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Estimation model of plate-out oil film in high-speed tandem cold rolling

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ABSTRACT

Out of all the variables associated with rolling, none is more important than friction in the roll bite. Friction in rolling, as in many other mechanical processes can be a best friend or a fatal enemy, and its control within an optimum range for each process is essential. The friction is the interconnected phenomena; material, lubrication and heat transfer at the contact surface in cold rolling. Moreover, the friction behavior in industrial environment is highly unclear. It is important to break down many tribological attributes in actual cold rolling into simple laboratory tests. The proposed hybrid lubrication system is helpful to achieve higher rolling speed and more stable rolling for improving the productivity of tandem cold rolling mills. In this paper, an estimation model of the oil film on the strip by the proposed system at the exit section of tandem cold rolling was proposed based on a combination of laboratory tests and a starvation model. The results of this research suggest that it is possible to clarify the lubrication characteristics in tandem cold rolling by using the proposed model.

1. Introduction

In high speed rolling for thin steel strips, mill vibration called chatter (Suzuki, 1996) is often due to lack of lubricity. And, a surface detect caused by a heat scratch (Yarita et al., 1981) between strip and work roll is easily generated. Therefore, lubrication technology for improving the productivity of tandem cold rolling mills is considered to be of large importance.

Recently, Kimura et al. (2014) reported effective plate-out oil film formation as a result of a study concerning the plate-out characteristics of emulsions. The Fujita and Kimura (2012) also examined the influence of the plate-out oil film at the entry section of rolling on lubrication characteristics, and reported the possibility of friction control by the plate-out oil film. These results suggested that lubrication characteristics in cold rolling can be controlled by the plate-out oil film while minimizing the influence in recirculation systems. Plate-out control by supplying a high efficiency emulsion was investigated in actual tandem cold rolling, and the results confirmed that the friction coefficient can be reduced under a high rolling speed of over 2000 m/min (Fujita et al., 2014).

This paper concerns estimation of the oil film on the strip in cold rolling with the aim of verifying the validity of the hybrid lubrication system for variable cold rolling conditions. Estimation of the oil film on the strip in tandem cold rolling was investigated based on a combination of laboratory tests and a starvation model.

2. Plate-out oil film formation by hybrid lubrication system

2.1. Hybrid lubrication system

The hybrid lubrication technology developed by the authors is shown schematically in Fig. 1. In recirculation systems, a hybrid lubrication system is set up at the entry section of the final stand in the tandem cold mill. A high concentration, large droplet emulsion is supplied on the strip. In recirculation systems, a conventional stable O/W emulsion is used, and is worked by dynamic concentration in the roll bite.

The hybrid lubrication system uses the same rolling oil as recirculation systems. High efficiency plate-out oil film formation comparable to that of direct application systems is realized by combined use of a high concentration, large droplet emulsion, and a sufficient lubrication effect can be achieved even with a small emulsion supply by improving the efficiency of plate-out oil film formation by the hybrid lubrication system.

As a result of these improvements, the amount of high concentration emulsion mixed in the recirculation tank can be reduced,

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Nomenclature

μ	friction coefficient
μ_b	friction coefficient in boundary lubrication
μ_l	friction coefficient in hydrodynamic lubrication
A	contact ratio between the work roll surface and the strip surface
P_0	amount of supplied oil per unit area (mg/m^2)
ω	flow quantity density (L/min/m^2)
τ	spraying time (s)
Q	flow quantity of the emulsion (L/min)
W	spraying area (m^2)
v	strip speed (m/min)
L	spraying width (m)
C	oil concentration (%)
ρ	density of the rolling oil (mg/L)
h_2	oil film thickness at the inlet of the roll bite (μm)
h_{2T}	oil film thickness formed by emulsion trapped at the inlet of the roll bite (μm)
h_{2PS}	oil film thickness formed on the strip (μm)
h_{2PR}	oil film thickness formed on the work roll (μm)
h_{2C}	oil film thickness carried over from the preceding stand (μm)
a	trap ratio
d	emulsion droplet size (μm)
f	plate-out efficiency
P_1	amount of supplied oil per unit of roll bite area (mg/m^2)
f_1	plate-out efficiency of the recirculation emulsion supplied to the roll bite (%)
P_2	amount of supplied oil of the hybrid lubrication system per unit of strip surface area (mg/m^2)
f_2	plate-out efficiency of the high concentration emulsion supplied in the hybrid lubrication system (%)
f_3	plate-out efficiency resulting from the change in oil film formation time (%)
t_{trans}	oil film formation time (s)
D_H	distance between hybrid lubrication spray and final stand (m)
v_s	inlet strip speed (m/min)
P	rolling pressure (MPa)
h	oil film thickness (μm)
h_1	hydrodynamic oil film thickness (μm)
U_1	speed of the strip (m/min)
U_2	speed of work roll (m/min)
θ	gap angle between the strip and the work roll (deg)
η_0	reference viscosity of the rolling oil (Pa s)
α	pressure viscosity coefficient (GPa^{-1})
β	temperature viscosity coefficient (K^{-1})
T_m	oil film temperature (K)
T_0	reference temperature (K)
σ_0	deformation resistance of the strip (MPa)
ν_0	reference kinematic viscosity of the rolling oil (mm^2/s)
ν_{T1}, ν_{T2}	kinematic viscosity of the rolling oil (mm^2/s)
T_1, T_2	temperature of the rolling oil (K)
r	rolling reduction
f_4	ratio at which the oil film is removed at the exit of the roll bite

and fluctuations in the concentration in the recirculation system can be minimized. Moreover, an oil consumption rate equal to that of recirculation systems can be maintained by reducing the spray quantity of high concentration emulsion.

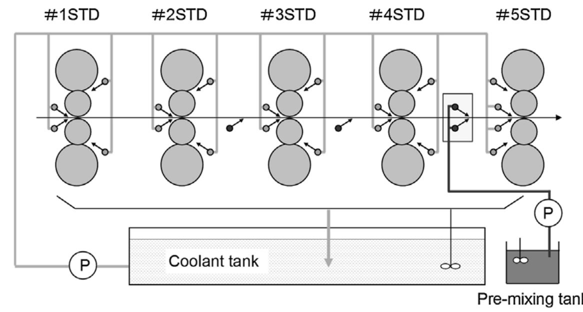

Fig. 1. Schematic illustration of hybrid lubrication system.

The friction coefficient in cold rolling is an important factor for verifying whether a sufficient lubrication effect can be achieved by the hybrid lubrication system. Basically, if the friction coefficient is constant, this may be interpreted as indicating stable cold rolling. However, even with the same coil, the friction coefficient varies depending on the strip tension balance and work roll roughness (Kimura et al., 2003). For this reason, estimation of the friction coefficient by extrapolation is considered difficult. Zhou et al. (2007) proposed the mathematical model of friction coefficient based on the artificial neural network.

A mixed lubrication condition is assumed to exist in the roll bite in cold rolling. Tieu et al. (2000) proposed a mixed film lubrication model based on Wilson and Chang's asperity flattening model. Generally, when the deformation pressure is high such as cold rolling, the friction coefficient under mixed lubrication is given by Eq. (1) (Azushima, 1978).

$$\mu = A\mu_b + (1 - A)\mu_l \tag{1}$$

where, μ_b is the friction coefficient in boundary lubrication, μ_l is the friction coefficient in hydrodynamic lubrication, and A is the contact ratio between the work roll surface and the strip surface.

In Eq. (1), the friction coefficient is affected by changes in A, μ_b and μ_l. The contact ratio A is variable depending on the inlet oil film and temperature and the relative slip in the roll bite (Lenard, 2013). μ_b is variable depending on the pressure and interfacial temperature in the roll bite, and μ_l is variable depending on the rolling oil viscosity.

If the inlet oil film thickness exceeds a certain level, a sufficient lubrication effect can be achieved. Hunder and Dwyer-Joyce (2012) reported monitoring of inlet oil film in the roll bite by a sensor embedded in work roll. However, it is difficult to measure the inlet oil film thickness directly in the high speed rolling region. Therefore, the inlet oil film thickness in the roll bite must unavoidably be evaluated indirectly from the oil film on the strip after rolling.

Based on these facts, this paper focuses on the oil film on the strip. The changes of the oil film on the strip and the lubrication conditions for obtaining the necessary lubricity were investigated.

2.2. *Experiments*

A schematic model as shown in Fig. 2 was assumed. The plate-out oil film on the strip is trapped in the roll bite and is influenced by the coolant spray in the recirculation system, as shown in Fig. 2. Only emulsion supply to the roll bite is considered from #1std to #4std, as shown in Fig. 2(a). At the final stand, where the hybrid lubrication system is applied, the model considers plate-out oil film formation by supply of a high concentration, large droplet emulsion and the influence of the outflow effects in addition to the roll bite coolant.

To estimate the oil film on the strip at the exit section of tandem cold rolling, calculations through multiple stands are necessary. In this paper, it is assumed that the oil film from the preceding stand