Relationship between Flow Characteristics and Surface Quality in Inclined Twin Roll Strip Casting

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Good surface quality is essential for the twin roll cast stainless steel strip to be directly cold-rolled. Thus, surface quality of AISI 304 stainless steel is one of the main problems for the twin roll strip casting process to be put into commercial production. The surface defects commonly appeared in the as-cast strip of twin roll process may include longitudinal and transverse cracks or wrinkles as well as unevenness which is mainly caused by gas trapping and surface vibration of meniscus between the two rolls.

In this study, a modeling software was applied to simulate the flow behavior of molten pool at quasi-steady state in inclined twin roll casting and to investigate the relationship between flow characteristics and surface quality of the produced thin strip. The flow characteristics was drawn from the calculated flow patterns and then correlated to the surface quality of thin strips produced in an experimental caster under the same casting condition as the calculations. Through this procedures, several correlations were then found. First, the surface wrinkles appeared on the thin strip when the pool levels were low. The problem was improved with a higher pool level due to less flow violence nor meniscus fluctuation. Second, the recirculation with a large vortex occurring around the triple intersection point of the roll/melt/air three phases was the main cause for the slag and/or dross trapping. Third, by using a higher roll angle along with an inclined feeding position nearer to the lower roll, a much stable flow on the meniscus surface could be obtained.

KEY WORDS: twin roll; strip casting; stainless steel; surface quality.

1. Introduction

The twin roll strip casting has been proven to be a feasible process to produce thin strips directly from molten metal. The process has the benefits of significant shortening of the production steps, enormous savings in energy, and elimination of segregation in the strip when compared to the conventional continuous casting by combining both casting and hot rolling into one operation.^{1,2)} Due to its great merits in both economic and metallurgical aspects, many activities have been conducted worldwide to develop this near net shape casting process for flat steel products. However, in spite of the considerable progress has been made in the process development and many problems already encountered in the process such as flow control, side-dam refractory, inclusion and heat crown have been gradually overcome, the surface quality and thickness deviation of cast strip still remain as the most serious impediments for the process to be put into commercialization in steel industry.³⁾ Basically, the profile and surface quality of the as-cast thin steel strips must meet the standard requirements of the current flat-rolled product. Otherwise, an additional post treatment of the as-cast steel strip such as edge-trimming and descaling will counter-

balance the merits of this process and lose its economic advantage. Thus, obtaining good surface quality of cast strips becomes the essential issue to commercialization.

Regarding the surface quality of as-cast strips, Mohri *et al.* categorized all the surface defects into five types. They include two types of longitudinal cracks/wrinkles and three types of transverse cracks/wrinkles.⁴⁾ Among these defects, type 2 one where longitudinal cracks or wrinkles occur in the center part of strip is caused by the entrapment of slag/oxides; and type 5 one where transverse cracks/wrinkles occur randomly and especially in the initial stage is caused by the fluctuation of melt surface. It suggests that these two surface defects may be related to the flow behaviors and the surface vibration in molten pool between the two rolls. To verify this hypothesis, Ohnaka *et al.* designed a mold horizontally moving across a melt to investigate the relationship between gas trapping and surface wrinkles.⁵⁾ It has been concluded that gas trapping is caused by the deformation resistance of meniscus fluctuation and the surface wrinkles or grooves are attributed to this gas trapping. This is verified by examining the places where gas is trapped would remain as the location of surface wrinkle when solidification occurs. Further, the contact region between the melt and the roll, especially at the roll/melt/

air three-phase intersection area, should be kept clean to produce strips with good surface. Miyazawa *et al.* also pointed out that the formation mechanism for surface wrinkles is due to locally delayed solidification which is caused by oxide film, gas foam or meniscus fluctuation at the roll/melt interface.⁶⁾ Yasunaka *et al.* conducted a water model experiment to investigate the effects of pouring conditions on meniscus level fluctuation and further extended to the surface quality of cast strip of AISI 304 stainless steel.⁷⁾ They obtained the achievements of uniform feeding rate along the width of the strip and small fluctuation of meniscus level by optimizing the pouring position, the ratio of molten steel weight on the two rolls to the pouring rate and the fall height of molten steel from a tundish to the two rolls in casting process. From these literature reports, it is obvious that the control of both flow behaviors and surface vibration in the melt pool has significant influence on the surface quality of strip casting.

In this study, an inclined twin roll caster of laboratory scale was used to produce thin strips of AISI 304 stainless steel and to investigate the correlation between the process parameters and surface quality of the strip. Also, a software, called ProCAST,⁸⁾ was used to simulate the flow pattern inside the molten pool between the two rolls under various casting conditions. ProCAST is basically a finite element code with the benefit of directly solving the equations for the solution domain containing the free surface. It is different from those methods which adopt body-fitted curvilinear coordinate system⁹⁻¹¹⁾ or boundary fixing scheme¹²⁾ to treat wedge-shaped pool and moving boundary where the meniscus is always assumed to be flat. The casting conditions including flow rate, casting speed, pool level, feeding position, as well as the inclined angle of the rolls were investigated in this study. Flow characteristics were carefully examined for various casting conditions where the correlated surface defects such as wrinkles, trapped dross/slag on the cast strips were inspected. Then the relationships between the flow characteristics and the surface quality of the produced strips were further established.

2. Description of the Physical Problem and Its Mathematical Model

2.1. Description of the Inclined Twin Roll Casting Method

Twin roll method for continuous casting was first conceived by Sir Herry Bessemer in 1846.¹³⁾ The process, in which the molten metal is top fed into the roll gap, has been recognized as a feasible method to directly produce strips. The process development up to now has generated several possible combinations for the twin roll method, depending on the alignments of the two rolls and the pouring method. They include 1) twin roll with equal diameter and top feeding, 2) inclined twin roll with inclined feeding, 3) unequal twin roll and inner-ring twin roll with pool feeding or overflow.³⁾ Detailed descriptions of these processes can be found in many reports.¹⁴⁻¹⁷⁾

Fig. 1. A schematic diagram of the inclined twin-roll caster used in this study.

A simple schematic diagram of the laboratory scale inclined twin roll caster used in this study is shown in Fig. 1. The inclined roll angle can be changed from 0° to 90°. The two rolls are the same size in dimension and made from a chromium-copper alloy. They are 400 mm in diameter and 300 mm in width. The basic idea of the inclined twin roll method is to obtain a steady flow at the roll tip by pouring the melt on the roll surface from one side of the caster, then the surface quality of the strip can be improved by a stabilized melt pool. When cast the strip, the molten metal is poured from a ladle to a tundish and overflow through an inclined nozzle into the wedge-shaped space between the two opposite-rotating and internally water-cooled copper rolls. The flow rate of molten metal is controlled by maintaining a constant molten metal head in the tundish, which can be achieved by connecting a level detector or a load cell to a personal computer with a data-acquisition system.

Unlike a vertical twin roll casting method with top feeding, the inclined twin roll is poured by inclined feeding so that the fluid flow and solidification characteristics are not symmetrical with respect to the center line of the caster. The inlet melt flow would first get in contact with the outer surface of either the lower roll or the upper roll, depending on the feeding position, feeding angle, and flow rate. Once the liquid metal contacts with the rotating rolls, a thin solidified shell is formed on the surface of each roll. The shells gradually grow in thickness, finally contact with each other and weld together at some position slightly above the roll tip (closest position between two rolls). The dummy sheet which is first suspended between the two rolls before casting is then pulled out and a continuous solidified strip subsequently follows. As the casting proceeds steadily, a quasi-steady state is reached where the inlet melt flow rate balances with the outlet speed of strip, and the melt between the rolls reaches a steady state.

2.2. Governing Differential Equations

Because the width of the plate-type nozzle almost equals to that of the rolls and the edge effect of the strip can be further neglected as employing heated side-dams, the mathematical consideration of the casting system can be reduced to a two-dimensional problem. To simplify

the mathematical model, some assumptions are developed:

- (1) The liquid steel is a Newtonian fluid.
- (2) There is no turbulence in the molten pool.
- (3) The effect of solidified strip on the fluid flow within the melt pool is neglected because the solidified strip almost moving with the same speed as the rotating roll.
- (4) The thermal physical properties of the melts such as density, viscosity and surface tension are constant during casting.

Based on the assumptions above, the governing differential equations describing the fluid flow behavior between the two rolls can be represented as follows:

- (1) Conservation of Mass

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad \text{.....(1)}$$

- (2) Conservation of Momentum (in x and y directions)

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{\partial p}{\partial x} + \nu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) + g \cdot \sin \theta \quad \text{.....(2)}$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -\frac{\partial p}{\partial y} + \nu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + g \cdot \cos \theta \quad \text{.....(3)}$$

where, u, v : velocity components in x and y direction; t : time; p : dynamic pressure; g : gravitational acceleration constant; ρ : density; ν : dynamic viscosity; θ : inclined angle of the two rolls.

- (3) Mass Transportation in the Melt Pool

For the twin roll casting process, the melt pool condition between the two rolls may vary with respect to different casting parameters. Certain schemes must be employed to represent the domain of the melt pool. It can be done quite efficiently by using a volume function, F . In this study, a VOF scheme⁽¹⁸⁾ is employed which use F to represent the melt pool domain and to track its evolution. The equation for the conservation of volume function can be written as

$$\frac{\partial F}{\partial t} + u \frac{\partial F}{\partial x} + v \frac{\partial F}{\partial y} = 0 \quad \text{.....(4)}$$

where F is the volume fraction as a step function whose value is between 0 and 1. The value of F in each element can be solved employing a donor-acceptor method⁽¹⁹⁾ after the velocity fields in the solution domain are calculated.

2.3. Initial and Boundary Conditions

2.3.1. Initial Conditions

The initial pool level in the beginning of the analysis (*i.e.* $t=0$), may be zero or an assigned value. The initial velocity of the fluid is set to zero ($u=0$ and $v=0$) in the solution domain.

2.3.2. Boundary Conditions

The boundary conditions of the solution domain are described as follows:

- (1) The inflow velocities at the exit of the nozzle are

$$\begin{aligned} u &= -u \cdot \cos \beta \\ v &= -u \cdot \sin \beta \end{aligned} \quad \text{.....(5)}$$

where β is the angle of inclined feeding at nozzle exit as shown in Fig. 1 and u is the absolute value of inflow velocity as indicated in Fig. 1.

- (2) The outflow conditions at the roll tip are

$$u=0; \quad v=-V_{\text{roll}} \cdot f(t); \quad p=0 \quad \text{.....(6)}$$

where $V_{\text{roll}} = r \cdot \omega$ is the linear velocity of roll (*i.e.* casting speed); r is the radius of the roll; ω is the rotating speed; $f(t)$ is a step function, where $f(t)=0$ when dummy sheet is suspended between rolls and $f(t)=1$ after it is withdrawn.

- (3) The interfacial velocities on the two outer surfaces of rolls are

$$\begin{aligned} u_i &= -V_{\text{roll}} \cdot \sin \alpha; & v_i &= -V_{\text{roll}} \cdot \cos \alpha & (\text{for the lower roll}) \\ u_i &= V_{\text{roll}} \cdot \sin \alpha; & v_i &= -V_{\text{roll}} \cdot \cos \alpha & (\text{for the upper roll}) \end{aligned} \quad \text{.....(7)}$$

where i : nodal number; α : angle of nodal position or contact arc angle (as shown in Fig. 1).

- (4) At free surface of melt front and meniscus between the two rolls:

For cells containing a free surface, that is, cells that contain fluid but have one or more empty neighbors, the following stress conditions have to be satisfied.

$$\mu \left[2n_x n_y \frac{\partial u}{\partial x} + (n_y^2 - n_x^2) \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) - 2n_x n_y \frac{\partial v}{\partial y} \right] = 0 \quad \text{... (8)}$$

$$p_s = p_a + 2\mu \left[n_x^2 \frac{\partial u}{\partial x} + n_x n_y \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) + n_y^2 \frac{\partial v}{\partial y} \right] \quad \text{.....(9)}$$

where p_s is the surface pressure; p_a is the atmospheric pressure; n_x and n_y are components of the unit normal to the surface. In the case of VOF (Volume of Fluid) method, the calculation of surface pressure (p_s) is following:

$$p_s = -\sigma \left(\frac{1}{R_{xy}} \right) \quad \text{.....(10)}$$

R_{xy} is the principal radius of curvature in x - y plane and σ is the surface tension of fluid.

3. Results and Discussion

In this study, both the mathematical modeling and the physical experiment were conducted simultaneously. The laboratory scale inclined twin roll caster was used to produce the strips under various casting conditions. The casting conditions include different pool level, feeding position, and inclined angle of rolls. The apparatus specifications and operating conditions under investigation are listed in **Table 1**. The surface quality of the strips was examined carefully. Those casting conditions where surface defects such as wrinkles and trapped dross/slag were found were specially marked.

For the mathematical modeling part, a software named ProCAST which has the capability to treat free

Table 1. Experimental conditions and apparatus specifications.

Casting material	SUS 304
Roll size	400 ϕ $\times$ 300 w mm
Roll angle	0–30 $^\circ$
Roll gap	2 mm
Roll material	1%Cr–Cu
Strip width	300 mm
Gap of nozzle tip	2–3 mm
Casting speed	12–24 m/min
Meniscus height	70–150 mm
Pouring temperature	1 733–1 773 K

Table 2. Principal physical properties used for the calculation.

Materials	SUS 304
Thermal conductivity (W/m $\cdot$ K)	20.0(l)
Specific heat (kJ/kg $\cdot$ K)	0.67(l)
Density (kg/m 3)	7 400(l)
Latent heat (kJ/kg)	270
Liquidus temperature (K)	1 713
Solidus temperature (K)	1 673
Viscosity (Pa $\cdot$ s)	0.0051
Surface tension (N/m)	1.5

(l): liquid state

Fig. 2. The full finite element model of the solution domain (Nos. 1, 2 and 3 represent the different feeding positions of nozzle tip).

surface flow and moving boundary problems was used to simulate the flow pattern in the melt pool between rolls. The flow pattern simulation is basically to solve the continuity and momentum equations; Eqs. (1) to (4), along with the assigned boundary conditions in Eqs. (5) to (10). The solution algorithm is basically transient and the quasi-steady state is considered to be reached a the flow pattern inside the melt pool does not change with time. **Figure 2** shows the full finite element model which totally includes 8 070 triangle elements and 4 240 nodes. The elements have various sizes of approximately 0.5, 0.8, 1.0, 1.2 and 1.5 mm respectively, depending on the mesh position. The material properties used for the numerical calculation are listed in **Table 2**, which are assumed to be constant throughout the flow analysis. The flow characteristics were carefully examined for those casting conditions where surface defects were found.

The results of the physical experiments and the mathematical modeling works for various casting conditions are discussed in the following sections. Correlations between the flow characteristics and the surface quality of the strips are also discussed.

3.1. The Effect of Pool Level

The stability of molten pool level is known as a major factor to obtain good surface quality of cast strips since the flow behaviors and solidification characteristics are closely related to the condition of molten pool. It is also found that improper control of the pool level will result in many defects as surface cracks, transverse surface wrinkles and thickness deviation *etc.* The effect of molten pool level on strip quality has been examined in this experimental work. **Figure 3** shows the appearances of cast strips with two different pool levels of 10 and 13 cm. The outlet of nozzle tip is located at the feeding position 2 as shown in Fig. 2. For the lower pool level, 10 cm, under the casting conditions of inflow velocity $u=0.4$ m/s, rotating speed of rollers $\omega=12$ rpm, pouring temperature $T_p=1\,753$ K, inclined angle of rolls $\theta=10^\circ$ and inflow angle $\beta=60^\circ$, many obvious transverse wrinkles are observed on the bottom surface of cast strips as shown in Fig. 3(a). It should be noted that the surface wrinkles are generally recognized as a depression of strip surface and leads to thickness deviation and irregular profile of cast strips as shown in the later figure. Whereas, for a higher pool level, 13 cm, under the casting conditions of $u=0.6$ m/s, $\omega=17$ rpm, $T_p=1\,753$ K, $\theta=10^\circ$ and $\beta=60^\circ$, a flat surface on the bottom of cast strips is obtained, as displayed in Fig. 3(b). In essence, the higher the pool level is, the better the surface quality obtained from this experimental trials is. **Figure 4** shows the thickness deviations of cast strips with the above two pool levels. For the lower one, the standard deviation of the cast strip thickness is about 15 %, and for the higher one, it is only 8 %, much less than the previous one. This means the appearance of strip surface directly correlates the thickness deviation of cast strips. The corresponding heights of pool levels in the above two casting experiments could be directly measured from the post-cast side-dams as shown in **Fig. 5**. The measured heights of pool level on the lower roll side are about 10 and 13 cm, respectively. The contact arc length at melt/lower roll interface is also revealed somewhat longer than the one at melt/upper roll interface in the same figure.

In order to study the effect of pool level on the strip

quality such as the appearance of surface wrinkle, both the flow patterns and surface vibrations of meniscus at various heights of molten pools were simulated by using the modeling system mentioned above. **Figure 6(a)** is the

Fig. 3. The appearances of cast strips on bottom surface at different pool levels with the casting conditions of (a) $u=0.4$ m/s, $\omega=12$ rpm, $T_p=1753$ K, $\theta=10^\circ$ and $\beta=60^\circ$, where pool level=10 cm, and (b) $u=0.6$ m/s, $\omega=17$ rpm, $T_p=1753$ K, $\theta=10^\circ$ and $\beta=60^\circ$, where pool level=13 cm (both at feeding position 2 as indicated in Fig. 2).

predicted flow patterns at quasi-steady state under the same operating conditions as in Fig. 3(a). The falling melt stream could directly hit the meniscus in the vicinity of the lower roll when it is fed into the wedge-shaped pool and then moves with the rotating roll. Because of the greater fall height, the inflow velocity of molten steel has been accelerated by gravity effect from 0.4 m/s at the feeding position 2 of Fig. 2 to about 1.2 m/s as it reaches the meniscus. This direct impingement of melt stream on the lower roll with such a great fall height and velocity due to its low pool level, tends to cause a violent fluctuation and unstable flow on the meniscus. Such a flow phenomenon would easily result in gas entrapment and form a thermal resistance layer on the melt/roll interface when solidification occurs. It is well known that vibration of the meniscus contacting with roll surface brings the variation of strip thickness, surface wrinkles and uneven solidification structure.⁶⁾ Therefore, the surface wrinkle formed on the bottom surface of cast strips with the low pool level as shown in Fig. 3(a) is mainly attributed to the violent vibration of meniscus and great surface velocity for the relatively large fall height. Furthermore, the incoming stream of molten stainless steel penetrates into the melt pool and forms a recirculation

Fig. 4. The thickness deviation of cast strips with two different pool level, 10 and 13 cm, respectively.

Fig. 5. The corresponding pool levels in the case of Fig. 3 as measured from the used side-dams, (a) pool level = 10 cm, and (b) pool level = 13 cm.

Fig. 6. The calculated flow patterns under different pool levels with the same conditions as in Figs. 3(a) and 3(b), respectively, (a) pool level = 9.6 cm, and (b) pool level = 12.8 cm.

inside the melt pool as shown in Fig. 6(a).

For the higher pool level with the same casting condition as in the case of Fig. 3(b), the computed flow pattern and the free surface condition is illustrated in Fig. 6(b). From this figure, the teeming of melt stream introduces a forced convection and generates two large opposite-rotating recirculation zones within the wedge-shaped pool after the melt stream penetrates into the pool. Besides, a clockwise vortex is formed around the meniscus/lower roll interface by the rotation of roll. However, the intensity of this vortex is not very strong, only slight amount of gas entrapment is expected to occur. And since the fall height of the melt is much less, the surface condition of the meniscus is smoother compared to that in Fig. 6(a). Thus, the apparent surface wrinkles on the bottom surface can be avoided and a relatively smooth and flat surface can be obtained. The above discussions indicate the successful explanation of the surface wrinkle forming on the bottom surface with a lower pool level, and none with a higher one by the predictions of flow patterns in different melt pools. In addition, the surface profiles of meniscus in various melt pool levels obtained from numerical flow analysis are in good agreement with the experimental trials shown in Fig. 5. The contact arc length on the lower roll/melt interface is also somewhat longer than that at upper roll/melt interface due to the inclination of the rolls.

3.2. The Effect of Feeding Position of Nozzle Tip

To study the effect of feeding position of nozzle tip on the surface quality of strip, three various positions of nozzle tip have been examined, which are 10, 30 and 58.2 mm horizontally away from the lower roll, respec-

tively, as shown in Fig. 2. Among these feeding positions, the calculated flow pattern and appearance of strip in the case of feeding position 2 have been shown in the previous section and the other two cases are discussed in the followings. Figure 7 shows both surface appearances of cast strip at feeding position 1 with the same operating conditions as the case in Fig. 3(b). It has some slag/dross randomly distributed on the top surface along the central part of the as-cast strip as well as some surface wrinkles developed on the bottom surface of the strip. However, in the case of feeding position 3, the slag/dross appears on the bottom surface instead of top surface of cast strips and a flat surface is obtained on the top surface as shown in Fig. 8. The appearance of strip surfaces is just the opposite of the case of feeding position 1. Thus, the feeding position of nozzle tip has a great influence on the strip quality.

The reason to cause such a discrepancy on the strip quality is suggested due to the variation of flow behaviors in the melt pool under various feeding positions. Figure 9 displays the calculated flow patterns and surface fluctuations at the quasi-steady state under the same casting conditions as the previous case except different feeding positions. As shown in Fig. 9(a), the feeding position 1 is only 10 mm horizontally away from the lower roll, so that the falling stream of melt tends to impact on the surface of the lower roll directly as it is fed into molten pool. The melt penetrates into the molten pool along the surface of rotating roll and forms a great clockwise recirculation driven by the forced convection. Meanwhile, another counter-clockwise recirculation is also constructed near the intersection of meniscus and upper roll. This strong circulating flow moves in the same direction as the rotating upper roll

at the triple point of upper roll/melt/air intersection. Therefore, it easily results in trapping of slag or dross. This explains the appearance of slag/dross on the top

surface of the cast strips at the feeding position 1 in the experiment.

The computed flow pattern at feeding position 3 where

Fig. 7. The appearances of cast strips on both surfaces at feeding position 1 under the casting conditions of $u=0.6$ m/s, $\omega=17$ rpm, $T_p=1753$ K, $\theta=10^\circ$ and $\beta=60^\circ$, where pool level=13 cm, (a) on top surface, and (b) on bottom surface.

Fig. 8. The appearances of cast strips on both surfaces at feeding position 3 with the other casting conditions same as in Fig. 7, (a) on top surface, and (b) on bottom surface.

Fig. 9. The calculated flow patterns under different feeding positions with the same casting conditions as in Figs. 7 and 8, respectively, (a) at feeding position 1, and (b) at feeding position 3.

the nozzle tip is located at the center between two rolls or 58.2 mm away from the lower roll is shown in Fig. 9(b). Owing to the inclined feeding, the inflow stream tends to impact on the surface of upper roll after the melt stream penetrates into the molten pool. Part of the melt flows upward against with the moving direction of the upper roll, and the others flow back to form a big recirculation in counter-clockwise direction in the middle part of molten pool. In addition, a large recirculation is also induced in clockwise direction at the triple intersection point of air/lower roll/melt three phases due to the motion of the rotating lower roll. This recirculation which moves in the same direction as the rotating lower roll tends to trap slag/dross from the meniscus and the slag/dross is stuck on the bottom surface of the strip as shown in Fig. 8(b).

From the calculated flow patterns, a pronounced recirculation phenomenon is always formed near the triple intersection points of upper roll/melt/air or lower roll/melt/air three phases, even if the feeding position is changed. With the difficulty to completely remove the recirculation at the triple points as well as slag/dross on the meniscus, it is strongly suggested that a protective atmosphere on the top of molten pool, even in the tundish, is necessary during casting process to eliminate the formation of slag/dross on the strip surface.

3.3. The Effect of Inclined Angle of Rolls

Two inclined angles of rolls, 10 and 30°, are examined in this study. The calculated flow pattern in the molten pool at $\theta=10^\circ$ and the corresponded surface quality of cast strips obtained from the experiments have been discussed in the previous section. The calculated flow

pattern and appearances of cast strips with a higher inclined angle of $\theta=30^\circ$ are presented here. **Figure 10** displays the calculated flow pattern with inclined angle of $\theta=30^\circ$ under the other casting conditions same as in Fig. 9(a). In the start-up filling stage of molten pool at 1.0 sec after pouring, the feeding melt stream touches the lower roll firstly as it is fed into the wedge-shaped cavity between the two rolls, and then moves along with the surface of rotating lower roll. It results in a long contact arc length between melt and lower roll as shown in Fig. 10(a). This melt flow forms a strong clockwise recirculation as it is poured into the molten pool. The calculated flow pattern for quasi-steady state is shown in Fig. 10(b). A recirculation zone is generated in the deep center region of molten pool and a small vortex is occurred beneath the meniscus near the lower roll. However, the flow velocity of melt near free surface is rather small that no significant recirculating flow is formed near the triple intersection point of upper roll/melt/air. Therefore, it is predicted that less slag/dross tends to be trapped into the molten pool by judging from the calculated flow pattern. Employing this inclined feeding angle ($\beta=60^\circ$) and inclined roll angle ($\theta=30^\circ$), the melt seems to be a relatively stable flow around the intersection area of meniscus and upper roll than the case of $\theta=10^\circ$ in Fig. (9). However, the drawback of this case is the great difference between contact arc lengths (or contact arc angle, α) of the upper roll and lower roll. As shown in Fig. 10(b), the contact arc lengths on the upper and lower roll are around 9.3 cm ($\alpha=26^\circ$) and 13.5 cm ($\alpha=40^\circ$), respectively. It is well known that the size of dendritic zone in cast strips is exponentially proportional to the contact arc length, i.e. $d=kt_c^n$ (d : the

Fig. 10. The calculated flow patterns with a higher inclined roll angle of $\theta=30^\circ$ under the casting conditions of $u=0.6$ m/s, $\omega=17$ rpm, $T_p=1753$ K and $\beta=60^\circ$ (at feeding position 1), (a) at filling time of 1.0 sec after pouring, and (b) at quasi-steady state.

Fig. 11. The appearances of cast strip on both surfaces at a higher inclined roll angle of $\theta=30^\circ$ with the same casting conditions as in Fig. 10, (a) on top surface, and (b) on bottom surface.

thickness of columnar zone, k : solidification constant, t_c : contact time and n : exponential constant).²⁰⁾ Therefore, the columnar dendritic zone of solidification structure grown from the lower free surface will be much greater than that grown from the upper free surface, and it may cause some serious problems in further cold working deformation and unsatisfactory mechanical properties.

The appearances of the cast strip on both surfaces with the high inclined roll angle $\theta=30^\circ$ from the corresponding experiment of Fig. 10 is displayed in Fig. 11. No slag/dross is trapped or stuck on both free surfaces of strip except a few ripple marks are observed on the bottom surface of the cast strip. Comparing to Fig. 7, the surface quality on the top surface of the cast strips is much improved by using a high inclined angle of rolls. Figure 12 shows the microstructure of cast strips in transverse cross section under two different inclined angles of rolls obtained from the experiments of Figs. 7 and 11. In Fig. 12(a), with $\theta=10^\circ$, the dendritic zone of cast strip grown from the lower surface is almost the same as that grown from the top surface (1.0 mm vs. 0.96 mm) because the contact arc lengths between lower side and upper side are very little difference. Further, the depression or groove is also observed on the bottom surface of cast strip due to the formation of surface wrinkle. On the other hand, with an increased inclined

Fig. 12. The microstructures of cast strips in transverse cross section under two different inclined roll angles obtained from the experiments of Figs. 7 and 11, (a) $\theta=10^\circ$, and (b) $\theta=30^\circ$.

roll angle $\theta=30^\circ$, the dendritic zone of cast strip grown from the lower surface is larger than that grown from upper surface as shown in Fig. 12(b) which are 1.0 and 0.8 mm, respectively. This means the higher the inclined roll angle is, the greater the difference between these two dendritic zones is.

4. Conclusion

From the calculated results of flow analysis and the experimental results of actual casting for the inclined twin-roll strip casting process, the following conclusions for the relationships between flow characteristics and surface quality of the cast strips can be drawn:

(1) Many surface wrinkles are observed on the bottom surface with shorter height of pool level, which can be improved with an increase in the height of pool level. This is because the greater fall height of molten steel at a lower pool level results in violent meniscus fluctuation and easily causes surface wrinkles.

(2) The recirculation around the triple intersection point of air/roll/melt three phases is the most serious mechanism to induce slag or dross trapped into the melt.

(3) The strong impingement of molten steel on the meniscus and even further towards the rotating roll tends to cause surface vibration on meniscus and results in surface wrinkle.

(4) The slag or dross is found to be easily trapped into the melt and stuck on the strip surface with a small inclined angle of rolls regardless of the feeding conditions.

(5) Optimization between the inclined angle of rolls and the feeding position of nozzle tip is necessary to achieve a stable flow on the meniscus and thus to obtain good surface quality of cast strips.

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