Journal of University of Science and Technology Beijing
Volume 11, Number 2, April 2004, Page 173

Analysis of the thermal profile of work rolls in the hot strip rolling process

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(Received 2003-04-06)

Abstract: A 2-dimension axisymmetric model was developed by the finite-difference method, which can be used to predict the transient temperature field and thermal profile of work rolls in the hot strip rolling process. To demonstrate the accuracy and reliability of the solution developed, the calculation results were compared with the production data of a 1700 mm hot strip rolling mill and good agreement was found between them. The effect of strip width and roll shifting on the thermal expansion of the work rolls was studied. It is found that the strip width has marked effect on the efficient thermal crown. Initially, when the rolling strip changes from narrow to wide, a bigger efficient thermal crown can be quickly achieved; afterwards, when the rolling strip changes from wide to narrow, not only the influence of uneven wear can be reduced but also the excessive efficient thermal crown can be avoided. It is also found that the work roll shifting has a determinate but not obvious effect on the reduction of the efficient thermal crown, and will make the strip shape unstable without being used properly.

Key words: hot strip rolling; temperature field; thermal crown; finite-difference method

[*This work was financially supported by the Excellent Young Teachers Program of the Education Ministry of China (No. 261).*]

In the hot strip rolling process, precisely predicting the thermal profile of work rolls is a key factor on strip shape control. By the finite difference method, a 2-dimensional axisymmetric model has been developed in this paper to calculate the transversal temperature field and thermal profile of work rolls, which can meet the needs of high speed and precision during the rolling process.

1 Creation of the thermal field and hot crown model

Investigations show that although the work roll periodically contacts with hot strips and cooling liquid and as a result the surface temperature changes drastically and the axisymmetric temperature field of the roll is over 99%. So when just analyzing the thermal deformation of the work roll, its thermal changes can be simplified as a 2-dimensional axisymmetric problem. Using the finite difference method and 2-dimensional axisymmetric model has simplified the problem and made it possible to apply to real on-line process control.

1.1 Differential and difference equations of heat conduction

The work roll is divided into different types of elements according to different boundary and geometric outlines, and different differential equations are put forward for each type of elements. For the strip contact element on the surface of the roll, take a micro cricoid volume on the surface as an example, while the thickness of the volume being Δr, its width being Δx and radius being r, the heat conduction differential equation in the cylindrical coordinate is as below in accordance with the law of conservation of energy:

$$\frac{\rho c}{\lambda}\frac{\partial T}{\partial t}=\frac{\partial^2 T}{\partial x^2}-\frac{\partial T}{\partial r}\frac{1}{\Delta r}-\frac{q_{\mathrm{equ}}}{\lambda \Delta r} \tag{1}$$

where T and t are the temperature field and time, respectively; ρ the roll density; c and λ are the specific heat capacity and heat conductivity, respectively; x is the position along the roll axis; q_{equ} the equivalent thermal flow density.

To meet the need of on-line prediction and the high speed and precision of calculation, the apparent difference method is used to do the numerical calculation. From the element position, which is shown in **figure 1**, the difference equation of element (i, j) derived from equation (1) is shown as follows:

$$T_{i,j}^{n+1}=T_{i,j}^{n}+\frac{\lambda}{c\rho}\Delta t\left[\frac{1}{(\Delta x)^2}T_{i,j-1}+\frac{1}{(\Delta x)^2}T_{i,j+1}+\right.$$

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$$\frac{1}{(\Delta r)^2}T_{i+1,j}-\left(\frac{2}{(\Delta x)^2}+\frac{1}{(\Delta r)^2}\right)T_{i,j}-\frac{q_{\text{equ}}}{c\rho\Delta r}\Bigg] \tag{2}$$

where Δt is the time step, $T_{i,j}^n$ the temperature of element (i, j) at the nth time unit. The time step Δt, space step Δx and Δr are specified by the following inequation which represents the stability of the difference equation:

$$1-2\times\left[\frac{1}{(\Delta x)^2}+\frac{1}{(\Delta r)^2}\right]\frac{\lambda}{c\rho}\Delta t\geq 0 \tag{3}$$

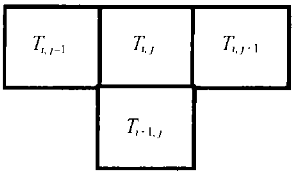

Figure 1 Element position.

Equation (3) shows that the smaller the space step, the larger the time step. Considering the calculated results, a conclusion can be gotten that all elements' difference equations will meet the stability condition when the axial step Δx and radial step Δr is larger than 40 and 20 mm, respectively, and the time step Δt less than 10 s.

1.2 Treatments of boundary conditions

The working process of the work roll can be defined as rolling, idling (water-cooling) and air-cooling period. There are 4 kinds of boundary conditions of the work roll that are known as water-cooling, contacting with the strip, air-cooling and axle end area. Taking elements contacting with the strip during the rolling period as an example, the boundary conditions are described as follows:

$$q_{\text{equ}}=\frac{A_s}{2\pi}q_s+\frac{A_{\text{rad}}}{2\pi}q_{\text{rad}}+\frac{A_w}{2\pi}q_w \tag{4}$$

$$q_s=h_s(T_r-T_s) \tag{5}$$

$$q_{\text{rad}}=\varepsilon\sigma[T_r+273)^4-(T_s+273)^4]^{[1]} \tag{6}$$

$$q_w=h_w(T_r-T_w) \tag{7}$$

where q_s, q_{rad} and q_w denote the thermal flow intensities of contact, radiating and water-cooling area of the strip, respectively; A_s, A_{rad} and A_w are the arc of contact, radiating and water-cooling area, respectively; ε is the heat radiation rate of the strip (0.2); σ the heat radiation Stefen-Boltzmemn constant (5.67×10^{-14}); h_s and h_w are the heat interchanging rate between the roll and the strip and between roll and cooling liquid, respectively.

1.3 Calculations of the thermal profile

The thermal expansion of roll diameter is formulated as:

$$u(x,t)=4(1+v)\frac{\beta}{R}\int_0^R[T(x,r,t)-T_0]\cdot r\cdot\mathrm{d}r \tag{8}$$

where $u(x, t)$ is the thermal expansion in diameter, T_0 the initial roll temperature (40°C), v, β and R denote the Poisson ratio, line expanding coefficient and radius of the roll, respectively.

The relative diameter thermal expansion in every part of the roll can be calculated from the above formula, and the whole thermal profile can be gotten too. The difference of thermal expansion between the middle and the edge of the roll is called the thermal crown. In order to analyze the effects of thermal expansion on roll gap and strip shape, two parameters are defined here: efficient thermal profile which represents the average relative thermal expansion between the upper and lower roll, and efficient thermal crown which denotes the thermal expansion difference between the middle and edge of the strip.

2 Validation of the model

In a hot strip plant, a series of data related to the thermal deformation of a roll are collected from the F7 stand of a finished hot rolling mill group (F1-F7). Those data collected are the rolling rhythm (rolling time/idling time), rolling pressure, strip temperature, axial shifting of the work roll, strip width and reduction *etc*. The tracking measurement of temperature on the surface of the roll was done after the work roll had been off-line.

Figure 2 shows the comparison of calculated and measured temperature distributions of a work roll on the F4 stand, which has served a whole typical rolling cycle and cooled down after some time's off-line air-cooling. Correspondingly **figure 3** shows the comparison of calculated and measured thermal profiles.

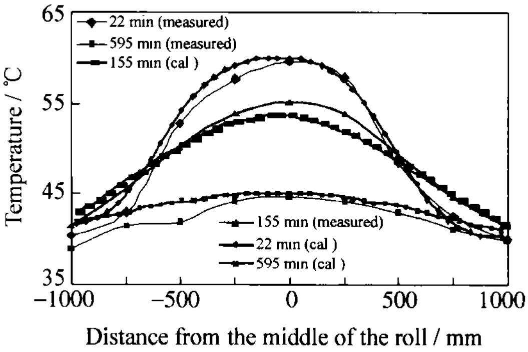

Figure 2 Comparison of the calculated and the measured surface temperature distributions of a work roll.

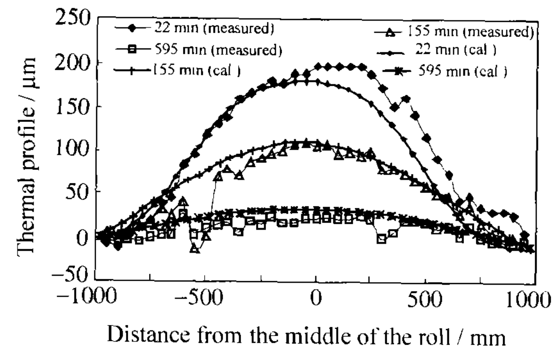

Figure 3 Comparison of the calculated and the measured thermal profiles of a work roll.

3 Simulation of the production process

The model above was employed to analyze the deformation rules of a hot wok roll under every working condition. Below are the simulating results for a rolling unit in which 115 strips had been rolled with an average rolling rhythm of 73s/55s (rolling time/intermitting time).

(1) Changes of work roll's thermal crown and efficient thermal crown of the F4 stand are shown in **figure 4**. It shows that the thermal crown achieves a round stable level of 300 μm after rolling approximately 30 coils, while varying drastically before the first 10 coils. The efficient thermal crown during stable rolling is 100 μm, and reaches quickly to 80% of the stable value after the 5th coil, and this value changes according to the arrangement of the rolling rules. In addition, it is obvious that both the thermal crown and efficient thermal crown are influenced by the rolling rhythm. To the thermal crown, the influence of the rolling rhythm, which is often changed, should be considered, together with some short-time intermission, which is often occurred during the production process.

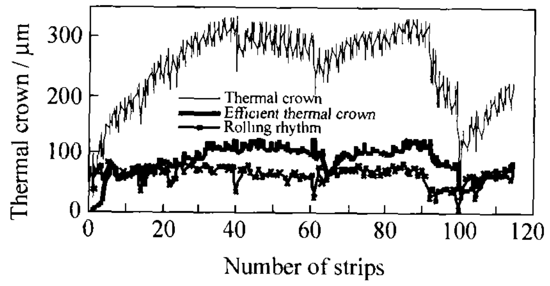

Figure 4 Changes of the work roll's thermal crown and the efficient thermal crown of the F4 stand.

(2) The thermal profile and efficient thermal profile when rolling the strip head and tail of the F4 stand during the stable rolling process are shown in **figure 5** (the 70th coil). The thermal profile looks like a box, which is flat in the middle of the roll and a little narrower than the strip, and varies drastically on the edge of the strip. So when exploring the influence of the roll's thermal deformation on strip shape, it is necessary to consider the configuration of the thermal crown as well as to calculate the thermal crown. The roll's thermal profile changes obviously when rolling the head and tail while the efficient thermal profile changes little.

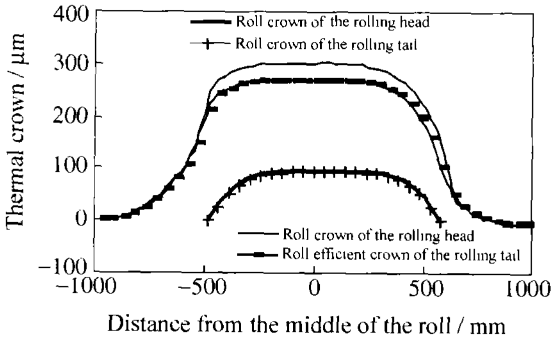

Figure 5 Thermal profile and efficient thermal profile of the strip head and the tail of the F4 stand during the stable rolling process.

(3) It is illustrated in figures 2 and 3 that the temperature distribution and thermal profile vary from box shape to binomial curve, and can be simulated to binomial curve‸20 min later. The temperature reduction and thermal profile fall to half of the initial value after 3 h cooling, while the temperature reduction is about 5°C and the thermal profile is about 40 μm (in **figure 6**) after 10 h air cooling. This conclusion is important for the work roll grinding: the off-line work roll should be grounded after 5 h cooling, otherwise the influence of the thermal crown should be considered in order to ensure the consistency of the real crown and target crown.

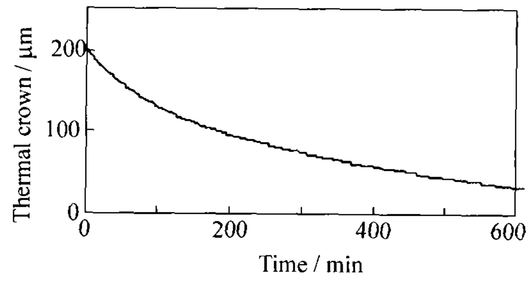

Figure 6 Changes of the thermal crown during the process of air-cooling.

4 Analysis of key factors affecting the temperature field and the thermal profile.

4.1 Influence of strip width on thermal profile

The hot rolling unit should be arranged first from the wide strip to the narrow one and then from the narrow to wide. To get the rules between the thermal profile and strip width, one rolling unit with 280 pieces of strips is calculated while taking the F4 stand as an object. The main parameters are listed as follows: the strip temperature, 1050°C; the reduction, 2.5 mm; the rolling force, 14.7×10^3 kN; the roll heat conductivity, 41 W/(m·°C); the temperature of cooling water, 38°C; the diameter of roll, 740 mm; the rolling rhythm, 0.64 (70 s rolling/40 s idling); and the width, from 850 to 1550 mm.

Changes of the thermal crown and its efficient form in one rolling unit are shown in **figure 7**. The thermal crown of the work roll seems to relate with the strip width: the wider the strip, the less the whole thermal crown; the thermal crown reduces 15 μm for every 100 mm's increase of strip width. The strip width has a marked effect on the efficient thermal crown. When the strip changes from wide to narrow, the efficient thermal crown decreases quickly due to the lag of the thermal profile's changes, after rolling 10 coils, however, the temperature field achieves a new balance, the efficient thermal crown rises to a value larger than the initial one. The thermal profiles when rolling strips with different widths under stable state are shown in **figure 8**. The middle of the roll shows a kind of convexity when the strip width is narrow and becomes flatter when the width is increased.

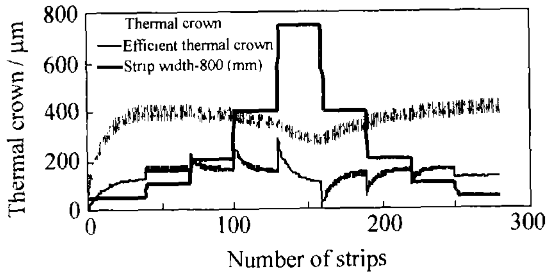

Figure 7 Changes of the hot crown and the efficient hot crown according to the strip width.

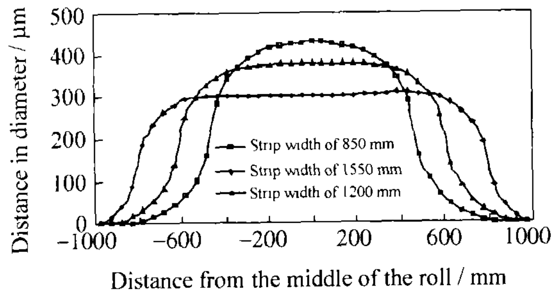

Figure 8 Roll thermal profiles of different strip widths.

The conclusion above is significant for the arrangement of the rolling regulations. Initially, when the rolling strip from narrow to wide, a bigger efficient thermal crown can be quickly achieved; afterwards, when the rolling strip from wide to narrow, not only the influence of uneven wear can be reduced but also excessive efficient thermal crown can be avoided, while the later has always been ignored.

4.2 Influence of roll shifting on thermal profile

For even wear, the downstream stands (F4-F7) of hot strip tandem mills have installed the function of work roll shifting. The same rolling parameters as above were adopted to simulate stand F4 rolling 80 coils, and to calculate under the condition of having roll shifting and no shifting respectively to review the efficient thermal profile and thermal crown of the roll.

The changes of the efficient thermal crown under different roll shifting policies (shifting 1 and shifting 2 whose corresponding efficient thermal crowns are represented by efficient thermal crown 1 and efficient thermal crown 2) are shown in **figure 9.** It shows that the roll shifting tends to decrease the thermal crown while in an unstable and irregular way since the roll thermal expansion is a slow accumulating process. The efficient thermal profiles of stable rolling without roll shifting, and of rolling the 41th and 76th coil with roll shifting are shown in **figure 10.** It can be seen that the efficient roll profile is flat without roll shifting; while having roll shifting, the longer the shifting distance is, the smaller the efficient roll profile flat area is and the curve, the closer to a binomial parabola.

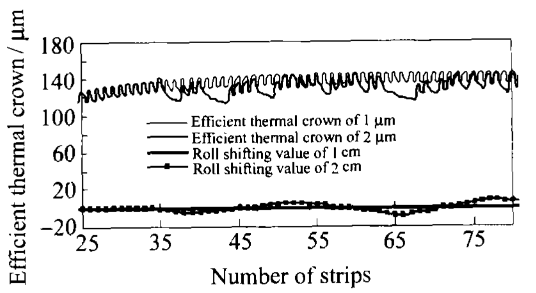

Figure 9 Relations of the efficient thermal crown and the roll shifting.

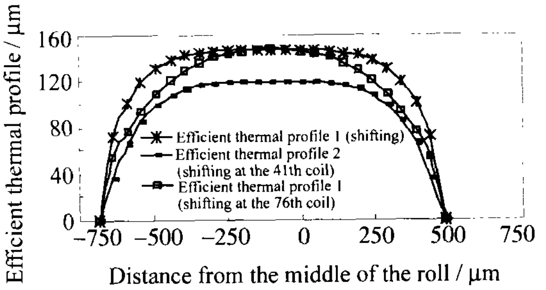

Figure 10 Relations of the efficient thermal profile and the shifting.

It can be concluded from the above that the work roll shifting has a determinate but not obvious effect on the reduction in efficient thermal crown, and will make the strip shape unstable without being used properly. It was found on the spot that the work roll shifting always caused unexpected results, and the strip shape would become uncontrollable.

5 Conclusions

The thermal profile model of work rolls was created with difference methods and verified by real production, while the speed and precision of the calculation met the needs of on-line control. It shows that strip width has a marked effect on the efficient thermal crown: initially, when the rolling strip changes from narrow to wide, a bigger efficient thermal crown can be quickly achieved; afterwards, when the rolling strip changes from wide to narrow, not only the influence of the uneven wear can be reduced but also the excessive efficient thermal crown can be avoided. It is also found that the work roll shifting has a determinate but not obvious effect on the reduction of the efficient thermal crown, and will make the strip shape unstable without being used properly.

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