NUMERICAL SIMULATION FOR WIDE MAGNITUDE AND HIGH SPEED ALUMINUM FOIL MILL ①

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ABSTRACT A mathematical model for wide magnitude and high speed aluminum foil 4-roll mill was established by considering the theories of roll system elastic deformation, roll thermal deformation and distribution of tension stress. Using the model, the shape and cross section profile of aluminum foil rolled were simulated, and the theoretical results are very close to the experimental ones. The theory has very important significance for studying the influence of technical parameters on the shape and improving the controlling accuracy of the foil shape.

Key words aluminum foil roll system elastic deformation roll thermal deformation shape

1 INTRODUCTION

The theory of the foil shape mainly includes the theories of roll system elastic deformation, roll thermal deformation and tension stress distributions. The theories of roll system elastic deformation and roll thermal deformation are relatively perfect among those theories, the theory of tension stress distribution is not perfect although much research works about it have been carried out, so it is difficult to effectively combine them to form a complete and accurate foil shape theory. In order to meet the demands for developing the foil shape technology, the shape calculation theory of high precision should be founded as fast as possible to make it fit wide strip and wide aluminum foil rolling. As the model of distribution of the front tension stress established by variation method can meet the demand of calculation precision in engineering, the theories of roll system elastic deformation, roll thermal deformation and tension stress distribution are combined organically to form the comparatively perfect foil shape theory, and establish the mathematic model of foil shape which is very close to practical production. The model in this paper is applied to simulate the cross section profile of the foil rolled and the shape, the calculated results have good agreement with experimental ones to prove that the theory is correct. The theory has important practical significance for studying the influence of technical parameters on foil shape and improving control precision of the aluminum foil shape.

2 MATHEMATICAL MODEL OF FOIL SHAPE

2.1 Model of roll system elastic deformation

The model of roll system elastic deformation of aluminum foil mill is based upon that of beam with simply supported ends, and is different from that of the strip mill because it has work roll kiss deformation. After appropriate simplification for bearing force state of roll system, the calculating model is shown as Fig. 1, the calculating equations of the roll system elastic deformation are given as follows.

(1) Deflection equation of backup roll in the vertical direction:

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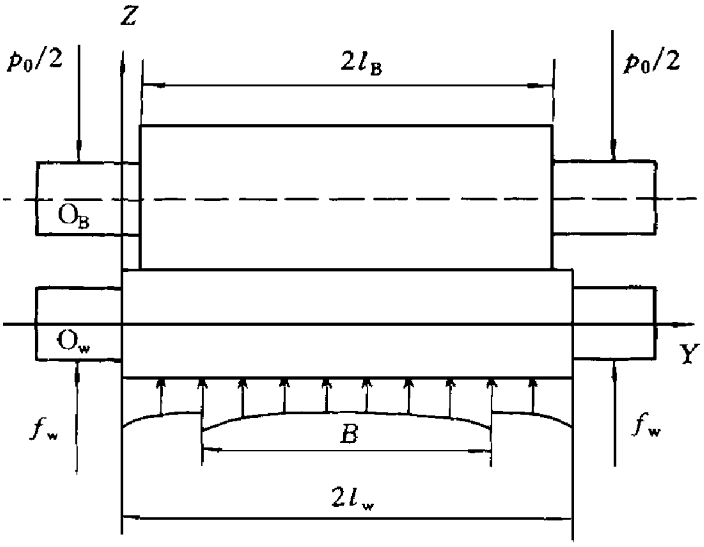

Fig. 1 Calculated model of roll system elastic deformation on aluminum foil mill

$$Z_B(y_i) = \sum_{j=m_S}^{m_T} \alpha_{Bij} q(y_j)\Delta y_j + \alpha_{Bi}\frac{p_0}{2} + \Delta B_{RL}\frac{y_i}{2l_w} + K_B \quad (1)$$

(2) Deflection equation of work roll in the vertical direction

$$Z_W(y_i) = \sum_{j=1}^{n_W} \alpha_{Wij} p(y_j)\Delta y_j - \sum_{j=m_S}^{m_T} \alpha_{Wij} q(y_j)\Delta y_j - \alpha_W f_w + \Delta W_{RL}\frac{y_i}{2l_w} + K_W \quad (2)$$

(3) Force and torque equilibrium equations of backup roll

$$\sum_{j=m_S}^{m_T} q(y_j)\Delta y_j = p_0 \quad (3)$$

$$\sum_{j=m_S}^{m_T} q(y_j) y_j \Delta y_j = p_0 l_w \quad (4)$$

(4) Equation of deformation compatibility between work and backup rolls:

$$Z_B(y_i) = Z_W(y_i) - q(y_i)C_{BW}(y_i) + M_W(y_i) + M_B(y_i) \quad (5)$$

(5) Contacting distinguish equation at the edge of work roll

$$Z_{WW}(y_i) = (Z_W(y_{n_w+1-i}) + Z_W(y_i) - 2Z_W(y_{m_I})) - (M_W(y_{n_W+1-i}) + M_W(y_i) - 2M_W(y_{m_I})) + (h(0) - 2Z_{WS}(0)) \quad (6)$$

If $Z_{WW}(y_i) \geqslant 0$, $p(y_i) = 0$, if $Z_{WW}(y_i) < 0$, corresponding $p(y_i)$ can be computed by Fopll formula.

In eqns. (1) ~ (6):

α_{Wij}, α_{Bij}, α_{Bi}, α_{Wi} —Influence functions of work roll deflection, backup roll deflection, backup push down force and bending force respectively;

$q(y_j)$, $p(y_j)$ —Distribution of pressure between work roll and backup roll and that of rolling pressure (including distribution of work roll kiss pressure);

ΔB_{RL}, ΔW_{RL} —Relative distances between two bearing points of backup and work rolls beam with simply supported ends;

K_B, K_W —Distances of the left extreme points of backup and work rolls relative to the left push down screw;

$M_B(y_i)$, $M_W(y_i)$ —Distributions of backup roll and work roll crown (including thermal crown);

$Z_{WS}(0)$ —Elastic flattening between work roll and aluminum foil at the $y = 0$ point;

m_E, m_F, m_I —Element numbers of the left extreme point, right extreme point and middle point of aluminum foil respectively;

m_S, m_T, n_W —Element numbers of the left extreme point, right extreme point of backup roll barrel and work roll element total numbers respectively;

$C_{BW}(y_i)$ —Distribution of flattening coefficient between rolls if the distributions of thermal crown, $q(y_j)$ and $p(y_j)$ are known, the roll system elastic deformation can be calculated according to eqns. (1) ~ (6).

2.2 Model of roll thermal deformation

The model of roll thermal deformation is the roll divided model of layers structure presented by Refs. [1− 4]. As shown in Fig. 2, the difference equations of the model are established according to the energy conservation law, and solved to get the unsteady state temperature field and distribution of thermal crown. Assume thermal crown of the backup roll is zero, the difference equations of the work roll are founded as follows[1-4].

The first layer:

$$\frac{2\pi}{S}\varphi_1\frac{\bar{\Phi}(j,2,t)-\bar{\Phi}(j,1,t)}{\bar{\varphi}_2-\bar{\varphi}_1}+[\bar{\Phi}(j+1,1,t)+\bar{\Phi}(j-1,1,t)-2\bar{\Phi}(j,1,t)]/\Delta^2=\beta^2\frac{\bar{\Phi}(j,1,t)-\bar{\Phi}(j,1,t-\Delta t)}{\Delta t}\qquad(7)$$

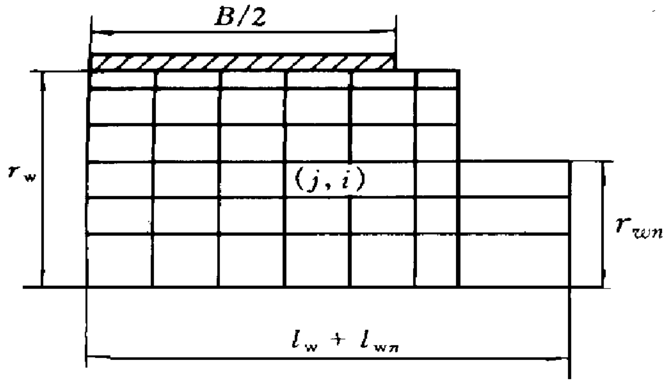

Fig. 2 Divided elements of temperature and thermal crown distributions of work roll

The middle layer

$$\frac{2\pi}{S}\varphi_i\frac{\bar{\Phi}(j,i+1,t)-\bar{\Phi}(j,i,t)}{\bar{\varphi}_{i+1}-\bar{\varphi}_i}-\frac{2\pi}{S}\varphi_{i-1}\frac{\bar{\Phi}(j,i,t)-\bar{\Phi}(j,i-1,t)}{\bar{\varphi}_i-\bar{\varphi}_{i-1}}+[\bar{\Phi}(j+1,i,t)+\bar{\Phi}(j-1,i,t)-2\bar{\Phi}(j,i,t)]/\Delta^2=\beta^2\frac{\bar{\Phi}(j,i,t)-\bar{\Phi}(j,i,t-\Delta t)}{\Delta t}\qquad(8)$$

The outer layer (n layer)

$$-\frac{2\pi}{S}\varphi_n H_0\bar{\Phi}(j,n,t)+\frac{2\pi}{S}\varphi_n(M+Q_0)-\frac{2\pi}{S}\varphi_{n-1}\frac{\bar{\Phi}(j,n,t)-\bar{\Phi}(j,n-1,t)}{\bar{\varphi}_n-\bar{\varphi}_{n-1}}+[\bar{\Phi}(j+1,n,t)+\bar{\Phi}(j-1,n,t)-2\bar{\Phi}(j,n,t)]/\Delta^2=\beta^2\frac{\bar{\Phi}(j,n,t)-\bar{\Phi}(j,n,t-\Delta t)}{\Delta t}\qquad(9)$$

In eqns. (7) ~ (9)

$$\beta^2=\frac{C_W\rho_W}{\lambda_W}r_W^2$$

$$H_0=\frac{r_W}{\lambda_W}(\alpha_R+\alpha_A+\alpha_C)$$

$$M=\frac{r_W}{\lambda_W}(\alpha_R\Phi_1+\alpha_A\Phi_A+\alpha_C\Phi_C)$$

$$Q_0=\frac{r_W}{\lambda_W\theta_0}[\varphi(1+\frac{1-\varphi}{\varphi}\cdot\frac{\alpha_R}{\alpha_F})Q_\mu+0.5\frac{\alpha_R}{\alpha_F}Q_m+Q_f]$$

$$\alpha_R=\frac{\alpha_F\alpha_W}{\alpha_F+\alpha_W}$$

$$\alpha_F=\frac{C\rho v_0 H}{2\pi r_W}$$

where φ —Ratio of friction heat absorbed by work roll;

C_W, ρ_W —Specific heat and density of work roll;

λ_W —Thermal conductivity parameters of work roll;

S —Each layer section;

t, Δt —Time and time step;

Δ —Relative quantity of divided width along roll barrel (no dimension);

$\bar{\Phi}$, Φ_1, Φ_A, Φ_C —Relative quantities of roll temperature, aluminum foil temperature at the entry, atmosphere temperature and coolant liquid temperature;

φ_i, $\bar{\varphi}_i$ —Radius and average radius of each layer;

α_A, α_C —Convection heat-exchanging parameters between work roll and atmosphere, work roll and coolant liquid;

α_W —Equivalent heat-exchanging parameter between work roll and aluminum foil;

Q_m, Q_μ, Q_f —Plastic deformation heat, friction heat and bearings generation heat of backup roll of unit time and unit section;

C, ρ —Specific heat and density of aluminum foil;

v_0 —Speed of aluminum foil at the entry.

2.3 Model of distribution of tension stress

The transverse distribution of the front and back tension stress can be expressed by the following equations[5, 6]:

$$\sigma_1(y)=\frac{T_1}{Bh}+\frac{E}{1-\gamma^2}(\frac{h(y')}{h}-\frac{H(y')}{H}+u'(y')-\frac{\Delta B}{B})\qquad(10)$$

$$\sigma_0(y)=\frac{T_0}{BH}+$$

$$\frac{E}{1-\nu^2}\left(\frac{\overline{H}h(y')(1+u'(y'))}{\overline{h}H(y')(1+2u(\frac{B}{2})/B)}-1\right) \tag{11}$$

where $y' = y - l_w$;

T_1, T_0 —Total front and back tensions;

$\overline{H}$, $\overline{h}$ —Integral averages of $H(y')$ and $h(y')$ across the whole width of aluminum foil;

$u(y')$, ΔB —Lateral displacement function of aluminum foil at the exit and wide spread;

E, ν —Elastic modulus and Poisson ratio of aluminum foil.

The lateral displacement function of aluminum foil at the exit can be calculated by the variation method[7]:

$$u(y') = \left(\frac{\Delta B}{2} - \sum_{i=1}^{6} C_{2i}\right) / [\mathrm{sh}(N)\mathrm{sh}(Ky')] + \sum_{i=1}^{6} C_{2i}\left(\frac{2y'}{B}\right)^{2i-1}$$

$$C_{2i} = \frac{8i(2i+1)}{K^2B^2}C_{2i+2} + \frac{4i}{K^2B}\alpha_{2i}$$

$$C_{14} = 0$$

$$N = \frac{KB}{2}$$

$$K^2 = \frac{8t_m(1-\nu^2)h_n}{E\Delta hl\zeta h_c}$$

$$\zeta = 1 + \frac{3k(1-\nu^2)h_c}{2E\Delta h}$$

$$h_c = 0.5(\overline{H} + \overline{h})$$

$$\Delta h = \overline{H} - \overline{h} \tag{12}$$

where l —Length of deformation zone, t_m —Average friction force, k —Yield strength of shearing stress, h_n —Thickness of central point.

The transverse distribution of unit width rolling pressure can be calculated by Stone formula modified. Above three models are combined to simulate the shape of aluminum foil.

3 SIMULATED RESULTS OF FOIL SHAPE

In order to verify the precision of the shape model, test was carried out on the 2200 4-roll aluminum foil mill, which is equipped with automatic flatness control, automatic gage control, automatic thermal crown control, automatic roll deflection control by work roll bending and automatic push down force control systems. Parameters of the distribution of thickness at the entry and exit were tested, and front and back tensions, rolling pressure and coolant liquid temperature, etc. were recorded[8]

The mathematical model of foil shape established in this paper is applied to the analysis of numerical simulation for the rolling pass. The distributions of steady state temperature and thermal crown for the work roll are shown in Fig. 3 and Fig. 4. The cross section profile and the flatness of the aluminum foil rolled are shown in Fig. 5 and Fig. 6.

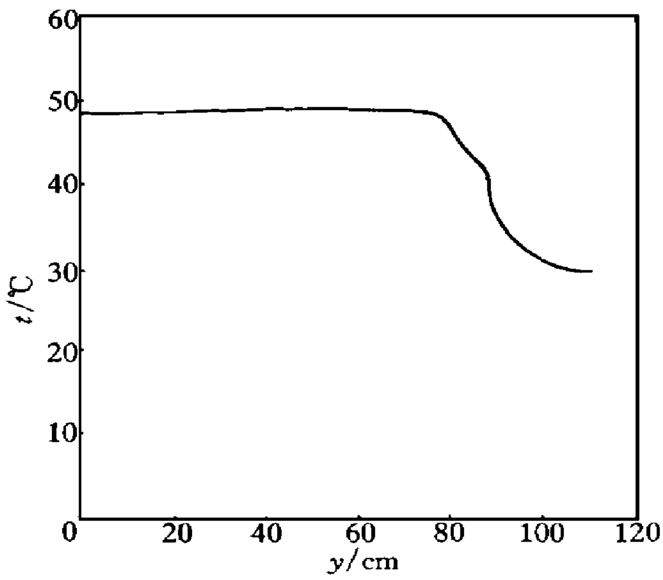

Fig. 3 Distribution of work roll surface temperature

From Fig. 5 and Fig. 6, it can be found that the calculated values are very close to measured values. From Fig. 4 it is seen that work roll thermal crown is very far away from aluminum foil edge about 100~ 200 mm, so wave always appears at this position in practical production because the coolant ability of the mill is limited. In order to increase the controlling ability of the foil shape at this position, the profile of the work roll should be changed.

4 CONCLUSIONS

In the paper, the roll system elastic defor-

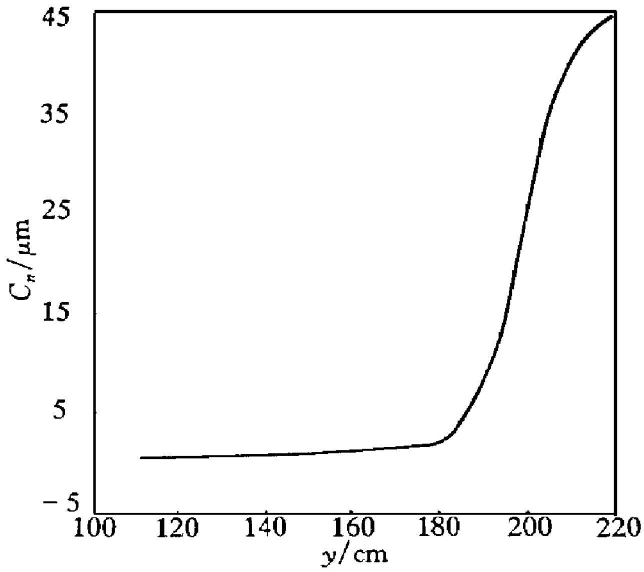

Fig. 4 Distribution of work roll thermal crown(C_n)

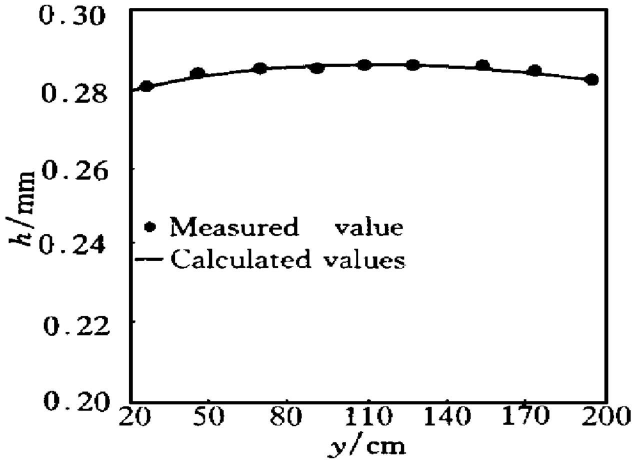

Fig. 5 Comparison of calculated and experimental results of cross section profile

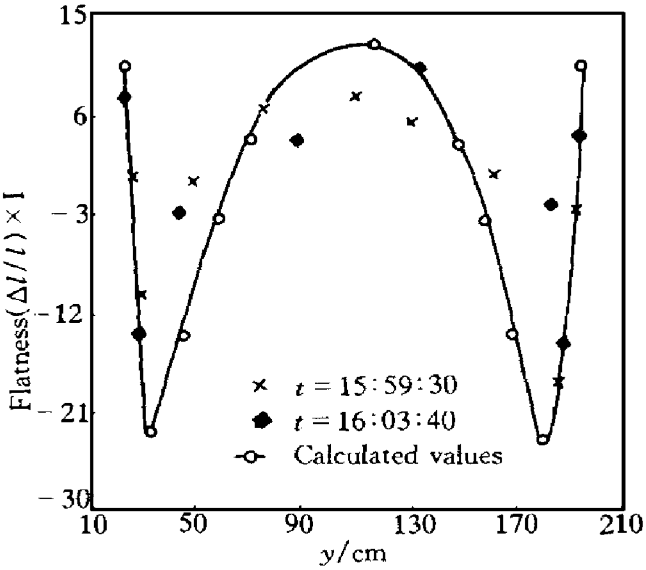

Fig. 6 Comparision of calculated and experimental results of foil flatness

mation is solved by the influence function method, the roll thermal deformation is calculated by difference method and the distribution of tension stress are solved by variation methods. Above three sorts of theories are combined organically to form rather complete shape theory, establish mathematical model of foil shape on 4-roll aluminum foil mill, and also simulate the cross section and the flatness of aluminum foil.

The theoretical values have good agreement with experimental ones. The theory has improtant practical significance for studying the influence of technical parameters on the foil shape and improving shape controlling precision of the aluminum foil mill.

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