FABRICATION OF THIN ALUMINUM ALLOY SLABS BY ELECTROMAGNETIC CASTING

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ABSTRACT Effects of bottom block, spout shape and casting rate on thickness, outward appearance and structure of aluminum alloy slabs were evaluated in order to improve the electromagnetic casting process for manufacturing thin slabs. Furthermore, thin slabs of 5052 aluminum alloy were directly cold-rolled and tensile properties of the rolled sheets were evaluated. Slabs with a flat surface, fine microstructure and about 7mm in thickness are obtained by using a bottom block having a thickness of 6mm and a spout with cover. Even when cold-rolling to a reduction of 75%, there is no surface defect. The cold-rolled sheet has tensile properties that satisfy the JIS requirements except for tensile strength of O-treated sheet, which has a value that is higher than that specified by JIS. However, the tensile properties are superior to those of the cold-rolled sheet obtained from DC hot plate.

Keywords: *electromagnetic casting, 5052 aluminum alloy, cold rolling, microstructure, tensile property*

1. INTRODUCTION

High quality products and near-net shape working for cost reduction are increasingly directing operations in the processing of materials. To meet these requirements in the rolling of aluminum, slabs are required to have an excellent surface appearance and fine microstructure. However, in the conventional direct chill (DC) casting, scalping is necessary before rolling due to the surface defect arising from the contact of the melt with the mold and the formation of inverse segregation near the mold surface [1]. Therefore, electromagnetic (EM) casting, in which the melt is formed to a desired shape by electromagnetic force instead of the mold and solidifies progressively by direct water-cooling [2], is attracting great attention. EM casting is a perfect moldless casting, so the fabricated slab has smooth surface and fine microstructure [3~7]. This implies that decrease or total elimination of scalping process is possible, and in case of mass production it is expected to reduce process cost.

It has been previously reported [7] that the appearance of slabs fabricated by EM casting is strongly affected by pouring method, and it is possible to fabricate smooth thin slabs having a thickness of about 12mm by using spout with cover to make the initial freezing part. However, the present aluminum rolling process involves hot rolling to a thickness below 10mm and then followed by cold rolling, therefore, with a thickness of 12mm the number of pass increases, and moreover, edge crack occurs during direct cold rolling.

In this study, in order to make it possible to directly cold-roll without the occurrence of edge cracks, an attempt was made to fabricate thin slabs of about 5mm thickness by EM casting. Then the influence of bottom block on the electromagnetic field together with its effect on the appearance and microstructure of the slabs, and the effects of casting rate and spout shape were investigated. Furthermore, the outward appearances, microstructures and tensile properties of the cold-rolled sheets were evaluated.

2. EXPERIMENTAL PROCEDURE

Fig.1 shows the EM casting apparatus [6] used in this research. It is composed of melt feeding, electromagnetic mold, and slab drawing parts. This apparatus can support the melting of 18kg of aluminum alloys and a maximum drawing length of 900mm.

In order to investigate the influence of bottom block on the electromagnetic force at the beginning of casting, bottom blocks of 12mm and 6mm thickness respectively were put at the mean

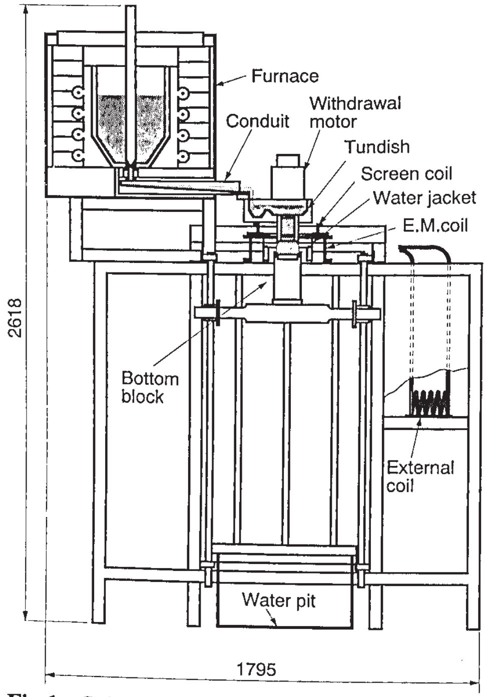

Fig.1 Schematic drawing of experimental apparatus for EM casting used in this study.

height of the electromagnetic coil. Furthermore, aluminum plate with a height of 2mm was placed on top of the bottom blocks. Electromagnetic forces were measured at points on a horizontal line parallel to the long side of the bottom block which is located at a distance of 5mm from the central line of the bottom block and 7mm above the bottom block. The EM casting conditions used in this research are indicated in **Table 1**. Al-2.5mass%Mg alloy, which is base alloy of 5052 aluminum alloy, was used to determine adequate casting conditions. Casting rates were varied from 720 mm/min to 960mm/min. The bottom block thickness was varied between 12mm and 6mm and spouts with cover having outlet cross sections of 50 x 5mm^2 and 50 x 2 mm^2 respectively were used. To control the thickness of slabs, a normal spout with cover as shown in **Fig.2** (a), and a center-thinned spout attached with the cover whose central part was restricted to 1.5mm, as shown in Fig.2 (b), were used. Thin slabs of about 5~13mm thickness and a drawn length of 200mm were obtained. Specimens for microstructural observation were extracted from a distance of 70~120mm from the bottom of the slab, which is assumed to be a stable region in relation to microstructure.

Finally, for direct cold rolling and evaluation of tensile properties, EM casting of 5052 aluminum alloy, which has Al-2.5mass%Mg alloy as a basic composition was carried out. Cold rolling was carried out with as-cast slabs fabricated by EM casting and, for comparison, hot-rolled plates fabricated by DC casting whose thickness was first reduced to 6mm through hot-rolling. Chemical compositions of the 5052 aluminum alloy used are shown in **Table 2**. The alloy for EM casting has higher amounts of Si and Fe than that for DC casting. Plates with a 50mm width and a 100mm length for cold rolling were extracted from positions of 70~160mm from the bottom of the slabs. Cold rolling was conducted under a reduction ratio of 3%/pass and a total reduction ratio of 75% in thickness. Cold-rolled sheets were stabilized at 170°C for 8h – H38 treatment, and annealed at 345°C for 2h – O treatment, respectively.

Microstructural observation of cold-rolled sheets was carried out at surfaces parallel and perpendicular (long transverse and short transverse)

Table 1 Experimental conditions for EM casting.

Casting alloy	Al-2.5mass%Mg, 5052 alloy	
EM coil size	300 x 50mm^2, 10turns	
EM coil current	710A	
Frequency	3kHz	
Magnetic flux density	0.08~0.1T	
External coil inductance	5.54μH	
Molten metal temp.	680°C	
Flow rate of cooling water	20l/min	
Casting rate	720, 840, 960mm/min	
Thickness of bottom block	12mm	6mm
Cross section of cover	50 x 5mm^2	50 x 2mm^2

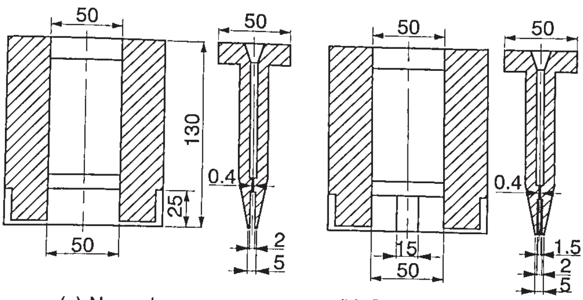

Fig.2 Schematic illustration of spouts.

Table 2 Chemical compositions of 5052 aluminum alloy. (mass%)

Specimens	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
DC, hot plate	0.09	0.26	0.02	0.07	2.46	0.21	0.02	0.01
EMC, slab	0.19	0.33	<0.01	<0.01	2.50	0.19	0.01	0.01

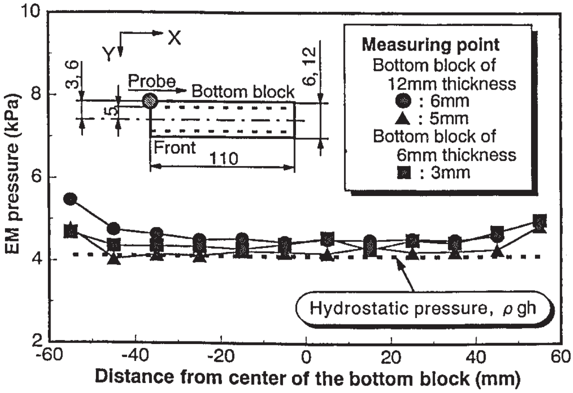

Fig.3 Distribution of electromagnetic pressure measured on a horizontal plane above 7mm from bottom block.

to the rolling direction. Tensile test specimens were extracted such that the tensile direction would be parallel to the rolling direction. Plates of 6.4mm width, 18mm gauge length and 1.5mm thickness for sheets from DC casting, and 6.4mm width, 19mm gauge length and 1.75mm thickness for sheets from EM casting were machined according to 14B type tensile test specimen as specified by JIS Z 2201.

3. RESULTS AND DISCUSSION

3.1 Distribution of Electromagnetic Pressure

Fig.3 shows the distribution of electromagnetic pressure measured on a horizontal plane above 7mm from the bottom block. The electromagnetic pressure exhibits uniform distribution in the range of ±45mm from the center of the bottom block, but increases at both ends of the bottom block. Also, the electromagnetic pressure on the edge line of long side of bottom block with thickness of 12mm is just over the hydrostatic pressure. On the other hand, the electromagnetic pressure at a distance of 5mm from the center of bottom block equilibrates the hydrostatic pressure. From the relationship between the electromagnetic pressure and hydrostatic pressure, it is expected that fabrication of thin slabs with thickness of about 10mm or less than 6mm is possible by using the bottom blocks with the thickness of 12mm or 6mm, respectively.

3.2 Effect of Fabricating Conditions on Thickness and Outward Appearance of Thin Slabs

In order to investigate the effect of variation of electromagnetic pressure with thickness of bottom block on the thickness and outward appearance of thin slabs, EM casting was carried out using the bottom blocks with thickness of 12mm and 6mm. Outward appearances of obtained thin slabs are shown in **Fig.4**. The thickness of thin slabs obtained using the bottom blocks having thickness of 12mm and 6mm are 13mm and 8.5mm, respectively. Both slabs have convex lines parallel to the casting direction, and ripples. Thickness in other parts except for convex lines are almost same as the thickness of bottom blocks and are about 12mm and 6.5mm, respectively, as is expected from the relation between the electromagnetic pressure and hydrostatic pressure. It is already known that ripples are formed due to unstableness, which sway away from side to side occurring by the generation of disturbed magnetic field at the upper part of the electromagnetic coil [8]. Therefore, an increase in casting rate may

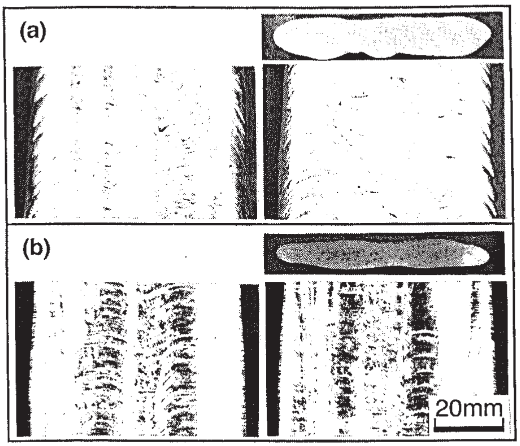

Fig.4 Outward appearances of thin slabs fabricated by EM casting using bottom block with (a) 12mm and (b) 6mm thickness.

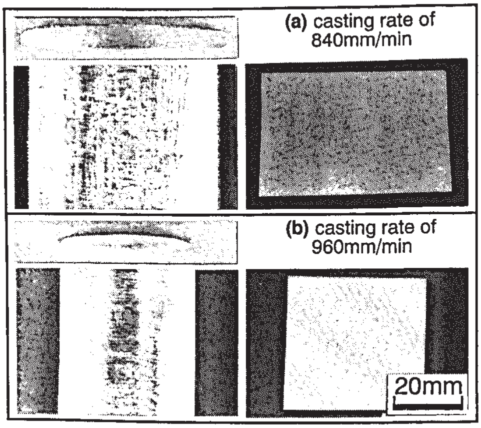

Fig.5 Effect of casting rate on outward appearance and macrostructure of thin slabs fabricated by EM casting.

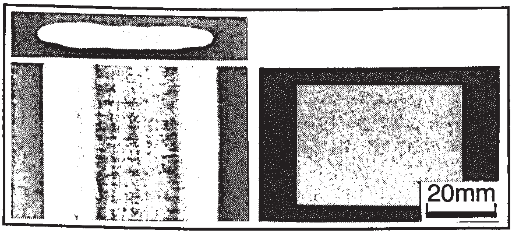

Fig.6 Outward appearance and macrostructure of thin slab fabricated by EM casting employing the spout with center-thinned cover shown in Fig.2

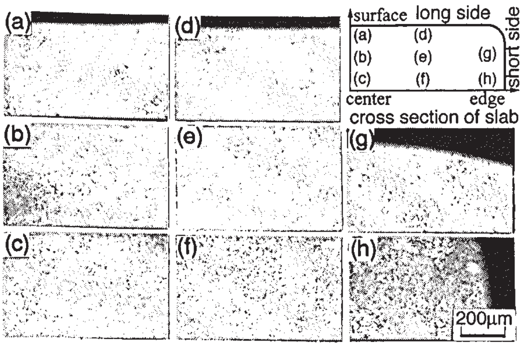

Fig.7 Microstructures of a cross section of the thin slab shown in Fig.6.

suppress the formation of the ripples.

Fig.5 shows outward appearances, shape of cross section and macrostructures of thin slabs fabricated using the bottom block with the 6mm thickness under casting rates of 840mm/min and 960mm/min, which are higher than that shown in Fig.4 (b). It is found that an increase in casting rate results in reductions in slab width and surface defects like convex lines and ripples. However, as shown in Fig.5 (a), higher casting rate causes an excessive reduction in the thickness of both ends of the slab. This may be because the melt preferentially flows at the center of the horizontal cross section of the spout and hardly flows at the both ends of the spout. Macrostructures are composed of fine equiaxed grains only.

From the above-mentioned results, casting rate of 960mm/min seems to be adequate for the fabrication of slabs with thinner thickness. As a next step, in order to make the slab thickness to be uniform by making the melt to flow uniformly in the spout, thin slabs were fabricated using the spout attached with the cover whose center part was thinned to 1.5mm, as shown Fig.2 (b). The outward appearance, shape of cross section and macrostructure of a thin slab fabricated using the spout with the center-thinned cover are shown in **Fig.6**. The obtained thin slab has a nearly uniform thickness of 7mm in cross section. Since pouring volume of melt is increased to maintain the continuous flow of melt in the spout, the thickness of the slab is somewhat larger than expected.

3.3 Microstructures and Distribution of Dendrite Arm Spacing (DAS) of Thin Slabs

Fig.7 shows the microstructures of a cross section of the thin slab shown in Fig.6. The microstructures are consisted of fine and uniform dendrites and some floating crystals, which are remarkably smaller than those observed in slabs fabricated by DC casting.

Distributions of DAS at the long side of the thin slabs are shown in **Fig.8**. DAS is independent on the thickness and the casting rate, and is in the range of 9 to 10μm, which is remarkably smaller than that observed in the slabs fabricated by DC casting. Moreover, its distribution is uniform in the whole slab. This means that the liquid-solid interface shape is flat and cooling rate is constant in the whole slab.

It is found that with the EM casting apparatus made in our laboratory, it is possible to produce the thin slabs having 7mm thickness, metallic luster surface and fine microstructure under the following conditions:

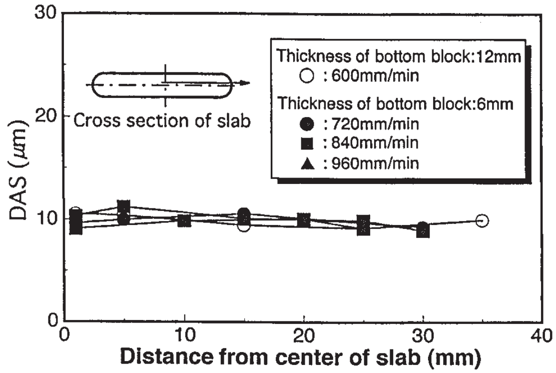

Fig.8 Distributions of dendrite arm spacing (DAS) at long side of thin slabs.

(1) Bottom block of 6mm thickness
(2) Spout with center-thinned cover
(3) Casting rate of 960mm/min.

3.4 Outward Appearance and Microstructure of Cold-rolled Sheet

Cold rolling was conducted using 5052 aluminum alloy thin slabs fabricated under the same conditions as indicated on Fig.6 without scalping and trimming. For comparison, DC castings of the same alloy was hot-rolled to the thickness of 6mm and then was cold-rolled to the 75% reduction in thickness after trimming to 50mm width and 100mm length. Outward appearances and microstructures of the cold-rolled sheets are shown in **Fig.9**. Both the hot-rolled plates of DC casting slabs and the EM casting slabs are possible to cold-roll to 75% reduction in thickness with no edge cracks and surface defects. The cold-rolled sheets obtained from EM casting slabs have larger amount of intermetallic compounds than those obtained from the hot-rolled plates of DC casting slabs because the former contains higher Si and Fe than the latter as shown in Table 2. However, the compounds observed in the sheets obtained from EM casting slabs are finer than those in sheets obtained from DC casting slabs mainly due to strong cooling effect.

3.5 Tensile Properties of Cold-rolled Sheet

Fig.10 shows tensile properties of H38- and O-treated sheets obtained from both DC and EM casting slabs. Both H38- and O-treated sheets from EM casting slabs exhibit higher tensile strength and 0.2% proof stress, but somewhat lower elongation than those of DC casting slabs. This may be caused by the fact that the larger amount of fine compounds, as observed in Fig.9, plays a role of dispersion strengthening. However, elongation did not decrease as much as was expected. H38-treated sheet has tensile properties that satisfy the JIS requirements [9].

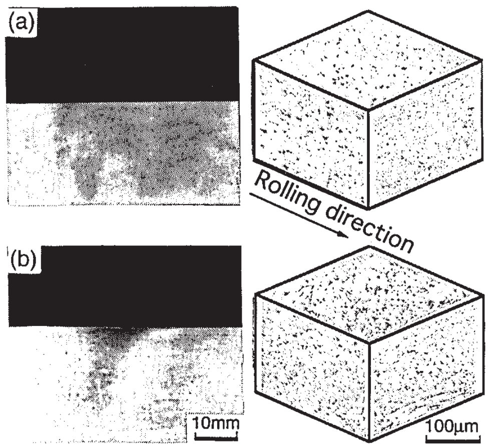

Fig.9 Outward appearances and microstructures of cold-rolled 5052 alloy sheets. (a) DC casting→Scalping→Hot rolling→Cold rolling, (b) EM casting→Cold rolling

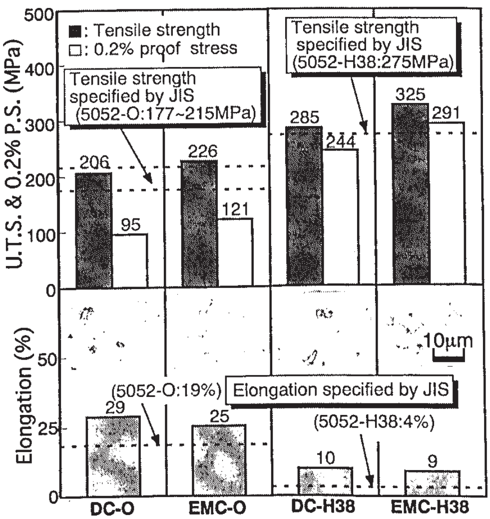

Fig.10 Tensile properties of O- and H38-treated sheets obtained from both DC and EM casting slabs.

Elongation of O-treated sheet also satisfies sufficiently that specified by JIS, but its tensile strength exceeds the upper limit of JIS specification.

Consequently, applying the EM casting even to the Si- and Fe-rich 5052 aluminum guarantees the JIS-specified tensile properties for the cold-rolled sheets except for tensile strength of O-treated sheet. Considerably higher tensile strength and 0.2% proof stress than those of the cold-rolled sheets of DC casting slabs can also be obtained. This means that it is possible to improve the quality of the cold-rolled sheet and also to remarkably reduce the manufacturing costs required for the initial hot rolling and homogenization treatment by applying EM casting for slab manufacturing.

4. CONCLUSIONS

In this study, an attempt was made to fabricate thin slabs with a uniform thickness of less than 10mm by EM casting. Attention was paid to the meniscus shape during the early stage of the fabrication, and therefore, the influence of bottom block on the electromagnetic field was investigated. Then, the relationship between manufacturing conditions and outward appearances of the thin slabs was evaluated by examining casting rate and spout shape. Furthermore, the effect of these conditions on macro- and microstructures and DAS was investigated. Finally, thin slabs of 5052-aluminum alloy were fabricated under conditions that made it possible to obtain a flat surface. The obtained slabs were directly cold-rolled without hot rolling and their outward appearance, microstructure and tensile properties were evaluated and compared with those from DC casting slabs. Obtained results are summarized as follows:

(1) At the early stage of casting, the meniscus thickness was nearly equal to the thickness of the bottom blocks. Therefore, the electromagnetic pressure is balanced by hydrostatic pressure at the edge of the slabs.

(2) Surface defects like convex lines and ripples are reduced, but both sides of the slabs decrease when the casting rate is increased. For this reason, the thickness in the center part of the cover attached to the spout was thinned. By using the spout with the center-thinned cover, a casting rate of 960mm/min and a flow rate of cooling water of 20 l/min, thin slabs of uniform thickness of about 7mm are obtained.

(3) The macrostructures of the slabs consist of equiaxed grains only, but the microstructure obtained from EM casting slabs consists of finer dendrites and intermetallic compounds than DC casting slabs. However, the influence of melt flow causes the formation of some floating crystals. DAS in EM casting slabs is very small and is about 9~10μm in the whole slabs.

(4) When the thin slabs of 5052 aluminum alloy fabricated by EM casting are cold-rolled to a final thickness reduction of 75%, there are no surface defects and edge cracks in the cold-rolled sheets. In addition, tensile properties of H38-treated sheet satisfy JIS requirements. O-treated sheet also has enough elongation for satisfying JIS specification, but it has a higher tensile strength than the upper limit of that specified by JIS. Considerably higher tensile strength and 0.2% proof stress than those of the cold-rolled sheets of DC casting slabs can also be obtained.

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