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A novel multi-scale statistical characterization of interface pressure and friction in metal strip rolling

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ABSTRACT

This paper presents a novel multi-scale method to investigate the interface pressure and friction in a 3D model of cold strip rolling. The key innovation is the introduction of an equivalent interfacial layer[1] to integrate the effect of lubricant with surface asperity deformation. This multi-scale method also enables to capture the microscopic roll-strip interface deformation associated with the random asperities and to treat all the lubrication regimes from hydrodynamic lubrication to mixed and boundary lubrication in a single program. The proposed method can predict well the experimental measurements, and is applicable to other contact sliding processes involving complex lubrication regimes.

1. Introduction

Interface pressure and friction play a critical role in a metal forming process. By taking the cold rolling of a metal strip as an example, the variation of the interface conditions throughout the rolling bite can lead to varied rolling pressure, friction, force and torque, and hence the surface quality of a rolled product. When a cold rolling process is operated in a boundary lubrication regime where the contact force is mostly carried by the surface asperities in contact, the high contact stress can generate high friction and roll wear due to the relative sliding of the two surfaces. On the other hand, if rolling is in the hydrodynamic regime where the surfaces are separated by a thin lubricant film, the friction and roll wear can be minimized. However, this can produce a poor surface quality because of the unconstrained grain deformation in the process [1]. To optimize the interface interaction conditions, it is desirable that a cold rolling process of a metal strip is operated in a mixed lubrication regime to reduce friction by the lubricant applied and to minimize the damage to a workpiece surface while guaranteeing an adequate frictional force to draw the workpiece into the rolling gap. When cold rolling is operated in a mixed lubrication regime, neither the asperity deformation nor the hydrodynamic lubrication can be ignored. As a result, the surface micro-properties, such as roughness and topography, will play a significant role. However, mixed lubrication cannot be the sole regime happening in cold rolling of metal strips. For instance, hydrodynamic lubrication inevitably exists at the inlet zone of the rolling bite where the rolling pressure is small, and boundary lubrication will take place in the area in which the strip undergoes severe plastic deformation. Hence, a sensible method for analyzing an interface friction containing all the three lubrication regimes, such as the metal rolling process described above, should be able to deal with the coupled effect of solid–solid (asperity–asperity) contacts, solid–liquid (asperity-lubricant) contacts and lubricant film interactions; and at the same time, be capable of integrating both the surface asperity deformation, which is microscopic and random, and that of the workpiece, which is macroscopic. All these have made the investigation into the tribology in metal forming difficult.

Sutcliffe [2] and Wilson and Sheu [3] investigated the real area of contact and friction for the transverse and longitudinal surface roughness, respectively, in the regime of boundary lubrication in metal forming. Sa and Wilson [4] developed a mathematical model that combines slab plasticity, hydrodynamic lubrication and thermal analysis for strip rolling in hydrodynamic regimes. However, since mixed lubrication is critically important to cold metal rolling, research attention has been very much attracted to understand its mechanism in determining the interface friction and contact pressure. Nevertheless, the existing investigations on mixed lubrication in cold rolling usually involve many assumptions. For example, Sutcliffe [2] used the slip-line method to describe the crushing of one-dimensional (ridge-like) asperities perpendicularly aligned to the direction of the bulk strain of the underlying materials. Wilson and Sheu [3] used an approximate energy method to deal with the asperities lined up in the direction of the bulk strain.

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[1] *Equivalent interfacial layer* (EIL).

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Nomenclature

A	solid–solid contact area
β	fraction of the asperity contact pressure
C	constant for γ, as defined by [16]
d	the thickness of the equivalent interfacial layer
Δv	the total relative velocity between the roll and strip surfaces
Δv_x	relative velocity in the rolling direction
Δv_y	relative velocity in the transverse direction
Δv_{crit}	the total critical relative velocity where the sticking takes place
E	the Young's modulus
E'	the reduced Young's modulus
ε_0	the hardening coefficient
ε_p	uniaxial plastic strain
$f(h)$	the height distribution of the asperities
γ	the surface pattern parameter
h	asperity height
H_{max}	maximum lubricant film thickness where hydrodynamic pressure decreases to zero
h_T	the average film thickness,
$\lambda_{0.5x}$	correlation length in the rolling direction
$\lambda_{0.5y}$	correlation length in the transverse direction
μ	the lubricant viscosity
μ_a	the Coulomb friction coefficient for asperity contact
μ_r	the resultant friction coefficient
N	asperity density
n	the hardening coefficient
P_a	asperity contact pressure
P_f	hydrodynamic pressure
ϕ_x	flow factor in the rolling direction
ϕ_y	the flow factor in the transverse direction
P_{tx}	shear traction in the rolling direction
P_{ty}	shear traction in the transverse direction
r	constant for the γ, as defined by [16]
R	the average asperity radius
S	the yield stress of the strip
S'	the strain hardening stress of the strip
σ	the standard deviation of the asperity height
τ_a	total frictional force due to the asperity contact
τ_{ax}	frictional force due to the asperity contact in the rolling direction
τ_{ay}	frictional force due to the asperity contact in transverse direction
τ_{fx}	lubricant shear traction in the rolling direction
τ_{fy}	lubricant shear traction in the transverse direction
υ	Poisson's ratio
U_{rx}	roll surface speed in the rolling direction
U_{ry}	roll surface speed in the transverse direction
U_{sx}	strip surface speed in the rolling direction
U_{sy}	strip surface speed in the transverse direction

In order to take into account the effect of surface roughness or specifically fabricated surface patterns on the mixed lubrication in rolling, some investigations have considered the contribution of lubricant with the aid of the Reynolds equation. Patir and Cheng [5,6] proposed an average Reynolds equation. Sheu et al. [7] developed an analytical model for strip rolling in the mixed lubrication regime. They combined the Wilson–Sheu model [3] of asperity deformation with an average Reynolds equation to take the surface roughness effect on lubricant flow. Chang et al. [1,8] used a similar method to study the lubrication of low-speed strip rolling in the mixed lubrication regime, and used a modified Reynolds equation to calculate the normal pressure, hydrodynamic pressure, lubricant film thickness, real contact area and frictional stress. However, most of the analytical models based on the plane-strain deformation of a strip require many assumptions. As a result, a comprehensive understanding of the mechanisms of the mixed lubrication in the rolling strip, which is essential to provide a reliable guideline for process design and production, has not been obtained.

To overcome the difficulties in analytical and theoretical modeling, numerical methods, such as the finite element (FE) method, have been widely used to investigate the interface friction in the metal rolling. For instance, Liu et al. [9] used the elastic-plastic FE method to calculate the velocity field, interface friction and normal pressure along the contact arc in cold rolling by introducing a friction layer in the contact surface. Hwu and Lenard [10] used the rigid-plastic FE method to investigate the flat rolling and interfacial friction based on the Eulerian formulation. Gratacos et al. [11] used a plane-strain elasto-plastic FE model to simulate the rolling process, and coupled strain with stress by an internal interface to accommodate sliding friction. These models require specific treatments to handle the contact in rolling; but cannot address the complex interaction of the solid–solid and solid–liquid contacts in the mixed lubrication regime in a rolling interface.

As aforementioned, mixed lubrication in rolling involves the coupled contributions of asperity–asperity and asperity–lubricant contacts. The deformation of the randomly-distributed and randomly-shaped surface asperities is microscopic; but the bulk deformation of a workpiece is macroscopic. To the authors' knowledge, none of the existing models or methods in dealing with the mixed lubrication in rolling can integrate such multi-scale deformation at the rolling gap in a practically sensible way. This not only limits the reliability of the model predictions, but also excludes the possibility of using such models to investigate the surface morphology evolution in rolling.

To overcome the above difficulties and obtain an in-depth understanding of the interface friction in the cold rolling process, this paper will develop a novel multi-scale statistical model incorporating with the finite element analysis to investigate the interface friction in the cold rolling of metal strips. This will be implemented by introducing an equivalent interfacial layer to capture the microscopic, statistical asperity deformation and the effect of lubricant. The model proposed in the paper will be capable of covering all the lubrication regimes that can occur in a cold rolling process and allowing a smooth transition from one lubrication regime to another by introducing an equivalent interfacial layer. Furthermore, the 3D analysis of the cold rolling will be carried out with the aid of the proposed multi-scale method. Hence, the assumption of plane strain deformation in previous studies is removed. The analysis is therefore closer to the reality, which enables us to reveal the effect of the transverse deformation of the metal strip and to explore the role of hydrodynamic pressure when lubricant flows in both rolling and transverse directions.

2. Modelling

2.1. Overall methodology

As illustrated in Fig. 1, the contact between two rough surfaces in rolling starts from their highest asperities in the rolling bite. With increasing the rolling force, therefore, the contact pressure and contact area will increase. The contact stresses in the rolling