Journal of Manufacturing Processes 34 (2018) 349–355

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

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

Three-dimensional analysis of edge rolling based on dual-stream function velocity field theory

Y.M. Liu[a,*], J. Sun[b], D.H. Zhang[b], D.W. Zhao[b]

[a] College of Mechanical Engineering, Taiyuan University of Technology, Taiyuan, 030024, Shanxi, PR China
[b] State Key Laboratory of Rolling and Automation, Northeastern University, Shenyang, Liaoning, 110819, PR China

ARTICLE INFO

Keywords:
Edge rolling
Rolling force
Dog-bone shape
Sine function model
Dual stream function

ABSTRACT

A three-dimensional mathematical model for edge rolling using sine function dog-bone shape and the dual-stream function (DSF) method is established to research the plastic deformation of the slab at the vertical roll gap. A kinematically admissible velocity field is derived through DSF based on sine function model and the slab total power functional is obtained according to the upper bound theorem. The upper bound solutions of dog-bone shape and rolling force are solved numerically via minimizing the total power function by using the Matlab Optimization Toolbox. Satisfactory results are given while compared with experimental data in reference and FEM simulation, with good convergence, in various rolling conditions such as engineering strain, initial thickness and roll radius.

1. Introduction

To promote the quality of hot rolled products and create better production conditions for the rear process, the width precision of the strip must be guaranteed. The edge rolling method is an important measure to control the width in actual production. In edge rolling, plastic deformation only occurs in a small zone on the edge and doesn't go deeper into the slab because of the high ratio of width to thickness, so the dog-bone shape is formed [1]. However, the dog-bone flattens in the width direction in the subsequent horizontal rolling. Therefore, to predict and control the dog-bone shape and rolling force in edge rolling is helpful to improve the practical control accuracy and produce high quality strip products.

The dog-bone shape has been studied by many researchers, but relatively few theoretical studies. Tazoe [2] derived a mathematical formula based on the experimental data obtained by Shibahara [3]. Later, it was modified by Ginzburg [4] whose physical experiment conditions are that the slab thicknesses are 5.0–25.0 mm, slab widths are 100.0–200.0 mm, the edger roll diameters are 90 and 120 mm, and the reductions are 1.0–7.0 mm. Xiong [5] proposed experience formula to describe dog-bone characteristic parameters according to physical experiments in which the lead is used as model material. And the experiment conditions are that the slab thicknesses are 6.0–32.0 mm, slab widths are 75.0–145.0 mm, the edger roll diameters are 62, 76, 80, 90 and 105 mm, and the reductions are 1.0–10.0 mm. But these formulas are only to describe the deformed shape at the exit.

FEM is one of the best ways to study complex deformation. Based on different types of FEM, Mori [6], Huisman [7], Xiong [8,9], Forouzan [10], Yun [11], and Ruan [12] investigated the effects of roll diameter, friction, engineering strain, etc. on rolling force or dog-bone shape in edge rolling. Whereas, the large number of computation times and huge memory capacity during modeling are the disadvantages of this method, especially for personal computers. Yun [13] established an abstract mathematical model of the dog-bone shape, some parameters of shape and force are received by fitting FEM simulation's data finally, but the explicit expression of shape was not obtained.

Nagpal [14] introduced DSF to analyze the three-dimensional process of extrusion from a cylindrical billet. Marques [15] adopted DSF concept and discretized the plastic deformation region into several tetrahedral elements to discuss the width spread and rolling force in plate rolling. The metal-forming processes including forging of blocks, rolling of a rectangular bar, piercing by rectangular punches, and extrusion of rectangular shapes were demonstrated by Nagpal [16] using DSF. The effects of various forming parameters such as the roll diameter, plate thickness, and friction factor in plate rolling are evaluated by Hwang [17] via DSF and cylindrical coordinates. The rolling force and the shape of rolled product during shape rolling of a V-sectioned sheet were researched by Hwang [18] utilizing DSF and upper bound theorem. The DSF was used by Aksakal [19] to investigate the metal flow and load requirements in open die forging of polygonal blocks. The DSF velocity field was derived by Sezek [20] to analyze cold and hot plate rolling based on the upper bound method. However, DSF hasn't

* Corresponding author.
E-mail address: liuymhpj@yeah.net (Y.M. Liu).

https://doi.org/10.1016/j.jmapro.2018.06.012
Received 28 February 2017; Received in revised form 9 June 2018; Accepted 10 June 2018

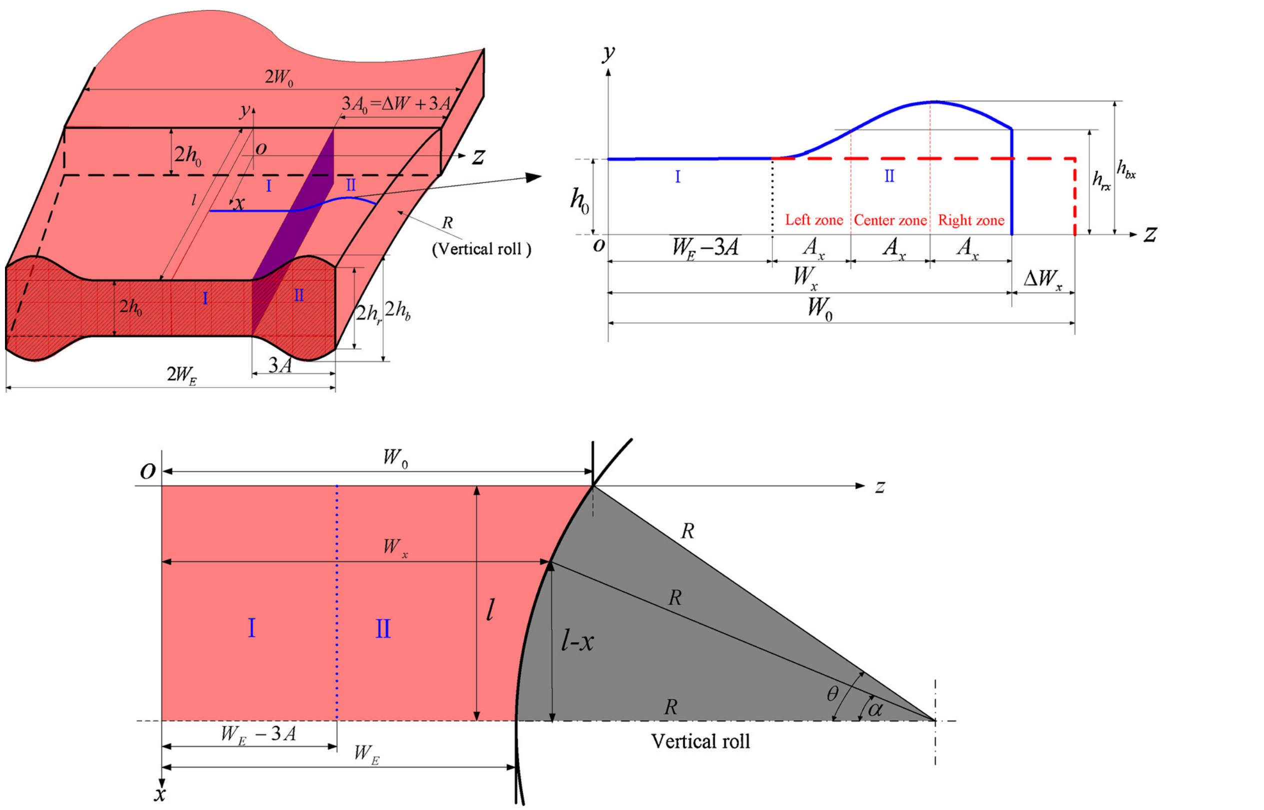

Fig. 1. Definition sketch of bite zone and sine function dog-bone profile in edge rolling.

been used to solve the edge rolling problem until now.

The difficulty to receive an upper-bound solution is that no systematic approach is available for choosing kinematically admissible velocity and strain rate fields. Therefore, the use of DSF in selecting an admissible velocity field for edge rolling according to sine function model is firstly demonstrated in this paper. The calculated shape parameters and rolling force will be compared with the available experimental data taken from previous publications.

2. Sine function dog-bone shape model

As shown in Fig. 1, a slab is rolled through a pair of vertical flat rolls. The roll radius is R and the initial slab thickness is $2h_0$. The slab width is reduced from $2W_0$ to $2W_E$ (unilateral reduction $\Delta W = W_0 - W_E$). A Cartesian coordinate system is set up in the center of the entrance cross section and the axes x, y, and z represent length, thickness, and width directions of slab respectively. The inlet velocity of slab is given by v_0 and the projected length of the roll-slab contact arc is given by l. The bite angle is $\theta = \sin^{-1}(l/R)$ and the contact angle is α. Because of the symmetry of deformation zone, only a quarter is considered. Half of the width W_x and the first order derivative equations W'_x of deformation zone are as follows:

$$W_x = R + W_E - \sqrt{R^2 - (l - x)^2} \tag{1}$$

$$l - x = R\sin\alpha,\ \mathrm{d}x = -R\cos\alpha\mathrm{d}\alpha \tag{2}$$

$$W'_x = -\frac{l - x}{\sqrt{R^2 - (l - x)^2}} = -\tan\alpha \tag{3}$$

Sine function dog-bone model with symmetry is proposed according to FEM simulation and experimental observation, as shown in Fig. 1. In order to describe the half thickness $h(x,z)$, the bite zone is divided into two parts (I and II) and the end part of the dog-bone (II) is further divided into three equal parts A_x (left zone, center zone and right zone) along the width direction. The width parameter A_x is

$$A_x = \frac{1}{3}[W_x - (W_E - 3A)] \tag{4}$$

From Eq. (4), $W_x - 3A_x = W_E - 3A$, at entry section: $A_0 = \Delta W/3 + A$, at exit section: $A_l = A$.

Zone I ($0 < z < W_x - 3A_x$) is the stem part of the dog-bone. Half thickness $h_I = h_I(x, z)$ is

$$h_I = h_0 \tag{5}$$

The contour lines of center and right zones are symmetric about $z = W_x - A_x$ and the contour lines of left and center zones are anti-symmetric about $z = W_x - 2A_x$. These characteristics can be satisfied by the sine function. So, zone II ($W_x - 3A_x < z < W_x$) is the end part of the dog-bone. Half thickness $h_{II} = h_{II}(x, z)$ is

$$h_{\mathrm{II}} = h_0 + \beta\frac{h_0\Delta W_x}{A_x} - \beta\frac{h_0\Delta W_x}{A_x}\sin\left[\frac{\pi(z - W_x)}{2A_x}\right] \tag{6}$$

where β is undetermined parameter. From Eq. (6), we can see that the function in district II satisfies the character of symmetry ($W_x - 2A_x < z < W_x$) and anti-symmetry ($W_x - 3A_x < z < W_x - 2A_x$). The stem part is assumed as rigid zone and the end part is plastic zone. The peak height of the dog-bone is

$$h_{bx} = h_0 + 2\beta h_0\Delta W_x/A_x \tag{7}$$

The edge height is

$$h_{rx} = h_0 + \beta h_0\Delta W_x/A_x \tag{8}$$

The obtained expressions of sine function dog-bone model satisfy the following boundary conditions: $h_{\mathrm{I}}(0, z) = h_{\mathrm{II}}(0, z) = h_0$; $h_{\mathrm{I}}(l, W_E - 3A) = h_{\mathrm{II}}(l, W_E - 3A) = h_0$; $\partial h_{\mathrm{I}}(x, z)/\partial z|_{z=W_x-3A_x} = \partial h_{\mathrm{II}}(x, z)/\partial z|_{z=W_x-3A_x} = 0$; $h_{\mathrm{II}}(l, W_E - A) = h_0 + 2\beta h_0\Delta W/A = h_b$; $h_{\mathrm{II}}(l, W_E) = h_0 + \beta h_0\Delta W/A = h_r$.

The value of A and β in various production conditions can be got by minimizing the total power functional.