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# Apparatus Design and Electromagnetic Continuous Casting Process for Near Net-Shaped Aluminum Alloy Billet

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A new method and apparatus for the fabrication of high-quality, near net-shaped aluminum alloy billets is developed by the combination of continuous casting and electromagnetic casting/stirring technique. Traditional machine for continuous casting process involves round, square and rectangular billets; therefore it requires additional multistep forging process to fabricate final products. A new process for the designed near net-shaped aluminum billets offers some advantages: the process of extrusion and forging is simplified and the cost of plastic working can be greatly reduced. In order to reduce the peculiar problems such as surface crack and internal defect due to inhomogeneous heat transfer through solidified billets, electromagnetic casting and stirring technique were adopted. Developed continuous casting machine for near net-shaped billets consists of mold, tundish, cooling system, electromagnetic casting and stirring apparatus. Prior to determine the geometry of mold, the effect of electromagnetic field induced by electromagnetic casting and stirring was studied by numerical simulation and induced current, heating effect, field intensity were characterized by changing the geometrical parameters. The effect of electromagnetic field was compared by observing the microstructure of billets. Grain refinement of aluminum billet was clearly observed by applying electromagnetic field to continuous casting process.

***Keywords:*** *aluminum alloy, continuous casting, electromagnetic processing, near net shape billet, numerical simulation*

## 1. Introduction

The use of aluminum alloy in the automobile industry is continuously increasing. The driving force is reduced green house gas emission resulting from light weighting of the vehicles. The estimated consumption of aluminum in passenger car is 120 kg per vehicle in Korea; these figures are expected to rise further in the near future. In order to maintain this momentum it is necessary to pay attention to manufacturing processing aspect of the alloy and optimize the properties. Considering manufacturing process, near net shape casting have been developed. Reducing traditional finishing such as machining or grinding eliminates more than two-thirds of the production costs in some industries. In case of optimizing properties, several methods were developed for grain refinement: the addition of inoculation substances, the use of rapid solidification conditions and stirring of the melts by mechanical means or by electromagnetic fields. Enhancing the fluid flow in the mushy zone by stirring is one of the means to suppress this dendritic growth. The stirring fluid flow detaches the dendrites from the solid-liquid interface and carries them into the mold to form slurry. The slurry has globular solid phase consisting of fragmented dendrites, instead of the conventional dendritic structure, immersed in liquid. [1-2]

The goal of this study is manifold. First, compared to conventional cast aluminum alloys, near net shape cast method is developed to fabricate 3-fold symmetry. Near net shape billet cast is less investigated because of complication of cooling systems. In this study, sectional cooling system was developed to compensate the difference of cooling rate. Sectional cooling system improves the homogeneity of microstructure. Second, electromagnetic casting and stirring technique were applied to improve the quality of near net shape billets. High frequency of electromagnetic field was applied near melt surface to compensate irregular solidification behavior of near net shape billet. Grain refinement also achieved by applying low frequency magnetic field. By adopting electromagnetic casting and stirring technique, surface and internal quality of billets was greatly improved. Finally, characterization of grain size and shape was evaluated to investigate the effect of electromagnetic filed on the quality of final product. [3-5]

## 2. Numerical Study and Experiment

### 2.1 Numerical Study

Prior to fabricate near net-shaped mold, numerical study was performed to investigate the effect of geometry and slits on the magnetic fields. Fig. 1 shows the geometry of near net shape mold. The mold has three-fold symmetry and its thickness is 10 mm. In the previous study, round mold has 16 slits, however, 18 slits were implemented for uniform distribution of slits. Electromagnetic field induced by EMC coils is investigated by numerical study in terms of heat generation and current density. In case of round mold, electromagnetic field penetrates into the mold uniformly and affects the aluminum melts homogeneously. However near net-shaped mold has only three-fold symmetry so that the distribition of electromagnetic field is changed. For numerical calculation, commericial code COMSOL/Multiphysics was used and the effect of electromagnetic field on the distribtuon of magnetic field and heating was observed. In order to reduce the computation time, only one third of mold was used for calculation. The cross-section area of near net-shaped mold has 175 cm$^2$.

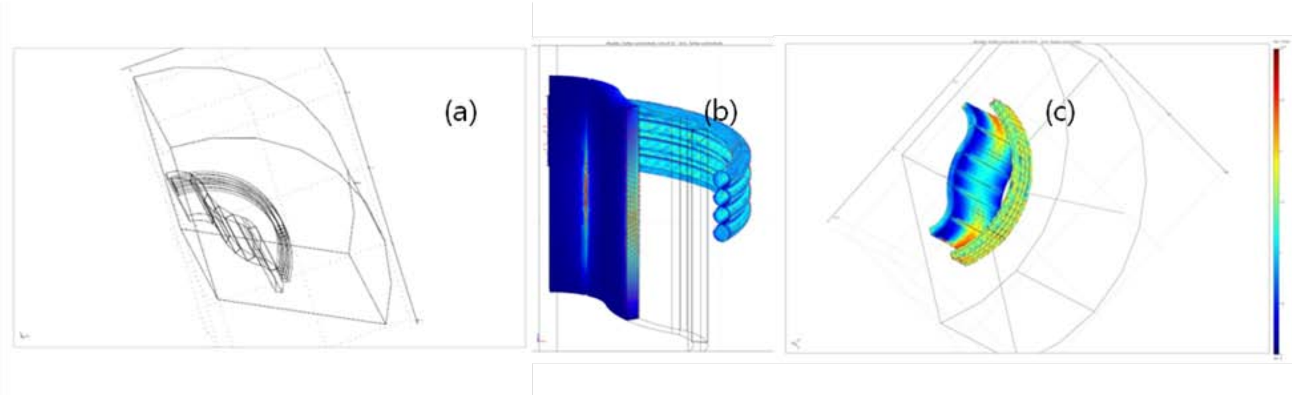


Figure 1. Three dimensional modeling of near net-shaped mold (a) and the heat distribution (b) and induded current density (c) by electromagnetic field

### 2.2 Experiment

Fig. 2(a) shows the schematic diagram of experimental apparatus which includes induction melting machine, tundish, near net-shaped mold, cooling water system, electromagnetic casting and stirring equipment, power supply and hydraulic pump. The melting furnace has maximum capacity of 50 kg and operated with induction melting method. The melt is supplied into tundish which has ceramic filter to remove sludge. The stopper is used to adjust the amount of melt precisely. The copper mold is surrounded by cooling system which is independently installed to control cooling capacity for each part. Between cooling water jacket and channel, electromagnetic casting coil is placed at the same level of melt top surface. Thus initial solidification is easily controlled by this coil which has 20 kHz and 1200 A alternating current. Electromagnetic stirrer is also equipped underneath the electromagnetic casting coil which utilizes low frequency electromagnetic field as 20 Hz and 80 A.

Near net shape mold is fabricated as shown in Fig. 2(b). The mold has three-fold symmetry and its thickness is 10 mm. The mold has 18 slits of 0.3 mm wide. In the numerical simulation of mold, optimum curvature and slit position was selected by considering the distribution of electromagnetic field. The target of near net-shaped billet is automotive parts which is similar to triangular shape. Electromagnetic field generated by coils is penetrated through these slits and enables Joule heating and Lorentz force. Three independent cooling systems were installed in this system and the amount of cooling water was 15, 25, 40 liter/min from top to bottom part of mold. Total amount of melt was 25 kg and casting speed was 10 cm/min. Al-Mg-Si alloy was selected for this study. After finishing the casting process, the surface of billet was observed and also cross-sectional view was also observed by optical microscope after polishing the surface. The grain size was measured by linear intercept method and image analysis.

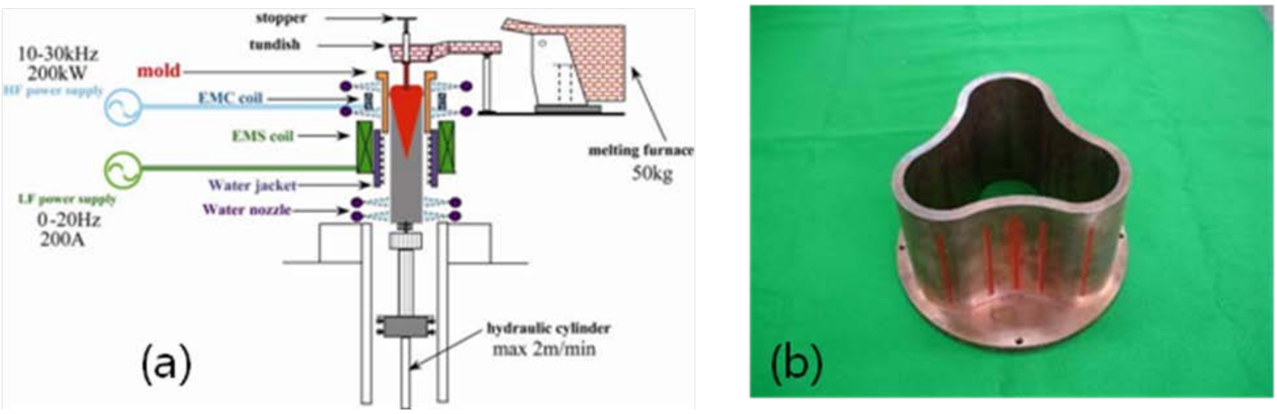


Figure 2. Schematic drawing of the continuous casting machine with electromagnetic casting and stirring apparatus (a) and near net shape mold (b).

## 3. Results and Discussion

### 3.1 Numerical Study

Magnetic field intensity was calculated and its result is shown in Fig. 1(b) and (c). Around the EMC coil, very high intensity of magnetic field is observed and its intensity is decreased as distance becomes larger. Magnetic field is penetrated into the mold along the slit. Inside the mold, magnetic field is relatively very low but its distribution is almost uniform. We can expect uniform magnetic field distribution is desirable and implies that slit design is proper for casting process. The heat generation by EMC coil was observed. Most of heat is concentrated on the convex region of mold. On contrast, heat generation of concave region is relatively small. This fact implies that the solidification rate of melts can be different if analogous cooling water is supplied on the mold. Irregular solidification will have harmful effect on continuous casting which possibly induce breakout. More cooling water pressure will be applied in the convex region so that we can expect that more heat generation will be compensated by more cooling water pressure. However, we adjusted the amount of cooling water on each position instead of adjusting water pressure. Its exact behavior cannot be revealed by numerical study, but it is necessary to find optimum condition of changing the amount of cooling water.

Also we calculated the induced current on the mold surface. Near surface region has high eddy current induction and far surface has low eddy current density. This result has good agreement with the result of heat generation. In Fig 1(c), high current density was observed in the convex region and low current density was found in the concave region. The EMC coil has round shape so that the distance between the surface of mold and coil is different depending on the shape of mold. This is the reason why the induced current is different by its position.

Figure 3. Continuously cast aluminum near net-shaped aluminum billet of (a) DC casting and (b) its microstructure, and (c) EMC/S applied billet and (d) its microstructure.

**3.2 Near net-Shape Billet Casting**

Near net shape billet was cast successfully with optimized experimental conditions and its photograph was shown in Fig. 3. Direct chill casting billet was shown in Fig. 3(a) and Electromagnetic casting applied billet was shown in Fig. 3(c). As shown in Fig. 3, frequent surface cracks and defects were found on direct chill casting billets, however, relatively smooth and defect free surface was obtained by applying high frequency electromagnetic field. In case of applying stirring, the quality of surface was degraded but the advantage of internal quality was expected.

The micrograph of cross sectioned billet was shown in Fig. 3(b) and (d). It is also observed that internal cracks were observed in Fig. 3(b) but there is no defect in Fig. 3(d) which means uniform heat transfer is helpful to improve the quality of near net shape billet. Fig. 3(d) shows the macrostructure of billet which is cast with electromagnetic casting and stirring. The rotation of melts was clearly observed when the electromagnetic fields were applied. In case of direct chill casting, the almost parallel growth of columnar grains is remarkably distributed. The columnar structures are directed toward the heat flow. In case of Fig. 3(d), the zone of equiaxed crystal growth is extended with electromagnetic field. Furthermore, the use of electromagnetic field promotes a distinct grain refinement. The features appear being typical for the application of forced melt convection to solidification process. Specifically, a region of fine grains can be observed in the entire of the specimen.

The contrast between the particular grains is sufficient to identify the grain boundaries. Values of average grain size are shown in Fig. 4. The grain size of electromagnetic casting and stirring billet was remarkably downsized by melt agitation with magnetic field. The grain size of electromagnetic field casting billets has comparable values to that of Al-Ti-B inoculated billets. Thus, it is presumed that the grain refinement was achieved by applying electromagnetic field; hence its internal quality was greatly improved. By applying both the near net shape mold and electromagnetic field, the cost of aluminum billet production can be further reduced.

## 4. Summary

Numerical study-assisted near net-shaped mold was designed for optimum condition processing. The apparatus of continuous casting for aluminum alloy was developed and successfully demonstrated. The internal quality of near net-shaped billet was enhanced greatly and surface quality was also improved by applying electromagnetic casting and stirring technique. It is expected that this study contributes on the reduction of production costs by reducing postprocessing.

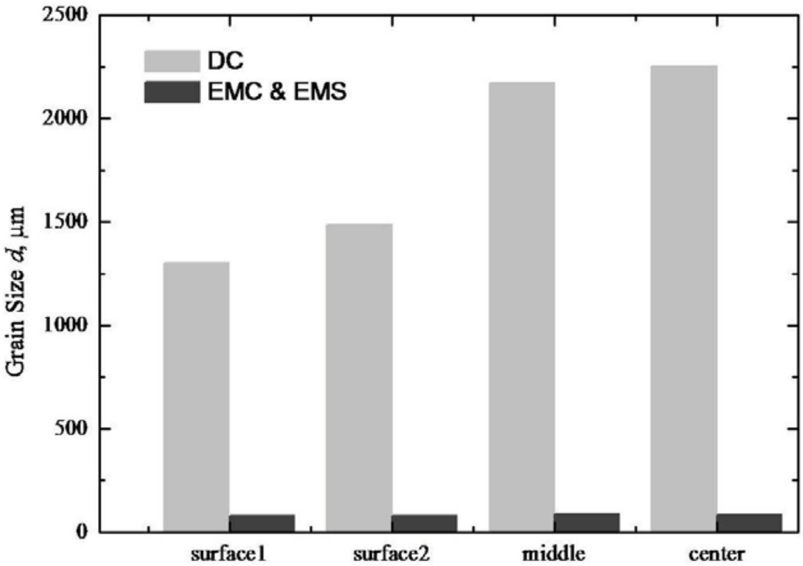


Figure 4. Plot of average grain size of near net-shaped billet of different positions.

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