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Mechanism and control of un-straightness of EMC large slabs①

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Abstract: The experimental study shows that the pull-in of the broad faces (rolling faces) of the EMC large aluminum alloy slabs mainly forms during the solidification process. The thermal bending moment caused by the thermal gradient of the solidified shell along the broad faces is the main reason for the formation of pull-in. The tangential forces resulted from the change of the solidification front curvature push the liquid metal of the solidification front from the hot section to the cold end and compensate the contraction of the cold end, thus form the irreversible deformation. Based on these mechanisms, the Tm-BD software system that can design the opening of molds was programmed. As an example, the straightness of the 1 300 mm × 480 mm slab with the using mold opening was calculated. The agreement of the calculated and measured results provides the basis to optimize the mold design with or without opening.

Key words: straightness; solidification process; thermal bending moment; tangential push force
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1 INTRODUCTION

Large aluminum slabs are usually produced in such electromagnetic casting (EMC), as shown in Fig. 1. The rolling faces or broad faces of the EMC large slabs tend to form pull-in defect during casting process, which directly influences the quality of the rolling faces. Because of this defect, the expense of scaling the rolling faces has to be added, besides, the high quality surface metal has to be scaled, the quality of slabs is decreased greatly. So to obtain original slabs with straight rolling faces which can be rolled directly is a significant task.

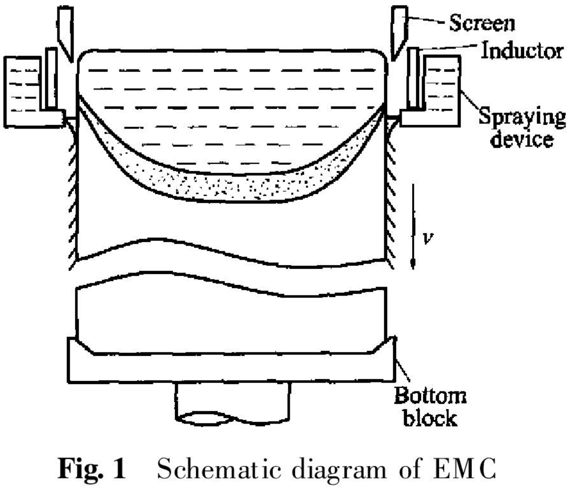

Fig. 1 Schematic diagram of EMC

At present, in order to obtain a rectangular shape of the cross section of the slabs, usually the inductor with opening (the anti-deformation) is used to compensate the contraction pull-in of the slabs. Weaver et al[1-4] have done many experiments to design the mold and they proposed two-straight-lines, three-straight-lines and sinusoidal shapes of the molds. Although this is helpful to improving the slab's flatness by experiment, challenges and technique issues still exist, which can be solved by means of mathematical modeling sometimes. In recent years, Drezet et al[4-8] have developed the elasto-viscoplastic models to calculate the thermodynamic deformation of the solid metal induced by the thermal stresses. The basic principle of their models is, when the liquid metal transfers to solid, the contraction due to the temperature decreasing or phase transform can be compensated by the upper liquid metal, and the pull-in only occurs at solid phase. The modeling results show that the pull-in only occurs at the section just below the liquid pool[2,8]. While the other sections already formed at the stationary phase doesn't deform. However, this phenomena (see Fig. 2) can not be seen in practice. Fig. 2 shows the EMC aluminum slab with the cross section of 1 300 mm × 480 mm. Although the parabola shape inductor has the opening of 16 mm, the whole slab has concave deformation of 4 mm at broad faces.

Fig. 3 shows the measured temperatures and pull-in of the EMC slab[3]. The cross section of the aluminum slab is 420 mm × 140 mm. The pouring temperature and cooling water flow rate are altered to investigate the effect of the surface temperature on the pull-in. Curves 1 and 3 correspond to the pouring temperature 700 ℃, water flow rate 1.6 m^3/h. The positions of the measured points are at the center of the slab cross-section and at the center of the rolling face respectively. Curves 2 and 4 correspond to the

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Fig. 2 Pull-in of wide face of EMC slab

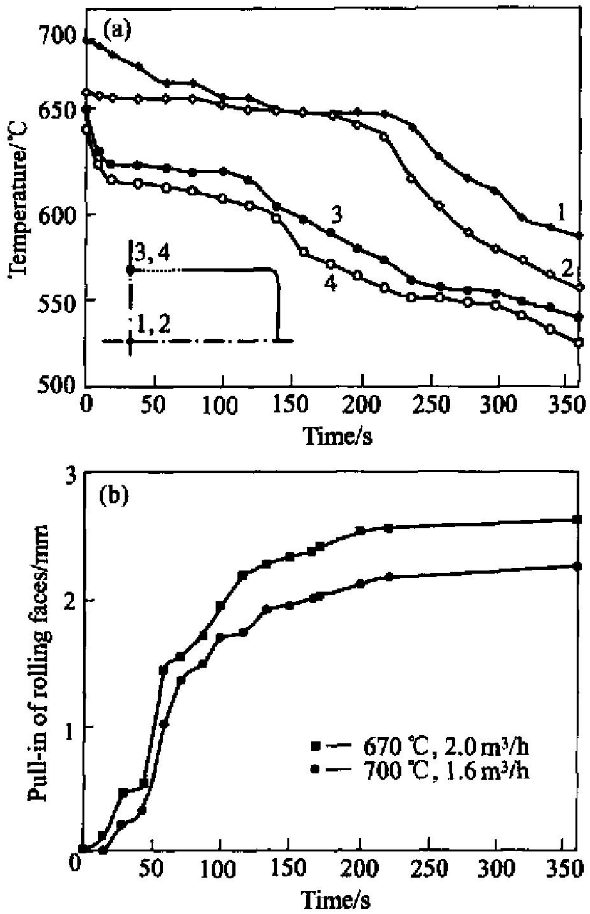

Fig. 3 Measured temperature and pull-in of rolling faces during casting

pouring temperature 670 ℃, water flow rate 2.0 m^3/h. The results show that a higher surface temperature of slab can decrease the pull-in. It is also indicated from Fig. 3(b) that when the center of the cross-section has become solid, the pull-in of the rolling faces are already 2.4 and 2.6 mm, respectively. In other words, the largest proportion of total deformation has already occurred when the cross-section turns completely into solid. The after-contraction of 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.

In this paper, the deformation mechanism during solidification is analyzed based on the experimental results. A mathematical model is proposed to predict and control the concave deformation of the EMC large slabs.

2 FORMATION OF CONCAVE DEFORMATION OF BROAD FACES DURING SOLIDIFICATION PROCESS

In the stationary casting phase, the length of the slab increases continuously at the casting speed. Considering any layer of the slab cross section forms with unit thickness from the time when is poured, the lowered down layer of the slab experiences the solidification process of liquid phase, liquid-solid phase, solid phase and the cooling after the solidification process. When the casting process is finished, the deformation process is ended.

Fig. 3 shows that the concave deformation (pull-in) of large slabs mainly forms during the solidification process. It almost amounts to 90% of the whole deformation, while the pull-in of broad face after solidification only amounts to 10% of the whole deformation. So study on the slab deformation mechanism during solidification process is the key to control the deformation.

2.1 Basic assumptions

When we discuss the formation mechanism of the concave deformation, the following deformation coordinations are assumed:

1) The slab layers are made up of linear element parallel to the symmetry axis line, the bending deflections of the solidified shell satisfy the plane assumption.

2) The liquid metal is uncompressible liquid, the cooling conditions satisfy the free shrinkage porosity in the center of the slab.

3) The deformation caused by the thermal moment is small, and satisfies the superposition principle when calculating.

4) The material properties change with the temperature.

2.2 Slab concave deformation caused by thermal moment in solidified shell

At t time after pouring (time as the steady casting phase), the slab layer forms with unit thickness at vt distance from the top, and the broad faces have the thickness of solidified shell F. As the corners of the slab face to two-direction cooling, the temperature of short sides decreases faster than that of the broad sides. So the solidified shell of the broad sides forms the beam supported by the solidified shells of the two short sides. Dividing the beam into n tiny sections, and considering any $\Delta x_i = x_i - x_{i-1}$, the coordinate system is shown in Fig. 4, in which ox is the bending central axis. Applying the superposition principle, and considering the linear element with the area of df, the distance f to the central axis (shown in Fig. 5), and the temperature change ΔT between the Δt time interval, according to the deform coordination assumption (1), the stress-strain constitutive relation is

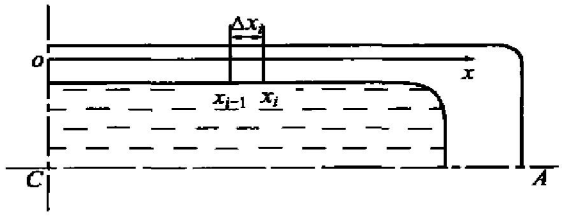

Fig. 4 Position of unit Δx_i at time t

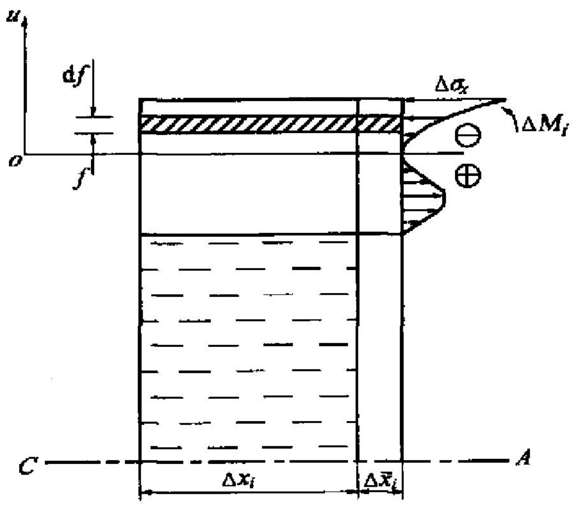

Fig. 5 Stress distribution at across section

$$\Delta\sigma_x = E(\overline{\Delta x_i}/\Delta x_i - \alpha\Delta T) \qquad (1)$$

where $\overline{\Delta x_i}$ is the mean linear shrinkage of unit Δx_i, $\Delta\sigma_x$ is the stress increment acted on the line element df. The stress distribution of the cross section is shown in Fig. 5.

According to the equivalent equation $\sum x = 0$, there is

$$\int_F \Delta\sigma_x df = \int_F E(\overline{\Delta x_i}/\Delta x_i - \alpha\Delta T) df = 0 \qquad (2)$$

Then the mean linear strain is

$$\bar{\varepsilon} = \overline{\Delta x_i}/\Delta x_i = \int_F E\alpha\Delta T df \Big/ \int_F E df \qquad (3)$$

where F is the cross sectional area of the solidified shell of the section Δx_j.

Eq. (1) indicates that the uneven temperature change ΔT among the linear elements df within the solidified shell, makes the stresses $\Delta\sigma_x$ to distribute unevenly on the cross section and forms the thermal bending moment acted on the Δx_i section as shown in Fig. 5

$$\Delta M_i = \int_F f \Delta\sigma_x df = \int_F E(\bar{\varepsilon} - \alpha\Delta T) f df \qquad (4)$$

Under the action of this bending moment, the solidified shell bends, as shown in Fig. 6. The curvature is directly proportional to the thermal bending moment

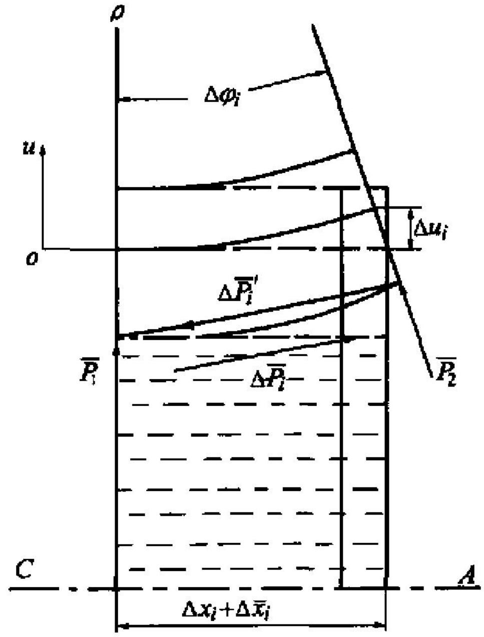

Fig. 6 Bending mechanism of unit Δx_i

$$1/\rho = \Delta M_i / EJ_y \qquad (5)$$

where EJ_y is the flexural rigidity, ρ is the radius of curvature. Considering small deformation, the curvature equation is

$$1/\rho = d^2u/dx^2 \qquad (6)$$

Combining Eqs. (5) and (6), the second order differential equation to describe the bending deflection of the solidified shell is

$$\frac{d^2u}{dx^2} = \frac{\Delta M_i}{EJ_y} \qquad (7)$$

Integrating Eq. (7) twice, the bending deflection equation of the solidified shell is obtained. Its discrete calculation model is

$$\Delta\varphi_i^t = \Delta\varphi_{i-1}^t + \Delta M_i \Delta x_i/(EJ_y) \qquad (8)$$

$$\Delta u_i^t = \Delta u_{i-1}^t + \Delta\varphi_{i-1}^t \Delta x_i + \Delta M_i(\Delta x_i)^2/(2EJ_y) \qquad (9)$$

where, the superscript t indicates the calculating time. $\Delta\varphi_i^t$ and Δu_i^t are the slope coefficient of the bending deflection curve and the increment of bending deflection respectively. Eq. (8) indicates the curvature of the bending deflection curve is its slope coefficient of the section Δx_i. While Eq. (9) indicates that when Δx_i is small enough, the bending deflection curve in the solidification shell is a quadratic curve. For the whole solidification and cooling process, the slope coefficient and the bending deflection at point i are

$$\varphi_i = \sum \Delta\varphi_i^t \quad (10)$$

$$u_i = \sum \Delta u_i^t \quad (11)$$

2.3 Tangential push force of liquid metal caused by bending deflection of solidified shell

At any time when the solidified shell of the large slab propels to center, owing to the effect of the thermal bending moment, the curvature of bending deflection curve changes, which makes the static pressure at the solidification front change. The pressure direction changes from the direction P_1 (before deformation) to P_2 (after deformation), as shown in Fig. 6. The direction change of the static pressure is because that the shrinking force $\Delta P'_i$ exists along the solidified shell at front. Thus the relationship is

$$\overrightarrow{P_2} = \overrightarrow{P_1} + \overrightarrow{\Delta P'_i} \quad (12)$$

$$\Delta P'_i = P_1 \Delta\varphi_i \quad (13)$$

That is, when bending occurs, according to the principle of action and reaction, the reaction $\overrightarrow{\Delta P_i}$ exactly induces the tangential push force in the liquid metal along the solidification front, the relationship is

$$\Delta P_i = \Delta P'_i \quad (14)$$

The shell curvature is also proportional to the slope coefficient. As the liquid metal is uncompressible liquid, when the tangential push force squeezes the liquid metal inside the pull-in deformation space along the solidification front to the warped section, the liquid metal flows from the hot end to the cold end, as shown in Fig. 7. The cold end obtains the liquid metal, compensates the solidification contraction of the short face, and keeps almost unchanged size of the short face in the designed size until the solidification finishes. However, the high temperature broad face loses liquid metal because of the bending deformation, and leads to the pull-in deformation. The deeper the pull-in is, the bigger the tangential push force is. While the shape of the liquid metal border changes as the shape of the solidification front after deformation, the liquid metal and the solidified shell become a continuum after deformation. As the solidification front propels, the pull-in deformation caused by the thermal bending moment propels and accumulates until the solidification process finishes, which makes the density of the slab be even everywhere and leads to the irreversible pull-in deformation.

The above discussion indicates that, the thermal bending moment due to the uneven temperature field of the broad faces causes the bending of the solidified shell, and the tangential push force causes the liquid metal flow from the hot end to the cold end, compensating the solidification contraction of the cold end . The bending deformation of

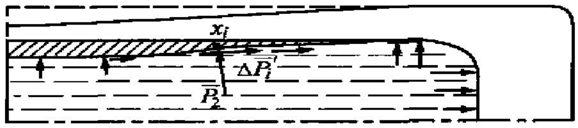

Fig. 7 Shrink force $\overline{\Delta p_i}$ induced by pull-in

the solidified shell fixes at the place where flows out the liquid metal. Although there's pull-in deformation, the uncompressible character of the liquid metal makes the density of large slab even and unchanged. Along with the advance of the solidification front, the pull-in deformation of the broad face of the slab caused by the thermal bending moment continues propel and accumulate toward the center, until the solidification process finishes. Thus the density of the slab is even everywhere and the slab has irreversible un-straightness.

According to the un-straightness formation mechanism, the software package Tm-BD has been programmed. When input the size of the slab, and thermal properties of the material and the casting parameters, the solidification process of the slab can be calculated and the bending deflection can be predicted. By realizing the mold design with and without opening, the purpose of controlling un-straightness can be achieved.

3 ANALYSIS AND DISCUSSION

3.1 Influence of temperature field during solidification process on un-straightness

The thermal bending moment caused by the uneven temperature field of the slab broad face makes the solidified shell bend, which generates the tangential push force and causes the liquid metal to flow from hot end to cold end and solidify at the cold end. As the density of the uncompressible liquid is even and unchanging, the border shape of the liquid metal changes with the solidification front after bending deformation. So the uneven temperature field of broad face during the solidification process is the main reason of un-straightness.

3.2 Influence of casting parameters on un-straightness

Both the lab study and the industry measured results[1, 2] show that the casting speed, pouring temperature, cooling conditions, width to thickness ratio of slab, alloy composition and other casting parameters, all affect the un-straightness of the slab. As an example, the influence of the casting speed is shown

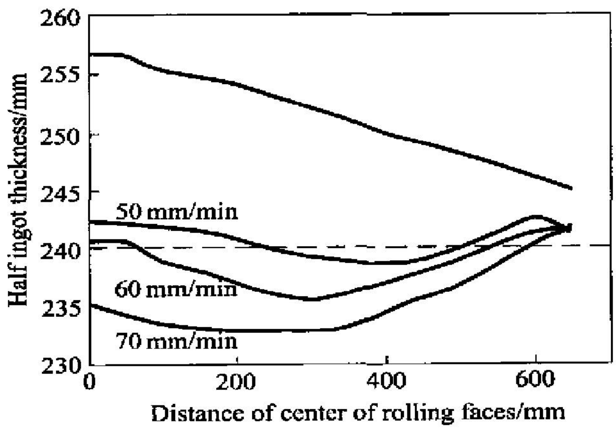

Fig. 8 Influence of casting speed

in Fig. 8. Among these casting parameters, the cooling conditions and casting speed have the most remarkable influences on the temperature field.

In fact, some casting parameters such as the width to thickness ratio of the slab and the alloy composition usually are certain and can not be changed during casting process. One of the parameters which can be controlled during the process is the cooling conditions. Changing the spray distribution of the cooling water can minimize the thermal bending moment formed by the temperature field[3, 6, 12, 13].

3.3 Control of surface temperature of ingot during solidification process

The depth of the liquid pool is determined by the casting speed and the surface cooling conditions. If the cooling intensity during this process is high, the surface temperature is far lower than the interior. Then the stiffness of the surface materials increases much rapidly, which makes the bending deflection of the solidified shell surface and the interior part be inconsistent, and thus the solidified shell will produce hot cracks along the solidification front. So the surface temperature should be controlled not to be too lower than the solidus temperature.

4 DESIGN OF MOLD WITH AND WITHOUT OPENING

The programmed Tm-BD software package according to the un-straightness formation mechanism can calculate the solidification process, un-straightness and butt curl of the slab. By applying the imagine design and computer simulation method, the mold design with and without opening can be carried out and realize the purpose of controlling un-straightness. Fig. 9 shows the measured and calculated pull-in of the broad faces of a large slab with the size of 1 300 mm × 480 mm. In Fig. 9, curve 1 is the shape of the mold opening in site. Curves 3 and 4 are the measured and calculated pull-in results of the broad face. The agreement between the numerical and measured results proves that the Tm-BD software system can be used to design mold with opening.

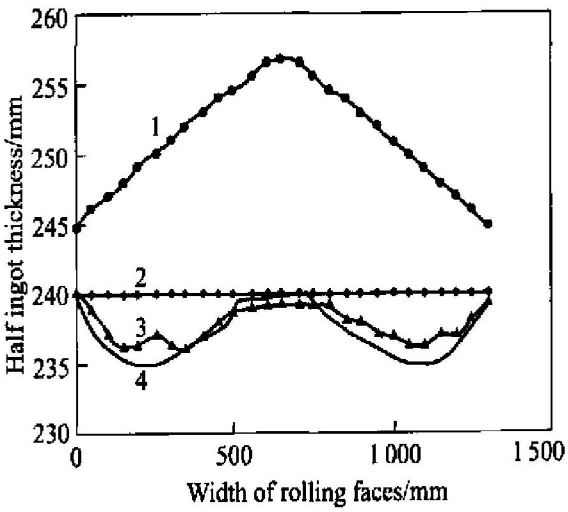

Fig. 9 Comparison between numerical and measured results

1 —Mold opening; 2 —Desired value;
3 —Measured value; 4 —Numerical value

4.1 Design of mold with opening

At present, the mold usually has opening and the water distribution along its periphery is even. Because the heat at the corners of the slab can be extracted through two directions, while the center of the broad faces is far from the corner (the corner effect range is about half the short side width), the heat is extracted almost through one direction, the temperature of the solidified shell of the broad face has gradient along the broad face, and the pull-in deformation certainly generates. Usually the mold with two-lines or three-lines shape outward opening is used, the liquid metal at the outward opening part is used to compensate the pull-in deformation of the slab. But the size of the opening basically depend on the in site experiences.

In Fig. 10, three kinds of inductors/molds (curves 1, 2, 3) were calculated. The calculation results (curves 1, 2, 3) shows that curve 3 is closed to the desired value of curve 4. Its un-straightness can be controlled within 2mm. It is evident that the programmed Tm-BD software pack can be applied to optimize the mold design with opening, achieve the purpose of controlling un-straightness of the large slabs.

4.2 Design of mold without opening

It is desirable that the mold is straight. As the thermal gradient along the broad faces is the reason leading to the thermal bending moment, if the thermal gradient along the broad faces is minimized during the solidification process, or near to be zero, then the solidified shell of the broad face can propel parallelly from surface to center and straight large slab can

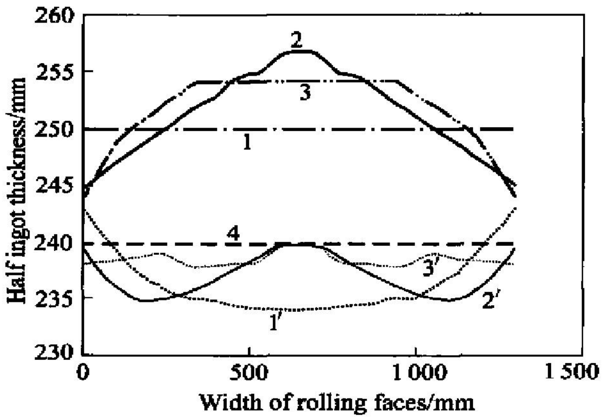

Fig. 10 Results when using mold with opening and even water jetting distribution
1, 1′ —One line opening and calculated;
2, 2′ —Two lines opening and calculated;
3, 3′ — Five lines opening and calculated;
4 —Desired half ingot thickness

be obtained.

If the water spray system is improved and satisfies the requirement of the liquid column, minimizing the thermal gradient along the broad faces can be used as the design basis, and the parallel propel of solidified shell of the broad faces can be realized.

Fig. 11 shows the comparison of the un-straightness of the 1 300 mm × 480 mm EMC slabs under different cooling conditions. When using the flat mold and applying the cooling intensity distribution of the rolling faces indicated by curves 1, 2, 3, 4, and the cooling intensity of all the short faces is 0.2, the concave deformation is different. The un-straightness can be improved by using the flat mold and the cooling conditions of 3 or 2, as shown by the deformation curve 3′ or 2′.

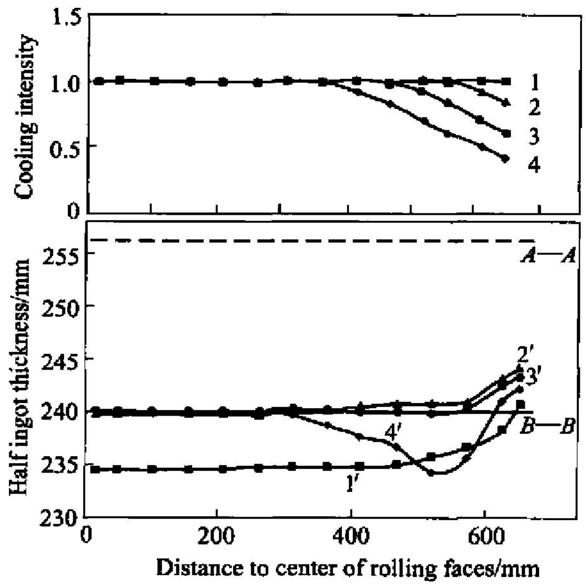

Fig. 11 Influence of cooling intensity to un-straightness of rolling faces
A —*A*: desired opening; *B* —*B*: desired thickness

It shows that the programmed Tm-BD software pack can be applied to optimize the flat mold (without opening) design with cooling conditions.

5 CONCLUSIONS

1) The bending deformation of the rolling faces of the slab is mainly formed during the solidification process. The thermal bending moment caused by the uneven temperature field of the broad faces is the main reason of the concave deformation of the rolling faces.

2) The liquid metal is uncompressible. The curvature changed by the pull-in of the slabs makes the tangential push forces at the solidification front push the liquid metal from hot center part to cold corners, causing the concave deformation at the solidification front.

3) The total pull-in of the slabs is the accumulated bending deformation during the solidified shell pushing inward. The deformation is irreversible and the density of the slab is even.

4) The Tm-BD software system can be used to predict the bending deformation of the large slabs. It can also be applied to design the molds with and without opening.

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