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A local approach to simulating bar forming in pass rolling

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Abstract

This paper presents a new approach to predicting the form of a bar deformed by pass rolling. The approach is based on four local rules describing transformations of points on the free surface of the bar. It is shown that predictions made by the model are in agreement with experimental results, providing empirical evidence in support of the model. The main advantage of the model is that it works for a wide range of pass shapes.

Keywords: Bar rolling; Surface profile; Mathematical model; Local rules

1. Introduction

The main defects in pass rolling are typically due to deviations of the deformed bar in its geometry and size. To avoid such defects, it is necessary to have a good prediction of the form of the strip during the pass design stage (see, for example, Refs. [1,2]).

Lee et al. [1] proposed an analytical model for predicting the curvature of the free surface of a bar in oval–round pass sequences. The model is based on the assumption that maximum spread happens along the horizontal plane of the bar's symmetry. A change in the curvature in one pass is described by a linear law that depends on the maximum spread of the bar. Lee et al. showed that there is a good match between calculated and experimental data sets, which provides good support for the above assumption.

The model, however, has a number of drawbacks. First, the model by Lee et al. cannot describe the cases where metal overfills the pass. Second, the model describes the oval bar forming only when the round pass height equals the diameter of the round. Finally, the model is only applicable when the lateral profile can be well approximated by an arc. Thus, for example, it cannot be used for such pass sequences as diamond–square, square–oval, and box–box.

Ref. [2] presents a theory of bar formation in passes with a simple shape. The approach represents the profile of the initial bar as a vector, and the pass—as an operator transforming this vector into another vector, defining the profile of the exiting bar. The components of these vectors correspond to distances of a chosen set of regularly spaced points to the bar axis. To determine the operators corresponding to particular passes, the author performed synthetic experiments using polar–optical models. The experimental conditions differed greatly from the actual rolling conditions.

In the papers discussed above, the shape of the rolled bar is determined by some global boundary transformation rules (i.e., an equation in Ref. [1] or a vector in Ref. [2]). Global methods are typically very specific to a particular problem. Thus, for example, the Ritz method is based on basis functions whose form strongly depends on the boundary of the area being analyzed [3]. For the problem of predicting the form of the rolled bar, global methods work only for a narrow range of rolling conditions (for example, only for a single pass type).

Methods based on local approximation are often much more flexible than global methods. For example, the finite element method, unlike the Ritz method, works for areas with arbitrary boundaries (see, for example, Ref. [3]). This suggests that local methods for predicting the form of the rolled bar may be more successful than global methods discussed above. Another problem where local methods (in particular, cellular automata [4]) proved to be successful is predicting deformation response to arbitrary stress paths [5].

This paper presents such a local approach to the problem of predicting bar forming. The main contribution of the authors is a general model that works for a wide range of pass forms. The

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bar profile is represented as an array of points and several local rules are developed to determine the speed of each point as a function of its position at any given moment.

2. The model

Fig. 1 shows two projections of the center of deformation for the oval–round pass sequence: (a) corresponds to a perpendicular cross-section and (b) shows a view from above.

The bar profile is specified parametrically. When the ray drawn from the origin crosses the strip profile at a single point, the polar angle of the ray φ can serve as a parameter. The parametric equation of the cross-section profile is then given by

$$y = r(\varphi)\cos\varphi_i, \qquad z = r(\varphi)\sin\varphi_i, \tag{1}$$

where $r(\varphi)$ is the radius-vector of the point on the cross-section profile.

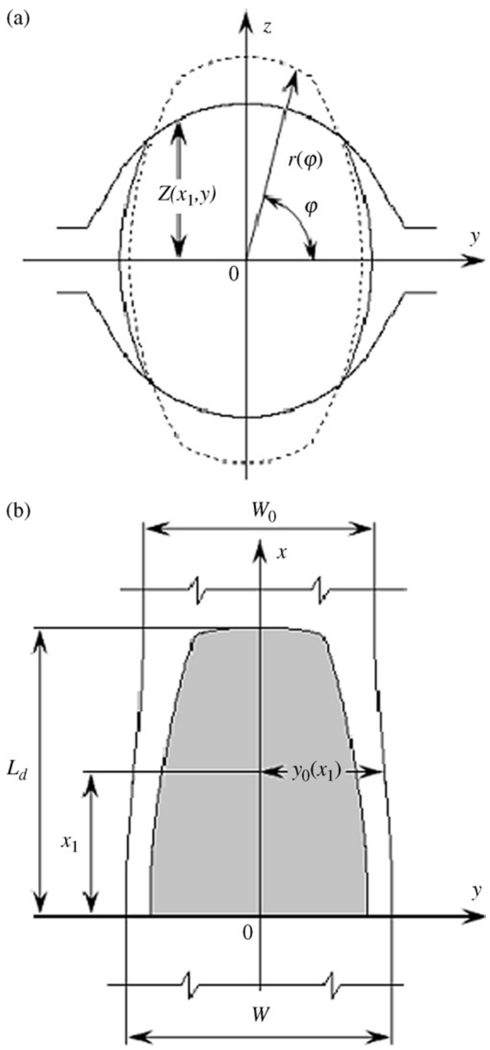

Fig. 1. Deformation zone layout for rolling of the oval in the round pass (pass grooves have a position corresponding to the x_1 coordinate): (a) cross-sectional view and (b) view from above.

N points are taken on the initial bar profile with coordinates:

$$y_i = r(\varphi)\cos\varphi_i, \qquad z_i = r(\varphi)\sin\varphi_i, \tag{2}$$

where $\varphi_i = (2\pi/N)i$, $i = 0\ldots N-1$. Taking $N \sim 100$ is typically sufficient.

Now it is possible to define transformation rules. The first rule is the rule of "transverse stickiness" determined experimentally by Sheppard and Wrigt [6], which says that once a point on the strip reaches the groove surface, it starts moving together with the corresponding point of the surface.

It is assumed that the points that are on the free bar surface and have no contact with the groove, experience an additional shift along the y-axis, in addition to the main longitudinal shift from the bar moving through the deformation zone. The speed of these points decreases monotonously with the z-coordinate so that when $z = 0$, $V_{y_0} = (\mathrm{d}y_0/dx)V_{x_0}$, where V_{x_0} and V_{y_0} are the components of the shift speed vector corresponding to point $i = 0$, and $V_y = 0$ on the groove surface.

The second rule states that the speed of the transverse motion decreases monotonously with the height.

It is also assumed that if $z = 0$, so $\mathrm{d}V_y/\mathrm{d}z = 0$. This is justified by the fact that in practice no angle is formed on the horizontal symmetry plane of the strip. The function satisfying such boundary conditions is given by

$$V_{y_i} = V_{y_0}\left[1 - \left(\frac{z_i}{Z(x_i, y_i)}\right)^n\right], \tag{3}$$

where V_{y_i} is the transverse component of the shift speed vector corresponding to point i; x_i, y_i, z_i are the current coordinates of the point, $Z(x, y)$ is the surface equation of the roll; $n > 1$ is a correcting coefficient. Eq. (3) is the third local rule.

Finally, it is possible to define the trajectory of the two surface points that lie on the horizontal symmetry plane of the strip ($z_0 = 0$); one of the points corresponds to $i = 0$. The trajectory must smoothly align with the undeformed ends of the strip. The function satisfying this condition is given by

$$y_0(x) = \frac{W_0}{2} + \frac{1}{4}(W - W_0)\left(1 + \cos\left(\frac{\pi}{L_\mathrm{d}}x\right)\right), \tag{4}$$

where W_0 and W are the initial and the final width of the strip, respectively and L_d is the length of the deformation zone. Alternative equations satisfying the conditions are possible, but, despite its simplicity, relation (4) agrees with experimental data. Eq. (4) is the fourth local rule.

3. Experimental validation

Data set obtained from the experiment described in Ref. [1] (plotted in Fig. 2a–e) was used to determine the correcting coefficient n from Eq. (3). Fig. 2 shows the profiles obtained experimentally, and the profiles calculated using the model of Lee et al. [1] and using the present model with $n = 3$. It is clear from the figure that taking $n = 3$ gives a good prediction of the profile. In both calculations, the width of the finished profile was taken to be the experimental width.

Fig. 2a–c shows the profile of a round bar with a diameter of 60mm after the oval pass "B" from Ref. [1] with collar gaps of (a) 2.5 mm, (b) 6.5 mm, (c) 10.5 mm. Fig. 2d–f shows the shape of the profile of the bar obtained in the oval passes (a–c), respectively, exits a round pass with a diameter of 47.5 mm.

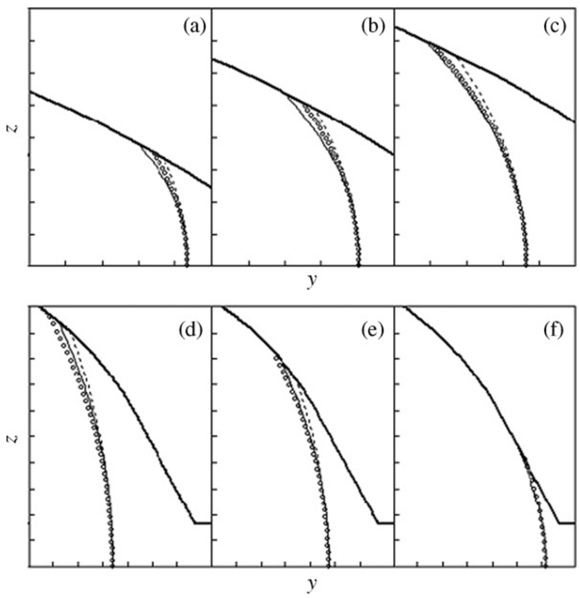

Fig. 2. Actual and calculated bar edge shapes after the oval (a–c) and round (d–f) passes. (— – pass; —— – present model; ∘∘∘∘∘ – experiment; - - - - – Y.Lee model.) Pass; (—) present model; (◯) experiment; (– – –) Lee model.

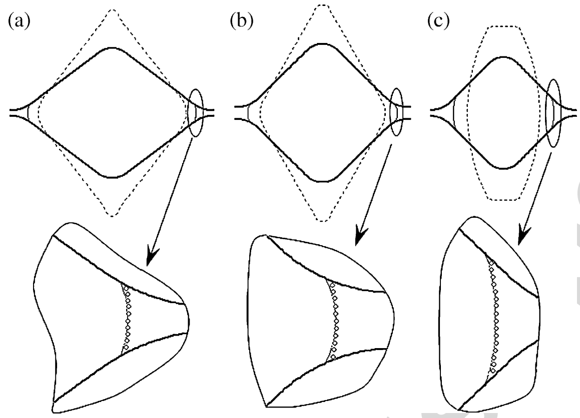

Fig. 3. Bar profiles before rolling and after the second pass through "diamond–diamond" (a), "diamond–square" (b), and "oval–square" (c) pass sequences. (— – pass; —— – present model; ∘∘∘∘∘ – experiment; - - - - – Y.Lee model.) Pass; (—) present model; (– – –) bar profile before rolling; (◯) experiment.

To illustrate the flexibility of the present model, the determined parameter ($n = 3$) was used to predict profiles in several cases when the model of Lee does not apply.

The first of such test cases, shown in Fig. 2f, was taken from the work of Lee et al. (Fig. 8(b) in Ref. [1]). In this case, the free surface profile cannot be represented as an arc [1]. Fig. 2f shows that the model gives a good prediction of the profile.

A large number of test cases were taken from the work of Zouhar [7] for pass sequences "oval-square", "diamond-square", and "diamond-diamond" where the model of Lee et al. [1] cannot be applied. Fig. 3 shows that the profiles predicted by the model agree with the ones obtained experimentally.

Table 1
Comparison of the experimental and calculated areas of the round bar cross-sections in case of changes in the pass filling

Round section size $h \times b$ (mm)	Cross-section areas (mm^2)		Deviation (%)
	Actual	Calculated	
5.50 × 5.52	23.9	24.1	0.8
5.50 × 5.20	23.3	23.2	−0.4
5.50 × 5.00	22.4	22.6	0.9
5.25 × 5.00	21.4	21.5	0.5
5.35 × 5.05	21.8	22.0	0.9
5.50 × 5.25	23.2	23.3	0.4
5.50 × 5.05	22.5	22.7	0.9
5.25 × 5.00	21.4	21.5	0.5
5.50 × 5.25	23.2	23.3	0.4
5.30 × 5.05	21.7	21.8	0.5
5.35 × 5.20	22.4	22.5	0.4

For breakdown profiles, it is important to predict the cross-section area since it determines the elongation of the profile. The worst-case squared loss of the predicted areas was 1.7%, 1.9%, and 2.3% for oval-square, diamond–square, and diamond–diamond pass sequences, respectively. The cross-section areas were defined by numerical integration.

Finally, the present model was validated on datasets obtained during the experiments on an industrial wire-rod mill, using a round pass with a diameter of 5.66 mm. The roll gap was measured for each sample. As the samples were collected over a period of 1 month, the dataset contains a wide variety of different cross-sections. This gives strong evidence that the present model is robust. The table below shows a good match between predicted and measured cross-section areas (Table 1).

4. Conclusions

A model for predicting free surface profiles for pass rolling is presented. The model is based on a set of local rules. Unlike existing models (in particular, the model of Lee et al. [1]), the present model is applicable to a wide range of pass sequences such as "oval–round", "diamond–diamond", "oval–square", "diamond–square".

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