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Inverse estimation of thermal parameters and friction coefficient during warm flat rolling process

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ABSTRACT

In this work, an inverse method for estimating the average thermal parameters and friction coefficient is proposed based on exit strip temperature and slip measurement. The inverse model makes use of a direct model for temperature determination, which uses the finite element method for the deformation analysis and an analytical method for the estimation of the temperature distribution. The direct model uses the temperature dependent thermal properties of roll and strip to estimate the temperature of exit strip. For minimizing the mean squared fractional error (MSFE) between the measured and computed temperatures of exit strip, a heuristic algorithm is used. The inverse method is tested by carrying out a number of numerical experiments on the warm strip rolling. Less than $\pm 7\%$ error is observed between the actual and estimated thermal parameters and friction coefficient.

1. Introduction

Flat rolling is the process of reducing the thickness of a sheet by passing it between two counter-rotating rolls. Rolling is classified into hot, warm and cold. Hot rolling is carried out at a temperature greater than $0.6T_m$, where T_m is the melting point of the metal in Kelvin [1]. Cold rolling is performed at a temperature lesser than $0.3T_m$ and warm rolling is carried out in the temperature range of $0.3–0.6T_m$. Warm rolling combines the advantages of hot and cold rolling [2]. It requires lower loads and energies compared to cold working. It achieves better surface finish and dimensional accuracy compared to hot rolling. Koohbor [3] studied the thermo-mechanical behavior of strip and roll in warm rolling under steady-state conditions. He also observed that warm rolling is becoming an efficient means to produce flat steel products due to its ability to obtain the desired product properties at reduced cost. For maintaining the proper productivity and quality of the product, mathematical modeling of the warm rolling process is an essential requirement. For finding out the temperature distribution in the roll and the strip, one needs to know their mechanical and thermal properties as well as the friction at the roll–sheet interface. One difficulty is unavailability of property data, especially when they are temperature-dependent *e.g.*, thermal conductivity and thermal diffusivity of the roll and strip. In view of it, the present work proposes to estimate the thermal properties of materials of the sheet and the roll and the coefficient of friction by measuring the temperature of outgoing sheet at two specified places and slip. Before describing the inverse estimation procedure, a brief review related to the topic is presented.

A number of analytical and numerical models have been developed for the estimation of temperature in rolling process. Patula [4] used a method of separation of variables with complex functions to obtain the steady-state temperature distribution in the roll. Tseng [5] estimated the temperature distribution in the roll and the sheet using the finite difference method (FDM). The input data for the heat generation was taken by the direct measurement of power. Further, the 6.5% of the 90% total power was assumed to dissipate as friction heat. Tseng et al. [6] estimated the temperature distribution in the roll using the Fourier transform. For estimating the temperature distribution in the strip, the method of separation of variables was employed. The condition of average temperature of roll and strip being equal was imposed. Galantucci and Tricarico [7] estimated the temperature distribution in the roll and the strip using the finite element method (FEM) based software ANSYS. In the model of Sheikh [8], the deformation analysis of strip was carried out by the upper bound technique and the steady-state temperature of rolling was estimated by the FEM. Khalili et al. [9] developed a combined numerical–analytical model for the steady-state warm rolling to analyze the effect of the initial strip temperature and rolling speed on the temperature and thermal stress of the roll. The authors used the slab method for the deformation analysis.

Apart from the steady-state analysis, the transient analysis is also attempted in the literature. Guo [10] proposed a Laplace transform method to obtain transient solution for a particular

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Nomenclature

a,b	inner and outer roll radii of roll
A,B,C	constants of J–C material model
f	friction factor
f_s	forward slip
h_a	convective heat transfer losses at surface of strip
h_e,h_i	convective heat transfer losses at outer and inner periphery of roll
h_1, h_2	inlet and exit thickness of strip
k_r,k_s	thermal conductivity of roll and strip
c_{pr}	specific heat of roll
c_{ps}	specific heat of strip
J_n,Y_n	Bessel function of first and second kind
l_d	contact length of roll and strip at the interface
L	length of bite zone
m,n	constants of J–C material model
m	positive integer in Eqs. (11)–(13)
n	positive integer or zero in Eqs. (11)–(13)
n_1,n_2	temperature dependent parameters in Eqs. (23) and (24)
$\overline{N}_{ux}$	Nusselt number
p	hydrostatic pressure
P_f	power due to friction
P_p	power due to plastic deformation
Pr	Prandtl number
q	heat flux input into the roll
$\dot{q}_s$	heat generated due to friction work
$\dot{q}_v$	heat generated due to plastic work
r–θ	polar coordinates in Eqs. (11) and (13)
r	reduction ratio
R	undeformed roll radius
R'	deformed roll radius
S_{ij}	deviatoric part of the stress tensor
S_1,S_2	sensor 1 and sensor 2 location
Re_x	Reynold number
t	time
t_a	time spent by strip at roll bite
t_n, t_s	interfacial normal and shear stress components
T	temperature
T_{amb}	ambient temperature
T_e,T_i	medium temperature at outer and inner periphery of roll
T_{i1c}, T_{i2c}	temperature computed at sensor 1 and sensor 2 locations
T_{i1m}, T_{i2m}	temperature measured at sensor 1 and sensor 2 locations
T_m	melting temperature
T_0	initial temperature of inlet strip
V_R	roll velocity
v_1,v_2	components of velocity vector
V_1, V_2	inlet and exit velocities of the strip, respectively
w	width of the strip
x–y	Cartesian coordinates of strip in Fig. 3
$x1,x2$	Cartesian coordinates

Greek letters

α	bite angle after roll deformation
α_r, α_s	thermal diffusivity of roll and strip
β	half arc of the heat source
β_m	roots of the characteristics Eq. (12)
$\varepsilon, \varepsilon_{eq}$	equivalent (plastic) strain
$\dot{\varepsilon}_{eq}$	equivalent strain-rate
$\dot{\varepsilon}_0$	reference strain-rate
$\dot{\varepsilon}_{ij}$	strain rate tensor
ϕ	angle
η	proportionality factor
λ	heat partition factor
λ_n	roots of the characteristics Eq. (18)
μ	coefficient of friction
θ	angular displacement of roll
ρ_r, ρ_s	density of roll and strip
σ_f	flow stress of strip
σ_Y	flow stress of the material in Eq. (6)
σ_0, σ_1	temperature dependent parameters in Eqs. (23) and (24)
ω	angular velocity of roll

boundary condition. Duhamel's theorem was used to obtain the complete solution for various boundary conditions. However, the thermal analysis of the strip was not carried out. Serajzadeh [11,12] developed two-dimensional FEM model to obtain the transient temperature distribution of the roll and the strip. Shahani et al. [13] carried out a transient two-dimensional thermal analysis by FEM.

A number of inverse models have been proposed for the rolling process. Lenard and Malinowski [14] estimated the friction coefficient by matching measured and calculated roll separating forces. Lenard and Zhang [15] estimated the friction coefficient through an inverse technique by matching measured and computed roll forces, roll torques and forward slips. McConnell and Lenard [16] described an inverse method to calculate the friction coefficient in cold rolling based on the measurement of roll forces, roll torques and forward slips. Lenard and Nad [17] estimated the coefficient of friction by matching the measured and calculated roll forces and roll torques.

Cho and Ngaile [18] proposed an inverse method to determine the flow stresses and friction coefficient. In their work, the rigid visco-plastic finite element formulation was used to predict the flow stresses and friction, while optimization algorithm adjusted the parameters used in the simulation until the calculated response matched with the experimental measurements within a specified tolerance. Han [19] applied a modified two-specimen method (MTSM) for the online determination of flow stresses and coefficient of friction in a rolling process. In their method, the strip is rolled twice with two different sets of roll radii. Instead of the real experiments, the ABAQUS FEM simulations were used for validating the methodology. Byon et al. [20] proposed an inverse method for the prediction of flow stress–strain curve and coefficient of friction using actual mill data. The measurement of roll force and forward slip is taken as the basis for inverse estimation.

Huang et al. [21] applied the conjugate gradient method to estimate the heat flux and the temperature distribution in the roll. The method requires the measurement of surface temperature of the roll. Yoneyama et al. [22]conducted the experiment to measure the temperature of roll surface at the contact zone during the hot rolling of aluminum sheet. A number of temperature sensors were embedded in the roll surface to analyze the influence of different rolling process parameters. Further, a one-dimensional FDM model was used to predict the heat transfer coefficient (HTC) at the interface between roll and sheet. HTC is calculated in an inverse way by comparing the measured and calculated temperatures. Hsu