Analysis on temperature jump during high-speed wire rolling of martensite stainless steel

J Cui and X X Li
School of Mechanical Engineering & Automation, Beihang University, Beijing, 100191, P.R. China

Corresponding author and e-mail: J Cui, Cuij98@163.com

Abstract. The method of upper bound triangular velocity field is used to calculate the temperature jump during high-speed wire finish rolling. Fourier's simplified heat conduction law is used to calculate the temperature drop during the wire finish rolling. Due to the high-speed and poor heat dissipation, it is simplified when calculating the temperature change of the finishing mill. The temperature jump and heat transfer between the roll and the rolling wire are calculated during the rolling deformation zone. The temperature drop caused by the heat radiation of the rolling wire is calculated in the non-deformed zone. Compared with the actual temperature change when a high-speed wire rod was rolled 1Cr13 martensitic stainless steel φ5.5mm wire, the results show that the calculated values of temperature change is about 3.64% lower than measured.

1. Introduction

The high-speed wire is rolled at high temperature. The heat transfer problem is a complex thermodynamic problem. Most of the plastic deformation work of the wire is converted into heat. The wire is subjected to heat exchange with the external environment through conduction, radiation, and convection through the surface while being deformed. Therefore, the heat transfer problem in the rolling process belongs to the transient heat conduction problem with internal heat source [1].

Some empirical formulas have been well applied in the actual rolling application process. Due to the complexity of the temperature field, the current method of wire temperature field is mostly based on the finite element method. Serajzadeh [2, 3] established a method based on the finite element method. The mathematical model is used to predict the temperature distribution during the rolling process of low carbon steel bars. The predicted surface temperature is consistent with the measurement. C X Yue [4] developed a multi-field coupling numerical simulation technique based on the finite element software MSC.Marc for bar and wire rolling process, and verified the correctness of the model. J Y Lu [5] and S Y Yuan [6] used the finite difference method to establish a three-dimensional temperature field calculation model for hot rolling.

D W Zhao [7] calculated the temperature rise of wire rolling in finishing mill using the analytical method—upper bound triangular velocity field. However, only the temperature rise caused by the deformation of the wire is calculated, and the temperature drop caused by the wire conduction, radiation, and convection is not considered, so the results show that the calculated values of temperature jump is about 11% higher than measured ones.
Due to the high rolling speed and poor heat dissipation conditions of the wire in the rolling process of the finishing mill, the temperature change of the wire in finishing mill is simplified: 1) It is considered that the temperature rise caused by rolling and the temperature drop caused by the heat conduction between the roll and the rolling wire when the wire is in the rolling deformation zone of the finishing mill. 2) The temperature drop caused by the heat radiation of the rolling wire is considered in the non-deformed zone. 3) The convective heat transfer between the rolling wire and the air and the temperature drop caused by the spray ring cooling water splashing are neglected.

2. Temperature rise model during the deformation process of finishing mill

There is no perfect analytical method to solve the temperature field of the rolling deformation zone of the finishing mill, and domestic researchers study it in a finite element method mostly. Johnson [8] proposed the upper bound method for analyzing metal forming using a triangular velocity field, and solved the problems of rolling and drawing successfully. D W Zhao [7] used the triangular velocity field to analyze the upper bound method of metal forming to study the temperature rise method of wire rod finishing mill.

2.1. Study on temperature rise of rolling mill in finishing mill

The temperature change of the wire during the rolling process of the finishing mill is mainly due to the temperature rise caused by the deformation of the deformation zone. The external work of the rolling area is almost all converted into heat. The heat of the wire temperature rise comes from the shear work done by the velocity field velocity discontinuous line in the deformation zone.

\[
\Delta T_d = \frac{\eta W}{mc} = \frac{\eta Pt}{\rho Vc}
\]  \hspace{1cm} (1)

Where the \(\Delta T_d\) is temperature rise caused by the deformation of the wire; the \(\eta\) is coefficient of transformation of plastic deformation into thermal energy, \(\eta=0.95\sim0.98\); the \(W\) is rolling deformation work; \(m\) is the quality of the rolled parts in the deformation zone; the \(P\) is rolling deformation power; the \(t\) is rolling time of the rolled part in the deformation zone; the \(\rho\) is the density of wire; the \(V\) is the volume of the rolled part in the deformation zone; the \(c\) is specific heat of wire.

A company's high-speed wire rolling production line is taken as the research object. It’s consists of 6 roughing mills, 8 medium rolling mills, 4 pre-finishing mills, 8 finishing mills, and 4 reducing sizing mills. The finishing mills of No.19 to No.26 are oval + circular-hole sharp systems, Odd-numbered stand are oval-shaped; even-numbered stand are circular-shaped.

In order to satisfy the condition of the upper boundary triangle velocity field of the plane deformation, assuming that the diameter of the circular rolling wire entering the odd stand is equal to the long axis of this roll pass. For the same reason, the short axis of the elliptical rolling wire entering even stand is equal to the diameter of this roll pass [7].

Figure 1 and Figure 2 are the velocity and velocity diagrams of the upper triangular boundary of plane deformation full-adhesion rolling of the even stand. According to the above, the width direction of the rolling wire is not deformed, and AC and BC are the discontinuous speeds line, that is, the temperature rise "hot line" [8].
According to Figure 1, Figure 2 and sine theorem it can be obtained as

\[ AC = \frac{D_h}{2 \sin \alpha_o} \quad BC = \frac{D_h}{2 \sin \alpha_i} \]  

\[ \frac{v}{\sin(180 - \alpha_o)} = \frac{\Delta V_{ac}}{\sin \phi} \quad \frac{v}{\sin \alpha_i} = \frac{\Delta V_{ac}}{\sin \phi} \]  

The speed discontinuity can be gotten, \( \Delta V_{ac} \), \( \Delta V_{bc} \) are given as

\[ \Delta V_{ac} = \frac{v \sin \phi}{\sin \alpha_o} \quad \Delta V_{bc} = \frac{v \sin \phi}{\sin \alpha_i} \]  

The power consumption per unit time in the AC and BC directions which is accorded with upper bound is given as

\[ P' = k \Delta V_{ac} AC + k \Delta V_{bc} BC \]  

Eq.(2), Eq.(3) and Eq.(4) are substituted to Eq.(5), it can be obtained as

\[ P' = kv \sin \phi \left( \frac{D_h}{2 \sin \alpha_o} + \frac{D_i}{2 \sin \alpha_i} \right) \]  

It can be seen from Figure 1 the length of contact arc is given by

\[ l = \frac{D_h}{2 \sin \alpha_o} + \frac{D_i}{2 \sin \alpha_i} \sin \alpha_o = D_h l (2l - \frac{D_i}{\sin \alpha_i}) \]  

Eq.(7) is substituted to Eq.(6), the \( P' \) can be obtained

\[ P' = kv \sin \phi \left( \frac{D_i^2 + D_h D_i}{2D_h \sin^2 \alpha_i} - \frac{2l D_h}{D_h \sin \alpha_i} \right) + \frac{2l^2}{D_h} \]  

Eq.(9) is obtained through Eq.(8), it is differentiated

\[ \frac{dP'}{d\alpha_i} = 0 \]

\[ \sin \alpha_o = \frac{D_h + D_i}{2l} \]  

Eq.(9) is substituted to Eq.(7), Eq.(10) can be obtained as fellow

\[ \sin \alpha_o = \sin \alpha_i \]
It can be seen from Figure 1 and Eq. (10) that when \( \alpha_0 = \alpha_1 \), the \( P^* \) equal to \( P^*_{\text{min}} \), which is minimum value of upper bound. Eq.(10) is substituted to Eq.(6), and according to the symmetry of the deformation region and the width is \( D_1 \), Eq.(11) is obtained as

\[
P^*_{\text{min}} = \frac{k\sin \varphi (D_0 + D_1)D_1}{\sin^2 \alpha_i}
\]  

(11)

2.2 Finishing mill temperature rise model

According to the upper bound theorem, the external power \( P^* \) is equal to the minimum upper bound power \( P^*_{\text{min}} \). The calculation model of the temperature rise derived from the upper bound triangle velocity field of deform of high-speed wire finishing is obtained by Eq. (11) bring into Eq. (1), which is rewritten as

\[
\Delta T = \frac{nTvD_1}{\rho C \sin^2 \alpha_i}
\]  

(12)

2.3 Calculation of the volume of the deformation zone

Considering that the rolling is a complex deformation process in the deformation zone, it is not well deformed according to the ideal hole type, and it is difficult to calculate it by conventional differential methods. According to the rolling program table, the entry area of the rolling wire is \( A_0 \) or the exit area \( A_1 \). Since the entrance speed of the rolling wire is \( v_0 \) and the exit speed \( v_1 \), the volume of the deformation area is given by

\[
V = A_0 v_0 = A_1 v_1
\]  

(13)

From Figure 2, according to the sine theorem

\[
v = \frac{v_1 \sin \alpha_i}{\sin(\varphi + \alpha_i)}
\]  

(14)

Eq.(13), Eq.(14) are substituted to Eq.(12), then the calculation formula for the temperature rise of the wire in the deformation zone of the even stand of the finishing mill which is given as

\[
\Delta T_e = \frac{nTv_1 (D_0 + D_1)D_1}{\rho A_0 C \sin \alpha_i \sin(\varphi + \alpha_i)}
\]  

(15)

Similarly, the formula of odd stand is given as

\[
\Delta T_o = \frac{nTv_1 (D_0 + D_1)D_0}{\rho A_1 C \sin \alpha_i \sin(\varphi + \alpha_i)}
\]  

(16)

3. Temperature drop model of finishing mill rolling process

For the high speed and small interval of two stand of the finishing mill, the temperature drop caused by convection is neglected. The temperature drop caused by conduction and radiation are considered.

3.1. Temperature drop caused by conduction

During the rolling process of the wire rod, especially for the rolling finishing zone of martensitic stainless steel, the temperature of the rolled wire is higher, and the roll needs to be cooled by the cooling water, the temperature of roll is lower than 100 ° C. The rolling wire and the roll are basically at fully adhered state, the heat transfer between the two is not negligible in the rolling deformation zone. This process of heat conduction is very complicated, so the Fourier simplify heat conduction law is used as follow

\[
Q = \lambda A \frac{T_i - T_{i-1}}{L}
\]  

(17)
Where $Q$ is the amount of heat transferred; $\lambda$ is thermal conductivity of the rolled wire; $A'$ is the cross-sectional area perpendicular to the heat flow; $L$ is the distance in the direction of heat flow; $T_1$ is the temperature of the rolled wire; $T_2$ is the temperature of the roll; $t$ is rolling time of the rolled part in the deformation zone.

The thickness of the two different media of rolling wire and roll are $\delta_w$ and $\delta_g$. The heat transfer formula between the two media is given as

$$Q = \frac{A(T_1 - T_2)\mu}{(\delta_w / \lambda + \delta_g / \lambda_h)}$$

(18)

The formula of heat transfer during the deformation process is given as

$$\Delta T_r = \frac{Q}{V \rho C_0} = \frac{Q}{A \mu V \rho C_0}$$

(19)

Eq.(18) is substituted to Eq.(19), the formula of temperature drop $\Delta T_r$ is obtained as fellow

$$\Delta T_r = \frac{A(T_1 - T_2)}{(\delta_w / \lambda + \delta_g / \lambda_h)A \mu V \rho C_0}$$

(20)

In the formula of $\Delta T_r$, the $\delta_w$ is taken according to the average thickness of the rolled wire in the deformation zone, that is $\delta_w = (D_w + D_i)/2$, since the bite angle of the model is small, so $\delta_i = 2D - (D_w + D_i)/2$

Where $\lambda = 0.036 \text{ J/(mm \cdot s \cdot °C)}$, $\lambda_h = 0.0293 \text{ J/(mm \cdot s \cdot °C)}$.

3.2. Temperature drop caused by radiation

For the roll gap is small and most of the area is wrapped by the roll when the rolling wire is in the deformation zone, so the heat radiation is negligible. A large amount of heat will be radiated to the periphery due to the higher temperature. The temperature drop formula of the rolled wire due to radiation is given as

$$\Delta T_r = 0.0067 \frac{F t_k}{m_j} \left( \frac{T}{100} \right)^4$$

(21)

Where the $F$ is the heat dissipation area of the rolled piece between the stand; $T_k$ is cooling time; $T$ is the absolute temperature of the surface of the rolled piece; $m_j$ is the weight of the rolled wire between the stand.

The cooling time is the distance between two adjacent stands to remove the deformation zone which is given as $t_k = 920 - (l_n + l_{n+1})/2$, so the $t_k$, $m_j$ are given as

$$t_k = \frac{d_j}{v_1}, \quad m_j = A_d \rho$$

(22)

The heat dissipation area of the rolled wire between two stands is divided into two cases, they are circle and ellipse which is given as

$$F_{ov} = d_j (\pi D_i + 2(D_w - D_i)), \quad F_c = d_j \pi D_i$$

(23)

Where $F_{ov}$ is the area of oval wire and $F_c$ is the area of circular wire.

Eq.(22) and Eq.(23) are substituted to Eq.(21), the temperature drop of the rolled wire due to the radiation can be determined.

4. Temperature change of the finishing mill rolling process

The temperature change of the rolling wire in a rolling mill of a finishing mill is:
Increasing the temperature drop between the two stands, it is the rolling temperature of next stand which is given as

\[
\Delta T = T + \Delta T_\text{d} - \Delta T_\text{i}
\]

(24)

4.1. Rolling temperature rise calculation of finishing mill

The temperature rise of rolling in No.19 is calculated firstly. The wire is martensite stainless steel 1Cr13, the diameter of the inlet of finishing mill is \(\Phi16.7\text{mm}\), the exit is \(\Phi7.1\text{mm}\). According to the finishing motor speed and speed ratio, the rolling speed of each stand can be calculated. The calculation parameters of finishing rolling are calculated according to the rule that the rolling second flow is uniform, as shown in Table 1.

| Pass | Shape | Mat section \(A/\text{mm}^2\) | Roll diam. \(D/\text{mm}\) | Output speed \(v_1/\text{ms}^{-1}\) |
|------|-------|-------------------------------|--------------------------|-------------------------------|
| 18   | round | 218.50                        | 313.9                    | 9.53                          |
| 19   | oval  | 172.40                        | 209.8                    | 12.08                         |
| 20   | round | 136.04                        | 206.6                    | 15.31                         |
| 21   | oval  | 112.70                        | 211.3                    | 18.48                         |
| 22   | round | 93.36                         | 208.9                    | 22.30                         |
| 23   | oval  | 74.10                         | 211.9                    | 28.10                         |
| 24   | round | 58.81                         | 210.1                    | 35.41                         |
| 25   | oval  | 48.19                         | 212.9                    | 43.21                         |
| 26   | round | 39.49                         | 211.3                    | 52.72                         |

The measured deformation resistance of martensite stainless steel is founded in Ref. [9], \(\sigma\) is given as

\[
\sigma = 15046.84 \times \exp(-3.4298 \times T) \times e^{(0.108572 \times (0.3774 - 0.35466 \times T))} \times \varepsilon
\]

(26)

\[
\varepsilon = \ln \left( \frac{D_0}{D_1} \right), \quad \bar{\varepsilon} = 2\pi \sqrt{\frac{D_0 - D_1}{R}} \times \frac{T_0}{T_1}
\]

(27)

Where the \(\sigma\) is deformation resistance. The \(\varepsilon\) and \(\bar{\varepsilon}\) are degree of deformation (relative deformation) and average deformation rate; \(T_0\) is rolling temperature (\(T = T_0 + 273\)).

The measured temperature of the inlet thermometer of finishing mill is 976.200\(^\circ\)C. According to the radiation formula, the temperature drop is 1.200\(^\circ\)C from the pyrometer to the entrance of the No.19 mill. So \(T_0 = 975.000\)\(^\circ\)C. The \(\varepsilon_0\) and \(\bar{\varepsilon_0}\) are calculated by Eq.(27). Then the \(\sigma\) is obtained by Eq. (26). \(\sigma = 326.151\) (MPa), and \(k_{\varphi} = 188.303\text{(MPa)}\) is obtained by \(k = \sigma / \sqrt{3}\).

According to the process of material forming [10], when the stable rolling stage is reached, the centre angle of the resultant action point is half of the bite angle, \(\alpha = 2\varphi\)

\[
\sin \varphi = \sin \frac{\alpha}{2} = \frac{1}{2} \sqrt{\frac{D_0 - D_1}{R}}
\]

(28)
It can be obtained \( \sin \varphi_0 = 0.0916, \varphi_0 = 0.0917 \). \( \alpha_i \) is given in Eq. (11) \( \alpha_i = \arcsin \left( \frac{D_i + D_j}{2l} \right) \), so \( \alpha_{19} = 0.8894 \).

For stainless steel 1Cr13 in the range of \( 950--1150 \) °, it can be obtained \( \rho = 7579 \) kg • m\(^{-3}\), \( \eta = 0.95 \), \( c = 550 \) J • kg\(^{-1}\) • °C\(^{-1}\).

The above formula was brought into Eq. (19) to obtain a temperature rise of 19.196 °C due to rolling of the finishing mill No. 19.

4.2. Finishing mill rolling process temperature calculation

Firstly, according to the finishing mill inlet temperature and the distances of thermometer to No. 19, the inlet temperature of 19 rolling mills was calculated by Eq. (24). According to Eq. (19) and Eq. (23), the rolling temperature rise and the conduction temperature drop of No. 19 are respectively obtained. Then, the radiant temperature drop between No. 19 and No. 20 is obtained according to Eq. (24). No. 20 inlet rolling temperatures is obtained according to Eq. (30). The inlet temperature of each mill and the calculated temperature of the outlet thermometer of finishing mill are obtained in turn, as shown in Table 2.

| Pass | Inlet thermometer | Rolling \( \Delta T_i \)/°C | Conduction \( \Delta T_c \)/°C | Radiant \( \Delta T_f \)/°C | Total \( \Delta T \)/°C |
|------|------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| 19   | 975.000          | 19.196                   | 0.202                    | 0.605                    | 18.390                   |
| 20   | 993.390          | 22.829                   | 0.206                    | 0.555                    | 22.068                   |
| 21   | 1015.457         | 16.430                   | 0.210                    | 0.521                    | 15.699                   |
| 22   | 1031.156         | 18.811                   | 0.214                    | 0.486                    | 18.111                   |
| 23   | 1049.268         | 23.559                   | 0.217                    | 0.503                    | 22.839                   |
| 24   | 1072.107         | 27.597                   | 0.222                    | 0.468                    | 26.907                   |
| 25   | 1099.014         | 21.360                   | 0.227                    | 0.450                    | 20.683                   |
| 26   | 1119.697         | 24.350                   | 0.232                    | 0.428                    | 23.690                   |
| Output thermometer | 1143.388 | ——                        | ——                        | ——                        | 167.188 |

The mean value of difference of the thermometer of the inlet and outlet temperature of finishing mill is 173.280.

4.3. Comparison of theoretical calculations and measured

In Table 2, the “measured” is the difference between the inlet and output thermometer of finishing mill when the Φ5.5mm 1Cr13 is rolled, it is 173.28 °C. The theoretical calculation of the temperature rise of finishing mill is 167.188 °C. The relative error is 3.64% as follow.

\[
\Delta = \frac{173.280 - 167.188}{167.188} \times 100\% = 3.64\%
\]

5. Conclusions

1) Based on the experience of the predecessors, the formula for calculating the temperature rise of the high-speed wire finishing mill by the method of upper bound triangular velocity field is modified.
2) Fourier simplified heat conduction law to solve the temperature drop of the rolling wire can be used to calculate the temperature drop of the high-speed wire finishing mill.
3) The temperature difference between the theoretical calculation results and the measured results in the finishing mill is smaller which is calculated for the Φ5.5mm martensitic stainless steel 1Cr13.
The cause of the deviation is analyzed as fellow: the upper bound method uses the assumption that the long axis is constant for the circle-elliptical pass and the short axis is constant for the elliptical-circle pass. The degree of deformation is reduced, so the temperature rise is smaller than measured results. For that error, this calculation method is in good agreement with the on-site thermometer, and the error is only 3.64%.

4) The analytic methods are used to solve the temperature change of the rolling process, and the accuracy of the results is verified by a large amount of data on site. It is the foundation for the coupling of rolling force and thermal for high-speed wire rolling.

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