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A thermal analysis of strip-rolling in mixed-film lubrication with O/W emulsions

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Abstract

Increase of both roll and strip surface temperatures can significantly affect a rolling process, roll conditions and strip mechanical properties. A comprehensive thermal analysis in cold rolling, especially in a mixed film regime, is needed to understand how thermal fields develop in roll and strip during rolling. It requires a simultaneous solution of the mixed film model for friction in the roll bite and the thermal model for roll and strip thermal fields. This paper presents a numerical procedure to analyse strip rolling process using lubrication with oil-in-water (O/W) emulsions. The thermal model includes the effect of heat generation due to the strip deformation and frictional shear stress at the asperity contacts. The numerical analysis employs a coupled thermal model and a mixed film lubrication model for calculating the friction and the asperity deformation in the bite. The thermal model considers the initial temperatures of the roll and strip, temperature rise due to the strip plastic deformation and friction. While the O/W mixed-film lubrication model takes into account the effect of surface roughness and oil concentration (%vol) of the emulsion. The thermal effect is analysed in terms of strip surface temperature and roll temperature, which are influenced by rolling parameters such as reduction, rolling speed, oil concentration in the emulsion. The results of the parametric study indicate that the effect of oil concentration on the thermal field is relatively small compared to that of reduction ratio and rolling speed. The reduction ratio increases the maximum interface temperature in the roll bite. In the mixed film regime, rolling speed also increases the maximum interface temperature and alters the temperature field of the strip. The numerical procedure was validated against known experimental data and can readily be extended to hot rolling or used to analyse roll strip temperature subjected to different cooling system.

Keywords: Frictional heat generation; Mixed-film lubrication; Oil-in-water emulsion; Plastic deformation heat generation; Strip rolling; Thermal field

1. Introduction

Thermal effects in strip rolling operations play a significant part in a cold rolling production line, leading to problems such as high roll–strip interface temperature and non-uniform roll and strip temperature. The thermal field of a work roll dictates the thermal crown of the roll and affects strip shape. To better control a rolling process, the knowledge of the thermal field in strip rolling is therefore needed in selecting process variables such as roll speed, roll cooling system, and lubricant types. A comprehensive analysis of the thermal effects must take into account several phenomena: (1) heat generation due to plastic deformation of the strip and that due to frictional shear stress at the roll–strip interface; (2) heat conduction within the roll and the strip; (3) heat transfer across the roll–strip interface; and (4) heat transported by the rolled strip. An analysis including all of these effects must incorporate the mechanics of rolling, the hydrodynamics effect of the lubricant flow and the heat transfer in the roll and the strip. To date, there have been few attempts to carry out such a comprehensive analysis. Early thermal analyses have been carried out by Lahoti et al. [1] and Tseng [2], but they were limited to the strip and roll bite segments of the roll. Consequently, convective heat loss through the roll surface was not adequately accounted for. In their models the interface conductance is assumed to be infinitely large, resulting in equal interface temperature of the roll and strip. Heat generation due to friction in the roll

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Nomenclature

A	fractional contact area
c	adhesion coefficient
G	non-dimensional pressure coefficient ($=\gamma\sigma_y$)
h	film thickness (m)
h_c	interface conductance heat transfer coefficient ($\mathrm{W\,m^{-2}\,°C^{-1}}$)
h_{cl}	heat transfer coefficient at roll surface ($\mathrm{W\,m^{-2}\,°C^{-1}}$)
h_{cf}	interface conductance heat transfer coefficient on the fluid part ($\mathrm{W\,m^{-2}\,°C^{-1}}$)
h_{cs}	interface conductance heat transfer coefficient on the solid part ($\mathrm{W\,m^{-2}\,°C^{-1}}$)
$\bar{h}_{cr}$	non-dimensional interface conductance heat transfer coefficient ($=h_c r k_r^{-1}$)
$\bar{h}_{cs}$	non-dimensional interface conductance heat transfer coefficient ($=h_c r k_s^{-1}$)
k_h	harmonic mean thermal conductivity ($=2k_s k_r(k_s+k_r)^{-1}$, $\mathrm{W\,m\,°C^{-1}}$)
k_r	roll thermal conductivity ($\mathrm{W\,m\,°C^{-1}}$)
k_s	strip thermal conductivity ($\mathrm{W\,m\,°C^{-1}}$)
$\bar{K}$	non-dimensional number ($=\sigma_{y0}\alpha_s k_s^{-1} T_{s1}^{-1}$)
$\bar{k}_{hr}$	non-dimensional interface thermal conductivity on the solid part ($=k_h k_r^{-1}$)
$\bar{k}_{fr}$	non-dimensional interface thermal conductivity on the lubricant part ($=k_f k_r^{-1}$)
$\bar{k}_{hs}$	non-dimensional interface thermal conductivity on the solid part ($=k_h k_s^{-1}$)
$\bar{k}_{fs}$	non-dimensional interface thermal conductivity on the lubricant part ($=k_f k_s^{-1}$)
M	non-dimensional hardness ($=\varepsilon^{0.26}$)
P	non-dimensional total interface pressure ($=p\sigma_{y0}^{-1}$)
Pe	Peclet number ($=r^2\omega\alpha^{-1}=\bar{\alpha}^{-1}$)
q'''_{def}	plastic deformation heat ($\mathrm{W\,m^{-3}}$)
q''_f	frictional heat flux ($\mathrm{W\,m^{-2}}$)
r	roll radius (m)
r^*	non-dimensional roll radius ($=rt_1^{-1}$)
R	strip thickness reduction ratio ($=(t_1-t_2)t_1^{-1}$) or roll radius (m)
R_q	RMS composite roughness (m)
R^*	non-dimensional composite roughness ($=R_q t_1^{-1}$)
S	non-dimensional speed
t	strip thickness (m)
t_1	initial strip thickness (m)
t_2	final strip thickness (m)
T	temperature (°C) or non-dimensional strip thickness ($=tt_1^{-1}$)
T_r	roll temperature (°C), T_{ri} indicates T_r at interface
T_s	strip temperature (°C), T_{si} indicates T_s at interface
T_{s1}	initial strip temperature (°C)
T_∞	ambient temperature (°C)
$\bar{T}_\infty$	non-dimensional ambient temperature $=(T_\infty \bar{T}_{s1}^{-1})$
$\bar{T}$	non-dimensional temperature (= $T\bar{T}_{s1}^{-1}$)
$\bar{u}$	non-dimensional x-direction velocity ($=u\omega^{-1}r^{-1}$)
U	non-dimensional contra-variant velocity (= $\bar{u}\bar{y}_\eta-\bar{v}\bar{x}_\eta$)
$\bar{v}$	non-dimensional y-direction velocity ($=v\omega^{-1}r^{-1}$)
V	non-dimensional contra-variant velocity (= $\bar{v}\bar{x}_\xi-\bar{u}\bar{y}_\xi$)
X	non-dimensional coordinate in x-direction ($=xt_1^{-1}$)
α_r	roll thermal diffusivity ($\mathrm{m^2\,s^{-1}}$)
α_s	strip thermal diffusivity ($\mathrm{m^2\,s^{-1}}$)
δ	skin layer depth (m)
ε	strain
$\dot{\varepsilon}$	strain rate ($\mathrm{s^{-1}}$)
λ_c	concentration of water phase (%)
λ_d	concentration of oil phase (%)
θ	asperity slope (rad)
τ	frictional shear stress (Pa)
ω	roll angular velocity ($\mathrm{rad\,s^{-1}}$)

bite was assumed constant. Both assumptions are unrealistic as there is finite thermal resistance in the bite, and the complex frictional heat generation depends on the local relative velocity between the strip and the roll, and the contact condition. Tseng et al. [3] proposed analytical models for roll and strip temperatures, and used a compatibility condition to link the two heat transfer models along the contact interface. The analysis provides a fast tool for performing parametric studies of the effect of changing geometry and operating parameters on the thermal behaviour. However, there are limitations of the analytical models due to their dependence on the number of terms included in the series type analytical solution as shown by Gecim and Winer [4] and Cerni et al. [5]. Moreover, as the friction and thermal models are not coupled, plastic deformation and friction heat input can only be supplied as specified values. More recently, Chang [6] developed a simple model combining deformation and thermal effects. The numerical analysis uses a combination of finite-difference and analytical solutions to reduce the computational time. However, this procedure leads to complications if one wishes to include a complete roll and a larger strip region in the analysis.

Numerically two approaches have been used: one is based on a Lagrangian coordinate system and the other on an Eulerian system. The Lagrangian system yields explicit differencing and is simple to solve, but for high roll speed it requires a considerable number of time steps to arrive at a