Direct chill casting with reversing rotational electromagnetic field

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Abstract
In order to achieve higher qualities of aluminum metal products, fine grain structures of materials are required. It is well known that agitation of a liquid metal during solidification process is effective to promote grain size refinement. In this research, the reversing RMF, i.e., the RMF that reverses rotation direction of an electromagnetic field at regular intervals, was applied to a molten metal pool in a cylindrical container of a round billet of DC casting. Electromagnetic fields generated by the reversing RMF stirrer were measured and compared with simulation results of electromagnetic analysis. The molten metal in the pool caused a clockwise and a counter-clockwise flow by applying the reversing RMF, and the flow field was simulated by a CFD calculation. It was found that the liquid metal was effectively stirred with the reversing RMF, resulting a higher turbulent intensity of the liquid metal. Grain sizes of a billet were measured and a relation between the flows and the sizes were investigated.

Key words: DC casting, electromagnetic stirring, reversing RMF, grain refinement

Introduction
Grain size and structure have a large impact on qualities of aluminum metal products. Many techniques are proposed and used to obtain finer and equiaxed grain structure, such as grain refiner (TiB₂ particle etc.) [1, 2], control of melt flow in a casting pool [3, 4], oscillating of melt [5], and so on. Among them, electromagnetic stirring is very attractive due to its nature of contactless, it is fitting well to solidification process in a DC casting mold.

Eckert et al. [4] reviewed effects of electromagnetic melt flow control on solidified structures. They showed that Rotating Magnetic Fields (RMF) and/or Travelling Magnetic Fields (TMF) have good effects of grain refinement and an earlier transition from columnar to equiaxed structure (CET). On the other hand, it was pointed out that electromagnetic stirring during solidification of metallic alloy might have frequently a drawback of macrosegregation as a result of strong convection. In order to overcome the flow-induced macrosegregation, Eckert et al. [6] and Willers et al. [7] proposed a pulsed RMF stirring with a constant or alternating direction. They concluded that the time-regulated RMF stirring have a potential to be a more suitable one than conventional continuous RMF stirring methods.

In this research, the reversing RMF, i.e., the RMF that reverses rotation direction of an electromagnetic field at regular intervals, was applied to a molten metal pool in a cylindrical container of a round billet of DC casting. Spatial distribution of magnetic flux density, which was generated by the reversing RMF, was measured and compared with simulation results of electromagnetic analysis. The molten metal in the casting pool caused a clockwise and a counter-clockwise flow alternately by applying the reversing RMF, and the flow field was simulated by a CFD calculation. A pilot test of DC casting of aluminum alloy with the reversing RMF was carried out and grain sizes of a billet were measured.

Electromagnetic Stirrer
Fig. 1 shows a photograph of the electromagnetic stirrer used in this study. The stirrer is an AC 3-phase 6-pole induction motor without a rotor. It generates a RMF to stir molten metal rotationally inside its bore. An inner diameter of the centre bore is 140 mm and a height of the stirring coil is 210 mm. An AC coil current of 35.7 A at a frequency 50 Hz was applied to the stirrer. Schematic diagram of a concept of the reversing RMF stirring is shown in Fig. 2. It changes alternately the rotation direction with a regular reversing interval.

¹ This stirring method is referred as “RMF Pulse Sequence of Alternation Direction (RMF-PSAD)” in the literature mentioned above [6, 7].
In order to estimate Lorentz force applied to the molten metal by the stirrer, an electromagnetic field analysis was carried out by using a commercial code JMAG (JSOL Corp.). Fig. 3 shows the result of vector field of magnetic flux density on a horizontal cross section at height of coil centre. The figure clearly shows that the stirrer has 6 poles along a circumferential direction. Radial distribution of tangential component of magnetic flux density inside the stirrer’s bore was measured by a gauss meter and compared with the electromagnetic analysis. The results are shown in Fig. 4 and the agreement between the experimental data and the numerical simulation is quite well. Spatial distribution of Lorentz force induced by the stirrer is shown in Fig. 5. The force is applied only to the limited area near the RMF coil. The tangential component of the force is much larger than the radial and the vertical components.
Flow Field driven by reversing RMF

Fluid flow of the molten aluminium in the casting pool was conducted by using a commercial CFD code FLUENT (ANSYS, Inc.). Lorentz force estimated by the electromagnetic analysis (shown in Fig. 5) was implemented as a source term of momentum equation. A diameter of the round billet is 92 mm and a height of the pool is from 202 mm (at side wall position) to 219 mm (at centre axis position), the shape of the solidification front (namely, the bottom of the pool) is determined experimentally. For the sake of reducing calculation cost, the following assumptions were used:

- A flow filed did not affect an electromagnetic field.
- No energy transportation and no solidification phenomena. Properties of melt were uniform and constant.
- No feed of molten metal and no casting withdrawal.
- 2-dimensional axisymmetric flow with swirl.

Temporal change of swirl velocity at the point of $r = 0.87 R$ (near side wall) and coil centre height is shown in Fig. 6. A reversing time is 0.3 s and the flow direction alternating periodically with the reversing time. Vector field of fluid flow is shown in Fig. 7. From the figure, it can be seen that it is not a simple swirl flow but a 3-dimensional complex flow. Due to the complexity, a turbulent intensity of a melt flow induced by the reversing RMF is much higher than that of a continuous RMF stirring.

Microstructure

Optical micrographs of grain structure of the billet obtained by the pilot test of DC casting of 7000 series aluminium alloy are shown in Fig. 8. Grain sizes are summarized in Fig. 9. The grain size became finer over the entire radius position by applying the reversing RMF stirring, it was about two thirds or less. The smallest grain size was less than 50 μm without addition of grain refiner.
Fig. 8: Polarized optical micrographs of grain structure of 7000 series aluminum alloy with/without stirring.

Fig. 9: Grain size of aluminum alloy with/without electromagnetic stirring corresponding to figure 8.

Conclusion
The reversing RMF stirring was investigated through numerical simulation of electromagnetic and CFD analysis. A 3-dimensional complex flow was generated by the alternation of rotation direction of RMF. A pilot test of DC casting was conducted and grain refinement effect by the reversing RMF was confirmed.

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References
1. D. G. McCartney, Int. Mater. Rev., 34 (1989), 247–260.
2. B. S. Murty, S. A. Kori, and M. Chakraborty, Int. Mater. Rev., 47 (2002), 3–29.
3. V. Metan, K. Eigenfeld, D. Räbiger, M. Leonhardt, and S. Eckert, J. Alloy Compd., 487 (2009), 163–172.
4. S. Eckert, P. A. Nikritnyuk, B. Willers, D. Räbiger, N. Shevchenko, H. Neumann-Heyme, V. Travnikov, S. Odenbach, A. Voigt, and K. Eckert, Eur. Phys. J. Special Topics, 220 (2013) 123–137.
5. K. Iwai and T. Kohama, Tetsu-to-Hagané, 96 (2010), 637–640.
6. S. Eckert, P. A. Nikritnyuk, D. Räbiger, K. Eckert, and G. Gerbeth, Metall. Mater. Trans. B, 39B (2008), 374–386.
7. B. Willers, S. Eckert, P.A. Nikritnyuk, D. Räbiger, J. Dong, K. Eckert, and G. Gerbeth, Metall. Mater. Trans. B, 39B (2008), 304–16.