International Journal of Mechanical Sciences 115-116 (2016) 180–189

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Mathematical model of neutral line on the contact zone in alloyed bar rolling by the round-oval-round pass sequence☆

Yong-gang Dong*, Jian-feng Song, Guo-ling Luo, Zhong-chao Ren

College of Mechanical Engineering, Yanshan University, Qinhuangdao 066004, China

ARTICLE INFO

Article history:
Received 14 December 2015
Received in revised form
23 March 2016
Accepted 24 March 2016
Available online 23 June 2016

Keywords:
Bar rolling
Contact zone
Flow line element
Reconstruction
Velocity
Neutral line

ABSTRACT

For determining the neutral line on the contact zone to determine the relative slip condition between the contact surface of rolling pieces and the roll, the contact boundary curve was proposed by obtaining the radius of flow line and the bite angle of points on the contact boundary based on the flow line method, and then the contact surface was discretized as flow line elements to build a novel analytic model to reconstruct the geometry of contact surface. Moreover, the velocity of flow lines on the contact surface along the direction of X-axis was derived by the condition of steady-state incompressible flow, and the function of neutral line was obtained by determining the neutral radius and the neutral angle of the points on the neutral line. In addition, the three-dimensional rectangular coordinates of points on the neutral line were derived.

Based on these mathematical models, the three dimensional geometry of contact surface and neutral line were drawn up by mathematical software. The validity of the theoretical model was verified by rolling experiments of alloyed bar and the numerical simulation by rigid-plastic FEM software. Compared with the experimental data and simulation results, the prediction error is acceptable and the results of the mathematical model is satisfying.

1. Introduction

Compared with products rolled with the oval-square-oval pass sequence, the bar or rod rolled with round-oval-round pass sequence have a better surface quality and mechanical performance, and the round-oval-round pass sequence is the most common roll pass in bar or rod continuous rolling recently. Xu [1] and Hu [2] pointed out the characteristics of non-uniform distribution of stain, stress and flow velocity on the deformation zone in bar rolling, and it is difficult to analyze the process of alloyed bar rolling in oval-square-oval pass sequence accurately.

In the past few years, the research on the alloyed bar rolling process was carried out by the simulation methods and experiments. Lee et al. [3–5] predicted the surface profile of a workpiece in rod rolling by round-oval-round pass sequence, and proposed a mathematical model for mean roll radius and cross-section profile of outgoing workpiece. Inoue et al. [6], Aksenov et al. [7], Graf et al. [8] and Nekrasov et al. [9] studied the strain, stress and geometry of deformation zone of bar rolling by the numerical simulation methods based on the FEM software, and Park et al. [10], Byon et al. [11] and Lee [12] analyzed the effect of roll gap, roll profile and rolling speed on the wear and exit section area by the single-pass rolling and multi-pass rolling experiments and FE analysis. Ragab et al. [13], Deng et al. [14] and Lee et al. [15] studied the rolling force and rolling torque of bar rolling and proposed analytic models for estimating the force energy parameters.

Because the contact surface between the rolling workpiece and shaped roll is not a cylindrical surface like flat roll rolling but a three-dimension curve with complex boundary, the distribution of flow velocity of rolling pieces and shaped roll surface on the contact surface is very complicated. Furthermore, the friction condition on the contact surface is not only influenced by the geometry of contact boundary but also influenced by the flow velocity distribution of the rolling workpiece and the shaped roll on the contact surface. In addition, the relative slip velocity between the rolling workpiece and shaped roll along the X-axis is different from each other except for the points on the neutral line. So the neutral line is a critical division line to determine the relative slip condition between the rolling workpiece and the shaped roll exactly. Therefore, it is indispensable for obtaining the accurate stress distribution and strain distribution on the contact surface in alloyed bar rolling to analytic the profile of contact boundary and the relative slip condition of contact zone exactly.

For getting the mathematical model of neutral line on the

☆Foundation Item: Item Sponsored by National Natural Science Foundation of China (50775196); Natural Science Foundation of Hebei Province (E2015203431); First-class Foundation of Post Doctoral Research of Hebei Province.

* Corresponding author.
E-mail address: dongyonggang@ysu.edu.cn (Y.-g. Dong).

http://dx.doi.org/10.1016/j.ijmecsci.2016.03.021
0020-7403/© 2016 Elsevier Ltd. All rights reserved.

Nomenclature

A_0	section area of incoming workpiece
A_h, A_s	noneffective reduction area without considering spread and considering spread, respectively
A_h	effective reduction area
A_{e0}, A_e	effective exit section area without considering spread and considering spread, respectively
(C_{y0}, C_{z0})	coordinates of intersection point between the profile of incoming workpiece and the roll groove
R_1	radius of the oval groove
R_a	radius of the curvature of the incoming cross-section
D_z	distance along the Z-axis direction between the origin coordinate
R_g	radius of the groove of round pass
H_p	maximum height of the groove of round pass
$W_{\max}$	maximum width of outgoing workpiece.
R_{m0}	mean roll radius without considering the spread
R_m	mean roll radius considering the spread
G	gap between the upper and lower roll
L_0, L	length of contact zone without considering the spread and considering the spread ,respectively
$\overline{H_0}$	equivalent height of incoming workpiece
$\overline{H_{m0}}, \overline{H_m}$	equivalent height of outgoing workpiece without considering the spread and considering the spread, respectively
(C_y, C_z)	coordinates of the critical point on the contact boundary at the exit-section
Y_{ef}, Y_f	flow plane ordinates at exit and any cross section along Y-axis
Z_{ef}, Z_f	flow plane coordinates at the exit and any cross section along Z-axis
V_{xf}, V_{ef}	flow velocity of flow plane along the X-axis and at the exit cross section,respectively.
V_e	exit velocity of deformed workpiece
w	angular velocity of the roll
θ_n	neutral angle of intersection points between the neutral line and the flow line
R_n	radius of flow line subject to points on the neutral line

contact zone, the contact surface was discretized by the method of flow line element firstly, and the analytic model for the geometry of contact surface was obtained by determining the radius of flow line and the position angle of points on the contact boundary. In addition, the velocity of flow lines on the contact surface along the direction of X-axis was derived by the condition of steady-state incompressible flow, and the function of neutral line was obtained by determining the neutral radius and the neutral angle of the points on the neutral line.

2. Geometry of contact zone between the roll and the rolling workpiece

2.1. Modified model for maximum length of contact zone

2.1.1. Shinokura and Takai model for maximum length of contact zone

Shinokura and Takai [16] proposed a formula to estimate the maximum contact length L of contact zone in alloyed bar rolling by ignoring the spread of outgoing workpiece.

The size of oval groove, round groove and corresponding incoming workpiece were shown in Fig. 1a and b respectively. $\overline{H_0}$ and $\overline{H_{m0}}$ were simplified as

$$\overline{H_0}=\frac{A_0-A_{s0}}{2C_{z0}} \tag{1}$$

$$\overline{H_{m0}}=\frac{A_0-A_{s0}-A_h}{2C_{z0}}=\frac{A_{e0}}{2C_{z0}} \tag{2}$$

In round-oval pass rolling, A_h and A_{s0} may be obtained by

$$\frac{A_h}{2}=\arctan\left(\frac{C_{y0}}{C_{z0}}\right)\cdot R_a^2-\left[\int_{-C_{y0}}^{C_{z0}}\left(\sqrt{R_1^2-y^2}-D_z\right)dy-C_{y0}\cdot C_{z0}\right] \tag{3}$$

$$\frac{A_{s0}}{2}=\arctan\left(\frac{C_{y0}}{C_{z0}}\right)\cdot R_a-C_{y0}\cdot C_{z0} \tag{4}$$

In oval-round pass rolling, the outgoing workpiece from oval pass sequence entered into the round pass sequence as an incoming workpiece, then A_h and A_{s0} may be given by

$$\frac{A_h}{2}=\frac{\pi}{8}W_{\max}\cdot H_p-\frac{A_{s0}}{2}-\arccos\left(\frac{C_{z0}}{R_g}\right)R_g^2-C_{y0}\cdot C_{z0} \tag{5}$$

$$\frac{A_{s0}}{2}=\arcsin\left(\frac{C_{z0}}{R_1}\right)\cdot R_1^2-(D_z+C_{y0})\cdot C_{z0} \tag{6}$$

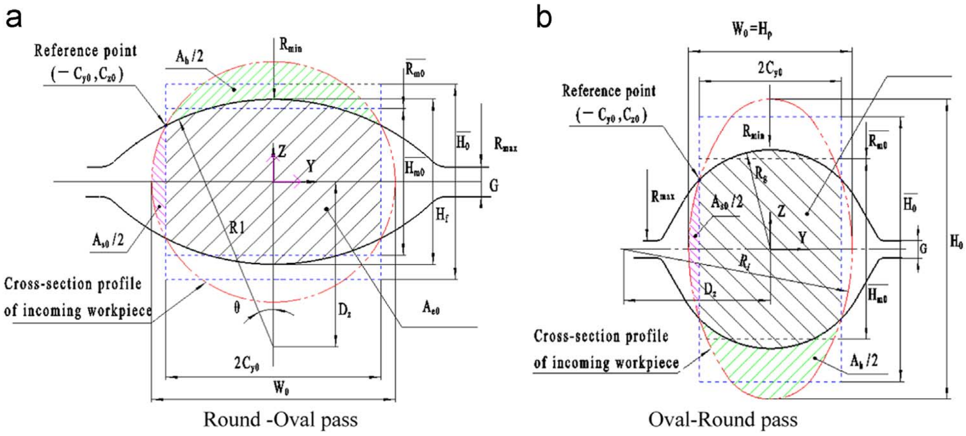

Fig. 1. Definition of pass profile and the incoming workpiece.