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Analytical approach for calculating the sheet output curvature in asymmetrical rolling: In the case of roll axis displacement as a new asymmetry factor

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ABSTRACT

In this paper, a less studied factor in the asymmetrical rolling process of sheets, namely the rolls horizontal displacement, is investigated using an analytical approach based on the slab method analysis. The presented method is capable of computing the force and torque of the process under different asymmetrical factors such as the rolls horizontal displacement, the interface friction inequality, and the rolls speed mismatch. A formula is presented to predict the outgoing sheet curvature induced by the rolls horizontal displacement. The results can be potentially used in producing curved sheets of various shapes by the asymmetrical rolling process. The analytical model is compared with a verified finite element code and good agreement has been observed.

1. Introduction

Generally, dissimilar conditions for the upper and lower rolls such as unequal rolls radius, unequal surface speed, and different contact friction lead to the asymmetrical rolling process. This process is widely used in industry for manufacturing of sheets and strips with a relatively lower force and power in comparison with the conventional rolling.

It is also capable of producing curved sheets of various shapes and sizes and creating intended bending in thin workpieces. These advantages encouraged several researchers to investigate different aspects of the asymmetrical rolling process. On the other hand, in most industrial applications the ski-effect (curved sheet) is undesired, since it hinders the further material transport due to crash with the transfer table and is a potential danger for the machine components in the proceeding processes.

Collins and Dewhurst [1] presented a slip-line field solution for the asymmetrical hot rolling process and compared the rolling force, rolling torque and outgoing curvature with available experimental data. Pan and Sansome [2] investigated the asymmetrical rolling process resulted from mismatching rolls speed and calculated the rolling force reduction. They showed that the rolling force can be reduced up to 30–40% by performing the process asymmetrically. Shivpuri et al. [3] presented an explicit finite element method simulation for the asymmetrical rolling process resulted from rolling speed mismatch and calculated the outgoing sheet curvature. Richelsen [4] numerically analyzed the asymmetric plate rolling resulted from different interface friction conditions at the two rolls. Hwang and Tzou [5], [7] investigated the asymmetrical hot rolling process via the slab method analysis and obtained the rolling force and torque using this model. Hwang et al. [6] presented an analytical model capable of predicting the force of the asymmetrical rolling process by entering a constant shear friction in the governing equations. Richelsen [8] investigated the asymmetrical rolling process via the finite element method. The asymmetrical factor in this solution was the rolls speed mismatch and unequal contact friction. Jeswiet and Greene [9] studied the asymmetrical rolling process using a finite element model. They obtained the outgoing sheet curvature resulted from the rolls speed mismatch. Tzou [10] investigated the relationship between the frictional coefficient and frictional factor, the effect of roll speed ratio, reduction ratio, ratio of effective radius to thickness and front and back tension in the asymmetrical rolling. Lu et al. [11] investigated the effect of the unequal rolls radius, rolls speed mismatch, reduction degree and initial sheet thickness on the outgoing sheet curvature by means of the finite element method. Nilsson [12] investigated the asymmetrical rolling process resulted from different peripheral speeds of work rolls, different reductions, a thermal gradient across the thickness of the plate and the position of the roller table in relation to the neutral axis of the roll gap. Tzou and Huang [13] developed an analytical model for the minimum thickness in PV rolling. Gao et al. [14] studied the

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Nomenclature

u,l	indices for upper and lower portions
K	curvature index
p	rolling force per unit width
q	horizontal normal stress in deformation zone
R	radius of rolls
T_u,T_l	rolling torque of the upper and lower rolls
c_u,c_l	average ratios of the shear stresses through thickness to surface shear stresses
h	variable sheet thickness in deformation zone
h_i,h_o	initial and final sheet thickness
k	mean yield shear stress
d	contact interface between the upper and lower rolls
L	starting point of deformation zone in global coordinates system
Δ,X_m	horizontal distance of two rolls and it is coordinates in the global system, respectively
m_u,m_l	friction factor of the upper and lower rolls, respectively
p_u,p_l	upper and lower roll pressures
Re	reduction in thickness
r	output radius
V_u,V_l	peripheral speeds of the upper and lower rolls
x	horizontal distance in local coordinate system
X	horizontal distance in global coordinate system
x_u,x_l	neutral points in local coordinate system
X_u,X_l	neutral points in global coordinate system
X_s,X_c	contacts starting points of sheet with upper and lower rolls, respectively
φ	rate of rotation of the deformation zone caused by the horizontal distance between two rolls
α	angular rotation of the vertical element
b	center to center distance of rolls
a	the amount of the thickness change by the rolls in local coordinate system
f_u,f_l	the amount of the thickness change by the upper and lower rolls in global coordinate system, respectively
θ	variable angles of contact of rolls
γ_u,γ_l	average shear strain at upper and lower portion of the sheet
$\sigma_x,\sigma_y,\tau_{xy}$	normal and shear stresses
$\bar{\varepsilon}_u,\bar{\varepsilon}_l$	average normal strain at upper and lower portion of plate
τ_u,τ_l	surface shear stress at the upper and lower rolls
$\bar{\tau}_u,\bar{\tau}_l$	average shear stress on the upper and lower portions
$\bar{\sigma}_{xu},\bar{\sigma}_{xl}$	average horizontal stresses in upper and lower portions at the roll gap
σ_f	flow stress
σ_{yield}	yield strength

effect of the difference in the coefficient of friction rather than the difference of roll radius and rotation speeds in asymmetrical cold rolling. Salimi and Sassani [15] presented an analytical model for the asymmetrical rolling process based on the modified slab method by considering unequal rolls radius, rolls speed mismatch and dissimilar contact friction. The rolling force, rolling torque and outgoing curvature were compared with the experimental data of other researchers, and very good agreement was observed. Knight et al. [16] investigated the asymmetrical rolling process via the finite element technique. In their solution, the asymmetrical factors were the workpiece temperature difference, rolls speed mismatch and unequal contact friction. Markowski et al. [17] presented a theoretical analysis of the asymmetrical rolling in the plate's hot rolling mill with finite element software. Kawałek [18] used analysis of asymmetric rolling process to obtain the range of admissible value of roll speed asymmetry coefficient. Salimi and Kadkhodaei [19] investigated the asymmetrical rolling process using the finite element method. In their model, non-uniformity of the normal and shear stresses were considered in equations. Jiang et al. [20] developed a modified influence function method model on the deformation compatibility when the roll speeds are different. Knight et al. [21] investigated the effect of roll speed mismatch on the direction and severity of strip curvature with finite element technique. Farhatnia et al. [22] employed a finite element model based on Lagrangian-Eulerian (ALE) method to simulate the asymmetrical sheet rolling process. The outgoing sheet curvature was obtained based on unequal rolls radius, rolls speed mismatch and unequal contact friction. Pan et al. [23] investigated the rolling force, rolling torque in asymmetrical rolling of two-layer unbounded clad sheet caused by different roll speed and roll radii. Mousavi et al. [24] performed a simulation of the asymmetrical sheet rolling via the finite element method. In their work, the effect of the rolls speed mismatch on the outgoing curvature, rolling force and rolling torque was investigated. Gong et al. [25] presented a formula for calculation of the outgoing sheet curvature. Their modeling indicated that by increasing the friction factor coefficient, reduction ratio and rolls radius the outgoing curvature decreases. Qwamizadeh et al. [26] investigated the outgoing curvature of the asymmetrical sheet rolling by a theoretical method based on the slab method analysis. They considered the rolls speed mismatch, unequal rolls radius and dissimilar contact friction as asymmetry factors. Non-uniformity of normal and shear stresses was considered in the governing equations. Zhang et al. [27] calculated the rolling force and rolling torque in the asymmetrical sheet rolling by considering rolls speed mismatch, different rolls radius and unequal contact friction. The shear stress acting along the vertical sides of each slab was considered in the governing equations. Anders et al. [28] present a thorough dimensional analysis coupled with copious finite element studies of the front-end bending phenomenon. Hao et al. [29] investigated the output curvature in asymmetric rolling process caused by different roll radii by two-dimensional explicit dynamic FEM model. Tang et al. [30] investigated the permissible minimum rolling thickness and rolling force in asymmetrical rolling by slab method analysis.

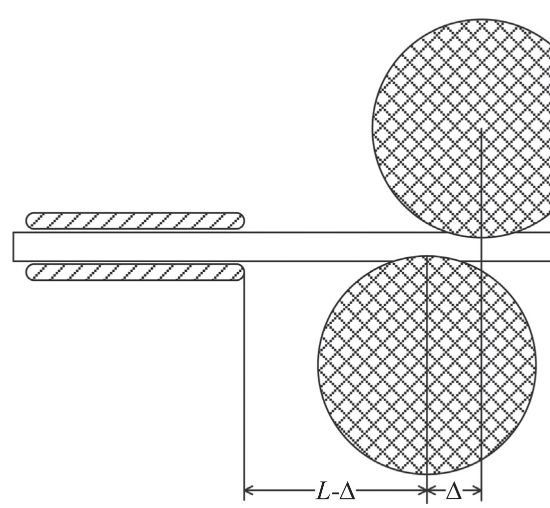

Fig. 1. Rolls horizontal displacement.