Determination of solidification end position of continues cast slab based on force model

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Abstract. For a better determination of solidification end position during the process of soft reduction to confirm the reasonable reduction position and reduction area and to get the better slab quality, by analyzing the force behaviour of slab shell during soft reduction process, a force dynamic determination model for the end position of liquid core of slab during soft reduction process has been built. The variation trend of reaction force and total pressure of segment clamping-roller with the changing of position of solidification end can be got by the using of model calculation, and by analyzing this trend, a force feedback-based model has been proposed for checking the end position of liquid core. The veracity of the force feedback-based model has been verified by using nail-shooting approach.

1. Introduction

To reduce the center segregation and center porosity of slab, an effective method is using the reduction technology on the slab surface at the solidification end position of liquid core [1]. Thus, how to determine the correct solidification end position of slab is the precondition for reduction technology.

At present, the commonly used predicating method of slab solidification end are nail-shooting method and heat tracking model method [2-4]. The nail-shooting method can check the thickness of slab shell directly and it is usually being used for checking and improving the solidification heat transfer model, however it cannot be used for online determination. Heat tracking model method can calculate the position of solidification end online according to the steel grade, casting temperature and casting speed. However, since the boundary conditions and the physical parameters are not accurate and the real production condition is not stable, the solidification end of slab is dynamically changing which caused the calculation result of model has some differences with the actual situation.

This article aims on the defect of current predication method of solidification end, establish a dynamic determination model for the soft reduction solidification end of slab based on force feedback. The variation trend of bearing reaction and total bearing reaction of segment roller with the changing of position of solidification end can be got by the using of model calculation has been studied and the method for determine the position of liquid core based on the force feedback model has been proposed. Also, the nail-shooting method has been used for verifying the validity of force feedback model.
2. Model of predicting slab solidification end position

2.1. Foece model of soft reduction segment

In real production, the reduction quantity is separated to different rollers in segment averagely and applied on slab. Before the slab is solidified completely, the liquid core separates the slab as top and bottom part, here we use the bottom part shell as the research object. The static pressure can be treated as uniformly distributed load \( q \) which acts on the top surface of the bottom part of slab. The roller distance with in one segment are \( l_1, l_2, \ldots, l_n \). Then the shell in reduction segment can be simplified as continues beam structure. After the slab is solidified, it can be treated as one. At this point the cross section angle of slab is 0 which can be simplified as fixed end. The constraint between slab and rollers forms the indeterminate structure which can be seen in figure 1. In figure 1, \( P_0 \) and \( M_0 \) are reaction force and torque on the slab section at the roller zero, \( q \) is the static pressure of liquid steel, \( 1, \ldots, n \) is the sequence number of supports. \( q \) can be got from formula (1).

\[
Q = \rho g h
\]

In the equation, \( \rho \) is density of liquid steel, \( g \) is gravity, \( h \) is height of liquid steel to the meniscus.

Slab is cut at the segment’s 0 roller and simplify the roller as movable hinge bearing. Since the usage of continuous beam, roller 0 is not only under the reaction force \( P_0 \) from the bearing, but also under the torque \( M_0 \) and all other rollers in segment are turning into movable hinge bearing. In the calculation of force model, the fixed bearing on the right of figure 1 can be replaced by a simply supported beam which has an infinitesimal span \( l_{n+1} \). When the span close to 0, the fixed bearing can be simplified as the fixed hinge bearing with 0 angle as shown in figure 2. In figure 2, \( P_n \) is the bearing \( n \) reaction force on beam, \( M_n \) is the bending moment of beam at the bearing \( n \). Imagine cut all the continuous beam among the intermediate bearing and install the hinge, the basic statically determinate system as shown in figure 3 can be got. Get any two of adjacent span \( l_i \) and \( l_{i+1} \) from the statically determinate system in figure 3, the deflection curve at the intermediate bearing \( i \) is smooth and continuous, so the section on two sides of hinge \( i \) should have the same angle which is:

\[
\theta_{i1} = \theta_{i2}
\]

In the equation, \( \theta_{i1} \) is the angle of right section of span \( l_i \); \( \theta_{i2} \) is the angle of left section of span \( l_{i+1} \).
When calculate $\theta_{i1}$, use span $l_i$ as simply supported beam, the force on it are: (1) uniformly distributed load $q$; (2) bending moment $M_{i-1}$ on left end; (3) bending moment $M_i$ on right end. Calculate the angle the generated by these three forces that mentioned above on span $l_i$ and superimpose it to get $\theta_{i1}$, see formula (3).

$$\theta_{i1} = \frac{M_{i-1}l_i}{6El_i} + \frac{M_il_i}{3El_i} + \frac{\omega_ia_i}{El_il_i}$$  \(3\)

In the equation, $E$ is the elasticity modulus of slab, $I_i$ is the inertia moment of the $l_i$ cross beam, $a_i$ is the distance between the $l_i$ cross beam’s centroid and the left end.

In a similar way, the angle of the $l_{i+1}$ cross beam can be got as:

$$\theta_{i2} = -\frac{M_{i+1}l_{i+1}}{6El_{i+1}} - \frac{M_il_{i+1}}{3El_{i+1}} - \frac{\omega_{i+1}b_{i+1}}{El_{i+1}l_{i+1}}$$  \(4\)

In the equation, $\omega_{i+1}$ is the integral area of bending moment diagram of the $l_{i+1}$ cross beam when external load working alone, $b_{i+1}$ is the distance between the $l_{i+1}$ cross beam’s centroid and the right end.

Substitute formula (3) and (4) into formula (2) and get the three bending moment equation at the segment of solidification end. Refer to formula (5).

$$\frac{M_{i-1}l_i}{l_i} + 2M_i \left(\frac{l_i + l_{i+1}}{l_{i+1}}\right) + \frac{M_{i+1}l_{i+1}}{l_{i+1}} = -6 \left(\frac{\omega_ia_i}{l_il_i} + \frac{\omega_{i+1}b_{i+1}}{l_{i+1}l_{i+1}}\right)$$  \(5\)

2.2. **Boundary condition**

According to the stress and deformation of the two end faces, using $M_0$ and $M_n$ as the boundary condition for confirmation.

2.2.1. **Entrance side of soft reduction segment.** As shown in figure 4, between two segments, the line of deflection of slab is continuous changing. At the middle point of $l_0$ cross beam, the angle of beam is 0. Split the beam at the middle point $A$, treat bearing 0 as fixed bearing. The right part’s cross beam is cantilever, at point $A$ there is bending moment $M_A$, on cantilever there is uniformly distributed load $q$. the angle at point $A$ is formed by bending moment $MA$ and uniformly distributed load $q$.

![Fig 4. Entrance end of soft reduction segment.](image)

2.2.2. **Exit side of soft reduction segment.** With the solidifying of liquid steel, center of slab changed as sticky mushy area and there is no static pressure of liquid steel but also not like the solid slab which has the deformation resistance. The mushy area can be treated as liquid area, it can be split as upper and bottom part. But the shell of mushy area has no static pressure of liquid steel. When the liquid core is moving forward at the cross beam of exit $l_n$, the stress form of cross beam $ln$ can be seen in figure 5.

![Fig 5. Force analysis of simply beam at outlet.](image)
3. Calculation of solidification end position of slab liquid core

3.1. Calculation of bearing reaction of segment rollers.

Take one slab caster in a factory as the research object and use the mentioned force model to build the relation between solidification end position and bearing reaction of rollers of soft reduction segment so that the solidification end position can be determined by detecting the bearing reaction of rollers. For segment which join the soft reduction there are 6 pairs of rollers, the relevant parameters under actual production conditions for calculating the bearing reaction of clamping roller can be seen in table 1.

According the stress status of slab under the different conditions, define the roller’s reduction force on slab as Fz1 when the slab has the liquid core and the roller’s reduction force on slab as Fz2 when the slab has no liquid core, also define the roller’s reduction force on slab as Fz3 at mushy area. The relation between solidification end position of liquid core and the bearing reaction is obtained by calculating the bearing reaction and total bearing reaction of the rollers of soft reduction segment. Here numbering the rollers of segment from 0 to 6 along the casting direction. The beam between roller 0 and roller 1 is the first span and so on. Totally there are 6 spans. When liquid core end position is in span 3, we can get the bearing reaction as shown in figure 6. Determine the total bearing reaction of the spans which has the liquid core end, so the trend of changing of segment total bearing reaction can be got, see figure 7.

Table 1. Parameter of soft reduction segment

| Parameter name                        | Value   | Parameter name                        | Value   |
|---------------------------------------|---------|---------------------------------------|---------|
| Caster meniscus height /m             | 13.2    | Roller distance of segment /m         | 340     |
| Slab section B×H/(mm×mm)              | 1650×250| Roller radius /m                      | 160     |
| Reduction quantity for a roller /mm   | 0.2     | Casting speed vc/(m • min-1)          | 1.2     |

(a) Trend of bearing reaction of 0; (b) Trend of bearing reaction of 1; (c) Trend of bearing reaction of 2; (d) Trend of bearing reaction of 3; (e) Trend of bearing reaction of 4-6; (f) Trend of bearing reaction of all bearing.

Figure 6. Support reaction of bearings when liquid core is on third span.
Analyzing the force trend of the changing of liquid core end position, we can get the follow law: (1) when the liquid core end position is moving along the whole segment, the curve of total bearing reaction is acting like global step decline, but when the liquid core end position is moving toward the exit of segment in every span, the curve of total bearing reaction is acting like monotone increasing; (2) the bearing reaction at side face of the span which has the end position of liquid core is changing obviously with the changing of liquid core end position. the bearing reaction of the bearing which close to the exit of segment is acting like monotone increasing when the liquid core end position is moving toward the exit of segment; (3) if the end position of liquid core is moving along the span which the liquid core end position is moving toward the exit of segment are all Fz2.

3.2. Determination of end position of liquid core
According to the changing rule of bearing reaction of each bearing and the total bearing reaction when the end position of liquid core is changing, the following two method for determining the end position of liquid core can be got. (1) first find out the maximum bearing reaction close to the exit of segment and compare with Fz2, if there is any bearing i has the similar bearing reaction with Fz2, the end position of liquid core can be confirmed in span i-1, then check the bearing reaction of bearing i-1. According to the changing curve of bearing reaction against the changing of end position of liquid core in this span, the end position of liquid core can be confirmed; if there is no bearing with similar value, it means the end position of liquid core is in the last span, the end position of liquid core can be predicated according to the changing curve of bearing reaction of bearing 6; (2) the total bearing reaction can be got directly as per the pressure of segment cylinder, compare it with the changing curve of total bearing reaction of segment against the changing of end position of liquid core in figure 7, then the end position of liquid core can be detected online.

3.3. Verifying force model
In this article, to check the determination result of the solidification end position of liquid core by using of force model, the nail-shooting test had been done on the casting site. The testing conditions can be seen in table 2.

Table 2. Experimental conditions for rivet pin-shooting.

| Steel grade | Section/mm | Casting speed / (m·min⁻¹) | Super heat/°C | Reduction quantity of segment/mm |
|-------------|------------|---------------------------|---------------|---------------------------------|
| Q345        | 1650×250   | 1.00                      | 30            | Segment 7                      |
|             |            | 1.05                      | 30            | Segment 8                      |
|             |            | 1.10                      | 25            | Segment 9                      |
|             |            |                            |               | 1.8                            |
|             |            |                            |               | 2.2                            |
|             |            |                            |               | 1.3                            |
After the slab is cooling, cutting the slab with the nail as the cubic with the size of 250 mm×100 mm×100 mm. Then use the miller to mill the cubic at the center section of nail. After polishing and pickling, execute the low power test. The thickness of shell and liquid core can be seen in table 3.

| Casting speed (m·min\(^{-1}\)) | Nail position | Shell thickness/mm | Calculated solidification end position by thickness of shell/m | Total pressure of segment cylinders/kN | Calculated solidification end position by force model/m |
|---------------------------------|---------------|---------------------|---------------------------------------------------------------|--------------------------------------|--------------------------------------------------------|
| 1.00                            | End of        | 111                 | 20.86                                                         | 3065                                 | 20.93                                                  |
| 1.00                            | End of        | 122                 |                                                               | 3195                                 |                                                        |
| 1.00                            | End of        | 125                 |                                                               | 4297                                 |                                                        |
| 1.05                            | End of        | 109                 |                                                               |                                      |                                                        |
| 1.05                            | End of        | 119                 | 21.82                                                         | 3055                                 | 21.91                                                  |
| 1.05                            | End of        | 125                 |                                                               | 3167                                 |                                                        |
| 1.05                            | End of        | 106                 |                                                               | 3562                                 |                                                        |
| 1.10                            | End of        | 115                 | 22.55                                                         | 3048                                 | 22.62                                                  |
| 1.10                            | End of        | 125                 |                                                               | 3155                                 |                                                        |
| 1.10                            | End of        | 2972                |                                                               |                                      |                                                        |

According to the site condition of nail-shooting test and the actual pressure of all cylinders, using the force model to calculate the position of solidification end. Then use the thickness of shell to calculate the position of solidification end and compare two results, refer to table 3. When the casting speed is 1.10m/min and using shell thickness to get the position of solidification end is 22.55 m while using the force model the result is 70mm rearward. Both of two results is between roller 6 and 7 in segment 9; when the casting speed is 1.00m/min, both of the result is between roller 1 and 2 in segment 9; when the casting speed is 1.05m/min, both of the result is between roller 4 and 5 in segment 9. From this comparison, the result from force model and the result from the position of solidification end by checking the actual shell thickness is basically match. So, the position of solidification end of liquid core of slab soft reduction can be checked by using force feedback model.

From the test result, we can see the current heat-transfer model of the caster the offset of the position of the solidification end is more than 1 roller distance by the influence of changing of working situations and the uncertain site conditions. But the result from force model has the offset with only 1/5–1/4 roller distance under the different working situations. The accuracy rating is 4–5 times better than the heat-transfer model. The method for determination of liquid core end position under different work situations based on force model can use the total pressure of segment cylinders to determine the liquid core position. For the segments of current caster, it only needs to read the pressure of cylinder and no need to modify the equipment structure or add additional pressure-detecting components. It is easy to achieve and good for extension in the slab caster.

4. Conclusion

By researching the force characteristic of the solid shell of the slab with liquid core during the soft reduction process, established a dynamic determination mathematic model of solidification end position of liquid core of slab soft reduction based on force feedback and provided the bearing reaction expression of roller of segment soft reduction.

Got the bearing reaction and total bearing reaction’s changing rule of clamping roller of soft reduction segments when the position of solidification end is changing among roller 0 to 6 in segment based on the calculation of force feedback model. And according to this rule, the determination of liquid core end position based on force feedback model has been proposed.
By using the nail-shooting experiment under 1.10m/min, 1.05m/min and 1.00m/min casting speed, the actual thickness of slab shell and the position of solidification end has been confirmed. The calculated solidification end position based on the force model that proposed by this article has only 1/5~1/4 roller distance difference with the nail-shooting result. Two results are consistent which verified the correctness of this force model.

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