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Establishment of mathematical moment model in twin casting rolling rolls①

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[Abstract] In continuous casting rolling process, the deformed body is different from the hot rolling strip. The metal in casting rolling zone is first assumed to be viscous fluid and the mathematical model of casting rolling force is established, then the calculating formula for casting rolling torque is derived. In addition, considering the effects of deforming cone and appendant torque of rotary junction's sealing ring, the calculating model which accords with casting rolling condition is found out. Theoretical formula is proved by experiment.

[Key words] continuous casting rolling; moment model; plate and strip; viscous fluid

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1 INTRODUCTION

Continuous casting rolling is a kind of new technology to produce metal strip. The melted metal is directly poured into a couple of rotational casting rolling rolls. In casting rolling zone, the melted metal is cooled, crystallized, deformed, then the strip is produced. When we determine the driven power in casting rolling, it is needed to find out the value of casting rolling torque. In the past people simply looked upon the casting rolling strip as hot rolling plate[1,2]. So they directly cited the calculating formula of rolling torque for hot rolling plate. This method brought on larger error. In fact, in the casting rolling deforming zone, metal is a viscous fluid that changing from semisolid state to solid state. However, the assumed premise of the rolling torque formula for the hot rolling strip is that the metal in the casting rolling deforming zone is a rigid-plasticity body[3]. The difference between two methods is very large. In this paper, the deforming metal of casting rolling zone is looked upon the viscous fluid, the effects of the deformed cone and additional torque of rotary junction's sealing ring are considered, therefore the calculating model is found out in accordance with casting rolling condition. The establishment of this computation model will provide theoretic reference for the design of casting rolling equipment.

2 CASTING ROLLING TORQUE

The driving torque M on the output axle of motor in casting rolling includes three resistant torques, i. e., casting rolling torque M_z, zero load torque M_k and friction torque M_m. They can be expressed in

$$M = \frac{M_z}{i} + M_k + M_m \tag{1}$$

where i is the ratio of the transmitting system.

The casting rolling deforming zone, as shown in Fig. 1, is different from the deforming zone of plate or strip. It is divided into three zones: condensed zone l_3, crystalline zone l_2 and solid state deforming zone l_1. Concerning the length of each zone it may be seen from Refs. [4, 5]. The crystalline zone and the solid state deforming zone are related to casting rolling torque. We obtain

$$M_z = 2M_{z1} + M_{z2} \tag{2}$$

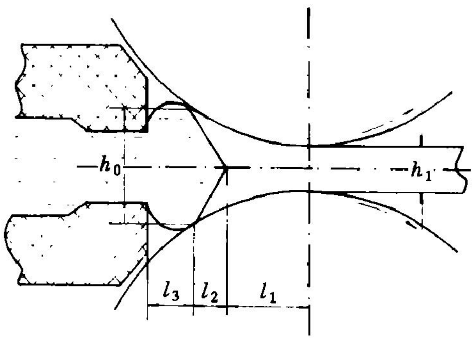

Fig. 1 Casting rolling deforming zone

2.1 Resistant torque M_{z1} resulted from plastic bending of solidification cone

The solidification cone in the crystalline zone may be simplified as cantilever beam whose thickness is variable(as shown in Fig. 2). When solidification cone in crystalline zone come on plastic bending, we have

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$$M_{z1x} = \frac{\sigma_s b h_x^2}{4} \quad (3)$$

where σ_s is the yield stress of solidification cone, MPa; h_x is the thickness of solidification cone at the point x, cm; b is the width of strip, cm.

From Fig. 2 we may obtain the following approximate relation.

$$h_x = \frac{h_0 x}{2l_2} \quad (4)$$

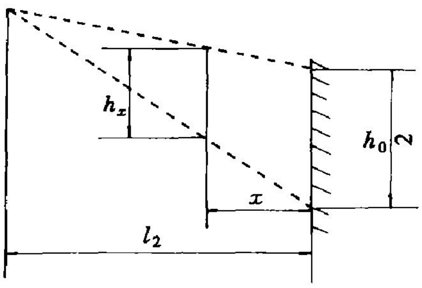

Fig. 2 Solidification cone of crystalline zone

when the solidification cone of crystalline zone come on plastic bending torque, we have

$$M_{z1} = \int_0^{l_2} \frac{\sigma_s b h_0^2 x^2}{16 l_2} dx = \frac{\sigma_s b h_0^2 l_2}{48} \quad (5)$$

where

$$l_2 = 2.1\frac{h\rho v_1}{t_0}(\xi + 0.5nct_0)\left[\frac{h_1+\Delta h}{4\rho}+\frac{1}{2}\right] - 8764.65\frac{nc\lambda\rho h_1 v_1}{\beta^2(h_1+\Delta h)} \ln\left[1+0.24\frac{\beta(h_1+\Delta h)}{\lambda}\right] \quad (6)$$

ρ is the density of solid metal, kg/cm^3; t_0 is the temperature of crystallizer whose of cooling wall is hypothesized to be zero degree, ℃; ξ is the latent heat coefficient in crystal, J/kg; n is the corrected coefficient when we allow for the practical deviation of cross section temperature distribution on metal surface which had curdled, usually, $n = 1/2$; c is specific heat of solid metal, J/(kg·K); λ is the heat transmission coefficient of solid metal, W/(m^{2}K); β is the heat-transfer coefficient of crystallizer's material, cm^2/s; h_1 is the outlet thickness of strip, cm; Δh is the absolute reduction (cm); h_0 is the entry thickness, cm; v_1 the is outlet velocity of strip, cm/s.

2.2 Casting rolling torque in solid-state deforming zone M_{z2}

The deforming torque M_{z2} of this zone can be found product by multiplying force and arm of force. From Fig. 3, we may see that the torque caused by horizontal force maintains equilibrium, and that the deforming torque M_{z2} can be found by multiplying vertical component force acted on a casting rolling roll by the element and the corresponding arm of force. We obtain

$$M_{z2} = b\int_0^{l_1} p_y x\,dx + b\int_q^{l_1} \tau_y x\,dx - \int_0^{q} \tau_y x\,dx \quad (7)$$

where p_y is the vertical component of unit pressure, MPa; τ_y is the vertical component of unit friction stress, MPa.

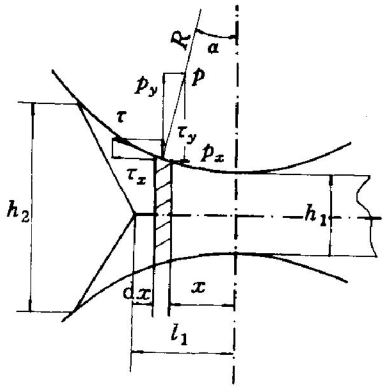

Fig. 3 Elementary forces acting on casting rolling deforming zone

Considering that the influence of unit friction stress τ_y upon deforming torque is far less than unit pressure p_y; so we can simplify that

$$M_{z2} = b\int_0^{l_1} p_y x\,dx \quad (8)$$

From Refs. [6, 7], we know that the distributing formula of unit pressure in deforming zone can be expressed as follows

$$P = \frac{\sigma l_1}{\sqrt{h_1 \Delta h}} \arctg \sqrt{\frac{\Delta h}{V}} x - \sigma \quad (9)$$

where σ is the resistance of deformation, MPa; V is the volumetric coefficient, cm^3.

Noting that

$$p_y = p\cos\alpha \quad (10)$$

Because α is the function of x, according to the geometric relation of Fig. 3, we can obtain

$$\cos\alpha = R - \frac{x^2}{R} \quad (11)$$

where R is the radius of casting rolling roll, cm.

Synthesizing Eqns. (9) ~ (11), we may write as follows

$$M_{z2} = b\int_0^{l_1} p\cos\alpha x\,dx = b\int_0^{l_1}\left[R - \frac{x^2}{R}\right] \cdot \left[\frac{\sigma l_1}{\sqrt{h_1\Delta h}}\arctg\sqrt{\frac{\Delta h}{V}}x - \sigma\right] x\,dx \quad (12)$$

Integration gets

$$M_{z2} = \frac{bKl_1^2}{4Rv}\left[\frac{R^2}{l_1}(2l_1^2\lambda_1 + \mu^3\lambda_1 - l) - \frac{l_1^2}{3}(3l_1\lambda_1 - 1) + v(l_1^2 - 2R^2)\right] \quad (13)$$

where $\lambda_1 = \arctg \mu l_1$,

$\mu = \sqrt{\frac{\Delta h}{V}}$,

$v = \sqrt{h_1 \Delta h}$.

3 IDLING TORQUE M_k

The idling torque is calculated from the weight of the rotating components and the radius of the frictional circles of their bearings. It is obviously equal to the sum of the torques, which are required to drive each component. After the idling torque is converted to the motor shaft, it can be express as follows[8]:

$$M_k = \sum \frac{G_n f_n d_n}{2 i_n \eta_n} \qquad (14)$$

where G_n is the load acting on bearing, being equal to the mass of the given component, kg; f_n is frictional coefficient in the bearings; i_n is the gear ratio of the motor to the calculated component; d_n is the average frictional diameter of the bearings, cm; η_n is the efficiency of transmission device from motor to calculated component.

4 TORQUE OF ADDITIONAL FRICTIONAL FORCES

Usually, when calculating the torque of additional friction force we mainly consider the torque of friction force caused by the bearing of the rolls and that in the driving mechanism of casting rolling mill. Because of the particularity of casting rolling technology, we must install rotary couplers which are used to feed and drain water for the rotary casting rolling rolls. Hence, the torque of additional friction force arises in a couple of sealing rings in the rotary coupler, when the casting rolling rolls are running. It can be expressed as follows:

$$M_{m1} = \frac{Ff_2}{20}(d_1 + d_2) \qquad (15)$$

where F is the casting rolling pressure (the load on the bearing of casting rolling rolls).

According to Refs. [6, 7], we obtain

$$F = FA = A\left[\sigma\sqrt{\frac{R\bar{h}}{\Delta h}}\ln\left(\frac{h_0 h_1}{\bar{h}^2}\right) + \frac{\sigma_q - \sigma}{2}\right] \qquad (16)$$

where A is the horizontal projection of the contact area in deforming zone(cm^2); σ is the deforming resistance of deformed metal at the exit (MPa). $\bar{h} = (h_0 + h_1)/2$ is the average thickness of strip, cm; σ_q is the forward tensile stress, MPa; f_2 is the friction coefficient of roll neck and sealing ring, its value ranging from 0.31 to 0.35 (when casting rolling rolls are new, we use greater value, per contra, we use smaller value); d_1, d_2 are the diameters of roll necks in the water feeding and draining, cm.

Thus, the total torque M_m of additional friction forces can be expressed as follows:

$$M_m = M_{m1} + M_{m2} + \left(\frac{1}{\eta} - 1\right)\frac{M_z + M_{m2}}{i} \qquad (17)$$

where M_{m2} is the torque of additional friction forces of the bearing in casting rolling rolls, $M_{m2} = Fdf_1$, KN·m; d is the diameter of casting rolling rolls at the bearing's join, cm; f_1 is coefficient of friction in the bearings; i is the ratio of transmitting system; η is total efficiency of transmitting system.

5 ANALYSIS AND COMPARISON BETWEEN THEORETICAL VALUE AND EXPERIMENTAL RESULT

The casting rolling torque is tested by experiment in practical casting rolling production to prove the exactitude of theoretical formulas. A gang of four strainometers respectively stick the upper and lower to transmission shafts in the direction of axis 45° angle. They combine with themselves into a pan bridge as the torque sender. Signal of slip ring is magnified by strain gauge. Then, it is connected to a device which portable computer of collect, measure and analyze by computer, so the signal can be recorded and analyzed.

Here, we make a special test for the friction torque caused by rotary couplers. Our method is that casting rolling mill is running under no-load. At this time we measure the torque in both cases, i. e., with rotary couplers and without them.

The measured data in the first case is the sum of the idle torque when the casting rolling torque is zero and the torque of additional friction in transmitting system. The measured data in the second case do not include the friction torque caused by the rotary couplers. Taking off the data of the second case from that of the first case, the result is the value of

Table 1 Comparison between theoretical value of casting rolling torque and measured value

Material	Raw data/cm		Measured data/(kN·m)		Theoretic data/(kN·m)		Error/%	
	Entry thickness	Radius of casting rolling roll	M	$M_{m1} \times 10^{-3}$	M	$M_{m1} \times 10^{-3}$		
L_3	0.621	6.5	0.676	31.69	0.647	32.44	−4.4	2.3
L_3	0.615	6.5	0.568	29.87	0.569	30.18	−1.6	1.0
L_3	0.986	32.0	58.8	3541	60.86	3532	3.3	−2.5
LF_{21}	0.986	32.0	88.2	3652	86.63	3599	−1.8	−1.47
L_3	1.500	49.0	139.7	6983	136.5	6835	−2.3	−2.2

the torque of additional friction that the rotary couplers bring about.

The theoretically calculated value and the measured value are given in Table 1. From it we can know that both values are identical. The torque of additional friction caused by the sealing ring of the rotary junction is about five percent of total driven torque, so we must consider it when the total driven torque is calculated.

6 CONCLUSIONS

1) The metal in casting rolling zone for the first time is assumed to be viscous fluid, therefrom, we establish the calculating formula for casting rolling torque.

2) The theoretical formulas consider the influence of the deforming cone and the additional torque caused by the rotary junction's sealing ring. So, the calculated result is much more near the practical value.

3) The correctness of the theoretical formulas is proved by experiment, and can be used in project calculation.

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