Research on the Bimetallic Composite Roll Produced by an Improved Electroslag Cladding Method: Mathematical Simulation of the Power Supply Circuits

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Bimetallic composite roll has been given more and more attentions because of its superiority in playing the advantages performance of the internal and external materials at the same time. In the present study, a 2D quasi-steady state mathematical model of the electroslag cladding technology for producing bimetallic composite roll was developed by the Fluent software with the UDS and UDF function. Characteristics of the electromagnetic field, flow field and temperature field of the composite roll system have been numerically simulated and the laboratory scale experiments with the different power supply circuits were also developed to provide a verification of the mathematical models. The results indicate that: simulation results of the temperature distribution in the composite roll were well verified by the corresponding experiments. With the using of current supplying mold (CSM[®]), the improved conductive circuit is more beneficial to improve the distributions of current density and Joule heat in the slag pool and keep the high temperature zone away from the roll core surface than the conventional conductive circuit. On one hand, it makes the roll core be no longer as a pole of the electroslag process and the temperature adjustment of the slag pool become more flexible. On the other hand, it leads to a partial micro-melting of the roll core surface which is beneficial to form a metallurgical bonding and effectively avoid the mechanical mixing of the liquid metal between the roll core and composite layer, so, it can improve the comprehensive performance of bimetallic composite roll.

KEY WORDS: numerical simulation; electroslag cladding; composite roll; temperature field; current supplying mold.

1. Introduction

In recent years, with the advent of advanced rolling mill and the high-efficiency rolling technology, the rolling production line has been developed towards the direction of large-scale, high-speed and automation which makes the using conditions of the roll as the main consumable equipment in rolling mill production become much harsher. In addition, the roll quality has a direct impact on the production efficiency of the rolling mill, the surface quality of the rolled material and the rolling cost.

A bimetallic composite roll contains a core and a composite layer composed of two different metals. The roll core material needs high strength and toughness to bear the heavy loading and impact forces that occur during operation while the composite layer material needs a high degree of hardness and excellent abrasion performance to improve roll durability. As the structure of a bimetallic composite

roll completely meets the hardness and toughness working requirements in the rolling process, it has been given more and more attention because of its superiority in playing the advantages performance of the internal and external materials at the same time. Compared with the single material roll, composite roll can not only has the above advantages but also can significantly reduce the material costs. Therefore, researches on the composite roll materials¹⁻⁴⁾ and the producing technologies⁵⁻⁹⁾ have become a common concern of the roll manufacture industry and metallurgical industry both in China and other countries.

Electroslag remelting technology has been widely used in the smelting preparation process of high-quality, high-performance special steel because it can give a purification of the molten steel and improve the ingot quality during the solidification and crystallization process. Therefore, researches on the production of bimetallic composite roll by electroslag remelting method have also received the important attention of researchers. At present, the research reports on the production of bimetallic composite roll by electroslag metallurgical method are mainly focused on the

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electroslag casting method,^{9–13)} electroslag surfacing with liquid metal,^{8,14–17)} composite roller based on dual electroslag technology¹⁸⁾ and so on.¹⁹⁾ Among the research reports, the consumable electrode→roll core conductive circuit was adopted to carry out an experimental research by the rotational ESR bimetallic method,¹⁰⁾ but the characteristics of the remelting process were not given as a valid description. While, both the numerical simulation and experimental research were carried out with the nonconsumable graphite electrode→roll core conductive circuit, but the effect of slag flow field on the temperature field of composite roll system was not considered.^{16,18)} In the study of different power supply circuit, a current supplying mold→roll core conductive circuit was adopted to give a numerical simulation research for producing the composite roll by the electroslag casting by liquid metal (ESC LM) method.¹⁵⁾ In addition, there are also several papers in terms of simulation model of current supplying mold for the ESR process. However, in the reports of Dong *et al.*,^{20–22)} the geometric model is very different with that in the present composite roll system, the presence of a roll core changes the characteristics of the power supply circuits. In the reports of Chen *et al.*²³⁾ and Jing *et al.*,²⁴⁾ although, its geometric model is similar to the composite roll system, but, the internal mold is not participated in the power supply circuits. In addition, no effective research on the influence of electromagnetic field and flow field on the temperature distribution in the slag bath was given. The objectives of using current supplying mold are focused on obtaining a shallow shape molten steel pool in order to improve the crystallization and segregation condition of the electroslag ingot in the previous studies. However, it is focused on the temperature distribution at the roll core surface in order to obtain a good bonding quality of the bimetallic bonding interface. Up to now, no reports with the consumable electrode→mold conductive circuit have been given for the production of bimetallic composite roll and such current circuit were only reported by L. Medovar *et al.*²⁵⁾ for solid ingots manufacturing.

In the course of our investigations, a 2D quasi-steady state mathematical model of producing composite roll with the different power supply circuits was developed, through the numerical simulation and the correspondence experiments, an improved electroslag cladding method was recommended. In order to have a further understanding of the improved electroslag cladding method for producing the composite roll, there were the detailed statements about the bonded mechanism and mechanical properties of the bonding interface in the future study.

2. Mathematical Simulation

2.1. Basic Description of the Electroslag Cladding Process

A schematic diagram of the electroslag cladding method for producing bimetallic composite roll with the different power supply circuit programs was shown in Fig. 1. It mainly included the consumable electrodes, current supplying mold, roll core, slag pool and a pair of metal level sensors. In addition, a lining electroslag furnace with the graphite electrode was used to provide liquid slag for the process. The entire producing process of the composite roll can be divided into the following three stages including the slag melting stage, pouring the molten slag stage and smelting of the bimetallic composite roll stage. As the third stage is the most important, the mathematical simulation is aimed at this stage in the present study.

The basic process can be described as follows in detail. Firstly, put the forged, casted or waste roll which will be used as the core of the composite roll into the mold center, in other words, the mold should be placed concentrically around the roll core to obtain a uniform thickness of the composite layer and improve the uniformity of physical parameters during the cladding process, which is beneficial to improve the bonded quality of the interface between roll core and composite layer. Secondly, liquid slag is melted by a lining electroslag furnace and poured into the annular space between the roll core and the mold. Thirdly, the power is switched on, and then, drop the consumable electrode used for the composite layer down and make it insert into the liquid slag pool. Then, the electrode is resistively heated to a temperature above its melting point as current passes through the slag pool. The electrode then melts and coalesces into droplets on the tip that eventually fall through the slag and collect in a liquid pool below the slag. The chemical reactions that remove inclusions and determine the final ingot chemistry occur at the electrode/slag interface as the metal droplets fall through the slag and at the slag/metal interface, so, it is beneficial to improve the pureness of molten steel used as the composite layer of the composite roll which can greatly improve the composite roll's performance. During the entire process, the slag pool is kept at a high temperature by Joule heating and the roll core surface is quickly heated as it passes through the slag pool. With the composite process between the cladding metal and the roll core under the slag/metal interface, the composite roll billet is withdrawn from the mold continuously until it reaches the demanded length.

Fig. 1. Schematic diagram of the electroslag cladding method with the (a) electrodes→roll core and (b) electrodes→mold conductive circuit for producing composite roll. (Online version in color.)

2.2. Physical Assumptions

As there are electromagnetic fields, fluid flow and heat transfer phenomena during the electroslag cladding process and they both interact and influence each other. In order to simplify the mathematical model, a number of simplifying assumptions have been made and the most important of these are listed in the following:

- (1) The electroslag cladding process for producing composite roll is considered as a quasi-steady state when the composite ingot reaches a certain height;²⁶⁾
- (2) The consumable electrode is a hollow tube with the uniform thickness and always coaxial with the roll core during the remelting process;
- (3) Slag/metal interface is presented by a horizontal surface;
- (4) Liquid slag is an incompressible fluid and the physical chemistry properties of the steel and slag are associated only with temperature;
- (5) Fluid flow equations are solved for the slag phase only and the motion in the molten steel pool is taken into account by the effective thermal conductivity;
- (6) Thermal resistance between the composite layer and the roll core is negligible;
- (7) Influence of the composition variations between the composite layer and the roll core owing to the mechanical mixing, chemical reaction and element diffusion is negligible.

2.3. Computational Models

Simplified 2D geometrical and grid models have been developed, including the roll core, slag pool and composite layer in the computation regions, as shown in Fig. 2. The geometrical parameters of the composite roll system are shown in detail. It is worth mentioning that depth of the slag pool contacted with the current supplying mold is 60 mm in the present simulation and its coordinates are $r = R_s$ and $Z_3 \leq z \leq Z_5$ as shown in Fig. 2. The R_c , R_s and R_w represent the radius of roll core, slag bath that contacted with the current supplying mold and the composite roll, respectively. The R_e and D_e represent the inner arc radius and thickness of the tubular electrode. The annotation of Z_0 , Z_1 , Z_2 , Z_3 , Z_4 , Z_5 , Z_6 in the Fig. 2(b) represents the different positions in Z

direction which are used to describe the boundary conditions of different physical fields in the cylinder coordinate system.

In the present simulation, just one half of the electroslag cladding process facility is meshed due to the axial symmetry. In order to ensure the mesh quality, the finite element volume is controlled by manual operation. Length of the cells for the roll core, composite layer and slag pool is set to be 0.0025 m and the interfaces among the three different zones have one time of refinement. The total number of cells is 27 198.

The governing equations and thermophysical parameters of the slag, roll core and composite layer in the present mathematical simulation are similar to that described in the earlier reports.^{15,27)} In addition, in order to give a clearer understanding of the simulation details, governing equations and boundary conditions of the electromagnetic field are given a brief explanation as it has a direct influence on the flow field and temperature field in the slag pool.

2.3.1. Governing Equations of Electromagnetic Field

The Maxwell equation, Lorentz Law, and Joule Law described the magnetic field are as follows:

$$E = -\nabla\phi \quad \dots\dots\dots (1)$$

$$\text{Ampere law : } \nabla \times H = J + \frac{\partial D}{\partial t} \quad \dots\dots\dots (2)$$

$$\text{Faraday law : } \nabla \times E = -\frac{\partial B}{\partial t} \quad \dots\dots\dots (3)$$

$$\text{Continue equation of magnetic flux : } \nabla \cdot B = 0 \quad \dots\dots (4)$$

$$\text{Constitutive relation : } B = \mu_0 H \quad \dots\dots\dots (5)$$

$$\text{Where } J = \sigma(E + V \times B) \quad \dots\dots\dots (6)$$

From the electromagnetic field equation, it can be combined to give:

$$\frac{\partial H}{\partial t} = \eta \nabla^2 H + \nabla \times (V \times H) \quad \dots\dots\dots (7)$$

$$\Gamma_H = 1/(\sigma\mu_0) \quad \dots\dots\dots (8)$$

Here Γ_H is the magnetic diffusion. The convective term (the second right-hand-side term of Eq. (7)) is to neglect, due to a small magnetic Reynolds number. The magnetic equations are solvable independently from the flow field.

The magnetic field is axial symmetric, therefore it shows only the peripheral component of the magnetic field intensity.

$$\frac{\partial H_\theta}{\partial t} = \Gamma_H \left(\frac{\partial^2 H_\theta}{\partial r^2} + \frac{1}{r} \frac{\partial H_\theta}{\partial r} - \frac{1}{r^2} H_\theta + \frac{\partial^2 H_\theta}{\partial z^2} \right) \quad \dots\dots (9)$$

A coupled system of two different equations is obtained from the Eqs. (1) and (9). This system is implemented in Fluent via "User Defined Scalars" (UDS).

The Lorentz force due to the electromagnetic field is implemented in the momentum equation as a body force which is described by the Navier-Stokes equations via following source terms:

Fig. 2. Geometrical (a) and grid (b) models of the composite roll system. (Online version in color.)

$$F = \mu_0 J \times H \dots\dots\dots (10)$$

The source term for the energy equation considering the Joule heat in the slag bath is:

$$Q_J = \frac{J \cdot J}{\sigma} \dots\dots\dots (11)$$

These terms are included in Fluent via “User Defined Functions” (UDF).

Where E : electric field, ϕ : electric potential, H : magnetic field intensity, J : current density, D : electric flux density, B : magnetic induction intensity, σ : electrical conductivity, V : velocity of the medium, F : Lorentz force, μ_0 : magnetic permeability of free space ($\mu_0 = 1.256637 \times 10^{-6} \text{ N} \cdot \text{A}^{-2}$).

2.3.2. Boundary Conditions of the Electromagnetic Field

In the electrode→roll core conductive circuit case, the physical constraints for electric field equation are shown as follows:

$$\begin{aligned} \phi &= \phi_1 \\ (r = R_e \text{ and } r = R_e + D_e, Z_4 \leq z \leq Z_5; z = Z_4, R_e \leq r \leq R_e + D_e) \end{aligned} \dots\dots\dots (12)$$

$$\phi = 0 \quad (0 \leq r \leq R_w, z = Z_0) \dots\dots\dots (13)$$

In the electrode→current supplying mold conductive circuit case, the physical constraints for electric field equation are shown as follows:

$$\begin{aligned} \phi &= \phi_1 \\ (r = R_e \text{ and } r = R_e + D_e, Z_4 \leq z \leq Z_5; z = Z_4, R_e \leq r \leq R_e + D_e) \end{aligned} \dots\dots\dots (14)$$

$$\phi = 0 \quad (r = R_s, Z_3 \leq z \leq Z_5) \dots\dots\dots (15)$$

Where, ϕ and ϕ_1 are the electric potential and the setting value in the present simulation.

In other boundaries, the electric potential gradient is defined as zero. At the free surface of slag bath, the electrical insulation is assumed, so, the electric current density is zero ($J_z = 0$) at the boundaries and it can be expressed by the electric potential as $(\partial \phi / \partial z) = 0$.

Meanwhile, boundary conditions for the magnetic field have been expressed by the Ampere’s Law as follows and implemented in Fluent via the UDF though the DEFINE_PROFILE macro:

$$\oint H \cdot dl = \int J \cdot ds \dots\dots\dots (16)$$

Where H : magnetic field intensity, J : current density.

2.4. Numerical Solution of the Governing Equations

Fluent software is used for the numerical simulation of the electrosag cladding process in the course of our investigations. Firstly, a coupled system of electric field and magnetic field governing equations are solved via the UDS function. Secondly, the Lorentz force is implemented in the momentum equation as a body force while the Joule heat as a source term in the energy equation for the liquid slag pool, and the latent heat of cladding metal for mushy zone is also treated as a source term of energy equation in the control volumes in the composite ingot, these terms as described above with the boundary conditions of tempera-

Fig. 3. Flow chart for the numerical simulating process of the composite roll system.

ture field and electromagnetic field are all implemented in Fluent via the UDF.^{28,29)}

Meanwhile, Fig. 3 is the simplified flow diagram for the computational scheme.

3. Results and Discussion

In the following, we shall present the computed results of the mathematical models with the different power supply circuit programs and give the corresponding experimental verification. Finally, the best one is selected for producing the bimetallic composite roll in the laboratory by a comparison of the composite effect of the two conductive circuit schemes.

3.1. The Electrode→Roll Core Conductive Circuit

Here, a 2D mathematical model with the parameters of operating voltage, slag pool depth, distance between roll core surface and electrode, insert depth of the electrode and diameter of roll core are 36 V, 60 mm, 30 mm, 20 mm, and 240 mm respectively has been developed to help us have an analysis of the basic characteristics of the electrosag cladding process with the electrode→roll core conductive circuit.

By solving the physical model after loading relevant boundary conditions, the electric potential, current density, magnetic field intensity, Lorentz forces and velocity distribution in the liquid slag pool and temperature distribution in the whole computation regions are obtained as shown in following figures.

Fig. 4. Distributions of the (a) voltage, (b) current density and (c) Joule heat in the slag pool. (Online version in color.)

Fig. 5. Distributions of the (a) electromagnetic force, (b) velocity and (c) temperature in the slag pool. (Online version in color.)

Fig. 6. Distributions of the (a) temperature, (b) liquid phase ratio of the roll core and (c) composite layer in the composite system. (Online version in color.)

Figure 4(a) illustrates the electric potential distribution in the liquid slag pool of the electroslag cladding process. It can be seen that a great and uniform electric potential gradient appears at the upper part of the liquid slag pool between roll core and electrode, whereas it is less at others areas. Features of the electric potential distribution result in a larger current density at the slag pool between the roll core and electrode and most of the currents flow towards the roll core vertically from the electrode as shown in Fig. 4(b). The largest value of the current density exists at the electrode tip near the roll core and its value is $8.34 \times 10^5 \text{ A} \cdot \text{m}^{-2}$, at the same time, a larger current density value is also obtained at the slope section of the slag pool bottom. Due to the current density distribution, it results in the features of Joule heat generation in the slag pool as shown in Fig. 4(c).

Figure 5(a) shows the Lorentz forces distribution in the slag pool of the electroslag cladding process, the largest value occurs at the electrode tip which is close to the roll core side. As we all know, the relationship between Lorentz forces, current density and magnetic induction intensity

should satisfy the condition of left hand rule. So, the Lorentz forces distributed in the slag pool have different directions in different areas as the different directions of current density and magnetic induction intensity. Finally, because of the Lorentz forces, it has a strong counterclockwise spiral vortex in the slag pool that is below the electrode and it forms a clockwise spiral vortex either between the roll core and the electrode or between the electrode and the mold as shown in Fig. 5(b). The counterclockwise spiral vortex is rather larger and occupies most of the regions of the slag pool.

Figure 5(b) shows that the largest velocity of the liquid slag pool appears among the counterclockwise spiral vortex and the least value is distributed in the slag area at the bottom of the current supplying mold as the current density and Lorentz forces are all close to zero in this area. As we all know, the heat transfer and temperature distribution are obviously affected by the flow field in the slag pool, for example the heat transfer is worse at the region of lower velocity. In general, an uneven velocity field always results in an uneven temperature field. Due to the distribution

characteristics of the Joule heat and velocity field, a large temperature gradient and uneven temperature distribution occur at the slag pool area between roll core and the electrode while a relatively uniform temperature distribution lies in the below area of electrode and the center area of the spiral vortices where the heat transfer is weak as shown in Fig. 5(c).

The temperature distribution in the composite roll, liquid phase ratio of the roll core and composite layer are shown in Fig. 6 respectively, the highest temperature of the composite roll system is 2 240 K occurring in the slag pool between the roll core and the electrode. As the highest temperature area in the slag pool is closed to the roll core surface, it strongly increased the heat transfer from the slag pool to the roll core which results in a large area melting of the roll core surface as shown in Fig. 6(b). The molten steel will slid down from the roll core surface and has a mechanical mixing with that of the composite layer, this will seriously change the chemical composition of the composite layer and affect the thickness of the bonding interface which will result in a serious decrease of the overall performance of the composite roll. In addition, for the composite layer, a deep metal pool is formed as shown in Fig. 6(c) due to the high temperature in the slag pool. As we all know, a deep metal pool is harmful to reducing the element segregation and improve the solidification quality of the composite layer, so, the electroslag cladding method with the electrode→roll core conductive circuit is not suitable to produce a high quality bimetallic composite roll.

3.2. Experimental Verification

In order to have an experimental verification to the electroslag cladding process with the electrode→roll core conductive circuit, an experiment was carried out in a water-cooled mold with 310 mm diameter and the diameter of the roll core is 150 mm, the distance between roll core surface and electrode is 30 mm which is similar to the parameters setting in the present simulation.

From the Fig. 7, the broken phenomena of the roll core happened during the producing process of the composite roll in the experiment. As the high temperature of the slag area is located between the roll core and electrode, the roll core surface melted rapidly, with the decrease of the roll core diameter, it was heated continuously by the high temperature slag pool between roll core and the electrode which can accelerate the melting and shedding phenomenon of the roll core until the break.

In order to have a clear and intuitive observation of the melting and shedding phenomenon on the roll core surface, a low melting point and transparent solution system refer to the existing report³⁰⁾ was carried out with the experimental apparatus as shown in Fig. 8. The apparatus comprises six major components: an automatic coupling voltage regulator, which together with an ammeter and a voltmeter was used to provide the power and control the electrical parameters; a quartz beaker was used to simulate the mold in the electroslag cladding process; a low-melting wood-alloy rod was used as the roll core; a certain concentration of NaCl solution was used as the slag; a molybdenum plate under the roll core was used as the base plate in practice; several steel rods were used as the electrodes to heat the slag pool.

Fig. 7. Electroslag cladding experiment with the electrode→roll core conductive circuit. (a) experimental apparatus, (b) fusion and fracture of the roll core and (c) composite ingot. (Online version in color.)

Fig. 8. Schematic of the apparatus used to simulate the electroslag cladding process. (Online version in color.)

Fig. 9. The melting and shedding phenomenon on the roll core surface. (Online version in color.)

As soon as the power was supplied, the state of the roll core surface was continuously observed to analyze the changes with the temperature changing in the slag pool.

Figure 9 illustrated that the area opposite the electrode tip was first melted because of the highest temperature distribution as shown in Fig. 6(a) while there was no obvious melting phenomenon in the areas between the two electrodes. The slag pool was heated continuously along with the melting process and the roll core surface which was in contact with the slag pool was also heated to a very high temperature. Finally, a melting and shedding phenomenon occurred on the roll core surface and the melting profile of the roll core as shown in Fig. 9(c) had a good consistency with the simulation result as shown in Fig. 6(b).

3.3. The Electrode→Current Supplying Mold Conductive Circuit

Base on a large number of simulation studies with the electrode→current supplying mold conductive circuit, the

Fig. 10. Distributions of the (a) voltage, (b) current density and (c) Joule heat in the slag pool. (Online version in color.)

Fig. 11. Distributions of the (a) electromagnetic force, (b) velocity and (c) temperature in the slag pool. (Online version in color.)

Fig. 12. Distributions of the (a) temperature, (b) liquid phase ratio of the roll core and (c) composite layer in the composite system. (Online version in color.)

parameters of operating voltage, slag pool depth, distance between roll core surface and electrode, insert depth of the electrode and diameter of roll core with the 40 V, 60 mm, 10 mm, 20 mm, and 240 mm respectively is more suitable for obtaining an ideal temperature distribution of the composite roll. So, a 2D mathematical model with the parameters above has been developed to help us have an understanding of the basic characteristics of the process with the electrode→current supplying mold conductive circuit.

Different from the electrode→roll core conductive circuit, an obvious change has occurred of the current flow direction as shown in Fig. 10(b) in the present conductive circuit. It can be seen that most of the currents flow to the current supplying mold vertically from the consumable electrode and the largest value of the current density is at the bottom of consumable electrode which is close to the mold side and its value is $4.73 \times 10^5 \text{ A} \cdot \text{m}^{-2}$, at the same time, a larger current density value is obtained at the slope section of the slag pool bottom. Due to the current density distribution, it results in the features of Joule heat generation in the slag pool as shown in Fig. 10(c).

Due to the changes of current flow direction, the Lorentz forces direction in the slag pool is also changed as shown in Fig. 11(a) according to the left hand rule, the largest value occurs at the bottom of consumable electrode which is close to the mold side. The Lorentz forces distributed in the slag pool between the electrode and the current supplying mold has an axial direction and leads to a strong counterclockwise spiral vortex in the above slag pool area as shown in Fig. 11(b). The spiral vortex is rather larger and occupies most of the regions of the slag pool. But, a relatively weak clockwise spiral vortex took place below the bottom of electrode due to the Lorentz forces distribution at this slag pool area. Figure 11(b) shows that the largest velocity of the liquid slag appears among the counterclockwise spiral vortex and the least value is distributed in the slag area between roll core and consumable electrode as the current density and Lorentz forces are all close to zero in this area. Due to the distribution characteristics of the Joule heat and velocity field, a large temperature gradient and uneven temperature distribution occur at the slag pool area between electrode and current supplying mold while a relatively uniform tem-

perature distribution lies in the below area of electrode and the center area of counterclockwise spiral vortex where the heat transfer is weak as shown in Fig. 11(c).

From Fig. 12, as the highest temperature area in the slag pool is away from the roll core surface as shown in Fig. 12(a), it reduces the heat transfer from the slag pool to roll core effectively which results in an only partial micro-melting of the roll core surface as shown in Fig. 12(b). The highest temperature of the composite roll system is 2 004 K occurring in the slag pool between consumable electrode and current supplying mold. The partial micro-melting of the roll core surface is beneficial to a good combination between roll core and composite layer and avoid the influence of composition variations between the two materials owing to the mechanical mixing. In the present study, when compared with the electrode→roll core conductive circuit, the adoption of current supplying mold makes the high temperature area lie in the upper area of the slag pool while a relatively low temperature is near the slag/metal interface, it decreases the heat transfer from slag pool to the molten steel pool which leads to a lower superheat of the molten steel pool and a much shallower shape of the molten steel pool for the electrosag cladding process than that for the conventional electrosag cladding process as shown in Fig. 6(c).

The bonding interface is an extremely important component of the composite material. The performance of the composite roll is closely related to its bonding interface properties which can be said to be the key to the success of producing composite roll. However, the temperature distribution of the roll core surface is a key factor affecting the bonding quality of the bonding interface. So, in order to have a clear understanding of the temperature distribution law at the different locations of the roll core surface, the values has been extracted along the longitudinal direction and plotted as follows as shown in Fig. 13.

In the course of our investigation, different areas of the roll core surface have been named according to the temperature characteristics. The area of the roll core surface which is above the slag surface is named as the radiation zone ($r = R_c, Z_5 < z \leq Z_6$). The area of the roll core surface which is in contact with the slag pool is named as the preheating zone ($r = R_c, Z_2 < z \leq Z_5$). The area of the roll core surface which is in contact with the composite layer (inside the mold, $r = R_c, Z_1 < z \leq Z_2$) is named as the composite zone. The area of the roll core surface which is in contact with the composite layer (outside the mold, $r = R_c, Z_0 \leq z \leq Z_1$) is named as the air cooling zone.

As shown in Fig. 13, in the radiation zone, the temperature at the top of the roll core surface is 406 K and it gradually increases to 435 K when it comes to the point which is 0.055 m from the slag surface, and then there is a significantly accelerated increase of the temperature until 1 242 K when it comes to the point of slag pool surface, then it comes to the preheating zone. In this zone, the roll core surface is further heated by the influence of high temperature slag pool, however, Fig. 11(c) shows that the temperature in the lower part of the slag pool is higher than that of the upper zone which results in that the surface of the roll core is preheated continuously until it reaches the maximum value of 1 793 K (as the liquidus temperature of the roll core is 1 767 K), at this time, the point is 0.021 m higher than

Fig. 13. Temperature distribution at the different locations of the roll core surface.

Fig. 14. Surface morphology of the roll core. (Online version in color.)

the bottom of the slag pool. It also can be obtained that the height of the partial micro-melting of the roll core surface in Fig. 12(b) is 0.029 m and the maximum melting depth is 0.0022 m. Then, by the effect of the low temperature near the bottom of the slag pool, it decreases gradually, when it comes to the slag/metal interface, the temperature of the roll core surface drops to 1 717 K (as the solidus temperature of the roll core is 1 683 K). At the slag/metal interface, the roll core is surrounded by the liquid cladding metal, the two metals interact with each other and it achieves a combination of the two materials. After entering the composite zone, the temperature of the composite system decreases rapidly due to the direct cooling by the water-cooled mold, the temperature of the bonding interface also decreases rapidly with the bimetallic composite ingot moving down, when it moves outside of the mold, the temperature of the bonding interface has dropped to 1 109 K. After entering the air cooled zone, the cooling effect on the composite ingot decreases obviously as shown in Fig. 12(a) which also leads to an obvious reduction of the cooling rate at the bonding interface as shown in Fig. 13. When it comes to the point which is 0.1 m below the water-cooled mold, the temperature at the bottom of the roll core surface is 989 K.

3.4. Experimental Verification

An experiment was carried out with the parameters used in the above mathematical simulation, but details of the test process and more results will be given in the experimental research on the bonding interface in the future study. In order to have an experimental verification to the mathematical simulation, the melting state of the roll core surface in contact with the slag pool was shown in Fig. 14 as follows.

From the Fig. 14, it can be seen that a partial micro-melting of the roll core surface occurs in the local area above the slag/metal interface and the melting depth is about 2 mm which is well consistent with the simulation results as shown in Fig. 12(b) and the analysis of the Fig. 13.

As described above, a satisfactory agreement between the numerical and experimental results of the temperature distribution of the roll core surface gives us confidence in the numerical model's ability to predict the temperature distribution in others area of the composite ingot.

4. Conclusions

In the course of our investigations, an improved ESR based cladding technology for producing high quality composite roll has been introduced, in which a current supplying mold is used. The 2D quasi-steady state mathematical models are developed with two different conductive circuits to give us an understanding of the basic characteristics of the different electroslag cladding process and help us choose a more suitable method for the producing of bimetallic composite roll by the use of Fluent software with the user-defined scalar and user-defined functions. The results indicate that:

Firstly, the highest temperature value occurs in the slag pool between roll core and consumable electrode which leads to a serious melting of the roll core and a mechanical mixing of the liquid metal between the roll core and composite layer with the conventional electrode→roll core conductive circuit. It affects the chemical composition of the composite layer and the thickness of the bonding interface between roll core and the composite layer which will result in a serious decrease of the overall performance of the composite roll. At the same time, a deep metal pool is harmful to reduce the element segregation and improve the solidification quality of the composite layer.

Secondly, adoption of the current supplying mold in the improved electroslag cladding process makes the highest temperature value occur in the slag pool between the consumable electrode and mold which is away from the roll core surface, it reduces the heat transfer from the slag pool to roll core effectively which results in an only partial micro-melting of the roll core surface. The partial micro-melting of the roll core surface is beneficial to a good combination between roll core and composite layer and avoid the influence of composition variations between the two materials owing to the mechanical mixing. At the same time, a much shallower shape of the molten steel pool than that for the conventional ESR process has been obtained which is beneficial to a rapid solidification and it can effectively reduce the elements segregation and improve the solidification quality of the ingots.

Through the comparative analysis of the two conduc-

tive circuits, the electroslag remelting method with the electrode→current supplying mold conductive circuit is more suitable to produce the bimetallic composite roll.

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