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A novel model-based approach for the prediction of wear in cold rolling

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ABSTRACT

The tribological interface between work roll and strip significantly influences the process parameters and mill performance in cold rolling as well as the final quality of flat products. Due to the severe contact conditions associated with the underlying plastic deformation of the strip and the elastic deformation of the work roll, the tribological mechanisms occurring at that interface are difficult to investigate by experimental methods or conventional cold rolling theories.

The model-based approach presented in this work utilizes a modular tribological cold rolling model to predict the local mixed lubrication interface conditions based on rolling mill, pass and lubricant parameters. The calculated values for pressure, temperature, etc. are used to estimate the wear extracted from the strip surface by utilizing a locally distributed implementation of Archard's equation.

The new model was validated against results obtained from a pilot reversing mill including the accumulated wear volume generated during rolling of various steel grades using different emulsions. The proposed modelling approach contributes to a better understanding of tribology and wear in cold rolling processes of flat products. In particular, the influence of significant rolling as well as lubrication parameters on rolling performance and wear generation can be estimated.

1. Introduction

1.1. *Mixed lubrication cold rolling model*

Tribological effects along the interface of work roll and strip in cold rolling of flat products significantly influence the process parameters and mill performance as well as the final product quality. On the one hand, force and power requirements of the mill are directly influenced by the lubricated tool-workpiece contact via shear stresses and contact pressure, on the other hand, the generation of wear particles heavily depends on the severity of this contact. Such particles being washed off to the circulated emulsion in turn affect the contact conditions and thus the coefficient of friction. Together with the underlying plastic deformation process of the strip and the elastic deformation of the work roll, a highly complex tribo-system emerges that is difficult to be simulated by experimental test methods or to be described by appropriate mathematical models. In this work, a coupled tribological and wear model for cold rolling is presented, which allows a reliable prediction of the rolling forces based on relevant parameters of the rolling pass, the mill and the lubricant. From these results, the amount of wear generated on the strip surface is calculated.

Regarding the underlying cold rolling process, a wide range of mathematical models exists from very basic analytical descriptions up to highly specialized finite-element calculations. However, these models usually rely on the assumption that friction between the work roll and the strip is a priori known. Such models are typically calibrated to specific rolling mills by evaluating measurement data from the mill and inserting this information into the model, e.g. by means of a recalculated and speed-dependent "effective" Coulomb coefficient of friction as adaptation parameter. Following this procedure, the general applicability of the model is partly lost, as it is calibrated to a specific parameter combination (e.g., to a certain steel grade with a certain roughness and a specific lubricant). Replacing this highly empiric part of the cold rolling model by a much more physically based model for the prediction of friction, the generality and overall accuracy of a mathematical rolling model can be significantly increased, and the reliable range of rolling conditions can be extended, leading to an improved and generalized model applicability.

A tribological model for the cold rolling process was developed

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Nomenclature

A	fractional area of boundary contact, also fractional contact area, or contact area, (%)
A_{pd}	contact area fraction at the beginning of the deformation zone, (–)
b	strip width, (m)
c_A	adhesion coefficient, (–)
c_o	concentration of oil in water, (%)
$c_{o,0}$	emulsion tank concentration, (%)
$c_{o,pd}$	averaged oil concentration at the beginning of the deformation zone, (%)
c_{pf}	specific heat of the emulsion, (J kg^{-1} K^{-1})
c_{pr}	specific heat of the work roll, (J kg^{-1} K^{-1})
c_{ps}	specific heat of the strip, (J kg^{-1} K^{-1})
d_{aam}	diameter of area associated with an adsorbed molecule, (m)
$d_{po,r}$	plate-out layer in the inlet zone on the work roll surface, (m)
$d_{po,s}$	plate-out layer in the inlet zone on the strip surface, (m)
$d_{po,\infty}$	thickness of plate-out layer at the beginning of the inlet zone, (m)
$d_{por,\infty}$	initial plate-out layer thickness on the work roll, (m)
$d_{pos,\infty}$	initial plate-out layer thickness on the strip, (m)
d_{rs}	sliding distance, (m)
$d_{rs,l}$	increase of sliding distance per contact angle (distributed along the contact zone), (m rad^{-1})
d_s	oil droplet diameter, (m)
D	diffusion coefficient, (m^2 s^{-1})
D_{app}	emulsion application rate per strip width, (m^2 s^{-1})
e_f	specific internal energy of the fluid, (J kg^{-1})
E	non-dimensional bulk strain rate, (–)
E_a	heat of adsorption of the lubricant on the strip surface, (J mol^{-1})
$f(z)$	probability density function of asperity peak height distribution, (m^{-1})
f_1	empirical function in the roughness flattening model
f_2	empirical function in the roughness flattening model
F_n	normal force, (N)
$F_{n,l}$	load increase per contact angle (distributed along the contact zone), (N rad^{-1})
F_r	rolling force, (N)
g_f	specific enthalpy of the fluid, (J kg^{-1})
h	strip thickness, (m)
Δh	absolute strip thickness reduction, (m)
h_f	film thickness, (m)
$h_{f,pd}$	entrained film thickness at the entry of the deformation zone, (m)
h_{in}	strip thickness at roll bite entry, (m)
h_{out}	strip thickness at roll bite exit, (m)
h_r	nominal surface separation, (m)
H	non-dimensional difference between boundary and lubricant pressure, (–)
H_s	hardness of the softer material, (Pa)
$H_{s,l}$	local hardness of the strip surface (distributed along the contact zone), (Pa rad^{-1})
k	Archard's wear coefficient, (–)
k_0	wear coefficient for dry sliding conditions, (–)
k_f	actual yield strength in the roll gap (distributed along the deformation zone), (Pa)
k_{f0}	initial yield strength of hot strip, (Pa)
k_l	local wear coefficient (distributed along the contact zone), (rad^{-1})
k_s	actual strip material shear yield strength in the roll gap (distributed along the contact zone), (Pa)
k_{s0}	strip material shear yield strength at bite entry, (Pa)
l	strip length of a coil, (m)
l_d	length of the deformation zone, (m)
l_y	mean asperity half spacing in strip width direction, (m)
m	Tresca friction factor, (–)
m_c	coil mass, (kg)
p	total rolling pressure, (Pa)
p_b	boundary contact pressure, (Pa)
$p_b{}^*$	non-dimensional boundary contact pressure, (–)
p_f	lubricant pressure, (Pa)
p_f^*	non-dimensional lubricant pressure, (–)
p_{pd}	total pressure at the beginning of the deformation zone, (Pa)
p_{ref}	reference pressure in Roelands equation, (Pa)
$\dot{q}_i$	specific heat flux components, (W m^{-2})
r	radial coordinate in the inlet zone, (m)
r_∞	radial position of the start of the inlet zone, (m)
r_{pd}	radial position of the transition from the inlet zone to the deformation zone, (m)
r_r	undeformed work roll radius, (m)
R	deformed work roll radius, (m)
R_a	composite R_a value of strip and work roll surfaces, (m)
R_g	universal gas constant, (J K^{-1} mol^{-1})
R_q	composite mean square surface roughness value of strip and work roll, (m)
s_0	Roelands temperature-viscosity index, (–)
s_f	specific entropy of the fluid, (J kg^{-1})
t	time, (s)
t_0	fundamental time of vibration of a molecule in adsorbed state, (s)
T_f	emulsion temperature, (K)
T_{ref}	reference temperature in Roelands equation, (K)
T_s	strip temperature, (K)
Δu	speed difference between work roll and strip, (m s^{-1})
u_f	emulsion velocity, (m s^{-1})
$\mathbf{u_r}$	work roll speed, (m s^{-1})
u_{rad}	radial velocity component of the lubricant in the inlet zone, (m s^{-1})
$\mathbf{u_s}$	strip speed in the deformation zone, (m s^{-1})
$u_{s,in}$	speed of incoming strip, (m s^{-1})
$u_{s,out}$	strip exit speed, (m s^{-1})
$u_{s,x}$	x-component of the strip speed, (m s^{-1})
$u_{s,y}$	y-component of the strip speed, (m s^{-1})
u_φ	angular velocity component of the lubricant in the inlet zone, (m s^{-1})
v_{ea}	emulsion application velocity (emulsion jet speed), (m s^{-1})
v_f	specific volume of the fluid, (m^3 kg^{-1})
v_i	velocity field components in directions x_i, (m s^{-1})
V_{cs}	strip volume in the contact zone (m^3)
$V_{cs,l}$	local rolled strip volume (distributed along the contact zone), (m^3 rad^{-1})
V_s	wear volume in Archard's equation, (m^3)
$V_s{}^*$	non-dimensional strip wear volume generated along the contact zone, (–)
$V_{s,l}$	increase of generated strip wear volume per contact angle (distributed along the contact zone), (m^3 rad^{-1})
$V_{s,l}{}^*$	local non-dimensional strip wear volume (distributed along the contact zone), (rad^{-1})