

Friction Estimation and Roll Force Prediction during Hot Strip Rolling

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Abstract: A mathematical model of friction coefficient was proposed for the roll force calculation of hot-rolled strips. The online numerical solving method of the roll force calculation formula based on the proposed friction model was developed and illustrated by the practical calculation case. Then, the friction coefficient during hot strip rolling was estimated from the measured roll force by force model inversion. And then, the expression of friction model was proposed by analyzing the calculation process of stress state coefficient, and the model parameters were determined by the shared parameter multi-model nonlinear optimization method. Finally, the industrial experiments demonstrated the feasibility and effectiveness of the related models. The accuracy of the new roll force model based on the built friction model was much higher than that of the traditional Sims model, and it could be applied in the online hot rolling process control.

Key words: hot rolling; roll force; friction coefficient; soft measurement; multi-objective optimization

Roll force is a key parameter in the online process control of hot strip rolling, and its calculation accuracy influences thickness precision, shape quality and rolling stability of hot-rolled strips directly^[1-3]. Under the assumption that full sticking friction occurs on entire contact arc, Sims solved the Orowan differential equation and obtained an analytical solution of rolling pressure, neutral angle and roll force for hot rolled strips^[4]. A major advantage of the Sims model is that the friction behavior is not required, and the friction effect is mainly considered in the geometric term formula of stress state coefficient. For hot strip rolling with a high and constant friction, the Sims model shows excellent prediction accuracy, together with a powerful online adaptation technique^[5]. It has been widely used in the online process control for hot strip mills now. However, the friction between rolled piece and work rolls can change significantly owing to variations of rolling conditions such as strip temperature, material grade, oxide scale, rolling speed and reduction, etc. The varying friction behavior with rolling conditions cannot be considered effectively in the Sims model because of the strict assumption mentioned above^[5].

Therefore, it is necessary to develop a new online roll force model to improve the setting and control accuracy, which is more realistic in terms of friction and sensitive under different rolling conditions.

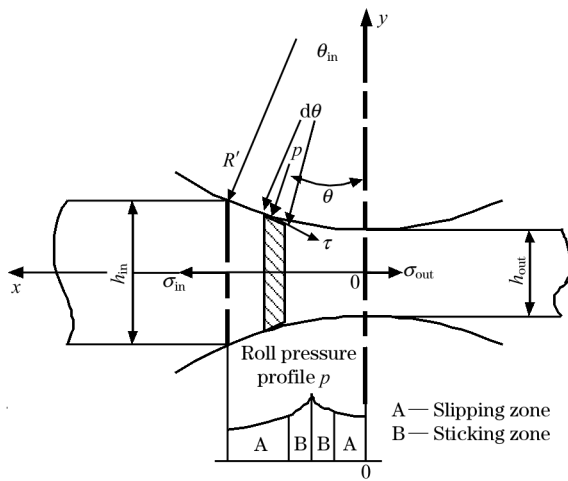
The friction between rolled strip and work roll plays a critical role in hot strip rolling process. Friction coefficient has a direct effect on the rolling pressure distribution along the contact arc and the roll force generated in the roll bite^[6]. Therefore, it is important to establish a mathematical model which can characterize the friction behavior under different rolling conditions^[7,8]. As is well known, the measurement or estimate of friction coefficient which can be obtained directly or indirectly during rolling process is required in developing the prediction model of friction coefficient. In the direct method, the pin transducers are imbedded into the roll surface to measure shear stress and normal pressure along the contact arc. The friction coefficient is then calculated from measured normal pressure and shear stress. This technique has been used extensively in cold rolling of steels as well as cold and hot rolling of Al and its alloys. However, it cannot be used reliably for hot rolling of steel because of surface oxide scale

of work rolls^[7]. Hence, the indirect measurement method such as force model inversion or forward slip model inversion is used to determine friction coefficient during hot strip rolling, which provides an approach to establish the mathematical model of friction coefficient^[9-11].

In this study, the online roll force model with friction effect was developed, based on the improved Karman equation with the slipping and sticking friction condition, and a new mathematical model of friction coefficient was proposed to calculate the online roll force for hot-rolled strips. Moreover, the prediction accuracy of the related models was validated by industrial experiments.

1 Online Roll Force Calculation Formula with Friction Effect

There is normal pressure perpendicular to roll surface tangent of contact arc and friction stress parallel to roll surface tangent. The related parameters are shown in Fig. 1.



θ_{in} —Contact angle of entrance plane; θ —Contact angle of any slice; R' —Deformed work roll radius; p —Normal pressure; τ —Friction stress; σ_{in} —Entrance tension; σ_{out} —Exit tension; h_{in} —Entrance thickness of rolled piece; h_{out} —Exit thickness of rolled piece.

Fig. 1 Stress balance relationship of a slice in roll bite

The roll force of unit width strip can be calculated by the integral calculus of the vertical component of normal pressure and friction stress^[6]:

$$P = R' \cdot \int_0^{\theta_{in}} p \cdot \cos\left(\theta - \frac{1}{2}\theta_{in}\right) d\theta + R' \cdot \left[\int_{\theta_N}^{\theta_{in}} \tau \cdot \sin\left(\theta - \frac{1}{2}\theta_{in}\right) d\theta - \int_0^{\theta_N} \tau \cdot \sin\left(\theta - \frac{1}{2}\theta_{in}\right) d\theta \right] \quad (1)$$

where, P is the roll force per unit width; and θ_N is the neutral angle.

The friction is divided into slipping friction and

sticking friction, and the corresponding friction stress of the contact surface is listed as follows:

$$\tau = \pm \mu \cdot p, \quad \mu \cdot p < k \quad (2)$$

$$\tau = \pm k, \quad \mu \cdot p \geq k \quad (3)$$

where, μ is the friction coefficient; and $2k$ is the flow stress. The plus sign in Eqs. (2) and (3) shows backward slip zone, while the minus sign shows forward slip zone. When friction stress is smaller than the shearing yield limit of materials, slipping friction occurs; otherwise, sticking friction occurs.

Combined with the stress balance relationship, friction rules, geometrical conditions and plastic equation, the modified Karman differential equation of the normal pressure in the roll bite is deduced as follows^[6,12]:

$$\frac{dp}{d\theta} = g_1(\theta)p + g_2(\theta), \quad \mu \cdot p < k \quad (4)$$

$$\frac{dp}{d\theta} = g_3(\theta), \quad \mu \cdot p \geq k \quad (5)$$

$$g_1(\theta) = \frac{\mp \mu \sec\theta(2R' + h \sec\theta)}{(1 \pm \mu \tan\theta)h} \quad (6)$$

$$g_2(\theta) = \frac{h \frac{d(2k)}{d\theta} + 2R'(2k) \sin\theta}{(1 \pm \mu \tan\theta)h} \quad (7)$$

$$g_3(\theta) = 2k \cdot \left\{ \frac{2R'}{h} \sin\theta \cdot (1 \mp \frac{1}{2} \tan\theta) \mp \left(\frac{R'}{h} \cos\theta + \frac{1}{2} \sec^2\theta \right) \right\} + (1 \mp \frac{1}{2} \tan\theta) \frac{d(2k)}{d\theta} \quad (8)$$

where, h is the height of any slice. The plus sign in the denominator of Eqs. (6), (7) and (8) represents backward slip zone, while the minus sign represents forward slip zone.

Eqs. (4) and (5) are the modified Karman equations involving slipping and sticking friction and overcome the disadvantage of the original Karman equation only involving slipping friction, which can be thus used to analyze hot strip rolling process^[6].

1.1 Numerical solving method

Eqs. (4) and (5) are the differential equations with boundary conditions, which can be solved by the numerical method. The boundary conditions are determined by stress balance equations of the entrance and exit slice in the roll bite. And then, the 5-order Runge-Kutta method is used to solve the differential equation to obtain the distribution of normal pressure along the contact arc^[6].

In the solving process, the deformation zone is divided into many slices, as shown in Fig. 2. At the entrance of the contact arc ($\theta = \theta_{in}$), the boundary condition is determined by the stress balance equation

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