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Abstract

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Keywords

work, stress, hot, numerical, simulation, roll, temperature, rolling, field, during, thermal, strip

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Numerical Simulation of Temperature Field and Thermal Stress Field of Work Roll During Hot Strip Rolling

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Abstract: Based on the thermal conduction equations, the three-dimensional (3D) temperature field of a work roll was investigated using finite element method (FEM). The variations in the surface temperature of the work roll during hot strip rolling were described, and the thermal stress field of the work roll was also analyzed. The results showed that the highest roll surface temperature is 593 °C, and the difference between the minimum and maximum values of thermal stress of the work roll surface is 145.7 MPa. Furthermore, the results of this analysis indicate that temperature and thermal stress are useful parameters for the investigation of roll thermal fatigue and also for improving the quality of strip during rolling.

Key words: hot strip mill; roll; temperature field; thermal stress; finite element method

During the hot strip rolling process, certain defects^[1-5] such as oxidation, abrasion, and thermal fatigue might occur on the surface of the work roll under the conditions of the reiterated high temperature and the rolling force. These factors influence the operating life of the work roll, and more severely, the strip surface. Meanwhile, variations in the surface temperature of the work roll bring about crown variations that influence the shape of the strip. Therefore, certain accurate calculations with regard to the thermal crown of the work roll are necessary for improving the shape of the strip. So the investigation of the temperature and thermal stress fields of the work roll is very important for improving the surface quality and the shape of the strip, and also for investigating the roll thermal fatigue.

Up to now, most temperature and thermal stress fields of two-dimensional (2D) work roll have been investigated using finite element method (FEM)^[6-8]. In the present study, the three-dimensional (3D) temperature field of work roll during rolling process and the interval rolling process was simulated using FEM, and the results were calculated by indirect coupling structural analysis to analyze the work roll thermal stress field during rolling.

The results are useful for the investigation of roll thermal fatigue and for improving the quality of strip steel during rolling.

1 Analytical Conditions

1.1 Investigation object

The object used in the present study for calculation is the work roll of F2 finishing mill of a hot rolling plant. The work roll of 850 mm in diameter is made of high-chromium cast iron; the strip steel rolled is SS400, the strip temperature at the entrance of F2 is 1 000 °C, the thickness of steel is 24 mm before rolling and 14 mm after rolling, and the width is 1 680 mm. The velocity of rotation of the work roll is 48 r/min, with the initial temperature of the work roll being 30 °C. The pressure of cooling water is 1 MPa, water flow is 1 000 m³/h, water temperature is 25 °C, air temperature is 30 °C, rolling force is 11 200 kN, and the other parameters are shown in Table 1.

1.2 Initial and boundary conditions

It is assumed that the work roll temperature is uniformly distributed when the novel rolling campaign begins and that all nodes exhibit equal distri-

Table 1 Parameters in calculation

Items	Value
Young's modulus/Pa	3×10^{11}
Coefficient of thermal expansion/ $^{\circ}\text{C}^{-1}$	9×10^{-6}
Poisson ratio	0.3
Specific heat capacity/ $(\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1})$	590
Density/ $(\text{kg} \cdot \text{m}^{-3})$	$7\,900 - 0.4\theta$
Coefficient of heat conduction/ $(\text{W} \cdot \text{m}^{-1} \cdot ^{\circ}\text{C}^{-1})$	$54.7 - 0.034\,2\theta$; $16.3 + 0.010\,9\theta$ ($\theta < 850\,^{\circ}\text{C}$)
Coefficient of thermal resistance/ $(\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1})$	1.16×10^{-4}
Heat radiating constant/ $(\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-4})$	5.67×10^{-8}

Note: θ is temperature.

bution of air temperature, $\theta_{t=0} = \theta_0(x, y, z)$. The circumrotation of the work rolls and the strip deformation in a plastically deforming area result in the changes in thermal boundary condition of the work roll during the rolling process. In practice, the work roll surface boundary can be divided into 10 parts (the heat exchanges are different), as shown in Fig. 1. The Part 1-2 is a high heat flow part between rolls and strip steel; the Part 2-3 is the strip radiation boundary at rolls' gap; the Part 3-4 is the water cooling part of the rolls at strip entrance; the Part 4-5 is the weak water cooling part at strip entrance; the Part 5-6 is the convection part between air and rolls; the Part 6-7 is the cooling part that comes in contact with work roll and backup roll; the Part 7-8 is the natural convection part between the rolls and the air at strip exit; the Part 8-9 is the water cooling part of the rolls at strip exit; the Part 9-10 is the weak water cooling part, where the heat is removed by the rolls at the strip exit; and the Part 10-1 is the heat radiation part from the strip to the rolls at the strip exit.

It should be noted that the heat generated by the strip deformation is not considered in this analysis because the heat generated in strip deformation has little effect on the work roll temperature.

Fig. 1 Cross section of boundary condition

1.3 Establishment of models and meshing

Owing to the rolls' symmetry, the investigation of a half of the work roll is feasible and efficient. The center of the work roll which was considered to have little influence on temperature was not taken into account in the analysis of FEM to reduce the calculation time. The ANSYS software was employed, and the model was built using SOLID70 element. Initially, a hollow circle was built in the 2D model using a roll section element, PLANE55, and then it was moved along the axis; therefore, a SOLID70 is formed. The model is made of 27 216 elements, and the geometry and the meshing of the work roll are shown in Fig. 2. After thermal analysis, the thermal element was changed to the structural element to analyze the thermal stress. In this analysis, the SOLID70 thermal element was changed to the SOLID45 structural element.

2 Results and Discussion

It was assumed that the temperature distribution on the work roll is uniform when the rolling campaign begins and that the strip width is lesser than the work-roll surface length; therefore, the roll does not come in complete contact with the strip. This

Fig. 2 Elements of roll

means that the roll part can be divided into the convection part between air and rolls in the work-roll surface boundary, which is not in contact with the strip. Through the second program code with APDL, several analyses can be carried out on the work roll temperature and thermal stress fields at any time during the rolling process. The time required for one

circumferential rotation of the work roll is 1.296 s. For simplification, the temperature and thermal stress fields of the work roll at 1.296, 2.592, 5.184, 10.368, 25.92, and 51.84 s were analyzed. The results of temperature and Von Mises equivalent thermal stress fields of the work roll at 51.84 s are shown in Fig. 3.

Fig. 3 Temperature field (a) and Von Mises equivalent thermal stress field (b) at 51.84 s

2.1 Temperature field

The temperature of, especially the surface, the interior of the work roll varies with time. Initially, the surface temperature rapidly increases to the maximum. After a period of time, due to the action of cooling water and cooling air, the rise and fall of the surface temperature nearly reach a dynamic equilibrium. Fig. 4 shows the variation in temperature field with time.

(1) The maximum surface temperature is 460 °C at 1.296 s, and after 2.592 s, 5.184 s, 10.368 s, 25.92 s, and 51.84 s, the surface temperature of the work roll is 508 °C, 521 °C, 539 °C, 584 °C, and

593 °C, respectively. Compared with the initial temperature, the increased value is 478 °C, 491 °C, 509 °C, 553 °C, and 563 °C. It can be found that the rate of increase in the work roll surface temperature is initially rapid, and then slows down during the later stages.

(2) The difference between the maximum and minimum surface temperature of the work roll at 1.296 s, 2.592 s, 5.184 s, 10.368 s, 25.92 s, and 51.84 s is 406 °C, 451 °C, 464 °C, 480 °C, 524 °C, and 536 °C, respectively. It is obvious that the difference in temperature increases as time increases.

(3) The temperature transformation of the work roll occurs within 50 mm from the surface layer, and the inner temperature exhibits only a slight change. The Part 1-2 of the work roll, i.e. the intensive heat current boundary area of the work roll in contact with the rolled piece, exhibits the maximum surface temperature. When the work roll departs from this boundary and passes through the water cooling area, the rate of the decrease in the temperature of the work roll shows the maximum value, and after 1.296 s, 2.592 s, 5.184 s, 10.368 s, 25.92 s, and 51.84 s, the minimum temperature of the work roll is decreased to 52 °C, 57 °C, 58 °C, 61 °C, 62 °C, and 67 °C, respectively.

Fig. 4 Variation of temperature of work roll during one rolling of coil

2.2 Thermal stress field

Fig. 3 (b) shows that the Von Mises equivalent

thermal stress on the surface of the work roll has maximum value of 164 MPa and minimum value of 18.3 MPa. The difference between the maximum thermal stress and minimum thermal stress is 145.7 MPa. The positive and the negative thermal stresses existed on the surface of the work roll in a rolling campaign. Thermal fatigue generated by the thermal stress occurs after a prolonged rolling.

2.3 Transformation curve of surface temperature

As discussed above, the variation in the surface temperature of the work roll is fast. Study of the surface temperature variation curve that represents the variation in surface temperature during the rolling process and the interval rolling process is important for further investigations on the thermal stress and thermal fatigue. An arbitrary node close to the center on the roll surface of the work roll is chosen, and the temperature variation curve for the rolling of three coils of steel and the rolling gap are shown in Fig. 5.

It can be seen from Fig. 5 that each time the work roll completes one rotation, the surface temperature increases from the initial 30 °C and reaches the maximum value of 593 °C after around 25 s; the minimum temperature is 156 °C, after which it basically stabilizes at the maximum and minimum values. The surface temperature of the roll is decreased to 61 °C after finishing rolling. Thereafter, the surface temperature of the work roll undergoes the same cyclic change along with the rolling of the subsequent strip steel.

It can be seen that the surface temperature of the work roll during the rolling process exhibits both increase and decrease. The surface of the work roll produces thermal stress in various directions and

Fig. 5 Curves showing variation in temperature of roll surface of 4 685 nodes

the variation of surface stress is the maximum. The variation in stress would cause thermal fatigue on the work roll surface within a given time, and the surface quality and shape of the strip steel are affected as a result of fatigue.

3 Conclusions

(1) The temperature fields of an arbitrary cross-section of work roll were calculated during the rolling process and the interval rolling process using finite element method, and the pattern of variation of the work-roll surface temperature was analyzed.

(2) The thermal stress field of work roll was calculated using indirect coupling structural analysis and thermal analysis. The result shows that the maximum equivalent stress is 164 MPa, the minimum value is 18.3 MPa, and the difference is 145.7 MPa.

(3) The analysis of the temperature and the thermal stress variation of the roll surface provides theoretical basis for the improvement of the quality of strip products and further analysis of the roll surface fatigue.

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