Technical Report

UDC 621 . 746 . 047 : 681 . 3

Numerical Simulation of the Continuous Casting Process and the Optimization of the Mold and the Strand

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Abstract

The phenomenon of the uneven solidification in the continuous casting process was examined by the numerical simulations. The simulation model which analyze the distortion behavior of the solidifying steel shell was developed. The influence of the mold shape to the growth of the solidifying shell was studied. It was found that the multiple taper design is useful to the even solidification. The numerical model that simulate the free surface flow of the spray water in the secondary cooling of the strand was developed using a particle-based method. The uneven water flow in the width direction was examined, and the over-cooling around the center in width direction was found.

1. Introduction

Continuous casting in the steel making process is a process that continuously solidifies molten steel in a liquid state to a solid state called slab. Molten steel is poured into a mold built up of cooled cupper plates on its four sides through refractory-made submerged nozzles and solidification starts at the periphery. Solidified periphery, called as the solidifying shell, is very thin as compared to the width and the thickness of the slab. Under this state, though periphery of the four faces is thinly solidified, molten steel in liquid state exists in the inner part. Length of the mold in the casting direction is about one meter and a plurality of roll is installed right below the mold to protect the thin solidifying shell. In order to solidify completely, spray nozzles are installed in between the rolls for cooling and cooling by water or mist of mixture of water and air is applied. The mold is termed as the primary cooling zone and the spray cooling zone right below the mold is termed as the secondary cooling zone.

In the mold of primary cooling zone, the solidifying shell is thin and in case a shell thinner than the one in other parts of periphery is formed due to uneven solidification, the solidifying shell becomes unbearable to the static pressure of the molten steel and the shell may break. Breakage of the shell causes flow-out of molten steel, triggering a break-out in worst case, which means leaking out of molten steel from right below the mold. As temperature decreases, the solidifying shell grows and thermally shrinks. In a slab rectangular in shape, the shell on the wide face mold (in the width direction of a slab) shrinks more than the one on the narrow face mold (in the thickness direction of a slab). Therefore, in the conventional slab continuous casting machine, mold cupper plates of narrow face mold determining the width are tapered and designed to reduce the slab width toward the lower end of the mold.

However, it is difficult to match the taper to the shrinkage of the solidifying shell completely and a gap tends to be developed between the shell and the mold in the neighborhood of the corner of a slab, wherein the narrow face mold plate edge contacts the wide face mold plate. Thermal resistance between the solidifying shell and the mold grows, decreasing heat transfer. This means that as heat transfer in the neighborhood of the slab corner decreases, uneven solidification tends to be developed more easily. An inappropriate taper in particular promotes solidification unevenness and triggers breakage in the solidifying shell or a break-out in worst cases. In order to make the heat transfer uniform in the mold, mold taper design is crucial; however, observation of the state of solidifying shell within a mold is practically impossible therefore clarification of the phenomenon by means of numerical analysis is effective. Then, a numerical analysis model that analyses the distortion behavior of a solidifying shell within a mold was developed and the effect of the mold shape over the development of uneven solidifying shell

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was studied.

In the secondary cooling, it is important to ensure the following: to solidify the cast slab completely before it reaches the last support roll, to solidify uniformly in width direction, and to prevent the occurrence of transverse cracks at edge positions in width direction. In order to obtain a uniform cooling in width direction, optimization of spray nozzle arrangement, cooling area of a single nozzle, and water flow rate distribution in width direction were conducted; however, in recent years, because rolls separated in width direction are used generally, uneven cooling in width direction has been caused more by the water collected on rolls since the water flows out and drops at an interspace in the width direction wherein the bearings of the separated roll are installed.

However, as observation of the water flow is difficult, analysis of spray water flow by means of flow analysis is effective. In addition, attention was paid to particle method as a means of flow analysis to realize visualization of free moving surfaces flow of spray water and visualization of the phenomenon was attempted. Furthermore, if visualization of the flow is realized, prediction of heat transfer coefficient in spray cooling becomes possible. By an experiment simulating the flow obtained by analysis with particle method, heat transfer coefficient was measured and by inputting the data to boundary conditions in the solidification calculation, the mechanism of development of uneven solidification in width direction was studied.

2. Optimization of Mold Shape by Solidifying shell Distortion Analysis

2.1 Analysis of solidifying shell distortion within mold

In almost all solidification distortion analyses, a non-steady method of fixing the coordinate system to an intercept of a cast steel¹) is used. This method calculates temperature and stress by changing the peripheral boundary conditions in accordance with elapse of time. However, the method cannot take into account the temperature gradient and stress gradient in casting direction. To solve the problem, a method of analysis in a velocity field on the coordinate system fixed to a space was proposed, taking into account the viscoplastic behavior and likewise the rigid plasticity analysis used in rolling analysis.^{2, 3)} However, the model is a two dimensional model based on the assumption of generalized plain strain and was insufficient to represent the cracks that are practically developed in actual slabs. It can be noted that since the solidifying shell thickness is very thin compared to cast slab size within a mold and that the temperature distribution in the shell thickness direction can be expressed in a relatively simple distribution form, a 3D finite element analysis model was developed by formularization using shell elements. The developed model takes into account substance movement and phase transformation, including solidification, thermal shrinking, and viscoplastic behavior.

As for the method of solidification calculation, there are various methods such as enthalpy method and equivalent specific heat method; however, in the model, assuming that the temperature distribution within the shell can be approximated by a quadric, method of solving the heat conduction equation with Runge-Kutta⁴⁾ method was employed. Since the model handles viscoplastic behavior, formularization of the model by means of strain rate was applied so that deformation rate can be taken into account. Overall strain rate is expressed by the following formula.

$$\dot{\varepsilon} = \dot{\varepsilon}^e + \dot{\varepsilon}^{vp} + \dot{\varepsilon}^t + \dot{\varepsilon}^m$$
(1)
where $\dot{\varepsilon}^e$ is elastic strain rate, $\dot{\varepsilon}^{vp}$ is viscoplastic strain rate, $\dot{\varepsilon}^t$ is ther-



mal strain rate, and $\dot{\varepsilon}^m$ is transformation strain rate.

As for viscoplastic strain, a model proposed by Wang²⁾ et al. was used. Relational expression between stress and strain rate obtained from the result of high temperature tensile test result⁵⁾ was used to determine physical properties for calculation.

Next, formularization with the finite element method is stated. Since shell thickness is small as compared to cast slab size (width, thickness, and casting length in longitudinal direction) and the temperature distribution within the solidifying shell can be expressed relatively in a simple manner (approximated by a quadric), while analyzing the distortion with the finite element method (FEM), formularization using 4-nodes thick shell elements as calculating element was executed. **Figure 1** shows the shell elements used in the FEM.

Regions of temperature distribution and plastic distortion were defined by several integration points of elements in thickness direction. With this FEM calculation using the elements, 3D analysis taking into account material transfer, phase transformation including solidification, and viscoplastic behavior in high temperature regions also became possible. Procedure of the calculation is to allot temperature distribution obtained with the aforementioned solidification calculation to each integration point in the element (four points on a plain and a plural of n point in shell thickness direction) and to repeat the calculation by changing loading rate until the displacement rate converges, while maintaining rigid matrix constant. When the displacement rate converges and the distortion state is calculated, state of contact of mold with solidifying shell is known. Heat transfer becomes low where a gap is developed and heat flux becomes smaller. Taking into account the smaller heat flux, solidification is recalculated and the abovementioned distortion analysis is repeated. This procedure is repeated until the temperature distribution and the shell distortion behavior converge ultimately.

2.2 Effect of narrow face mold taper shape on development of solidifying shell

While studying the effect of the taper shape of the narrow face mold on the development of the solidifying shell using the analysis model, solidification uniformity ratio was newly proposed as an assessment index. Extent of delay in solidification at a corner can be assessed, judging from the shape of a white band observed on a section perpendicular to the direction of casting, which is considered to be produced at the location wherein the discharge flow impinges on the narrow face mold and inverts. Solidification uniformity ratio is defined as the value of smallest shell thickness at the delayed solidification location in the neighborhood of a corner divided by the shell thickness at normal locations. Using this index, effect of the narrow

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Fig. 2 Comparison between single and multiple taper narrow face mold

face mold taper shape on the development of the solidifying shell was studied. It is generally known that the narrow face mold taper shape improves the state of contact of the cast slab with the mold, equalizing solidification by making the mold closely match the thermal shrinkage in width direction.

As shown in **Fig. 2**, a narrow face mold is used generally in an inclined state to match shrinkage and a mold with a single taper of a constant gradient from the top end to the bottom end (the narrow face mold on the right side in Fig. 2) is conventionally used. However, since the amount of the thermal shrinkage is larger in the initial stage of casting and becomes smaller in later stage, a multiple taper (the narrow face mold on the left side in Fig. 2) with larger taper on the upper stage has been proposed to provide better matching.⁶ As shown in Fig. 2, with the multi-tapered narrow face mold, the gap between the solidifying shell and the mold is considered to become smaller.

In order to verify the effect of the multi-tapered narrow face mold, casting under the following condition was analyzed using the developed numerical analysis model: casting speed of 1.5 m/min, cast slab width of 1 200 mm, and cast slab thickness of 250 mm. A 1/4 model of half of the width and the thickness, taking into account symmetricity was used. Mesh size was 5 mm in width and thickness, and in the shell thickness direction, thickness of 20 mm was divided into 20 elements. **Figure 3**(a) shows the solidifying shell thickness (in the upper figure) and the gap between the mold and the cast slab (in the lower figure) about the case of a single taper narrow face mold with a constant gradient. In the representation of the gap, the extend of contact force is represented by the color changing in the contact area of the mold with the cast slab. Since the gap is developed in the neighborhood of a corner, delayed solidification is occurs at the corner section of the wide face mold edge.

Figure 3 (b) shows the result of calculation in the case of the multi-tapered mold having a larger taper in the upper section and a smaller taper in the lower section. The gap at the corner section becomes smaller and shell uniformity ratio was improved. This is related to the phenomenon that thermal shrinkage rate along with the progress of solidification is larger at the upper section of the mold and smaller at the lower section of the mold. Since the gradient from top to bottom is constant for a single-tapered mold, the taper is insufficient in the initial stage of casting wherein shrinkage is large. Therefore, a gap is developed at a corner and solidification is delayed. In contrast, in case of a multiple taper mold, a sufficient taper provides shrinkage in the initial stage and the gap at the corner becomes smaller and the heat sink effect is improved.

Comparison of calculation and measured values of solidification uniformity ratio is shown in **Fig. 4**. An example of a measured value of shell thickness is shown in **Fig. 5**. Uniformity ratio is improved



Fig. 3 Calculated shell thickness and gap between shell and mold



Fig. 4 Comparison between calculated and measured uniformity ratio of the shell



Fig. 5 Measured shell thickness near the corner

both in calculation result and measured values by employing a multiple taper mold. It has been proved that the accuracy is sufficient for taper designing. The narrow face mold shape of the mold was optimized using the developed model and was applied to an actual machine.

3. Numerical Simulation of Secondary Cooling Spray Water Flow by Particle Method

In secondary cooling, cooling is conducted by a plurality of nozzle installed in between rolls in the width direction and uniform cooling in the width direction by a single nozzle was directed.⁷) However, there are no reports that have sufficiently analyzed in a quantitative manner the sprav water flow of the water that falls through the space opened for installing complicatedly laid-out split roll bearings and the water collected between a roll and the cast slab (collected water). Therefore, the cooling uniformity in the width direction is not sufficient. In recent years, in order to support the cast slab of thin solidification thickness from being cast at a higher speed, the pitch of rolls of a continuous casting machine has been made smaller. In accordance with this, another problem of larger roll deflection due to smaller roll diameter and deteriorated rigidity has emerged. Then, a long roll was separated to a plurality of short rolls in the width direction and the deflection of a roll has been lessened. However, installation of a plurality of bearings in the width direction became necessary and a phenomenon that casts slab cooling spraying water drops unevenly along and over such bearings emerged.

In order to analyze the effect of the flow on uneven solidification, it is important to grasp the flow of the spray water in a quantitative manner. Although flow analysis is effective, the conventional method using a mesh cannot comply with the flow of complicated free moving surfaces and application of a meshless particle method⁸⁾ was considered. Using the flow of spray water obtained by the analysis, the heat transfer coefficient between cooling water and the cast slab was measured under various conditions. Solidification analysis of the cast slab was conducted by inputting the measured heat coefficients to boundary conditions. In the conventional solidification analysis,9,10) one-dimensional calculation at the center in the width direction of a cast slab and/or two-dimensional analysis on a cross section perpendicular to the direction of casting are generally conducted; however, analysis that takes into account the unevenness in the width direction was not conducted sufficiently in a quantitative manner. Therefore, a model was developed that can take into account the effects of spray, each roll, location of a bearing, dropping water, and collected water. The cause of development of uneven cooling in the width direction was studied using the model.

3.1 Actual state of cast slab temperature unevenness

Figure 6 shows an example of cast slab surface temperature within a strand of a general vertical bending type slab continuous machine measured by a radiation thermometer. The surface temperature was measured by a width-direction-scanning type radiation



Fig. 6 Comparison between the measured and the calculated surface temperatures at 18 m below the meniscus

thermometer installed at 18 m downstream from the meniscus under the condition of constant casting speed of 1.0 m/min for the slab of 300 mm × 2200 mm in size. The secondary cooling zone of a continuous casting machine is generally composed of segments each of which consists of a plurality of roll, and the surface of a cast slab can only be observed in between the segments. Since roll pitch is small, measurement was conducted above the upstream location of the unbending segment wherein a relatively large spacing is provided for the ease of extracting a segment for maintenance work. A scanning type monochromatic radiation thermometer (measurement wave length: 1.0 μ m) was used.

As shown in Fig. 6, it was found that the temperature at the center of the width is lower by more than 100°C as compared to edge section. The following two causes have been considered as the cause of such unevenness in the width direction. The first is the effect of reducing the water flow rate at the edge position in the secondary cooling to prevent over cooling at the edge,¹¹⁾ and the second is the effect of the flow of the molten steel in the mold. However, the conventional way of thinking has failed to explain the reason of the extreme temperature drop in such an example. Therefore, to seek for a cause of uneven cooling, effect of arrangement of split roll bearings and flow of water that flows thereon was studied.

3.2 Formularization of water flow model

In order to analyze spray water flow by calculation, the particle method (MPS)^{12,13)} was applied and analysis was conducted using the all-purpose particle method fluid analysis software "Particleworks"14) with addition of a function. The particle method was employed because with generally applied method, such as finite difference method or finite volumetric method using a calculation mesh in a space, sufficient analysis cannot be conducted for flow analysis as spray water flow consists of mainly free-moving surfaces. The particle method is one of the meshless methods and division of a calculation space to mesh is unnecessary. Therefore, it is excellent in representing free-moving surfaces. The applied MPS method is a method that uses particles in a continuum as calculation points for solutions. To solve the formula of continuity and Navier-Stokes formula (Formula (2)), which are also calculated in finite volumetric method, the gradient term is discretized using the interparticle interaction model, as shown in Fig. 7.

$$\frac{D\rho}{Dt} = 0, \quad \frac{Du}{Dt} = -\frac{1}{\rho} \nabla p + v \nabla^2 u + f$$
(2)

where *u*: flow speed, *p*: pressure, ρ : density, *v*: dynamic viscosity coefficient, *f*: external force (gravity), and *t* : time.

Figure 7 shows the discretization of gradient vector of physical quantity ϕ at the position of a particle *i*. Where *r*: the position of a particle, *d*: number of dimension of space, n^0 : particle density, *w*: weight-related function, set so as to exert less effect as interparticle distance becomes larger, and <> is a symbol that denotes the identity of the interparticle interaction model.

In the calculation, for formularization of the model, particle diameter of 3 mm, 30° of contact of angle of water with roll-slab, and oval nozzle spray pattern were assumed.¹⁵



Fig. 7 MPS method and formulation of gradient Φ

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A typical bearing arrangement within a strand was taken up and three rows of rolls and two rows of spray zone in between were also taken up for forming the model for analysis. **Figure 8** shows the model. The upper spray consists of eight nozzles and the lower spray consists of seven nozzles and they are arranged in a staggered manner with respect to casting direction. There are three separated rolls and two intermediate bearings installed in the center position of width. Distance between the spray nozzle and the slab is 155 mm and the spray angle of a nozzle was 100° in width direction and 30° in casting direction.

3.3 Spray water flow analysis by particle method and verification by actual measurement

Figure 9 shows the result of analysis based on the model shown in Fig. 8. It is a view from the slab side at five minutes after the start of spray.

Figure 9 shows the result with the spray of water flow rate of 20 L/min per spray nozzle and it was found that the cooling water sprayed to the cast slab drops unevenly via over the bearings and the water is collected on the upper side of the downstream rolls, overflowing backward. The accuracy of the model was confirmed by a water model. In the water model, pipes made of acrylic resin were pressed onto an acrylic plate simulating a slab, and water was sprayed from nozzles laid in between pipes. An example of the view of the result of the experiment is shown in **Fig. 10**. Flow rate of a nozzle was 20 L/min, which is same with that of the calculation shown in Fig. 9.

It was found that flow of spray water dropping via over a bearing and the flow of water collected over the roll are represented well by calculation. In order to assess the analysis result more quantitatively, calculation and experiment results of the quantity of the water flowing out at bearing section and slab edge were compared. The result is shown in **Fig. 11**.

In regions 1–8 defined in Fig. 8, water flow rates obtained by calculation and measurement quantitatively show good agreement. Three graphs show each result in cases wherein the water flow rates from a spray nozzle were 5 L/min, 10 L/min and 20 L/min. In regions 6 and 7, the difference between the calculated value and the measured value in water flow rate appears on the high water flow



Fig. 8 Simulation model for spray water flow between rolls (unit: mm)



Fig. 9 Calculated spray water flow (view from slab side)

rate side; since the diameter of the acrylic pipe is slightly different from the diameter of the pipe used in the calculation, amount of water collected on a roll became different, causing difference in the amount of water overflowing outside the system.

Based on the analysis, it was found that the amount of water collected on the middle separated roll of the whole split rolls is large, the water collected on the roll drops at the bearing position, and the



Fig. 10 Measured spray water flow from the water model (view from slab side)



Fig. 11 Comparison between the calculated and the measured water flow rates (a) Water flow rate of each nozzle is 5L/min, (b) 10L/min, (c) 20L/min

flow of cooling water causes over cooling in the neighborhood of the slab center in the width direction. Therefore, solidification analysis needs to be conducted taking into account the spray water flow. **3.4 Assessment of uneven temperature distribution in width direc**-

tion with solidification calculation in secondary cooling zone

In order to grasp the solidification condition in the secondary cooling zone, solidification calculation taking into account the abovementioned dropping water and the like is necessary. Experiment for measuring heat transfer coefficient in spray cooling was conducted ¹⁶) by heating a steel plate installed with a plurality of thermocouple and simulating the state of dropping water and collected water. **Figure 12** shows an image of an experiment for measuring heat transfer coefficient. A steel plate heated up to 900°C in an atmosphere-controlled furnace was cooled by a single spray nozzle immediately after being extracted from the furnace and the heat transfer coefficient was sought for by inversely analyzing the measured temperature.¹⁷

Experiments were conducted for various spray nozzle water flow rates and steel plate temperatures and the heat transfer coefficient was arranged as a function relative to spray water flow density on the surface of the plate, steel surface temperature, and spray impinging pressure.

Effect of dropping water on heat transfer coefficient was measured by providing water flow from above the spray simulating dropping water over a bearing. Flow rate of dropping water was decided by referring to the water flow rate obtained by the result of the particle method (Fig. 11). The effect of the collected water was studied in a cooling experiment wherein a plate simulating a roll made contact with the plate. Water that was simply collected and stayed on the roller does not exert big cooling effect; however, it was found that when collected water interfered with sprayed water, cooling was promoted in the interference region as the water was stirred. As heat coefficients of a spray nozzle itself, dropping water, collected water, interference region, and so on could be measured from these experiments; they were used as boundary conditions of solidification calculation within a strand. The boundary condition of heat transfer was divided to four regions in between rolls (**Fig. 13**).

I is the roll cooling region, II is the air cooling or cooling by dropping water region, III is the spray cooling region, and IV shows the collected water cooling or cooling region by spray dropping water. As for the slab width direction, the heat transfer coefficient, provided to the region wherein dropping water interferes with spray water (II), was 1.1 times higher than the value of the case of dropping water only. Similarly, heat transfer coefficient 1.5 times higher than the value of the case of collected water only was provided to the region wherein collected water interfered with spray water (IV). These magnification rates of coefficients were calculated from the result of the aforementioned heat transfer coefficient measurement experiment wherein dropping water and collected water were taken



Fig. 12 Experimental image (water is sprayed on the heated steel plate)

into account.

As a result, overcooling at the center of the slab width was found and uneven distribution of solidification in the width direction was proved (**Fig. 14**). Figures 14(a), 14(b), and 14(c) show surface temperature, heat transfer coefficient, and solid faction at the center of the slab thickness respectively. Heat transfer coefficient in Fig. 14(b) measured at the position apart from the meniscus by 5 m is higher in the neighborhood of the center of the width due to the aforementioned interference of collected water with sprayed water. With this effect, surface temperature at the position apart by 5 m from the meniscus becomes lower, and from the center solid fraction distribution in Fig. 14(c), it is found that at width center portion, solidification is completed earlier than at a near edge portion.

Figure 6 shows the comparison of results of surface temperatures calculated and measured by the aforementioned radiation thermometer. The trend of temperature at the width center was lower by more than 100°C as compared to the temperature at the near edge portion. Cause of overcooling at the width center is considered to be attributed to spray dropping water being collected on the center split roll, interfering with spray water and thereby increasing the heat transfer coefficient.



Fig. 13 Boundary conditions for the simulation model of solidification



Fig. 14 Calculated results of solidification (a) Surface temperature, (b) Heat transfer coefficients, (c) Solid fraction at the center of the slab in thickness

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4. Conclusion

- A 3D model that analyses the solidifying shell distortion behavior in a continuous casting mold was developed and the effect of the mold narrow face taper on the development of shell was quantitatively assessed. It was found that a gap is developed between the solidifying shell and the mold in the neighborhood of a corner and a delay in solidification takes place when a single taper narrow face mold is used. It was found that by employing a multiple taper (larger taper on upper section), the gap at the corner decreased, and solidification becomes uniform. Measured values of solidification uniformity ratio show good agreement with the quantitatively calculated values and the accuracy of analysis was confirmed. By using the model, narrow face mold shape design was optimized and applied to an actual machine.
- In order to research the cause of the phenomenon of uneven solidification in the cast slab width direction developed in secondary cooling in continuous casting, flow of spray water within a strand was numerically analyzed by the particle method. With the analysis of spray water flow with particle method, states of spray dropping water over bearings and spray water being collected on a roll were clarified. An experiment measuring heat transfer coefficients by simulating the interference of dropping water and collected water made clear by the flow analysis was conducted. From the result of solidification calculation using measured heat transfer coefficients, it was found that dropping water over the bearing in the secondary cooling within a strand and collected water on a roll effected in the un-

evenness of solidifying shell in width direction. The temperature distribution in width direction obtained by the analysis showed good agreement with the values measured with a radiation thermometer. The extreme drop in temperature at the center of the width is considered to be influenced by over cooling by interference of collected water on the middle part of a roll with spray water.

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