論　文

Effect of Reversing Rotational Magnetic Field on Grain Size Refinement*

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In order to achieve high quality aluminum ingots, fine grains are required. The electromagnetic stirring process is known as one of the processes that promotes grain size refinement in aluminum alloys. In this study, a reversing Rotational Magnetic Field (reversing RMF) that reverses the rotation direction of the electromagnetic field at regular intervals was applied to a molten aluminum in the cylindrical container of a round billet for DC casting. The molten aluminum underwent a clockwise and counter-clockwise flow by applying a reversing RMF. In the case that the periodic time of the reversing RMF is long, the grain size of the billet was finer than that of the mono-directional rotational flow. On the other hand, the grain size of the billet center was not fine in the case that the periodic time of the reversing RMF was short. The flow field was calculated by a CFD simulation for comparison with the experimental results. It was found that the development of the flow field affected the grain size refinement.

Keywords: *DC casting, electromagnetic stirring, reversing RMF, grain refinement*

1. Introduction

In order to achieve a fine grain structure in aluminum alloys, a grain refiner, such as the Al-Ti-B system[1), 2)] is added to the molten aluminum during casting. The grain refiner has heterogeneous nucleation sites (TiB_2 particles, etc.), but it is well known that most of the heterogeneous nucleation sites become inclusions. For that reason, many processes are proposed in order to obtain a finer grain structure without the grain refiner such as generating a rotational flow in the melt pool[3)], ultrasonic treatment[4)], etc. Among them, electromagnetic stirring is a useful method because it is a contactless process with the molten metals.

A Rotational Magnetic Field (RMF) generates a rotating flow in the melt pool. As a result of the convection, the ingot, which has a grain-refined microstructure, is achieved. However, a vortex, which causes oxide film inclusions, occurs in the center of the flow when the flow rate is high. The reversing RMF, i.e., a RMF that reverses the rotation direction of an electromagnetic field at regular intervals, is an effective way to generate a strong flow without forming the central vortex. Eckert et al.[5)] calculated the flow which is caused by pulsed RMF stirring with a constant or alternating direction. They concluded that the time-regulated RMF stirring has the potential to be a more suitable method than the conventional continuous RMF stirring methods. Li et al.[6)] verified the effect of grain refinement by applying the reversing RMF. They found that the microstructures become finer with an increasing period of the reversing RMF. Although the fundamental phenomena have been investigated, there are few examples where a reversing RMF was applied to the aluminum DC casting process.

In this study, a reversing RMF was applied to a molten aluminum pool in the cylindrical header on the round billet mold for DC casting, and the relationship between the grain size and the periodic time of the reversing RMF was investigated. The electromagnetic field and flow field were simulated by CFD calculations. The simulation results were compared to the experimental results.

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2. Experimental Setup

An electromagnetic stirrer was installed on the ϕ 92 mm hot-top mold. **Fig. 1** shows a schematic diagram of the experimental apparatus. The electromagnetic stirrer was installed above the mold because the attenuation of the magnetic flux density is low. **Table 1** shows the stirrer specifications. In order to reduce the risk of overflow of the molten aluminum from the header, the current frequency, which correlates with the flow velocity, was set to 50 Hz. **Table 2** shows the stirring conditions and additional conditions of the grain refiner, and **Fig. 2** shows a schematic diagram of the time variation of the rotation direction of the RMF. In order to investigate the relationship between the grain size and the periodic time of the reversing RMF, the inversion time was set to 0.3 s, 0.5 s and 1.0 s. The reference sample was cast with mono-direction stirring. Grain refiner was not added to the molten aluminum when the RMF was applied to the molten aluminum. Two ingots without applying the RMF were cast for comparison. Grain refiner was added to one and not to the other. 7xxx series alloy was used for this study. A target composition was Al-10 wt%Zn-2.5 wt%Mg-1.5 wt%Cu-0.15 wt%Zr. The temperature of the molten aluminum in front of the inlet of the header was 700℃, and the casting speed was 100 mm/min. Samples were cut from the half of radius, and the center positions of the diameter, and a cross section, which is perpendicular to the casting direction, was polished and observed using an optical microscope.

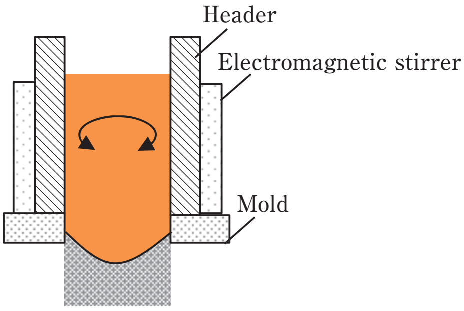


Fig. 1 Schematic diagram of the experimental apparatus.

Table 1 Specifications of the electromagnetic stirrer.

Inner diameter of the bore (mm)	140
Power supply format (–)	AC 3-Phase
Number of poles (–)	6
AC coil current (A)	35.7
Current frequency (Hz)	50

Table 2 Stirring conditions and adding conditions of the grain refiner.

Test No.	RMF	Inversion time (s)	Grain refiner
1	Applied	0 (mono-directional stirring)	Not added
2	Applied	0.3	Not added
3	Applied	0.5	Not added
4	Applied	1	Not added
5	Not applied	–	Not added
6	Not applied	–	Al-5Ti-1B : 0.2 mass%

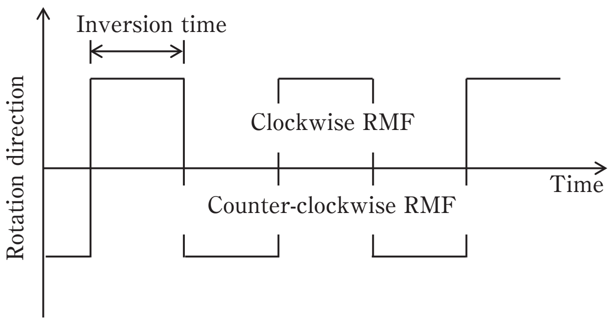


Fig. 2 Schematic diagram for the time variation in the rotation direction of the RMF.

3. Numerical method

In order to estimate the flow field at the interface of the solidification, an electromagnetic field analysis and a flow field analysis were carried out. The Lorentz force, which is applied to the molten aluminum at the inside of the header, was calculated using the commercial code JMAG (JSOL Corp.). The shape of the mushy zone was estimated by a thermal analysis. **Table 3** shows the material properties of the molten aluminum used for the electromagnetic field analysis. In this analysis, it was assumed that the temperature of the molten metal was constant at 650℃.

Table 3 Parameters used for the electromagnetic analysis.

Temperature (K)	923
Electric resistivity (Ω·m)	2.58×10^{-7}
Density (kg / m^3)	2.56×10^{3}
Viscosity (Pa·s)	1.44×10^{-3}

The flow field of the molten aluminum inside of the header was calculated using the commercial CFD code FLUENT (ANSYS, Inc.). The Lorentz force calculated by the electromagnetic analysis was used for the flow field analysis as a source term of the momentum equation. Since the direction of the RMF is reversed at regular intervals, this analysis is an unsteady calculation. For the sake of reducing calculation time, the following assumptions were used: 1: The flow field did not affect the electromagnetic field, 2: No energy transportation or solidification phenomena, 3: Properties of the molten metal were uniform and constant, 4: No feed of molten metal or casting withdrawal, 5: 2-dimensional axisymmetric flow with swirling. The inversion time was set to three conditions, i.e., 0.0 s (mono-direction stirring), 0.3 s and 1.0 s. Time variations of the flow rate at the positions corresponding to the observation points of the microstructure were recorded.

4. Experimental results

Fig. 3 shows an example of the molten aluminum surfaces to which the reversing RMF was applied. These photographs were taken during the crucible test. Strong flow was generated when the inversion time was 1.0 s. **Fig. 4** shows the microstructures of the ingots that were cast in this study. The grain sizes of the RMF-applied ingot were finer than ingot that was cast without applying the RMF and adding the grain refiner. There was a difference in grain size depending on the inversion time in case that comparing the RMF-applied ingots. Some of the grains of the RMF-applied ingot did not have a dendrite structure, but a smooth geometry. **Fig. 5** shows the result of the grain sizes measured from the photographs of the microstructures. In case that the inversion time was short, it was found that the grains are not refined near the center of the ingot. On the other hand, in case that the inversion time was 1.0 s, the grains are finer than the ingot to which was applied the mono-direction RMF.

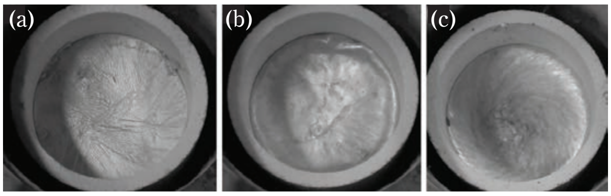


Fig. 3 Photographs of the molten aluminum surfaces applied the RMF (inversion time a: 0.3 s, b: 0.5 s and c: 1.0 s).

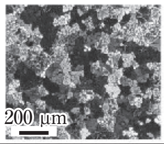
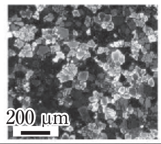
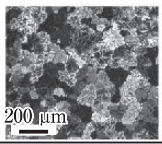
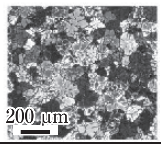
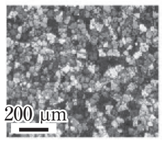
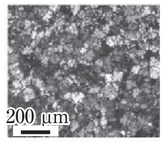
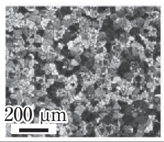
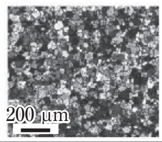
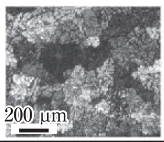
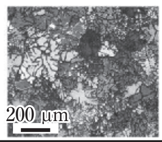
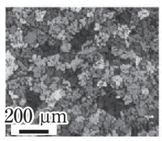
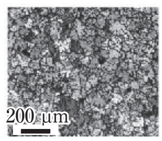
Test No.	Grain refiner	Inversion time	1/4 position of diameter	1/2 position of diameter
1	No addition	0.0s (Mono-directional stirring)	 200 μm	 200 μm
2	No addition	0.3s	 200 μm	 200 μm
3	No addition	0.5s	 200 μm	 200 μm
4	No addition	1.0s	 200 μm	 200 μm
5	No addition	Without RMF	 200 μm	 200 μm
6	Addition	Without RMF	 200 μm	 200 μm

Fig. 4 Microstructures of DC billets with/without RMF billets.

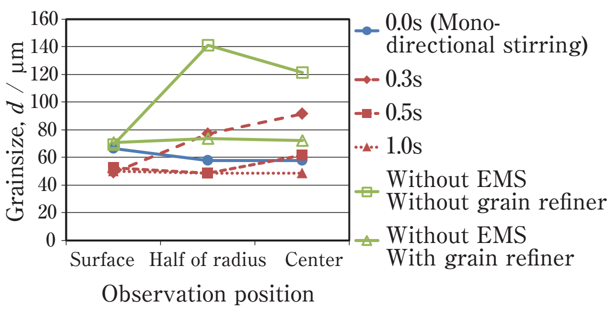


Fig. 5 Relationship between the grain size and the stirring condition.

5. Numerical simulation result

Fig. 6 shows the result of the vector field of the magnetic flux density on a horizontal cross section at the height of the coil center. The figure shows that the magnetic flux density is strong near the surface of the coil. Radial distribution of tangential component of magnetic flux density inside the stirrer's bore was measured by a gauss meter and compered with the electromagnetic analysis. The results are shown in **Fig. 7**. The experimental data and the numerical simulation were in good agreement. **Fig. 8** shows the spatial distribution of the Lorentz force in the molten aluminum induced by the stirrer. The force is applied only to the limited area near the RMF coil and not only the tangential component of the force, but also the radial and vertical components are applied to the molten aluminum. **Fig. 9** (a) and Fig. 9 (b) show the vector fields of the fluid flow when the inversion time is 0.3 s and 1.0 s respectively. It can be seen that it is not a simple swirl flow, but a complex 3-dimensional flow. **Fig. 10** shows the comparison between the maximum tangential velocity and the inversion time at r = 20 mm and r = 40 mm, respectively (the center axis is r = 0). The heights of the output positions are the solidification fronts. It was found that the tangential velocity is low near the diameter center when the inversion time was 0.3 s. The maximum velocity of the mono-direction stirring was higher than that of the reversed stirring.

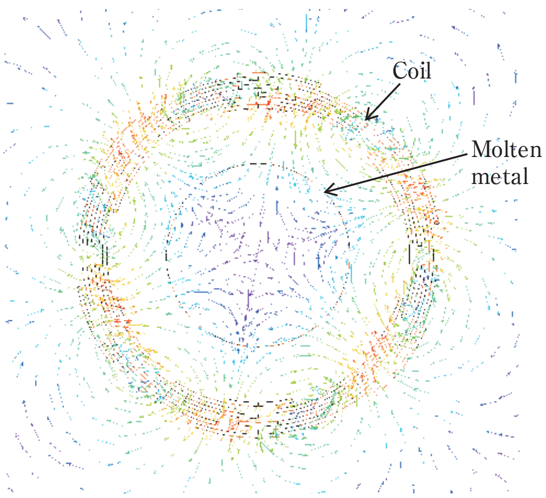


Fig. 6 Vector field of the magnetic flux density.

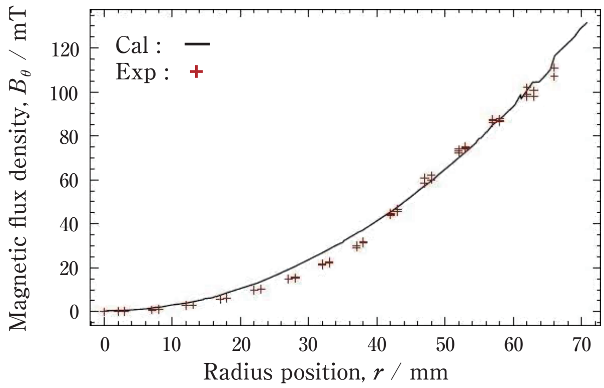


Fig. 7 Radial distribution of the magnetic flux density.

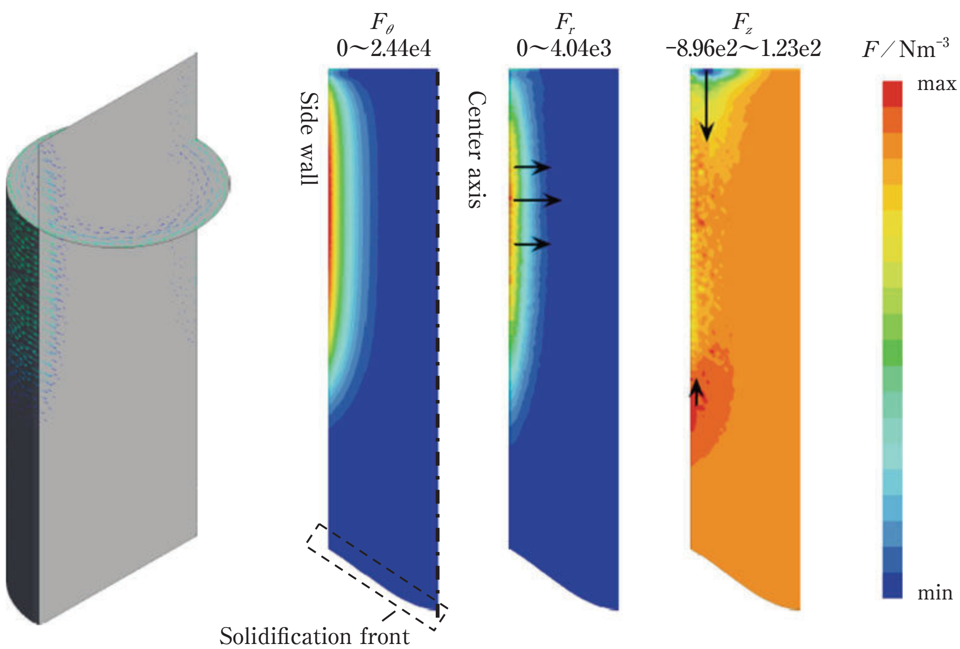


Fig. 8 Spatial distribution of Lorentz force acting on the molten aluminum in the casting pool.

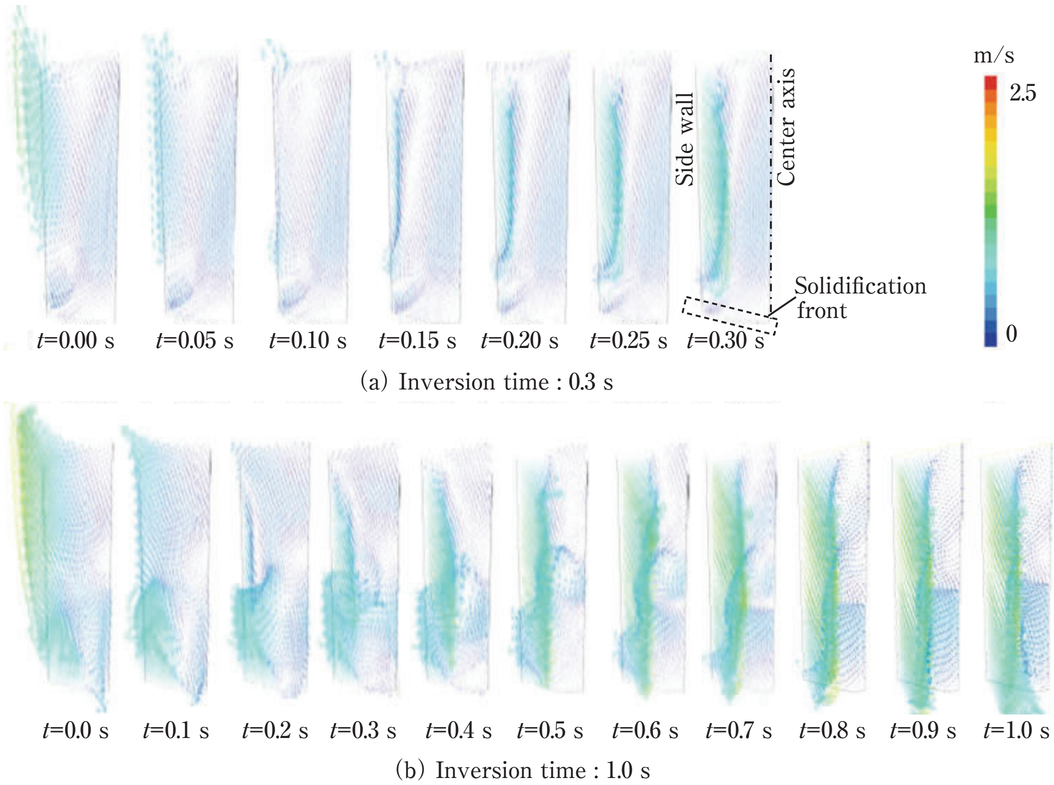


Fig. 9 Flow fields generated by the reversing RMF stirrer during the reversing intervals of 0.3 s and 1.0 s.

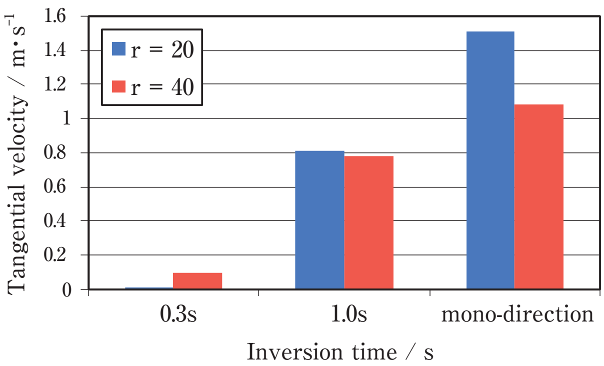


Fig. 10 Comparison between the maximum tangential velocity and the inversion time (at r = 20 mm and 40 mm, z = solidification front).

6. Discussion

It is found that the grains are not refined near the center of the ingot when the inversion time was short. As a result of the flow field analysis, it was shown that the maximum velocity at the diameter center is nearly zero when the inversion time is 0.3 s. Therefore, it was estimated that the grains were not refined since the flow field had not developed. In this study, the most of the driving force of the molten aluminum at the center was the viscous force because the Lorentz force was exerted only near the surface of the molten aluminum. In order to refine the structure at the central position, it is necessary to increase the inversion time or exert the Lorentz force to further inside the molten aluminum.

Fig. 11 shows the relationship between the maximum tangential velocity and the grain size. The maximum velocity of the molten aluminum for the mono-direction stirring was higher than that of the reversing stirring; however the grain size of the mono-direction stirring ingot was not refined compared to that of the reversing stirring ingot.

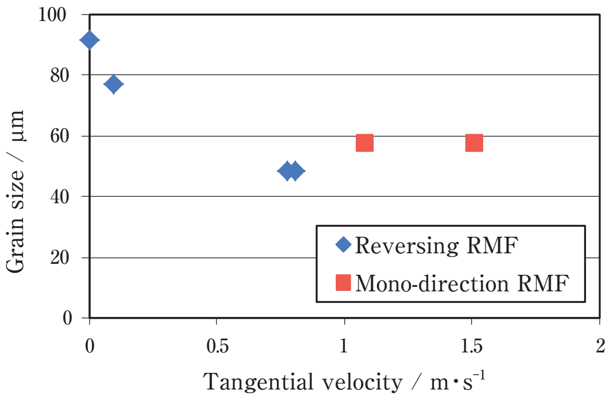


Fig. 11 Relationship between the maximum tangential velocity and the grain size.

Therefore, it is estimated that the influential factor of the grain size is not only the velocity. The difference between the mono-direction stirring and reversing stirring is the time variation of the flow velocity. The velocities of the solid and liquid phases are not equal when applying the reversing RMF because these properties are different. It is considered that the velocity gap between the solid and liquid phases facilitate the homogenization of the solute concentration. If the solute concentration is uniform, the growth of dendrites is inhibited and the solidification interfacial velocity decreases, and as a result, the grains are refined.

7. Conclusion

1. The structure at the center of the billet was not refined in case that the inversion time was short. It is estimated that the flow field was not developed because the inner portion of the molten aluminum is stirred only by the viscous force and not the Lorentz force.
2. When the inversion time was long, the grain refinement by applying the reversing RMF showed a greater effect than by the mono-direction stirring. It was estimated that the intermittent velocity variation generated by applying the reversing RMF leads to the homogeneous fine grain structure.

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