SURFACE ROUGHNESS EFFECTS IN ALUMINIUM ROLLING ①

Tan Jianping, Zhong Jue, Yang Ping
College of Mechanical and Electrical Engineering
Central South University of Technology, Changsha 410083

ABSTRACT The present work on oil film thickness in rolling deformation zone was introduced briefly, and the calculation model of oil film thickness considering surface roughness effects was established by using average flow model. In addition, the effects of surface roughness and the directionality on oil film thickness were quantitatively analysed.

Key words rolling oil film thickness surface roughness

1 INTRODUCTION

Oil film thickness in the deformation zone has a crucial influence on the rolling lubrication condition and product surface quality[1]. Because early theories about lubrication mechanisms were mostly based on the hydrodynamic lubrication theory[1,2], the calculating equations of oil film thickness developed from them could fairly satisfy the full-film lubricating rolling processes. Wilson and Walowit[1] deduced the calculation equation of film thickness at inlet side of the deformation zone. Tsao and Sargent[3] analysed the influence on friction of the surface asperity contacts in the deformation zone in mixed lubrication. Based on Wilson's equation, they presented the calculating equation of oil film thickness at inlet of the deformation zone considering the elastic deformation of the roll. But in fact, the hydrodynamic lubrication condition appears very seldom in rolling processes[3,5], and the actual frictional surfaces are always rough instead of ideally smooth. Reid and Schey[4] observed that the directionality of surface roughness has a large effect on forward slip, and transverse roughness is helpful in carrying more lubricant into the deformation zone. Lu and Cheng[6] systematically measured the correlation among the value and directionality of surface roughness, and reduction ratio, forward slip, rolling force and moment. They pointed out that the directionality of surface roughness under mixed lubricating condition has a powerful influence on the lubrication process in cold rolling. Some other scholars also made lots of research on the roughness effects in rolling process.

But up to now, the study of surface roughness effects in rolling process still remains on the stage of experimental and qualitative research. The classical Reynolds equation analysing method is difficult to describe accurately the actual engineering surface. If the information of roughness was taken into account, the meshes should be divided much more denser, thus the calculating work would become enormous. Even with today's highly developed computers, this kind of calculation is hard to complete.

2 AVERAGE FLOW MODEL

In 1978, Patir and Cheng[1] presented the theory of "average flow model". They achieved great success either on theory or on experiment, and made the theory of three-dimensional rough surface lubrication take a big step forward. The lubrication equation appears as

① Supported by the National Natural Science Foundation of China Received Jun. 15, 1995; accepted May 22, 1996

$$\frac{\partial}{\partial x}\left(\varphi_x \frac{h^3}{12\eta}\frac{\partial \bar{p}}{\partial x}\right) + \frac{\partial}{\partial y}\left(\varphi_y \frac{h^3}{12\eta}\frac{\partial \bar{p}}{\partial y}\right) = \frac{U_1 + U_2}{2}\frac{\partial \bar{h}_T}{\partial x} + \frac{U_1 - U_2}{2}\sigma\frac{\partial \varphi_s}{\partial x} + \frac{\partial \bar{h}_T}{\partial t} \tag{1}$$

$$\left.\begin{aligned} \bar{q}_x &= -\varphi_x \frac{h_T^3}{12\eta}\frac{\partial \bar{p}}{\partial x} + \frac{U_1 + U_2}{2}\bar{h}_T \\ &\quad + \frac{U_1 - U_2}{2}\sigma\varphi_s \\ \bar{q}_y &= -DU\varphi_x \frac{h_T^3}{12\eta}\frac{\partial \bar{p}}{\partial y} \end{aligned}\right\} \tag{2}$$

where h is the nominal film thickness, $\bar{h}_T$ is the actual average film thickness, η is the viscosity, U_1 and U_2 are velocities of two rough surfaces. φ_x and φ_y are pressure flow factors in x, y direction, φ_s is the shear flow factor, $\bar{q}_x$ *and* $\bar{q}_y$ are the average flow rates, $\bar{p}$ is the average pressure, t is time.

A direct result of the average flow model is that it reveals the influence of the directionality features of three-dimensional rough surface on the average flow rate. The direction parameter which Patir and Cheng used is

$$\gamma = \lambda_{0.5x} / \lambda_{0.5y} \tag{3}$$

where $\lambda_{0.5x}$ and $\lambda_{0.5y}$ separately represent the correlative lengthes while the values of self-correlation function in x and y section drop to 0.5. It indicates the direction of surface roughness lay, and vividly express the length-width ratio of asperity contacts. As shown in Fig. 1, $\gamma > 1$ indicates longitudinal roughness lay, $\gamma < 1$ indicates transverse roughness lay, $\gamma = 1$ indicates isotropical roughness lay. The dotted lines in the diagram express the flowing directions of lubricant.

Fig. 1 Surface direction parameter
(a) $-\gamma > 1$; (b) $-\gamma = 1$; (c) $-\gamma < 1$

Obviously the classical Reynolds equation is the special case of the average flow model while $\varphi_x = \varphi_y = 1$ and $\varphi_s = 0$ (ideally smooth surface). Therefore the average flow model has widespread significance in analysing the lubricating property of rough surface.

3 OIL FILM THICKNESS IN ROLLING DEFORMATION ZONE CONSIDERING THE SURFACE ROUGHNESS EFFECTS

Considering the roughness asperity contacts between two relatively sliding surfaces, the real film thickness is

$$h_T = \begin{cases} h + \delta_1 + \delta_2 & \\ 0 & \text{(contacting point)} \end{cases} \tag{4}$$

where δ_1, δ_2 are the heights of roughness asperities. Apparently in full-film lubrication, the actual average film thickness $\bar{h}_T$ is equal to h, but in fact most of the frictional surfaces are in partial fluid lubricating condition, when $\bar{h}_T \neq h$. The relation between $\bar{h}_T$ and h_T under Gaussian distribution is[11]

$$\bar{h}_T = \begin{cases} h_T & |\delta| > 3\sigma \\ h_T + \frac{105}{32}\sigma\left(\frac{1}{8} - \frac{16}{35}Z + \frac{1}{2}Z^2 - \frac{1}{4}Z^4 + \frac{1}{10}Z^6 - \frac{1}{56}Z^8\right) & |\delta| < 3\sigma \end{cases} \tag{5}$$

where $Z = \delta/(3\sigma)$. For stable rolling process, we can make the following assumption:

$$\frac{\partial \bar{h}_T}{\partial t} = 0 \tag{6}$$

$$q_x = \text{const} \tag{7}$$

$$q_y = 0 \tag{8}$$

Assuming U_r is the roll speed and U_0 is the inlet velocity of workpiece, Eqn. (2) appears as

$$q_x = -\varphi_x \frac{h^3}{12\eta}\frac{\partial \bar{p}}{\partial x} + \frac{U_r + U_0}{2}\bar{h}_T + \frac{U_r - U_0}{2}\sigma\varphi_s \tag{9}$$

Obviously we have $U_r - U_0 \ll U_r + U_0$, and for most of the rolling processes, especially in finishing rolling stages, the roll surface and strip surface are similar in surface parameters[1], and φ_s tends to 0. The value of σ is of the same quantity range with $\bar{h}_T$ or much less. So the third term in the same part of equation (9) is far less than the second term in the right part and can be neglected. Thus we have

$$q_x = -\varphi_x \frac{h^3}{12\eta}\frac{\partial \bar{p}}{\partial x} + \frac{U_r + U_0}{2}\bar{h}_T \quad (10)$$

where $\bar{h}_T = h_0$ (h_0 is the oil fim thickness at inlet).

So we have

$$\bar{q}_{x0} = \frac{U_r + U_0}{2} h_0 \quad (11)$$

According to the assumption (Eqn. (7))

$$\bar{q}_x = -\varphi_x \frac{h^3}{12\eta}\frac{\partial \bar{p}}{\partial x} + \frac{U_r + U_0}{2}\bar{h}_T = \frac{U_r + U_0}{2} h_0$$

we have

$$\varphi_x \frac{h^3}{12\eta}\frac{\partial \bar{p}}{\partial x} = \frac{U_r + U_0}{2}(\bar{h}_T - h_0) \quad (12)$$

Considering the pressure-viscosity effect[12, 25]

$$\eta = \eta_0 \exp(\theta p) \quad (13)$$

where θ is the pressure-viscosity coefficient. Substituting Eqn. (13) into Eqn. (12) and replacing $\bar{p}$ with p, we obtain

$$\exp(-\theta p)\,\mathrm{d}p = 6\eta_0 \frac{U_r + U_0}{\varphi_x h^3}(\bar{h}_T - h_0)\,\mathrm{d}x \quad (14)$$

To solve Eqn. (14), using the functions of the same angle variable φ to express h and x (see Fig. 2), we have

$$\mathrm{d}h = -\mathrm{tg}\,\varphi\,\mathrm{d}x \quad (15)$$

$$h = R\cos\alpha - R\cos\varphi + h_0 \quad (16)$$

$$\mathrm{d}h = R\sin\varphi\, d\varphi \quad (17)$$

From Eqns. (15) and (17) we obtain

$$\mathrm{d}x = -R\cos\varphi\,\mathrm{d}\varphi \quad (18)$$

Substituting Eqns. (15) ~ (18) into Eqn. (14), we have

$$\exp(-\theta p)\,\mathrm{d}p = -6\eta_0 \frac{U_r + U_0}{\varphi_x(\varphi) h^3(\varphi)} \cdot [\bar{h}_T(\varphi) - h_0]\, R\cos\varphi\,\mathrm{d}\varphi \quad (19)$$

The inlet mechanical boundary conditions

Fig. 2 Schematic diagram of rolling lubrication

are given as

$$\begin{cases} \varphi = \alpha: \ p = p_0 = K - \sigma_s,\ h = h_0; \\ \varphi = \dfrac{\pi}{2}: \ p = 0 \end{cases} \quad (20)$$

where K is the yielding strength, σ_s is the back tension.

Integrating Eqn. (19) by using the boundary conditions of Eqn. (20), we obtain

$$\int_{p_0}^{0} \exp(-\theta p)\,\mathrm{d}p = -6\eta_0(U_r + U_0) \cdot \int_{\alpha}^{\frac{\pi}{2}} \frac{\bar{h}_T(\varphi) - h_0}{\varphi_x(\varphi) h^3(\varphi)} R\cos\varphi\,\mathrm{d}\varphi$$

$$\exp(-\theta p_0) = 1 - 6\eta_0\theta R(U_r + U_0) \cdot \int_{\alpha}^{\frac{\pi}{2}} \frac{\bar{h}_T(\varphi) - h_0}{\varphi_x(\varphi) h^3(\varphi)} \cos\varphi\,\mathrm{d}\varphi \quad (21)$$

Eqn. (21) is the mathematical model for calculating oil film thickness at the inlet of the rolling deformation zone considering roughness lubricating effects. Using Simpson optional step integral method to solve the integral in Eqn. (21), we obtained curves with various surface direction parameters $p_0 h_0$ (shown in Fig. 3). It is seen that corresponding to the same p_0, the increase of γ leads to the decrease of oil film thickness, i. e., transverse roughness lay is helpful in increasing the oil film thickness. But when oil film thickness is greater than a certain value, the influence becomes weak, or even can not be obviously observed.

The turning point of surface roughness effects can be regarded as the boundary between hydrodynamic lubrication and mixed lubrication. From Fig. 3 we can see that this point can be set as $h/\sigma = 3$.

Fig. 3 Oil film thickness in deformation zone
(The figures in the diagram are roughness direction parameters)

4 CONCLUSIONS

In rolling process, the surface roughness of roll and workpiece has an important influence on the formation of oil film in the deformation zone. This influence has a close relation with the directionality of roughness lay. The calculating model of oil film thickness in deformation zone, which is established by using the average flow model, can quantitatively calculate surface roughness on the theoretical plane. Thus the cognition of surface roughness effects in rolling lubrication process is advanced from qualitative analysis to quantitative analysis.

REFERENCES

1 Wilson W R D, Walowit J A. In: Proc Tribology Convention Inst Mech Engrs. 1971: 164– 172.
2 Alkins A C. 1st J Mech Sci, 1974, 16: 1– 19.
3 Taso Y H, Sargent L B Jr. ASLE Trans, 1977, 20 (1): 55– 63.
4 Reid J V. Schey J A. ASLE Trans, 1978, 21(3): 191– 200.
5 Schey J A. Lubr Eng, 1983, 39(6): 376– 382.
6 Lu S S, Cheng Y H. Trans ASME, 1985, 107: 522.
7 Howes V R, Lamb H J. Lubr Eng, 1983, 39(3): 156 – 161.
8 Aderson A N, Bruce R W. Lubr Eng, 1986, 42(6): 614– 619.
9 Patir N, Cheng H S. Trans ASME, 1978, 100(1): 12.
10 Patir N, Cheng H S. Trans ASME, 1979, 101(4): 200.
11 Chow L S H, Cheng H S. ASME Trans, 1976, 98: 117– 124.

(Edited by He Xuefeng)