Journal of Manufacturing Processes 20 (2015) 162–171

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Technical Paper

An analytical model of asymmetric rolling of unbounded clad sheets with shear effects

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ARTICLE INFO

Article history:
Received 16 January 2015
Received in revised form 23 August 2015
Accepted 28 August 2015
Available online 10 September 2015

Keywords:
Asymmetrical rolling
Clad sheet
Pressure distribution
Slab method
FEM

ABSTRACT

Based on the slab method analysis, a new solution for asymmetrical rolling of unbonded clad sheet is presented in this paper. The non-uniformity of the shear stresses and the uniformity of the normal stresses at the vertical sides of each slab across the portion of the deforming material all over the plastic region are considered. The effects of the process parameters such as reduction, work rolls radii ratio and work rolls speed ratio on process outputs are investigated. In addition, the asymmetrical clad sheet unbonded before rolling process is simulated wholly using ABAQUS/explicit software. Comparisons of analytical results from present model with those from experimental studies of the other investigators and the finite element simulation have showed good agreements.

1. Introduction

Due to some unique features such as high strength, high resistivity against corrosion, and high electrical conductivity, the usages of laminated sheets have been risen. There are many different methods for mass production of laminated sheets in which the asymmetrical rolling is one of the efficient processes. In the asymmetrical clad sheet rolling, the work rolls radii, speeds, surface roughness and thickness of the sheets may be different. Compared to symmetrical process, the rolling force, pressure, and torque can be decreased in the asymmetrical process and the energy can be saved.

Up to now, a number of studies have been done in the field of the asymmetrical sheet and clad sheet rolling processes. A mathematical model for analysis of the asymmetrical clad sheet rolling process based on the stream function and the upper bound methods were done by Hwang and Chen [1]. Lee and Lee [2] used the slab method and experimental analysis to study roll bonding of silver clad phosphor bronze sheets. Some experimental studies were done by Johnson and Needham [3] to investigate the asymmetrical sheet rolling.

Finite element method (FEM) analysis is one of the powerful methods to determine the stress–strain distribution in the metal forming processes. But, a lot of time and cost are required to carry out this method. FEM was used to evaluate the effects of shear yield stress ratio and thickness ratio on the stress, strain, and rolling force in clad sheet rolling process [4,5].

The slab method is a proper method can be used to analyze metal forming processes like symmetrical and asymmetrical sheet and clad sheet rolling. Via this method, the rolling force and torque can be predicted rapidly and a large amount of solution time can be saved. Studies on the asymmetrical rolling process can be categorized into two groups, the asymmetrical sheet rolling and the asymmetrical clad sheet rolling.

Although some researchers have used the slab method to investigate the asymmetrical sheet and clad sheet rolling processes, but this method with considering the non-uniform distribution of shear stress acting on a vertical slab across the section of the deforming material has never been applied to clad sheet rolling process.

An analytical model for analysis of relationship between frictional coefficient and frictional factor in asymmetrical sheet rolling was proposed by Tzou [6]. Based on that analysis, the frictional factor can be obtained rapidly and easily when the frictional coefficient is known. In author's previous study [7], an analytical solution for ring rolling process was presented according to the slab method theory in which the non-uniformity of the normal and shear stresses across the section of the deforming material throughout the plastic zone was considered. Taking into consideration the

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http://dx.doi.org/10.1016/j.jmapro.2015.08.007
1526-6125/

Nomenclature

F	rolling force of the asymmetrical clad sheet rolling
F_1, F_2, F_3, F_4	rolling forces in zone *I*, *II*, *III* and *IV*, respectively
h	variable sheet thickness at the roll gap
h_1, h_2	upper and lower element heights with respect to horizontal axis, respectively
h_i, h_o	sheet thicknesses at the entry and the exit of the roll gap, respectively
m_1, m_2	friction factors at the upper and the lower rolls respectively
m_3	friction factor at the interface of the clad sheet
k_1, k_2	mean yield shear stresses of the upper and the lower sheets, respectively
L	contact length
p	vertical stress at the roll gap
p_1, p_2	rolling pressures at the upper and the lower interfaces, respectively
p_3	contact pressure between the clad sheet
r	reduction in thickness (%)
R_1, R_2	radii of the upper and the lower work rolls, respectively
R_{eq}	equivalent work roll radius
T	total rolling torque of the asymmetrical clad sheet rolling
T_1, T_2	rolling torques of the upper and the lower rolls, respectively
V_A	ratio of the lower to the upper work roll speeds
x_{n1}, x_{n2}	positions of the upper and the lower neutral points, respectively
x_b	position of the bonding point
σ_1, σ_2	normal stresses at the upper and the lower slab element in the roll gap
τ_1, τ_2	frictional shear stresses at the upper and the lower interfaces, respectively
τ_3	shear stress at the interface of the clad sheet
$\bar{\tau}_1, \bar{\tau}_2$	average shear stresses along the vertical side of the upper and the lower slab element, respectively
θ_1, θ_2	variable angles of contact for the upper and the lower rolls, respectively
$\sigma_{yp1}, \sigma_{yp2}$	flow stresses of the upper and the lower sheets, respectively

strain-hardening effects, Gudur et al. [8] attempted to analyze the asymmetrical rolling process in order to estimate the curvature of the rolled sheet. Using the slab method, the analysis of the asymmetrical sheet rolling process was carried out by Yong et al. [9]. They investigated the influence of asymmetrical rolling factors on deformation area and rolling pressure by dividing the deformation area into three zones. An analytical solution was proposed by Tzou and Huang [10] to investigate the minimum thickness for the asymmetrical PV cold rolling of sheet. They considered two analytical models with the same and the different frictional coefficients at the upper and lower rolls. In addition, another model was proposed by Tzou and Huang [11] to analyze the minimum thickness for asymmetrical hot-and-cold PV rolling by considering the constant shear friction.

Based on the slab method theory, an analytical solution was presented by Hwang and Tzou [12] for asymmetrical sheet rolling process in which the effects of the shear stress and internal moment at the roll gap were considered. Gao et al. [13] studied the asymmetrical cold rolling by considering the differences in the coefficient of friction between rolls and sheets rather than the differences of rolls radii or rotation speeds. According to the slab method, Salimi and Kadkhodaei [14] considered non-uniformity of the normal and shear stresses in deriving the governing equations for analysis of plane strain asymmetrical rolling. Likewise, Zhang et al. [15] presented a new stress field for asymmetrical sheet rolling in which the uniform normal and non-uniform shear stresses on the vertical sides of each slab were considered. In the earlier works on clad sheet rolling, the slab method mainly was applied to evaluate the rolling pressure and force. Furthermore, the slab method was also applied to investigate the plastic deformation of clad sheet, considering constant shear friction and hybrid friction, respectively in [16,17].

An analytical model was presented by Pan et al. [18] for analysis of asymmetrical cold and hot bond rolling of unbonded clad sheet. In their model, they assumed uniform normal stress, but ignored the shear stress distribution in the vertical sides of the slabs. However, the physical condition of the asymmetrical rolling of unbounded clad sheets in which different friction states exist at the interfaces of clad sheet with the upper and the lower rolls and at the interface of two layers necessitate to consider a non-uniform distribution of the shear stress on the vertical sides of the slabs. Therefore, this postulate is taken into account in this study as a novelty to extend the Pan et al. [18] study and obtain a more accurate model.

In this paper, a solution based on the slab method of analysis is presented for asymmetrical clad sheet rolling process. At first, a mathematical model for the stress field acting on a vertical slab in the roll gap is presented in which the uniformity of the normal stress and non-uniformity of shear stress across the section of the deforming material are considered. After that, imposing the force balance on the slab with differential thickness, one dimensional differential equation for pressure at the roll gap is obtained. Finally, imposing relevant boundary conditions on the differential equation provides an analytical solution for the rolling pressure. In the analytical solution, a variety of factors for asymmetrical clad sheet rolling process such as the friction factor, the friction factor ratio, the roll speed ratio, and the roll radii ratio have been used to investigate the behavior of the process. Based on the present analysis, complete expressions for the asymmetrical clad sheet rolling pressure, force and torque are obtained and the position of the bonding point and neutral points are determined. Eventually, by using ABAQUS/explicit software, the asymmetrical clad sheet rolling process is simulated and the results are used to evaluate the accuracy of present model.

2. Mathematical models

In Fig. 1, the schematic illustration of the asymmetrical clad sheet rolling unbonded before rolling is shown. According to this figure, two unbonded metal sheets with uniform unit thickness and a total heights h_i and h_o at the entry and the exit, respectively are rolled through the asymmetrical rollers. The upper sheet is softer than the lower one and has lower yield stress. The horizontal distance from the exit point in the roll gap is taken as the x-axis and the origin is its intersection with the normal plane passing by centers of two rolls.

The plastic deformation zone at the roll gap can be divided into four different zones. Zone *I* for the unbonded zone ($x_b \le x \le L$) in which only the softer sheet, the upper layer, is yielded. When the harder sheet is also yielded, the bonding point (x_b) is generated and after that, the sheets are bonded together completely. In zone *II* ($x_{n1} \le x \le x_b$), the peripheral velocities of the upper and the lower rolls are larger than that of the sheets, thus the direction of both the upper and lower frictions on the clad sheet are in the forward direction. Zone *III* ($x_{n2} \le x \le x_{n1}$) is a cross shear zone in which the clad sheet velocity is less than that of the lower roll and greater than