Effect of process parameters on mechanical behavior in hot-slab rolling

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1. Introduction

The hot continuous involves in material, geometry and contact nonlinearities, and it is difficult to obtain analytical solution. Trial-rolling method and physical experiment method have thus been often used to study rolling properties over the past decades at the expense of time and cost. Recently, 3D numerical simulation technology has been used to solve rolling problems based on FEM, as numerical simulation method can shorten development periods, and reduce the cost of research and development.

The study of rolling force and energy parameters in the hot rolling process has attracted a lot of attentions in the literature. For example, prediction of rolling pressure and rolling force of wire [1], calculation of rolling pressure of strip [2], simulation of stress and temperature [3], study of plastic deformation of strip [4, 5], and discussion of strain and stress. FEM method and numerical simulations have been proved to be a very powerful tool for prediction of rolling force and energy parameters in rolling process. Some commercial software packages have also been used to simulate the rolling process, for example, the program FORGE3 [6]. The effect of rolling parameters on rolling properties has not yet been fully understood. The effect of rolling parameters on temperature [7], friction stress, rolling force [8, 9], and effective stress and strain [10] were discussed. Friction is the reason for the rolling process to actually take place. It acts as the driving force and has major effect on the product quality and the stability of rolling process. Some researchers studied the effect of reduction [11], width spread [12], and frictional coefficient [13] on the distribution of temperature, stress, and separating force using the frictional shear stress model. To improve calculation accuracy, stiffness of frictional element was corrected by the thickness of frictional element and friction factor [14].

In the present paper, the hot rolling process of a slab is studied by using the rigid-plastic finite element method. The 2D models of the roll and the slab are developed to investigate the effect of different process parameters such as initial rolling temperature, slab thickness, rolling speed, friction coefficient, and reduction rate on the rolling force, normal force, and effective stress distribution. Moreover, friction distribution in the deformation zone is also studied based on 3D models.

2. Modeling

2.1. Analytical formula of rolling force

The microelement body in the deformation zone was usually employed to develop the modeling of rolling force, as shown in Fig. 1.

Under the basic assumptions and equilibrium conditions, the analytical equation of unit force (Karman equation) is obtained based on any microelement body (abcd) in the deformation zone.

$$\frac{dN(x)}{dx} - K \frac{dy}{dx} + \frac{F(x)}{y} = 0$$

where $N(x)$ is unit force, $K$ is metal natural intensity and $F(x)$ is unit friction. It is assumed that contact condition in the deformation zone obeys Coulomb friction model. If the chord is used to represent the contact arc, the distribution of unit pressure can be expressed as

$$N(x) = \frac{K}{\delta} \left[ (\delta + 1) \left( \frac{h_0}{h(x)} \right)^{\delta} \right]$$

where $\delta = 2lh/h_0$, $h_0$ is reduction rate, $h_0$ is initial workpiece height, and $h(x)$ is the height after rolling. It is found that the main factors affecting unit pressure are friction coefficient, roller diameters, reduction rate, workpiece height and tensile force. In fact, the hot rolling of slab belongs to typical thermo-mechanical coupled problem. To describe the relation, the equation shows...
where \([C], \{K\} \text{ and } \{A\}\) are the specific heat matrix, stiffness matrix and conductivity matrix, respectively, \([u], \{T\}, \{F\}\) and \([\Omega]\) are the vectors of displacement, temperature, structural load and heat flow, respectively. The governing partial differential denotes

\[
\frac{\partial}{\partial x}\left(\lambda_{ij} \frac{\partial T}{\partial x}\right) + \dot{q} - \rho c \frac{\partial T}{\partial t} = 0
\]

where \(\dot{q}\), \(\rho\), \(c\), \(t\) and \(\lambda_{ij}\) are heat generation rate per unit volume, density, specific heat, time and thermal conductivity coefficient, respectively. The following conditions are used to solve Eq. (4).

1. Initial and boundary conditions

\[
T(y, t) = T_0 \quad (t = 0), \quad \frac{\partial T(y, t)}{\partial y} = 0 \quad (y = 0)
\]

where \(T_0\) shows initial workpiece temperature.

2. Heat generation due to plastic deformation and friction work.

\[
\dot{q}_{def} = \eta \sigma \varepsilon, \quad \dot{q}_f = \sigma_A v \delta t
\]

3. Heat loss due to thermal exchanges. The main thermal exchanges include conductivity, convection, radiation, and water cooling, which causes the metal surface to be cooled and conversely the rolls gain heat

\[
q_1 = \lambda (T_c - T_s) , \quad q_2 = h_c (T_c - T_a) , \quad q_3 = h_t (T_t - T_s) + \sigma r \varepsilon (T_r - T_s)
\]

where \(q_1\), \(q_2\) and \(q_3\) are heat loss of the metal by conductivity, convection and radiation, and the forced convection of water, respectively \(\lambda\), \(h_c\) and \(h_t\) are conductivity coefficient, convective coefficient and heat transfer coefficient for water cooling, respectively. \(T_c\), \(T_a\) and \(T_t\) show the temperature of workpiece, roll, air and water, respectively. \(\sigma\) and \(\varepsilon\) are Stenfar-Boltzmann constant, and \(r\) is the surface emissivity.

2.2. Material properties

To reduce the computational time, only one half of the geometric model is considered in numerical simulation due to rolling symmetry. The meshes are very dense in the contact zone, as shown in Fig. 2. Thermo-mechanical coupling FEM and isoparametric technology are used to develop the models. The rolls are assumed to be rigid and heat transfer body, and their material is an iron steel of high chromium and the chemical composition is given as: 1.5% C, 0.75% Si, 0.67% Mn, 5.5% Cr, 2.6% Mo, 1.43% V and 1.82% W. The workpiece material is a typical carbon steel and its chemical composition is defined as follows: 0.14% C, 0.62% Mn, 0.27% Si, 0.032% P and 0.041% S. It obeys Von Mises yield criterion and the flow rule. Uniform temperature distribution is assumed throughout the original workpiece. The density of the material is 7850 kg/m³ and the Poisson’s ratio is 0.3. The material’s elastic modulus, heat expansion factor, heat conduction rate and specific heat are the function of temperature.

3. Results and discussion

3.1. Effect of initial workpiece temperature and reduction on rolling force

For the slab rolling, the variation of rolling force \(F\) with initial workpiece temperature \(T_0\) and reduction rate \(r\) is shown in Fig. 3. It is seen that \(F\) reduces with the increasing \(T_0\). Moreover, when \(T_0\) attains certain value, i.e. approximate 1200°C, \(F\) remains invariant even with the continuous increase of temperature. If other conditions are kept unchanged, the increasing \(r\) will increase the length of contact arc and unit pressure. This in turn causes an increase of \(F\) applying on the roll, which results from the increase of contact area and the increase of unit pressure. By comparing reduction rate \(r\) of 20%, 30% and 40% with the reduction rate of 10%, the rolling force increases by 83%, 156% and 226% for the same \(T_0\) of 1000°C, respectively.

3.2. Effect of friction coefficient and roll’s radius on rolling force

Fig. 4 shows the variation of rolling force \(F\) with friction coefficient \(f\) and roll’s radius \(R\). When \(f\) increases, the unit pressure \(p\) increases fast from the entry and exit position to neutral point (a point where shear stress
changes its sign). Accordingly, the total pressure of the workpiece applying on the roll also increases. \( F \) rises with the increasing \( R \). It can be explained that the length of contact arc \( L \) and \( p \) will increase with the increasing \( R \). By comparing \( R = 400 \text{ mm} \), 500 mm and 600 mm with \( R = 300 \text{ mm} \), \( F \) increases by 12\%, 25\% and 39\% for the same \( f \) 0.3, respectively.

3.3. Effect of rolling speed on rolling force

Fig. 4 shows the effect of rolling speed \( v \) on rolling force \( F \). It is found that the larger \( v \) or rotational angular speed \( \omega \) is, the bigger \( F \) is, and the rolling force curve is more remarkable. Rolling time is shorter when the value of \( v \) or \( \omega \) is larger. By comparing speed 500 mm/s with 500 mm/s, there are more peak forces for the lower speed case under the same time step. For example, for No. 188 time increment steps and 0.0002 s per time step, there are 13, 8, 5 and 2 peak forces, respectively. Rolling speed leads to increase the deforming process of the workpiece, and the metal plasticity reduces in the deformation zone. If rolling speed is too high, metal flow speed will increase along rolling and spread directions. The effect of forming then becomes poor and reduces the product quality.

3.4. Effect of workpiece thickness on rolling force

Under the condition of the same other parameters, the effect of different entry thickness \( h_0 \) of the slab on the rolling force is shown in Fig. 6. It is observed that the contact pressure between the slab and the roll increases in the hot rolling process when initial thickness of the slab decreases. When the reduction rate keeps the same, \( h_0 \) is smaller and its deformation is more severe. The curve of rolling pressure reveals multiple pressure peaks in existence, and the amplitude of the rolling force increase with the decreasing \( h_0 \). When the reduction value \( \Delta h \) equals to 20 mm, the rolling force reduces by 33\%, 42\%, 48\% and 52\%, respectively, comparing the initial thickness \( h_0 \) 40 mm, 50 mm, 60 mm and 70 mm with the thickness 30 mm.

3.5. Stress distribution

In hot rolling process, strain, strain rate and temperature can affect stress distribution in the deformation zone.

1. The lowest temperature of the slab occurs at the exit of the deformation zone because the position is in the contact with the roll for more time, which results in more heat loss.

2. The maximum strain rate generally is produced in the entry position of the deformation zone because the deformation occurs in this zone suddenly.

3. Large plastic deformation occurs in the contact zone because the continuous deformation and flow of mental occurs along rolling direction and spread direction. It is observed from Fig. 7 that the maximum effective stress occurs under the roll and at the contact zone. This indicates that the effect of strain is dominant.

3.6. Effect of tension on rolling force

Tension is a major phenomenon in continuous rolling process. It is produced by noncompatibility velocities or reduction among tandem mills. For the multitandem mills (Fig. 8), the tension increases if the exit velocity of stand I (\( v_i \)) is reduced and the entry velocity of stand II (\( v_0' \)) increases. When \( v_1 \) drops, the corresponding forward slip
quantity \((\nu_1 - R \nu_0)/ R \nu_0\) decreases due to the variations of roll speed \(R \nu_0\) or other process parameters, for example, reduction rate \(\nu_1\). In addition, when \(\nu_0\) increases because of the increasing roll speed \(R \nu_0\) or the drop of the backward slip magnitude \((\nu \cos \alpha - \nu_0 \cos \alpha)\), where \(\alpha\) is the biting angle (Fig. 1), thus these cause the slab between mill I and mill II tauten and the increase of the tension.

Since this discontinuity in the friction value causes numerical difficulties, an updated Coulomb model is used for a given normal force, friction force has a step function behavior based upon the relative sliding velocity. This indicates that friction force direction is the opposite of rolling direction, moreover, \(F_f\) is positive in forward slip zone where the exit velocity of the workpiece \(\nu_1\) (Fig. 1) is more than the linear velocity of the roller \(\nu\). It indicates that friction force direction is the opposite behavior based upon the relative sliding velocity. Moreover, if the exit velocity of mill I (\(\nu_1\)) increases or the entry velocity of mill II (\(\nu_0\)) is less than the horizontal component of the linear velocity of the roller \(\nu \cos \alpha\). From Fig. 10, the maximum positive friction force 79.52 kN is more than the maximum negative friction 74.39 kN along the rolling direction. The area of the positive friction zone is bigger than the negative friction zone. It indicates that friction force is the driving force and is also the reason for the process of rolling to actually take place. There is the sticking zone between positive and negative friction, i.e., friction and relative sliding velocity all equal to zero.

For a given normal force, friction force has a step function behavior based upon the relative sliding velocity. Since this discontinuity in the friction value causes numerical difficulties, an updated Coulomb model is used.

\[
f_f = -m \nu_0 \frac{2}{\pi \tan^{-1} \left( \frac{\nu}{\nu_0} \right)} \nu_0 \nu F_f = -m \nu_0 \frac{2}{\pi \tan^{-1} \left( \frac{\nu}{\nu_0} \right)} \nu_0 \nu
\]  

(8)

where \(f_f\) is tangential friction force, \(f_s\) and \(m\) denote contact normal force and friction factor, respectively. \(\nu_1\) is the relative sliding velocity and \(\nu_0\) is a small positive number. Fig. 10 shows 3D finite element models of rolling process and friction distribution. The other parameters of material are identical to those of 2D model. Along rolling direction, \(F_f\) is negative in forward slip zone where the exit velocity of the workpiece \(\nu_1\) (Fig. 1) is more than the linear velocity of the roller \(\nu\). It indicates that friction force direction is the opposite of rolling direction, moreover, \(F_f\) is positive in backward slip zone where the entry velocity of the slab \(\nu_0\) is less than the horizontal component of the linear velocity of the roller \(\nu \cos \alpha\).
10 and 30 with $r$ 10%, the maximum normal force increases by 13.51 and 32.38%, respectively, and this keeps the same with the results of Shahani [15].

4. Conclusions

Based on thermo-mechanical coupled FEM, a mathematical model has been developed to predict flow stress, rolling force, contact normal force and friction force during hot continuous rolling process. The simulation results were found to be in good agreement with the reported results in the theoretical analysis and experiment measurements in the literature. The conclusions have been obtained and verified by numerical simulation for the hot rolling process.

1. An increase of the initial slab temperature and thickness will reduce the rolling force. Temperature, train and train rate have major effect on stress distribution and the effect of strain is dominant.

2. When the percentage reduction, work-roll radius, friction coefficient and rolling speed increase, the corresponding energy-force parameters increase.

3. The positive friction is more than the negative friction, suggesting that friction acts as the driving force in the rolling process.

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References


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Summary

This paper studies hot rolling process of typical low carbon steel by using rigid-plastic finite element
method. Numerical simulations are carried out to examine the effects of the percentage of reduction rate, work-roll radius, frictional coefficient, rolling speed, tension, initial rolling temperature and initial slab thickness on rolling force and deformation behavior of the slab. It is found that rolling force increases with the increases of reduction rate, rolling speed, frictional coefficient and radius. The initial rolling temperature, initial slab thickness and tension have also important effects on rolling force, and it will decreases remarkably by increasing the parameters. Moreover, it is also found that rolling force remains unchanged when initial slab temperature reaches certain value. The friction and effective stress distribution in the slab are obtained for the steady-state rolling process. The positive friction in backward slip zone is found to be greater than the negative friction in forward slip zone along rolling direction, indicating that friction acts as the driving force in the rolling process.

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