Experimental study of concavity of large EMC slab

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Abstract

To simplify the complex electromagnetic casting (EMC) techniques, a simulated experimental setup has been designed. With this apparatus, the contraction of the lateral faces of pure aluminum and Al–4.5%Cu slabs, which are different in width-over-thickness ratio, pouring temperature or cooling water flow rate was recorded during the casting process. The cross-section deformation of cold slabs was also measured. The greatest contraction was found to have occurred before the complete solidification of the ingot cross-section. It was concluded that the contraction of the lateral faces is due mainly to the bending of solid shell induced by the thermal stresses. The surface temperature of the ingots is the critical factor influencing the unevenness of the contraction of the cross-section. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

During the electromagnetic casting (EMC) of large slabs of aluminum alloys, the solidified shell contracts toward the liquid pool and makes the shape of the cross-section of the slabs non-rectangular. This is a very undesirable phenomenon because otherwise the EMC slabs can be rolled directly and keep their high quality surfaces. Thus, it is important to solve this problem as soon as possible [1–5].

At present, the contraction of slabs is usually expected to be solved by compensating it with a convex shape of the inductors. Weaver has done many experiments to design the mold, and proposed several kinds of mold shape [1]. Recently, Drezet et al. [2] developed their elasto-viscoplastic models to calculate deformation. As the deformation of the cross-section of slabs is related to the ingot size, alloy composition, casting parameters, and so on, it is necessary to investigate the deformation process and make clear how these factors affect it. However, heretofore, few reports have been presented to show the deformation mechanism and the corresponding control method.

2. Experimental procedure

During electromagnetic casting, the liquid metal is poured into the inductor and is supported by the bottom block and the electromagnetic forces acting at its periphery. When the bottom block moves downward, the slab follows and is cooled by the water sprayed onto it from around. Fig. 1 shows a schematic diagram of EMC. The total casting process can be divided into three phases, i.e. the starting phase, the stationary phase and the ending phase. During the starting phase, the poured liquid is chilled by the bottom block and cooling water and quickly solidifies to the center of cross section. The liquid pool is very shallow. The pull-in of slab is small so the slab has a nearly straight contour. At the end of casting, liquid metal is no longer poured and the descent of the bottom block is stopped. The stationary slab is cooled by sprayed water regardless. At this time, the pull-in is also much reduced.

While in the stationary phase, the size of the lateral faces of the liquid pool remains unchanged: the pull-in occurring in this phase is also the largest, [4] which has been shown by many practical measurements. Hence, the pull-in in the stationary phase is the main object of study in this paper.

In the stationary phase, the heat transfer reaches a dynamic balance. At this time, the cooling effect of the bottom can be neglected. Liquid metal and solid shell are mainly cooled by the cooling water sprayed onto it. Any layer of metal finishes its transformation from complete liquid to complete solid when it moves down from the top to the bottom of the liquid pool. The casting speed, water cooling intensity and so on will all have influences on this process. Clarifying their influences is the fundamental work to develop a numerical control model. Due to the comparatively

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complicated technology of EMC, a substitute set-up was designed, as shown in Fig. 2. A water-cooled copper tank is used to sustain the poured liquid metal. The intense cooling effect of the copper wall can be regarded as equal to the intense cooling effect of spraying water in EMC. The base and top of the set-up are insulators. Thus, the hear of the hot liquid metal can only be extracted from the four side faces, just like the liquid metal poured in EMC in the stationary phase. A displacement sensor (DS) combined with a displacement meter (DM) is used to measure the pull-in history of the rolling faces. The probe of the DS adheres to a quartz rod, which was introduced into the cavity of mold wall through a tube welded into the mold. When the solidified shell forms and contracts from the wall, the ‘welded’ rod follows, its displacement being recorded by the DS and the DM. Further, thermocouples are placed to measure the temperatures at some positions simultaneously. A group of experiments that change the slab size, pouring temperature, cooling water flux, alloy composition were carried out to explore the mechanism of deformation.

3. Results and analysis

During the solidification of a metal, there are essentially two contributions to ingot contraction. The first one is the phase change (about 6.5% in volume for aluminum) and the second is the solid state thermal contraction during subsequent cooling (about 1.5%) [2]. Because the liquid feeding from the top can well compensate for the density variation during phase change, it can be concluded that it is the deformation of solid shell that results in the large pull-in of the rolling faces.

Fig. 3 shows the measured temperature and pull-in. The size of the cast pure aluminum slab is 420 mm × 140 mm. The pouring temperature and cooling water flow rate were changed to investigate the effect of surface temperature acting on the pull-in. In the upper section of the figure, there are four temperature curves. Curves 1 and 3 correspond to the casting parameters: pouring temperature 700°C, water flow rate 1.6 m³/h and the positions are at the center of the slab cross-section and at the center of rolling face respectively. Curves 2 and 4 have the same positions but the casting parameters are: pouring temperature 670°C, water flow rate 2.0 m³/h. As is shown, higher pouring temperature combined with smaller water flux makes the pull-in of rolling face smaller. Thus it can be said that a higher surface temperature of slab can decrease the pull-in. It is also indicated in the figure that when the center of the cross-section has changed into solid, the pull-in of the rolling faces are already 2.4 and 2.0 mm, respectively. That is to say, the largest proportion of total deformation has already occurred when the cross-section turns completely into solid. The after-contraction of the solid is very small. This conclusion indicates that the pull-in of the rolling faces is the accumulated result due to the bending of the solid shell during the solidification process of the whole cross-section [6].

Figs. 4–7 give the measured final pull-in (when the slabs are cooled to room temperature) and the corresponding casting conditions. They are analyzed as follows.
1. The effect of aspect ratio: Four pure aluminum slabs with the same thickness (140 mm) but with different width (aspect ratio: 2:1, 2.5:1, 3:1, 3.5:1) were cast with a pouring temperature of 670°C, and a water flow rate 1.6 m³/h. From Fig. 4 it can be seen that the pull-in increases with the aspect ratio, but when the aspect ratio reaches 3:1, its influence is less obvious and the profile of the deformation curve is not parabolic. The center of the rolling face has an even smaller deformation. The thermal stresses are compressive at the surface, but tensile further inside the solidification front. The solid shell bends toward the center under the compressive stress. An increase of the aspect ratio means an increase of the force arm, so that the pull-in of the rolling faces increases, but when the width of the slab reaches a certain value, as the center of slab can keep high temperature for a long time, the time during which the solid shell is plastic is also prolonged. Under the static pressure of the liquid metal, the center of the slab will expand before the hard solid shell forms, so the deformation of the surface center is even smaller than that of its vicinity. It is also found when stainless steel is used as the mold during direct continuous casting, because of the low heat conductivity of steel the higher surface temperature of slab even causes swell at the rolling faces.

2. The effect of pouring temperature: The effect of pouring temperature on the pull-in is not notable. The pull-in decreases a little with the increase of pouring temperature (shown in Fig. 5. pure aluminum with aspect ratio 2.5:1, 3:1). This is because that higher pouring temperature reduces the cooling rate difference between the surface and center, which leads to lower bending of the solid shell and smaller pull-in.

3. The effect of cooling intensity: The effect of cooling intensity on the pull-in of the rolling faces is shown in Fig. 6. The metal is pure aluminum, the pouring temperature is 670°C, and the aspect ratios are 3:1 and 3.5:1. It is clear the pull-in increases with a larger water flow rate. A larger cooling intensity means a larger cooling rate of the slab surface and a larger cooling rate difference between the surface and center. This leads to larger bending of the solid shell and larger pull-in.

4. The effect of the linear expansion coefficient: In order to investigate the influence of the linear expansion coefficient on the final pull-in, aluminum alloy Al-4.5%Cu and pure aluminum were cast under the same conditions (pouring temperature 670°C, water flow rate 1.6 m³/h, aspect ratio 2.5:1 and 3:1). The experimental results are shown in Fig. 7. It can be seen that the pull-in of Al-4.5%Cu alloy is larger than that of pure aluminum, so larger linear expansion coefficient leads to larger deformation. This phenomenon agrees well with the general idea held by many researchers. At the same time, as the Al-4.5%Cu alloy has a higher elastic modulus than pure aluminum, which means a higher bending strength, the deformation difference between the two metals is not significant.

The above experimental results and discussion shows that...
the size of the slab and cooling intensity have comparatively larger influences on the final pull-in of the slab cross-section. With the same aspect ratio, the surface temperature is the critical influencing factor. Because increasing the pouring temperature and decreasing the water cooling intensity increases the surface temperature, the stress in the solid shell will be smaller [5], so that the pull-in of the rolling faces can be decreased.

4. Conclusions

1. The largest proportion of total deformation has already occurred when the cross-section turns completely into solid. During the electromagnetic casting process, under the chilling effect of the cooling water, the solid shell bends inward. The large pull-in of the rolling faces is the result of accumulated bending of the solid shell during the solidification process of the whole cross-section.

2. Increase of the pouring temperature and decrease of the water flow rate can decrease the bending of the solidified layers and decrease the pull-in.

Acknowledgements

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References

[1] C.H. Weaver, Light Metals, TMS-AIME, Warrendale, PA, 1976, p. 441.
[2] J.M. Drezet, M. Rappaz, B. Carrupt, M. Plata, Metall. Trans. B 26B (1995) 821.
[3] H.G. Fjaer, Asbjørn Mo, Metall. Trans. B 21B (1990) 1049.
[4] J.M. Drezet, M. Rappaz, Metall. Mater. Trans. A 27A (1996) 3214.
[5] Xianshu Zheng, Junze Jin, Acta Metall. Sinica 31B (1995) 511.
[6] K. Schwerdtfeger, M. Sato, K.-H. Trcke, Metall. Trans. B 29B (1998) 1057.