Effects of Mechanical Stirring and Vibration on the Microstructure of Hypereutectic Al-Si-Cu-Mg Alloy Billets

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A hypereutectic Al-Si-Cu-Mg alloy billet was fabricated by a semi-solid forming method that combined a simple mechanical stirring treatment with the vertical semi-continuous casting process. Higher rotational speeds and higher casting temperatures during stirring yielded a finer as-cast structure and more uniform distribution of primary silicon particles in the matrix. However, these stirring conditions also led to transverse cracks on the billet surface. A mechanical vibration treatment using smaller amplitudes and lower frequencies during casting improved the cracked surface considerably, resulting in a structure comparable to that of the billet stirred at the same time.

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1. Introduction

The semi-solid forming (SSF) process is increasingly recognized as a new forming technology for near-net shape manufacturing, applicable, for example, to automotive components made from commercial aluminum foundry alloys. Compared to various other forming methods in terms of cost and performance index, the SSF process is located exactly in between casting and forging. This means that SSF would simultaneously improve on the quality and cost performance of conventional processes. The thixoforming process, an SSF method used for forming materials reheated to the semi-solid state, has been attracting attention as a fundamental technique for improving the hot workability of high-strength wrought alloys such as A7075.\textsuperscript{1,2} In order to obtain formed products with good formability and superior mechanical properties, it is necessary for the feed stock billet to have a globular, non-dendritic, fine structure because such a structure enhances the fluidity of slurries directly related to the formability at the semi-solid state.\textsuperscript{3} These billets are typically cast by various electromagnetic stirring (EMS) methods.\textsuperscript{4} Instead of the EMS methods, which yield expensive billets, we have attempted to manufacture A7075 billets for SSF more simply and at a lower cost, by combining a simple mechanical stirring treatment with the vertical semi-continuous casting process using a heat insulating mold. In our previous study,\textsuperscript{5} we obtained a billet with a non-dendritic fine-grained structure with a mean grain size of about 30 \textmu m under certain stirring conditions. Thus, we believe that mechanical stirring strongly promotes refinement of the non-dendritic structure. However, in the case of the hypereutectic Al-Si-Cu-Mg alloy, which is used as a functional material, \textit{e.g.}, as compressor parts, coarsening and aggregation of the primary silicon particles lead to unsatisfactory formability and mechanical properties. This has necessitated microstructural refinement of this alloy. Components made of this alloy are typically manufactured by the casting process because the alloy is difficult to work.\textsuperscript{6} If the SSF process can be applied to this alloy, it is expected that its hot formability would be improved, and the final products would have better quality than conventional castings. In the present study, we first attempted to fabricate a hypereutectic Al-Si-Cu-Mg billet for SSF through the same stirring procedure as that used in the case of the fine-grained A7075 alloy in our previous study. We then employed mechanical vibration, rather than mechanical stirring, to obtain both the optimal as-cast structure and high billet surface quality.

2. Experimental Procedure

A direct chill (DC) semi-continuous casting billet (Al-14.8 mass\%Si-4.5 mass\%Cu-1.1 mass\%Mg alloy; see Table 1 for exact composition) was prepared, from which all samples of the present study were derived. The pieces cut from this DC billet were remelted and billets 50 mm in diameter were semi-continuously cast using a casting machine equipped with a mechanical stirring or vibration device, as schematized in Fig. 1(a).\textsuperscript{5} The casting temperature was 993 K or 1043 K. The casting speed was 1 mm/s, and the flow rate of cooling water was $4.2 \times 10^{-4}$ m$^3$/s. These conditions were selected on the basis of preliminary experiments. The length of each billet was about 700 mm. The stirring or vibration treatment was started after the casting

\begin{table}[h]
\centering
\begin{tabular}{cccccccccc}
\hline
Si & Fe & Cu & Mn & Mg & Cr & Zn & Ti & Al \\ \hline
14.8 & 0.01 & 4.50 & 0.01 & 1.10 & 0.01 & 0.01 & 0.01 & Bal. \\
\hline
\end{tabular}
\caption{Chemical composition of hypereutectic Al-Si-Cu-Mg alloy (mass\%)}
\end{table}
length reached about 100 mm. The trials were carried out using a thin cylindrical rotor at rotational speeds ranging from 8.3 s\(^{-1}\) to 60 s\(^{-1}\). The vibrator was located at position B, as shown in Fig. 1(b). The vibrations were of relatively low frequency (\(f\)), ranging from 5 to 40 Hz, and large amplitude (\(w\)), ranging from 1 to 18 mm. The microstructure of the longitudinal sections of the billets obtained were observed by optical microscope, and the crystallographic orientations of the primary silicon particles were measured by an electron back-scattered pattern (EBSP) system on an SEM.

3. Results and Discussion

3.1 Effect of Stirring Conditions on Billet Microstructure

First, a billet for SSF was cast semi-continuously at a casting temperature of 993 K and a rotational speed of 20 s\(^{-1}\). These conditions were similar to those used in the case of a fine-grained A7075 billet in our previous study.\(^5\) The dendrites observed in the billet fabricated without stirring (Fig. 2(a)) were almost completely broken up as a result of the stirring, yielding a matrix structure seemingly suitable for semi-solid forming (Fig. 2(b)). However, most of the primary silicon particles had coalesced and formed large aggregates.

Thus, we deemed it necessary to elucidate the cohesion mechanism of the primary silicon particles in order to obtain a billet for SSF with a non-dendritic structure and fine, uniformly dispersed primary silicon particles, whose crystallographic orientation was analyzed by SEM-EBSP. Figure 3 shows a typical silicon aggregate in the stirred billet. As seen in Figs. 3(a) and (b), an individual aggregate is formed by multiple crystals (regions A, B, C and D) even
though the aggregate appears to be a single particle. Regions A and D exhibit a twin relationship; the others are randomly oriented with respect to each other. Regions A and B are rotated along nearly the \( \{110\} \) direction with respect to each other.

For such silicon aggregates, Lee et al. have proposed a cohesion mechanism consisting of two models (Fig. 4).\(^7\) According to their model, the vigorous stirring in the semi-solid state causes the primary silicon particles to break along the \{110\} or \{100\} plane of silicon. The long stirring treatment also causes them to aggregate; the cohesive interface has a specific orientation, rotated along the \{110\} or \{100\} direction of silicon. The relationship between regions A and B (see Fig. 3) is nearly in agreement with Type B of the model. These results suggest that it is effective to shorten the stirring time further and perform cooling more rapidly so as to avoid silicon aggregate formation. Thus, the effects of rotational speed and casting temperature were investigated in order to obtain faster stirring and more rapid cooling conditions.

Figure 5 shows optical micrographs of the longitudinal section of the billet stirred at a casting temperature of 993 K and a rotational speed of 10 s\(^{-1}\). It was found that at rotational speeds below 11.3 s\(^{-1}\), the primary silicon particles had coarsened and aggregated as shown in Fig. 5(b). Furthermore, larger particles and aggregates had segregated macroscopically toward the billet surface.

Figure 6 shows the microstructure of the billet stirred at a rotational speed of 46.7 s\(^{-1}\). Here, the primary silicon particles were dispersed more uniformly than in the sample fabricated at 10 s\(^{-1}\), and there was an increase in the globular regions (Fig. 6), although some aggregates of silicon particles were retained. A billet stirred at a rotational speed above 46.7 s\(^{-1}\) had also the \( \alpha \) matrix refined as the same degrees as that of Fig. 6. However, silicon aggregates were formed in this case as well.

Figure 7 shows optical micrographs taken from the longitudinal section of the billets stirred at various rotational speeds and casting temperatures. Microstructural date for the rotational speeds of 10, 33.3, 46.7 and 60 s\(^{-1}\) were checked at a casting temperature of 993 and 1043 K, although the microstructural data pertaining thereto were omitted. As seen in Fig. 7, the condition of 46.7 s\(^{-1}\) and 1043 K showed a
typical good microstructure. The trend observed was that higher rotational speeds and higher casting temperatures yielded a finer non-dendritic matrix structure and a more uniform distribution of the primary silicon particles with finer sizes. At the relatively high casting temperature of 1043 K and rotational speed of 46.7 s⁻¹, the silicon particles were dispersed most uniformly. However, the periodic transverse cracks on the billet surface deepened with increasing rotational speed.

3.2 Effect of Vibration Conditions on the Microstructure and Billet Surface Quality

To improve the unsatisfactory billet surface quality mentioned above, a simple mechanical vibration of relatively low frequency and large amplitude was investigated. First, the vibrator was located at position B within the chamber (see Fig. 1(b)). The molten metal in the chamber was agitated by a vibrator at a constant amplitude of 18 mm. Figure 8 shows the microstructure of the billet vibrated at a frequency of

Fig. 5 Optical micrographs of the longitudinal section of a billet stirred at a casting temperature of 993 K and a rotational speed of 10 s⁻¹: (a) center region and (b) near the half-radius.

Fig. 6 Optical micrographs of the longitudinal section of a billet stirred at a casting temperature of 993 K and a rotational speed of 46.7 s⁻¹: (a) center region and (b) near the half-radius.
20 Hz and a casting temperature of 1043 K. While the dendrites observed in the vibration-free zone were to some extent broken up by the vibration treatment (see Fig. 8(b)), the primary silicon particles were dispersed sparsely in the matrix and segregated toward the top of the billet as shown in Fig. 8(c). The tendency was almost the same even at vibration frequencies above 20 Hz. This indicates that an amplitude of 18 mm is not optimal (it is too large) in terms of the distribution of the primary silicon particles.

Thus, the following experiments were carried out at amplitudes smaller than 4 mm. Figure 9 shows the effect of frequency and amplitude on the microstructure of the vibrated billet. While frequencies below 10 Hz scarcely affected the billet microstructure, the α matrix obtained at a frequency of 20 Hz and an amplitude of 4 mm was non-dendritic and was globular over a relatively wide area. Furthermore, the primary silicon particles were distributed almost uniformly in the α matrix notwithstanding some large aggregates. On the other hand, as the effect of vibration was not felt at the higher frequency of 30 Hz, these conditions caused the same macrosegregation as in the billet vibrated at an amplitude of 18 mm. Also, the distribution of the primary silicon particles was somewhat more uniform at an amplitude of 2 mm and a frequency of 20 Hz than at an amplitude of 4 mm at the same frequency. From the industrial viewpoint, the billets obtained by the vibration treatment with a frequency of 20 Hz and an amplitude of 2 and 4 mm seem to be suitable for thixoforming.

Furthermore, in this experiment, molten metal temperatures within the chamber and outside the vibration chamber were measured during casting. Figure 10 shows the temperature distributions during casting of the billets that were vibrated at a frequency of 20 Hz and an amplitude of 2 and 4 mm. There are no clear differences between the amplitudes of 2 and 4 mm at any point in a region of about 30 mm from the lower end of the mold, but at the top of the chamber, the temperature was higher in the case of 2 mm than in the case of 4 mm, and lay above the crystallization line of the primary silicon particles. This probably means that at small amplitudes, most of the primary silicon particles do not crystallize at the upper side of chamber, while they do crystallize in the whole chamber at large amplitudes. Thus, the primary silicon particles generated by vibrations of large amplitude were agitated for longer times than those generated by vibrations of small amplitude. This difference may cause slight decreases in the number of aggregates and the size of individual particles themselves at small amplitudes.
Figure 11 shows the exteriors of billets fabricated with and without vibration treatment at a frequency of 20 Hz. With regard to billet surface quality, every vibration treatment in this study improved the surface roughness considerably compared to that of the billet fabricated without vibration. In particular, the billet produced by a vibration treatment at a frequency of 20 Hz and an amplitude of 2 mm had a relatively smooth surface, as shown in Fig. 11(c) and this vibration treatment was most effective not only for the microstructure but also the surface quality.

4. Conclusions

Simpler and lower cost methods of manufacturing a hypereutectic Al-Si-Cu-Mg alloy billet for SSF have been investigated by combining simple mechanical stirring or vibration with the vertical semi-continuous casting process. The results obtained can be summarized as follows:

1. A hypereutectic Al-Si-Cu-Mg alloy billet for semi-solid forming could be semi-continuously cast by a simple mechanical stirring treatment at a relatively high rotational speed and high casting temperature. While the as-cast structure of this billet had more uniformly distributed primary silicon particles as well as appreciably broken dendrites, periodic deep transverse cracks were generated on the billet surface.

2. At the vibration treatment with an amplitude of 2 and 4 mm and a frequency of 20 Hz, almost all primary silicon particles were distributed uniformly in the matrix. Simultaneously, the microstructures of the α matrix became non-dendritic.

3. The vibration treatments using smaller amplitudes and lower frequencies considerably improved the low

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**Fig. 9** Optical micrographs taken at a point about 300 mm from the bottom of the longitudinal section of billets vibrated at various amplitudes and frequencies.

**Fig. 10** Temperature distributions within the vibration chamber during casting of billets vibrated at \( f = 20 \text{ Hz} \): • \( w = 4 \text{ mm} \) and △ \( w = 2 \text{ mm} \). ○, ◯ and ⊙ correspond to the primary silicon particles, α phase crystallization and solidus temperature, respectively.

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**Table**: Frequency

<table>
<thead>
<tr>
<th>Amplitude</th>
<th>Frequency</th>
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<tbody>
<tr>
<td>20 Hz</td>
<td>20 Hz</td>
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<tr>
<td>30 Hz</td>
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*Figure 10* Temperature distributions within the vibration chamber during casting of billets vibrated at \( f = 20 \text{ Hz} \): • \( w = 4 \text{ mm} \) and △ \( w = 2 \text{ mm} \). ○, ◯ and ⊙ correspond to the primary silicon particles, α phase crystallization and solidus temperature, respectively.
surface quality of the billets with and without mechanical stirring.

(4) The crystallographic orientation analysis of the primary silicon particles by SEM-EBSP showed that the aggregates observed in the stirred billet were in partial agreement with the cohesion model proposed by Lee et al.

REFERENCES


