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3D finite element analysis of surface roughness and friction in hot strip rolling

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3D FINITE ELEMENT ANALYSIS OF SURFACE ROUGHNESS AND FRICTION IN HOT STRIP ROLLING

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Summary

Surface roughness of oxide scale and strip in hot strip rolling has a significant influence on the friction and lubrication conditions. In this paper, the authors present the measured surface roughness of oxide scale and strip by Atomic Force Microscope (AFM) and Surface Profilometer respectively for hot rolled strip on a Hille 100 experimental rolling mill. Based on the friction coefficient determined through a sensor roll on the rolling mill, a 3D rigid visco-plastic finite element simulation was carried out, and the relationship between the surface roughness and friction coefficient was investigated. Results show that the lubrication in hot strip rolling can reduce the rolling load and torque, and the friction coefficient and surface roughness decrease when the rolling speed increases. Calculated results are in good agreement with the experimental values.

Keywords: surface roughness, friction coefficient, AFM, hot strip rolling, lubrication

1 Introduction

The hot strip produced in hot strip mill has a wide application in industry and the surface of strip affects the use or the further cold rolling. In hot strip rolling, the produced roughness has a significant effect on the processing parameters and surface quality of strip, and it also plays a major role in the driving of the metal strip between the rolls [1]. There is a need for the manufacturers to understand the surface roughness of strip, and the relationship between the surface roughness and friction coefficient in order to optimize the parameters (rolling load, speed, torque etc.) of the process and the quality of finished products.

Previous research showed that by improving the rolling conditions at the interface of the strip and rolls, such as lubrication in the roll bite, the rolling load can be reduced and the surface quality can be improved significantly [2]. Luong and Heijkoop [3] concluded that with respect to friction the scale thickness appears to be more important than scale composition. Munther and Lenard [4] investigated the friction at the interface of strip/roll in hot strip mill. Mechanical and tribological characteristics of the oxide scale have been assessed. Wilson and Schmid [5] conducted experiments in rolling with different lubricants and speeds, they found three mechanisms control the roughening process. Beynon et al. [6] reported the tribology of hot metal forming. However, the relationship between the surface roughness and friction has not been reported.

3D Finite Element Method (FEM) has been used in the analysis of steel rolling processes [7] in the past. There is a major handicap to producing accurate and reliable models for hot strip rolling due to a lack of well-defined friction boundary conditions [6]. In order to model realistically, it is necessary to employ a variable friction model in the roll bite. The aim of this paper is to present the experimental results of surface roughness of the oxide scale and rolled strip by AFM and Surface Profilometer respectively, and the friction coefficient determined from the rolling test on Hille 100 experimental rolling mill. Based on the empirical models of the friction coefficient, a simulation of the hot strip rolling was carried out by a 3D rigid visco-plastic FEM with material slightly compressible method. The calculated results obtained from the dry and lubricated conditions are compared with the experimental values.

2 Experiments

An experiment was carried out on a Hille 100 experimental rolling mill to determine the friction in hot strip rolling. Rolling pressure measurements are provided by two groups of pin sensors embedded in the top roll, one mounted with full-bridge strain gauges, and the other pressing against highly sensitive. The embedded pins in contact with the load cells and strain gauges are 2 mm in diameter and were ground flush with the roll surface. One pin with load cell and one strain gauged pin are mounted radially and the other pin with load cell and one strain gauged pin are mounted at an angle of 25 degrees from the radially embedded ones. The sensor roll sectional view is shown in **Figure 1**.

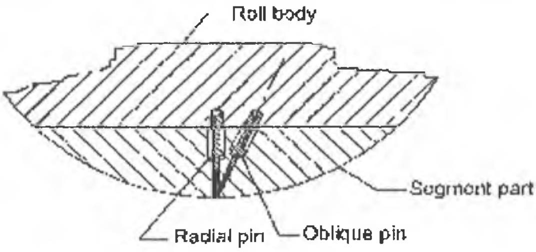

Figure 1: Sensor roll sectional view.

The oil Quakerol HB-98A was atomized and sprayed on the roll via nozzle. The work roll was lubricated before rolling and ample lubricant was built up at the entry to the roll bite for lubricated case. The heating temperature of the rolled strip is 1000 °C, and the rolling temperature is measured by infrared thermometers installed on both entry and exit sides of the rolling mill. Carbon steel samples 20 mm thick by 100 mm width by 700 mm length were used for the experiment. The chemical composition of this carbon steel is given in **Table 1**.

Table 1: Chemical composition of the tested steel

Grade	C Max	Si Max	Mn Max	P Max	S Max	Al Max	Ti Max
250	0.22	0.55	1.7	0.04	0.035	0.1	0.04

3 Theoretical analysis

3.1 3D material slightly compressible rigid visco-plastic FEM

A 3D rigid visco-plastic FEM with material slightly compressible method has been employed in the analysis of this rolling problem. According to the variational principle, the real velocity field must minimise the following functional:

$$\Phi = \iiint_v \bar{\sigma}\dot{\bar{\varepsilon}}dv + \iint_{s_f} \tau_f \Delta V_f ds + \iint_{s_K} \tau_K \Delta V_K ds \pm \iint_{s_v} T_1 v ds = \phi^p + \phi^f + \phi^j + \phi^t \tag{1}$$

where the first term on the right hand side is the work rate of plastic deformation (ϕ^p), $\bar{\sigma}$ is the equivalent stress and $\dot{\bar{\varepsilon}}$ is the equivalent strain rate, they are relevant to the slightly compressible factor [8]. The second term on the right hand side is the work rate of friction (ϕ^f); ΔV_f is the relative slip velocity at the interface of the rolled material and the rolls where the frictional shear stress τ_f is applied. To take into account the friction variation in the roll bite, in this study the modified frictional stress model was used [8] as follows:

$$\tau_f = K_i \frac{m_1 \sigma_s}{\sqrt{3}} \left(\frac{2}{\pi} \tan^{-1} \left\{ \frac{V_g}{k_1} \right\} \right) \tag{2}$$

where m_1 is the friction factor, σ_s yield stress, K_i a coefficient describing the changes of frictional shear stress in the deformation zone with K_1 used in the forward zone and K_2 in the backward zone, k_i is a positive constant, k_1 is for forward slip zone and k_2 backward slip zone. The relative slip velocity, V_g, between the rolled material and roll refers to [8]. The third term on the right hand side is the additional shearing work rate (ϕ^j) at a surface on which there is a velocity discontinuity. ΔV_K is the velocity discontinuity across the velocity discontinuity surface s_K within the volume V, $\tau_k = k$ (k the shear yield stress). The fourth term on the right hand side is the work rate (ϕ^t) of tension. T_1 is the tension and v is the velocity of the cross section with tension. Here "-" indicates the front tension, and "+" the back tension. The solution for the nodal velocity vector is obtained as it makes the above functional minimum [7]. The rolling force can be calculated by Eq. (3):

$$P = \int_0^l \int_0^{b_x} \sigma_z dydx \tag{3}$$

where l, b_x are respectively the projected length and width of strip in the deformation zone; σ_z is the stress in the thickness direction. The torque can be calculated by rolling torque and additional frictional torque as shown in Eq. (4):

$$M = M_P + M_f = Pl\lambda_1 + 0.5Pf_1 d \tag{4}$$

where M_p and M_f are rolling and bearing frictional torque respectively; P the roll separating force; l the projected length of deformation zone; λ_1 a force arm coefficient which has been determined from experience; f_1 bearing friction coefficient and d neck diameter of roll.

3.2 Flow stress model of metal

The flow stress model of carbon steel is as follows [9]:

$$\sigma_p = 9.8\,\sigma_f\, f\left(\frac{\dot{\varepsilon}}{10}\right)^{m_3} \quad \text{(MPa)} \qquad (5)$$

where $\sigma_f = 0.28\exp\left(\frac{5}{T} - \frac{0.01}{[C]+0.05}\right)$, $T = \frac{(T_2 + 273)}{1000}$, T_2 is the temperature, °C, $[C]$ is the carbon content in the steel (weight %); $f = 1.3(5\varepsilon)^n - 1.5\varepsilon$, n=0.41-0.07[C], ε is the true strain; $\dot{\varepsilon}$ is the strain rate and m_3 = (-0.019[C]+0.126)T+0.075[C]-0.05. So, the strain rate, strain, temperature and its variation have been taken into account.

4 Results

As the deformation is symmetric, one quarter of the deforming workpiece was studied. Isoparametric hexahedral elements with eight Gauss points were used throughout the strip, including the corner at entry to the roll gap. The number of elements along the x, y and z directions are 10, 8 and 5. The strip temperature is considered in the simulation, but it does not couple with the 3D visco-plastic FEM.

4.1 Experimental results

Based on the rolling pressure distribution obtained from the radial and oblique pins of sensor roll, the friction coefficients can be determined through the relationship between the oblique pin and radial pin [10]. **Figure 2** clearly demonstrates the variation of the friction coefficient in the roll bite, and the average friction coefficient is 0.26 for oil lubrication. The neutral plane is located where the value changes direction, and there is a change in direction of the frictional shear stress at the interface. The change in the direction of the variable friction verifies the friction variation. It can also be seen that for the lubricated case, the neutral plane is closer to the exit of roll bite. The measured friction coefficient reduces as the rolling speed increases, and the friction coefficient for lubricated case is lower than that for dry condition, which is shown in **Figure 3**. There is more experimental scatter in the lubricated case.

Based on the measurement of AFM, the oxide scale surface roughness for dry condition is shown in **Figure 4**. The measured surface roughness of strip for the case of lubricated condition by the Surface Profilometer is shown in **Figure 5**. It can be seen that the strip surface roughness decreases when the rolling speed increases, which is in accord with the measured result of friction coefficient obtained from the sensor roll (see **Figure 3**).

4.2 Simulation results

Based on the experimental conditions and friction variation model in the roll bite, a 3D rigid visco-plastic FEM was performed for the hot strip rolling with lubricated and dry friction conditions. In the simulation of hot strip rolling with lubrication, the frictional shear stress (see Eq. (2)) was determined with $K_1 = 0.6$, $K_2 = 0.3$, $k_1 = 0.5$ (forward slip zone) and 1.0 (backward slip zone). For dry friction condition, $K_1 = 0.6$, $K_2 = 0.3$, $k_1 =$

0.1 (forward slip zone) and 1.0 (backward slip zone). Comparison of the calculated rolling force with measured values is shown in **Figure 6**. It can be seen that the experimental value of the rolling force with oil lubrication is lower than that with dry rolling condition, and the rolling force increases as the reduction increases. The difference between the measured rolling forces for dry and lubricated rolling conditions is not as significantly as expected. This could be due to the experimental scatter, low speed effect and non-uniform temperature of the specimen between the surface and centre, and from head and tail. Comparison of the measured torque with the calculated value is shown in **Figure 7**. It can also be seen that the rolling torque increases with reduction and the calculated torque is in good agreement with the measured value.

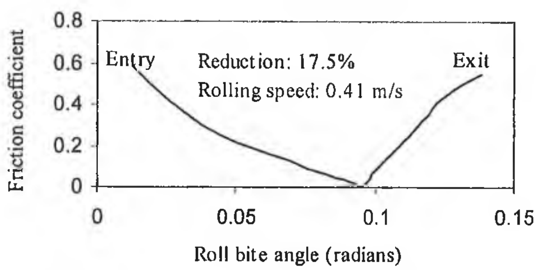

***Figure 2:** Friction coefficient for lubricated condition.*

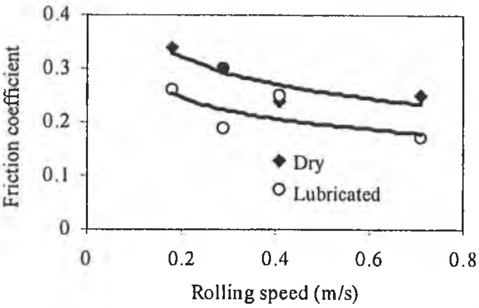

***Figure 3:** Effect of rolling speed on friction coefficient.*

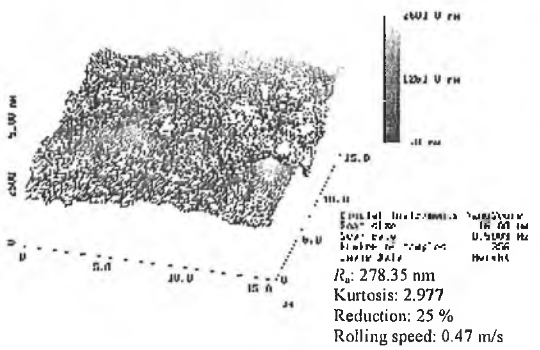

***Figure 4:** Oxide scale surface roughness.*

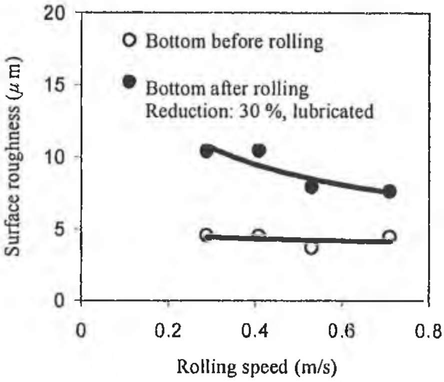

***Figure 5:** Effect of rolling speed on strip surface roughness.*

5 Conclusions

In hot strip rolling, the produced oxide scale has an effect on the processing parameters and surface quality of strip. The surface roughness of oxide scale and rolled strip measured by AFM and Surface Profilometer respectively are obtained, and the friction coefficient is determined by sensor roll. The friction coefficient and surface roughness increase with an increase of reduction. Based on the model of the friction variation, a simulation of the hot strip rolling was carried out by a 3D rigid visco-plastic FEM. The rolling force and torque reduce with lubrication, and the rolling force and torque increase with an increase of reduction. The calculated results are in good agreement with the experimental values.

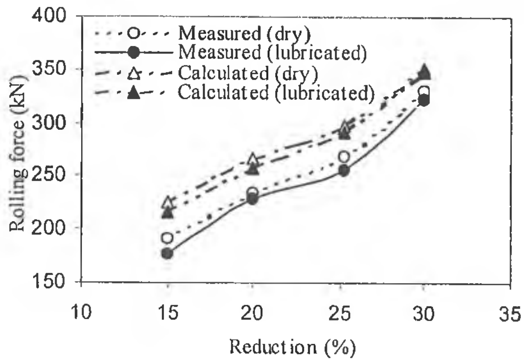

Figure 6: Comparison of the calculated rolling force with measured values.

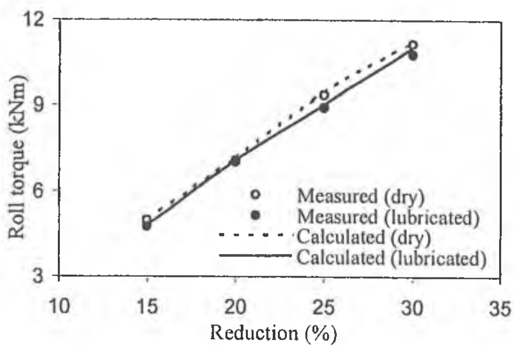

Figure 7: Comparison of the calculated torque with measured value.

6 Acknowledgments

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