New Approach for the Prediction of Stress Free Surface Profile of a Workpiece in Rod Rolling

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1. Introduction

In continuous rod rolling process, one of the most important things is keeping the balance of mass flux between passes (stands), represented by the multiplication of pass area and rolling speed of a workpiece. Rolling speed can be obtained from by-product of roll diameter with forward slip and roll rpm at a pass. Meanwhile, the calculation of pass area of a workpiece requires information of the stress free surface profile, which is defined as a curve except contacting part between roll grooves and the workpiece at the roll throat. From here onwards, the stress free surface profile will be called simply as the surface profile for convenience.

The FEA1,2,3,4) is very effective in predicting the surface profile but takes at least several hours to run program for a single pass since three dimensional analysis is required in nature. In case that one wants to know the surface profile of workpiece at a pass quickly, development of analytical model is absolutely required.

Shinokura and Takai5) presented an experimentally based model for the surface profile in oval pass rolling. The surface profile was approximated as a curve that consisted of two arcs. Hence, the surface profile was not smooth at the point of maximum spread. Kemp6) proposed a model for the surface profile of a workpiece in oval and round groove rolling, and compared the experimentally determined surface profile of the workpiece with those calculated by the model. Kemp,6) however, did not present the equation for the surface profile used in his model.

In this study, an analytical model that predicts the surface profile of a workpiece in oval-round (and round-oval) pass rolling has been proposed. The surface profile of a workpiece can be modeled when the maximum spread of it is known beforehand. Then, the surface profile of an outgoing workpiece was formulated by using a weighting function and a linear interpolation of the radius of curvature of an incoming workpiece and that of roll groove to the roll axis direction. The requirements we placed on the choice of the weighting function were to ensure boundary conditions. The validity of surface profile model presented has been examined by hot rod rolling experiment. A two-high laboratory mill with DCI (Ductile Casting Iron) roll of 310mm diameter was used.

2. The Analytical Model for the Surface Profile

The formulation of analytical model is strictly based on a weighting function and a linear interpolation of the geometry of an incoming workpiece and roll groove to the roll axis direction. Emphasis is placed on these aspects that the new model presented is neither made up any empirically based model nor based on experimental data.

2.1. Oval–Round Pass Rolling

Figure 1 shows an oval workpiece incoming and a round groove, and one of the possible surface profiles of deformed workpiece. D and G are, respectively, roll depth and design roll gap. \( \alpha \) is the relief angle designed for workpiece in roll groove to flow out smoothly in the case of overfilling. \( R_i \) is the radius of curvature of the oval workpiece incoming. \( R_g \) is the radius of round groove and is also assumed as the final surface profile of workpiece after rolling. \( R_{g_{out}} \) is the radius of the surface profile of deformed workpiece at the roll throat and is modeled by the linear interpolation of \( R_i \) and \( R_g \) when the maximum spread, \( W_{max} \) is known, i.e.,

\[
R_g = R_i \cdot W_i + R_g \cdot (1 - W_i), \quad ...............(1)
\]

where

\[
W_i = \frac{2 \cdot R_{g_{out}} - W_{max}}{2 \cdot R_g - W_{max}} \quad ...............(2)
\]

\( W_i \) is a weighting function of \( R_i \) and \( R_{g_{out}} \). \( W_{max} \) is the maximum spread of outgoing workpiece and can be calculated by Shinokura and Takai’s equation.5) The requirements we placed on the choice of the weighting function stem from the need to ensure Eq. (1).

To confirm the validity of Eq. (1), boundary conditions of the proposed model are examined. If the incoming oval workpiece with the radius of curvature \( R_i \) is not deformed at all, \( W_{max} \) is just \( W_i \). Then, \( W_i = 1.0 \) is obtained from Eq. (2). Consequently, Eq. (1) yields that \( R_g = R_i \) which makes it sense. On the other hand, when the incoming oval workpiece is deformed and the maximum spread, \( W_{max} \) reaches round groove diameter \( = 2R_g \), Eq. (2) yields that \( W_i = 0.0 \). Then, Eq. (1) gives that \( R_g = R_{g_{out}} \), which is right. It should be noted that Eqs. (1) and (2) are valid under the condition that the maximum spread of the outgoing workpiece is not greater than round groove diameter, and \( (D+G)/2 \) is equal to \( R_g \). If \( (D+G)/2 \) is not equal to \( R_{g_{out}} \), the round roll groove is not a round shape any more.

The cross points, \( C_x \) and \( C_y \) (Fig. 1), can be obtained by solving two simultaneous circular equations for the round roll groove and the surface profile of workpiece. Once \( C_x \) and \( C_y \) are known, the calculation of pass area of workpiece is straightforward.

2.2. Round–Oval Pass Rolling

The linear interpolation technique employed in oval–round pass rolling can not be used directly because it is impossible inherently to define the final surface profile, \( R_{g_{out}} \) in oval groove. Here, an assumption is introduced to get it. According to this assumption, the incoming round workpiece spreads to the roll axis direction and at last reaches at the face width of oval groove, \( W_{a} \), when it is deformed at the...
inside of oval groove. This simplification was made to facilitate the solution of surface profile problems, which would otherwise be difficult to solve. Then, as shown in Fig. 2, the final surface profile is assumed to be a circle with radius of \( R_s \). \( R_s \) is centered at some point of \( x \)-coordinate. Thus, if \( R_s \) is obtained, the linear interpolation technique employed in oval–round pass rolling can be used immediately. The next step is to set up the equations to obtain \( R_t \).

In Fig. 2, the line \( O_1–B \) in \( x_1–y \) coordinate system is expressed as

\[
y = ax_1, \quad \text{where} \quad a = \frac{R_t - H_p / 2}{W_t / 2 - R_t} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3)\]

An equation representing the upper part of oval groove is

\[
x_1^2 + y^2 = R_s^2 \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (4)\]

Substituting Eq. (3) into Eq. (4) yields

\[
B_y = \sqrt{R_s^2 - a^2} (1 + a^2) \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots (5)\]

The coordinate, \( B_y \), can also be obtained from the geometric similarities

\[
B_y = h + (R_t - H_p / 2), \quad \text{where} \quad h = \frac{R_t (R_t - H_p / 2)}{R_t - R_t} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (6)\]

Equating Eqs. (5) and (6) gives

\[
\left( \frac{R_t - H_p / 2}{a^2} \right)^2 = \frac{R_s^2}{(R_t - R_t)^2} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots (7)\]

Substituting “\( a \)” in Eq. (3) into Eq. (7) gives

\[
\frac{(W_t / 2 - R_t)^2}{(R_t - R_t)^2} = \frac{1}{1 + \left( \frac{R_t - H_p / 2}{W_t / 2 - R_t} \right)^2} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots (8)\]

Rearranging Eq. (8) yields

\[
(W_t / 2 - R_t)^2 + (R_t - H_p / 2)^2 = (R_t - R_t)^2 \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots (9)\]

Thus, \( R_t \) can be expressed explicitly in terms of \( R_t, H_p \) and \( W_t \)

\[
R_t = \frac{R_tH_p - 0.25(W_t^2 + H_p^2)}{2R_t - W_t} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (10)\]

Once \( R_t \) is obtained, the radius of surface profile, \( R_s \), can be formulated by a linear interpolation of \( R_s \) and \( R_t \)

\[
R_s = R_t + W_t(1 - W_t) \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (11)\]

where

\[
W_t = \frac{W_t - W_{\max}}{W_t - W_t} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (12)\]

\( W_t \) is a weighting function of \( R_t \) and \( R_s \), and \( W_t \) is the face width of oval groove. Hence, in round–oval pass rolling, one of the possible surface profiles, \( R_s \), can be illustrated as shown in Fig. 3.

In order to check the validity of Eq. (11), boundary conditions of the proposed model are examined. If the incoming round workpiece with the radius of \( R_a \) is not deformed, there is no spread at all. Then, \( W_{\max} = W_t \), and \( W_t = 1.0 \) is obtained from Eq. (12). Consequently, Eq. (11) yields that \( R_s = R_a \), which makes it sense. On the other hand, if the maximum spread reaches the face width of oval groove after rolling, i.e., \( W_{\max} = W_t \), Eq. (12) is equal to zero. This implies that \( R_s \) in Eq. (11) becomes \( R_s \), which is correct.

3. Experiment

Hot rod rolling experiment with a single stand mill has been carried out to examine the validity of the surface profile model proposed. A two-high laboratory mill with DCI (Ductile Casting Iron) roll of 310 mm diameter was used. The roll has a round groove and an oval groove. Rolling speed is set at 34 rpm. The rolling conditions (dimensions of grooves and gap, etc.) are illustrated in Fig. 4. Plain low carbon steel (0.1%C) specimen with round cross section (60 mm and 66 mm in diameter) is first rolled into the oval pass (Fig. 4(a)). The oval workpiece produced is turned 90° and rolled into the round pass (Fig. 4(b)).

The initial round specimen was heated up to 1030°C in an atmosphere of nitrogen and rolled at 1 000°C without lubrication. In order to measure the rolling temperature of the workpiece, a thermocouple was embedded in 40 mm deep holes drilled in the tail ends of the specimen. The workpiece after each rolling pass was cooled in air. The cross sections with 30 mm thickness were obtained by cutting the middle part of workpiece to the length direction. Then, milling machine smoothed the cross section of workpiece. Finally, the coordinates of surface profile were obtained by using the surface profile reading program7) followed by scanning the cross section of workpiece.

4. Results and Discussion

In Fig. 5, the surface profiles predicted by the analytical model proposed are compared with one experimentally obtained when the specimen (6046) is rolled into the oval–round pass. Quarters of surface profiles predicted and measured are presented because of its symmetric configuration. The pass area measured at room temperature after experiment is inevitably smaller than that predicted because the surface layers oxidized by air are scaled off after air cooling of the hot workpiece.

As can be seen in Fig. 5(a), the predicted maximum spread exceeds slightly the measured one. Meanwhile, the surface profile predicted is consistent with the one measured. For oval pass rolling, the surface profile predicted by Shinokura and Takai’s model13) is also compared with one measured. Result shows that predicted surface profile is quite different from measured one, but Shinokura and Takai’s model13) is good if one is interested in only the calculation of pass area in oval pass. Figure 5(b) demonstrates that the incoming oval workpiece was slightly rotated along its length direction during rolling. This phenomenon might be caused by a loose clearance between the entry guider and the incoming workpiece at round pass rolling. The predicted surface profile, however, is very good agreement with the measured one.
Figure 6 shows that maximum spread reaches almost the face width of oval groove when the specimen (66 phi) is rolled. As expected, the increasing specimen diameter causes the maximum spread to increase. In overall, the surface profile of workpiece predicted by the proposed analytical model is fairly good agreement with the one measured when even the incoming specimen size is changed. Figures 5 and 6 illustrate that differences between measured pass area and predicted one are in the range of 2.2–2.7%. Considering the surface layers scaled off during air cooling of workpiece, these differences are reasonable.

5. Conclusions

In this study, a new analytical model for the prediction of the surface profile of a workpiece during oval–round (and round–oval) rolling has been developed, and validity of the model has been examined by hot rod rolling experiment. The conclusions are summarized as follows:

1. The idea employing a linear interpolation of the radius of curvature of an incoming workpiece and that of roll groove to the roll axis direction has proved very powerful in predicting the surface profiles and pass area of an outgoing workpiece.

2. The new analytical model not only has accuracy for practical usage but also save a large amount of computational time compared with finite element method.

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