown in Fig. 2. After pouring the alloy into the mold, the cooling was continued

| Table 1. The composition of the alloy used in the present study. |
|---|---|---|---|---|---|---|
| Element | Si | Cu | Ni | Mg | Fe | Al |
| Content (%) | 12 | 3.3 | 3.4 | 0.9 | <0.7 | balance |

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quiescently for 95 sec and then quenched the ingot into the water for microstructure observation. The primary α-phase has both the coarse rosette-like and dendritic morphology, as shown in Fig. 2.

Lu [9] has reported that the magnetic induction intensity has a linear relationship with the output voltage of the transformer. It is well known that the magnetic induction intensity correlates with the intensity of the electromagnetic stirring of the conductive metal alloy. In this study the output voltage of the transformer was used instead of magnetic induction intensity for the sake of simplicity.

Fig. 3 shows the effect of EMS intensity which was changed by the output voltages of the transformer on solidified microstructures of the ingots. The stirring time was 5 sec and the holding time \((t_{\text{holding}}\): the time from the end of applying EMS to the beginning of quenching) 95 sec. The output voltages for (a), (b) and (c) were 60, 80 and 120 V, respectively. It can be seen from Fig. 3(a) that when the voltage is 60 V, the primary α-phase exhibits the mixed form of rosette-like, dendritic and globular morphology. When the voltage is 80 V, the globular particles of α-phase can be formed. When the voltage reaches 120 V, the primary α-phase indicates the globular morphology and the distribution of α-phase is more uniform than that of Fig. 3, (b). The size of globular α-particles is in the range of 30–60 µm.

Ohno [10] believes that, in order to obtain a fine equiaxed structure, the separation of crystals should be promoted by dynamic movement in the liquid. And the pouring temperature of a alloy must be as low as possible to prevent the remelting of the free crystals in the liquid. In the present experiment, the pouring temperature is low as 567 °C. The high separation efficiency of crystals formed from the cup wall can be achieved with the turbulent flow induced by EMS and pouring simultaneously. Thus, the microstructure can be refined and the distribution of primary α-phase can be uniform with the appropriate intensity of EMS.

### 3.2 Effect of stirring time

The effect of stirring time on microstructure was verified experimentally. The pouring temperature, the quenching temperature and the mold temperature were 567 °C, 555 °C and 300 °C, respectively. In the experiments, the output voltage of the transformer was kept at 120 V, and the stirring time was varied as 5 sec, 30 sec and 120 sec. The process time of the three samples was 120 sec. Figure 4 indicates the microstructures of the three samples for various stirring times. It can be seen from Fig. 4, (a) that when the stirring time is 5 sec, the globular particles of α-phase are fine and uniform. The average size of the...
globular particles is about 52 µm. When the stirring time increases to 30 sec and 120 sec, as shown in Fig. 4, (b) and (c), there are no significantly differences in the size and the distribution of the globular α-particles when compared with Fig. 4(a).

The experimental results indicate that when the stirring time is longer than 5 sec, there is no visible improvement of the microstructure with further increase of the stirring time. The reason is that most of α-nuclei can be formed on the cup wall during the pouring stage (3~5s) since the cup temperature is lower than the liquidus temperature. However, when the pouring process is over, the cup temperature increases, and the probability of nucleation decreases. The flow patterns are shown in Fig. 5. Vertical flow is mainly induced by pouring, but EMS can churn up the alloy in the horizontal direction. After the pouring stage, the probability of survival of the nuclei will be decreased since the dominating flow is horizontal one induced by EMS in the alloy. According to the present study, the proper stirring time should be 5 sec for the present alloy system.

### 3.3 Effect of casting parameters

Casting parameters play important roles in obtaining high quality of semi-solid slurry. The effects of the pouring temperature and the holding time have been examined on the solidification microstructures after quenching of semi-solid slurry. In the present experiment, the output voltage of the transformer, the electromagnetic stirring time and the temperature of the slurry making cup were kept at 120 V, 5 sec and 300 °C, respectively.

Fig. 6 shows the microstructures of the ingots with various pouring temperatures as 585 °C, 570 °C and 567 °C. The holding time was varied as 30 sec for (a), (b) and (c), and 90 sec for (d), (e) and (f), respectively. From Fig. 6 (a) and (d) it can be seen that the primary α-phase exhibits the dendritic morphology under a high pouring temperature of 585 °C. When the pouring temperature decreased to 570 °C as indicated in Fig. 6, (b) and (e), the primary α-phase indicates the rosette-like and dendritic morphology. When the pouring temperature is 567 °C, the primary α-phase exhibits the globular morphology as shown in Fig. 6, (c) and (f). It can also be seen that the morphology of the primary α-phase is not changed significantly even with further increase of the holding time after pouring. However, the size of the primary α-particles increases as the holding time increases from 30 to 90 sec.

The effect of the pouring temperature on solidification morphology in semi-solid metal processing have been reported. Casting at low pouring temperature is regarded as the least expensive alternative to produce rheo-cast billets. It not only leads to the formation of equiaxed grains but also reduces casting defects by lowering gas and shrinkage porosity [11]. According to the previous report [12], the transition of the primary α-phase for hypoeutectic Al-Si
alloys was found from the globular, to rosette-like and finally to dendritic morphology with the increase of pouring temperature. These phenomena are considered to be due to different nucleation conditions which depend on the pouring temperature.

It is also to be noted that in order to obtain high quality of semi-solid slurry with fine and uniform globular microstructures it is necessary to enhance the nucleation density in the beginning stage of solidification. The nucleation density of the primary $\alpha$-phase depends not only on the pouring temperature of the melt, but also on the wall temperature of the slurry making cup. The nucleation density might increase as the cup temperature decreases. When the cup temperature is too low, for example, as low as 100°C, initial solidification might occur on the surface of the slurry making cup in the present alloy system, which results in the decrease of fluidity of the slurry significantly. Low fluidity of semi-solid slurry might cause some difficulty in forming of complicated casting products using semi-solid slurry. Under preliminary experiments, the appropriate cup temperature for the slurry making in the present alloy system is in the range of 250~350°C.

4. Conclusions

In the present study, fabrication of the slurry of a near-eutectic Al-Si alloy was investigated and the quality of the slurry was evaluated in terms of process parameters. The results are summarized as follows:

1) The EMS intensity affects the morphology of the primary $\alpha$-phase significantly. Without EMS, the primary $\alpha$-phase exhibits both the coarse rosette-like and dendritic morphologies. When the voltage is 60 V, the primary $\alpha$-phase exhibits the mixed form of rosette-like, dendritic and globular morphology. When the voltage is 80 V, the globular particles of $\alpha$-phase can be formed. When the voltage reaches 120 V, the primary $\alpha$-phase exhibits the globular morphology and the distribution of $\alpha$-phase is uniform.

2) The fine and uniform globular $\alpha$-particles can be formed during the pouring stage with EMS. However, there is no visible improvement on the microstructure of the solidified ingot with further applying EMS. In case of a near-eutectic Al-Si alloy, the proper stirring time to achieve fine and uniform globular microstructures was found to be 5 sec.

3) With the decrease of the pouring temperature, the primary $\alpha$-phase morphology changes gradually from dendritic to rosette-like, and finally to globular structure.

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References


