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The continuous casting of a semisolid aluminum alloy billet with a multiple magnetic field imposed

Z.F. Zhang*, J. Xu, Z.F. Tian and L.K. Shi
General Research Institute for Non-ferrous Metals, Beijing 100088, P.R. China

In order to obtain semi-solid aluminum alloy billets of high quality, an investigation was carried out of imposing multiple magnetic fields from the outside of a cold-crucible copper mold in a continuous casting process. $AlSi_6Mg_2$ (wt.%) alloy designed for a semi-solid metal (SSM) process was continuously cast through a submerged entry nozzle under various conditions. By means of optimizing the distribution of multiple magnetic fields in the mold, the effect of multiple magnetic fields on both the meniscus motion and billet quality was examined. The experimental results showed that meniscus disturbance could be controlled efficiently and the surface quality of a semi-solid aluminum alloy billet was improved greatly by imposing multiple magnetic fields, and also a uniformly fine, globular microstructure across the transverse section of the billet was achieved by optimizing the distribution of the multiple magnetic field.

Key words: continuous casting, multiple magnetic field, aluminum alloy, semi-solid, microstructure.

Introduction

The implementation of semi-solid thixoforming in the automotive industrial series production of high-grade components is directly dependent on the quality of feedstock material, which should exhibit a uniformly globular grain structure to improve its handling properties at the heating stage and to ensure the appropriate shear strength reduction for the pressure die casting process [1, 2]. There are several methods proposed for semi-solid feedstock material production [3], a combination of a conventional continuous casting process with an electromagnetic field characterized by cleanness, high energy density and easy manipulation, has been recognized as the most efficient way to produce suitable feedstock material with thixotropic behavior [4].

Electromagnetic casting (EMC) of aluminum alloy is one example of grain refinement in continuous casting by imposing middle-frequency electromagnetic field. Because aluminum alloy is cast without contacting a physical mold entirely depending on the electromagnetic forces, the liquation build-ups and dendrites are excluded, and consequently, the ingot surface is usually smooth enough to be hot rolled without a hot scalping operation. But the disadvantage of the technology is that the microstructure in the billet center improves little due to imposing a middle-frequency magnetic field, and its microstructure does not meet the needs of SSM processing [5]. Another example is that electromagnetic stirring (EMS) in combination with a special mold design based on the conventional continuous casting process is used to produce feedstock material, and different processes such as rotating EMS [6, 7] or linear EMS [8] were developed in terms of the stirring mode. As the most common technique to produce pre-material in industry, however, there still exists unfavorable dendritic structure in the billet surface in spite of its indisputable good structure in the billet center. To solve this problem, a scalping operation of the slug for reheating is demanded, which leads to higher production costs.

In order to obtain semi-solid pre-material of high quality, an attempt was made in the continuous casting of an aluminum alloy by imposing multiple magnetic field, which was realized by setting a high frequency electromagnetic coil (HFC) and a commercial frequency electromagnetic coil (CFC) around a cold-crucible copper mold, and also this technology has been studied in the continuous casting process of a steel and the billet quality was improved greatly [9]. $AlSi_6Mg_2$ (wt.%) alloy designed for a SSM process was continuously cast through submerged entry nozzle under various conditions. By means of optimizing the distribution of the multiple magnetic fields in the mold, the effect of the multiple magnetic fields on meniscus motion behavior was examined, and the microstructures of billets continuously cast by imposing multiple magnetic field are presented.

*Corresponding author:
Tel : +86-10-82241229
Fax: +86-10-62355099
E-mail: zhangzf@grinm.com

Experimental

A schematic view of experimental apparatus is shown in Fig. 1. Two types of electromagnetic coils were installed on the outside of the cold-crucible copper mold with an inner size of ϕ 70 mm and outer size of ϕ 90 mm. The upper one, a 3-turn solenoid, mainly producing a large electromagnetic pressure force to realize soft-contact solidification between the mold wall and the liquid metal, is linked with a high-frequency electric generator with a maximum power capacity of 100 kW and maximum frequency of 1 kHz; the lower, an electromagnetic stirrer, consisting of a four-pole stator, will induce a rotating magnetic field inside the mold to realize the grain refinement; powered by a commercial frequency multiple phase AC. current, the intensity of the rotating magnetic field can be accurately controlled.

$AlSi_6Mg_2$ (wt.%) alloy designed for a semi-solid process was used to verify the effect of multiple magnetic fields on both the meniscus disturbance and the billet quality in the continuous casting process. The magnetic flux density was measured along the central axis of the mold without a charge by a sensor coil. In order to examine the variation of the meniscus shape, an aluminum foil was inserted into the mold when the multiple magnetic field was imposed, and the meniscus shape could be marked after the aluminum foil was burned. During the continuous casting of $AlSi_6Mg_2$ (wt.%) alloy, the meniscus level was kept at a position of 30 mm from the top of the mold, the pouring temperature was 710°C, the cooling water flux was 80 Lh^{-1}, the casting velocity was 160 mm/minute, the maximum high-frequency current to the solenoid was 200 A and the maximum commercial-frequency current to the stirrer was 8 A. The solidification grain structures were observed across the transverse section of billets after etching with Keller solution.

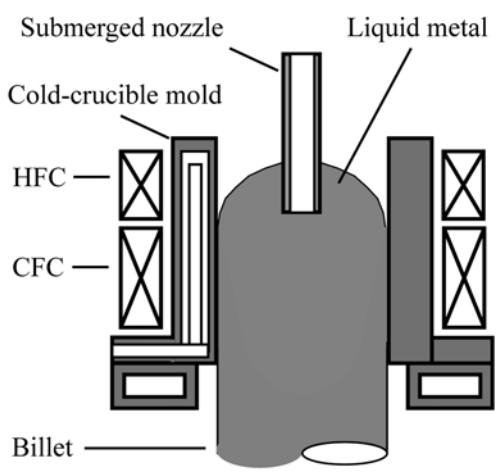


Fig. 1. shows a schematic view of the experimental apparatus.

Results and Discussion

Distribution of magnetic field in the mold

Figure 2 shows the distribution of multiple magnetic fields along the central axis of the mold without the charge. Curves 1 and 2 indicate the magnetic flux density parallel and perpendicular to the casting direction, respectively. It is noted that, in the upper part of the mold, the magnetic flux density parallel to the casting direction (B_z) is not only uniform but also larger than that perpendicular to the casting direction (B_r), which contributes to keep the meniscus stable and to ensure a soft-contact solidification between the mold wall and the liquid metal; by contrast, in the lower part of the mold, B_r, larger than B_z, will produce a stirring motion around the axis of symmetry of the billet for the grain refinement.

Effect of multiple magnetic field on the meniscus

Figure 3 shows the effect of the multiple magnetic field on meniscus shape. As illustrated in Fig. 3, when only the commerical frequency magnetic field is imposed, the meniscus shape is concave, and the depth

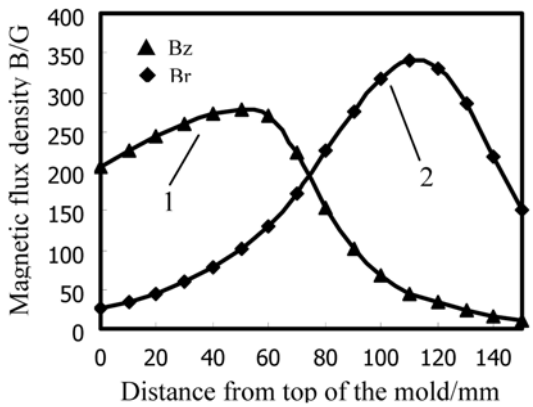


Fig. 2. shows the distribution of multiple magnetic fields in the mold.

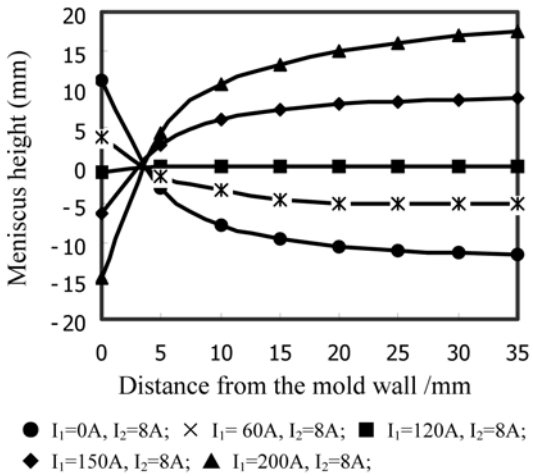


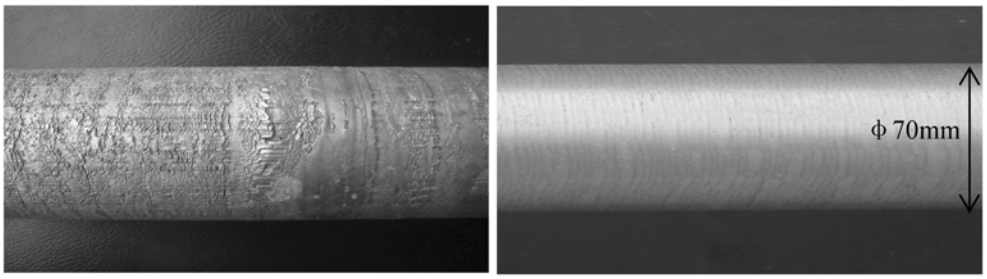
Fig. 3. shows the effect of the multiple magnetic field on the meniscus shape.

of the meniscus concavity increases with an increase of current I_2 input to EMS coils. It is also noted that, after the high frequency magnetic field is imposed with current I_2 of 8 A, the depth of the meniscus concavity decreases with an increase of the high-frequency current I_1 to the solenoid; when I_1 increases up to more than 120 A, the meniscus concavity disappears, the meniscus begins to turn into a convex shape, when I_1 increases up to more than 200 A, the convexity height of the meniscus arrives at 20 mm. These results imply that the meniscus shape can be controlled by imposing the multiple magnetic fields.

Effect of multiple magnetic field on the billet quality

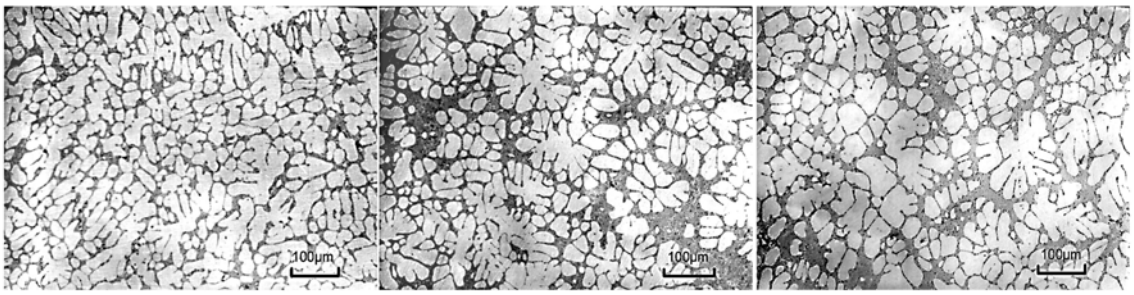
The surface appearances of semi-solid billets under conditions with and without multiple magnetic fields are shown in Fig. 4. In the case without a multiple magnetic field, liquiation build-ups and dendrites are found on the surface of the billet; after imposing a multiple magnetic field, the billet surface becomes smooth, and also the stability of the casting process is markedly improved.

Figure 5 shows the microstructures of different parts of a billet with a rotating magnetic field, R indicates the distance from the central axis of symmetry in the transverse section of billets. It is obvious that in the case without a high-frequency magnetic field, the microstructure in the surface of the billet, shown in Fig. 5(a), is mainly made up of frozen dendritic grains in spite of the uniformly globular microstructure in the billet center, shown in Fig. 5(b), (c). Figure 6 shows the microstructures in different parts across the transverse section of billets in the case of a multiple magnetic field, R indicates the distance from the central axis of symmetry in the radial direction. After the high



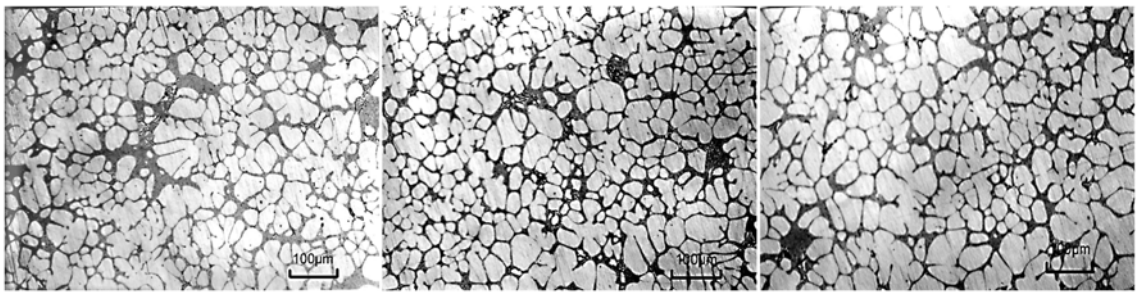
(a) Without multiple magnetic field (b) With multiple magnetic field

Fig. 4. shows the effect of multiple magnetic field on surface quality.



(a) R=30mm (b) R=20mm (c) R=0mm

Fig. 5. shows the effect of a rotating magnetic field on the microstructure.



(a) R=30mm (b) R=20mm (c) R=0mm

Fig. 6. shows the effect of multiple magnetic fields on the microstructure.

frequency magnetic field is simultaneously imposed, uniformly globular grains appear in the billet surface, and the microstructure of billets can be greatly improved with an increase of I_1 to 200 A.

It is well known that coarse columnar dendritic grains appear in the solidification structure of billets due to unidirectional transfer of heat in a conventional continuous casting. In the absence of electromagnetic stirring, the temperature decreases continuously from the liquid to the solid, and a positive temperature gradient always exists ahead of the solidification front, where considerable latent heat is released. The positive temperature gradient in the liquid ahead of the solidification front towards the central region leads to dendritic grain growth. However, in the presence of electromagnetic stirring, the strong stirring flow quickly dissipates the latent heat released from the solidification front to the bulk liquid, leading to a relatively uniform temperature distribution in the liquid, which is considered to be necessary for simultaneous nucleation. Under this situation, copious potential nuclei, originating either from heterogeneous nucleation or from the convective transport of dendritic debris sheared by fluid flow, are induced to appear in the bulk liquid, which is virtually attributed to grain refinement. However, the microstructure in the outer part of billet is mainly made of frozen equiaxed dendrite crystals just because only the central liquid metal can be efficiently stirred by electromagnetic stirring, and the outer part of the liquid metal seems to solidifies too quickly to be stirred. When a high-frequency magnetic field is simultaneously imposed, the electromagnetic force created by the high-frequency magnetic field decreases the heat transfer between the mold wall and the liquid metal, and retards the rapid solidification in the outer part of the liquid metal, which benefits the efficient mixture of the liquid in the entire liquid region and subsequent instantaneous heterogeneous nucleation, resulting in uniformly fine, globular grains. Furthermore, without the high-frequency magnetic field, the initial solidified shell was thin and long, and defects such as liquiation build-ups and dendrites appear easily; in the case with the high-frequency magnetic field, the initial solidified shell became thick and short, and thus these defects could be avoided, More detailed information has been provided in the literature [9].

Conclusions

(1) The meniscus disturbance generated by electromagnetic stirring can be controlled efficiently by imposing multiple magnetic fields;

(2) Both the external and internal quality of billets were improved greatly and a uniformly fine, globular microstructure across the transverse section of billets was achieved by optimizing the distribution of the multiple magnetic field;

(3) The potential of the peculiarities of continuous casting aluminum alloy by imposing multiple magnetic fields requires further detailed investigation.

Acknowledgements

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