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Dimensional Analysis in Steel Rod Rolling for Different Types of Grooves

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Sequence design for shape-rolling processes consists of roll pass and profile design, i.e., transforming the billet into a final shape. For the prediction of the mean effective strain of the workpiece during rod rolling, an analytical model by Shinokura and Takai was used. They verified the formula by applying it to a variety of rod-rolling geometries (oval-square, oval-round, square diamond, and diamond-diamond). Today, on the other hand, the finite element (FE) techniques allow analysis of rolling processes in such a way as to simplify the work of design engineers. In this study, a round-oval pass and a round-flat oval pass are analyzed for steel rod rolling. In particular, the analysis of the spread, the surface profile, and cross-sectional area of the workpiece were conducted during rolling. Experimental data such as the maximum spread and the radius are compared with the results of the analytical model and FE analysis.

Keywords FEM analysis, groove profile, hot rolling

1. Introduction

In shape rolling, the determination of the roll pass and profile design is very important. To better design the shape-rolling process, many studies have been carried out, but it is very difficult to obtain experimental results due to the complexity of the process. In some of these studies, area strains, calculated by considering the natural logarithm of the ratio of the reductions in cross-sectional area through the rolling stands, have been determined for rod rolling without any experimental data control (Ref 1, 2). In particular, Maccagno calculated the mean effective strains by simply multiplying a constant factor by the area strains (Ref 1). For a round-oval (or oval-round) pass, the mean effective strain was assumed to be a constant factor of 1.7 times the area strain for roughing stands, and 2.5 times the area strain for finishing stands. Kemp also proposed a new theory based on the assumption that the mean effective strain per pass should be 1.5-2 times the area strains in the roughing stands and 2-3 times the area strains in all subsequent stands (Ref 2).

In the last few years, many studies simulating rod rolling have been presented using three-dimensional (3D) finite element (FE) analysis (Ref 3-6). However, when a 3D FE model is used, it takes a large amount of computing time (Ref 3, 7, 8). Therefore, considering computational time requirements and the complicated mechanical/thermal boundary conditions necessary in FE models, a mathematical model for predicting the mean effective strain remains a useful tool for practical use. Shinokura and Takai, therefore, developed an analytical model for round oval (or oval-round) pass rolling (Ref 9). They assumed that the maximum spread may be expressed as a function of the roll mean radius, maximum radius of the incoming workpiece, and the area fraction between the inlet cross section and the roll groove area.

In the present investigation, the spread and the profile of the workpiece after rolling were analyzed for two types of passes. These parameters are the most important factors required for calculating the other rolling characteristics. In particular, a classic round-oval and round-flat oval pass were considered. The research compared the experimental data with the results obtained by the Shinokura and Takai formula and FE modeling. The experimental data were obtained directly considering two passes in an industrial plant.

The major aims of the research were to verify the use of FE modeling as a tool to calculate the geometrical characteristics of the work-piece and the possibility of using the Shinokura-Takai formula for both round-oval and round-flat oval pass.

2. Analytical Model

In the Shinokura and Takai model, the maximum spread of an outgoing workpiece is computed considering the roll radius, the maximum size of incoming workpiece, and the area fraction between the incoming workpiece and the roll-groove area. Thus, the maximum spread (W_{max}) can be calculated as follows:

$$W_{max} = W_i\left(1 + \gamma\,\frac{\sqrt{R(H_{iS} - H_{0S})}}{W_i + 0.5H_i}\cdot\frac{A_h}{A_o}\right)$$

where

$$H_{0S} = \frac{A_0 - A_s - A_f}{B_c}$$

and

$$H_{iS} = \frac{A_0 - A_s}{B_c} \qquad \text{(Eq 1)}$$

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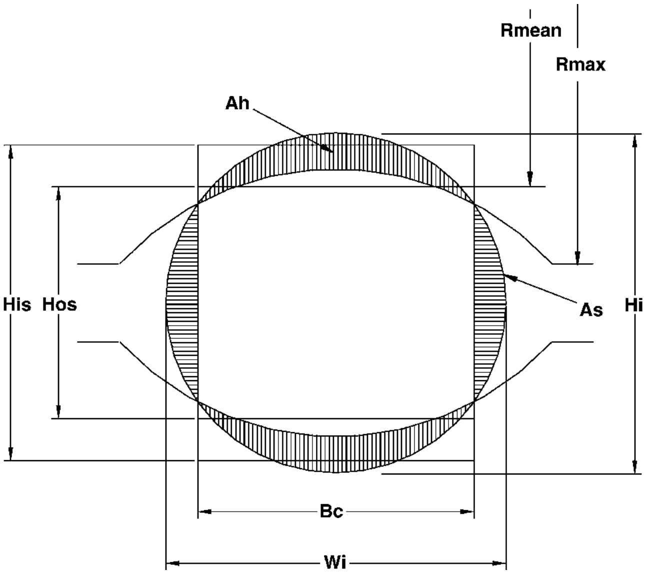

Fig. 1 Geometrical parameters for the maximum spread in the analytical formula

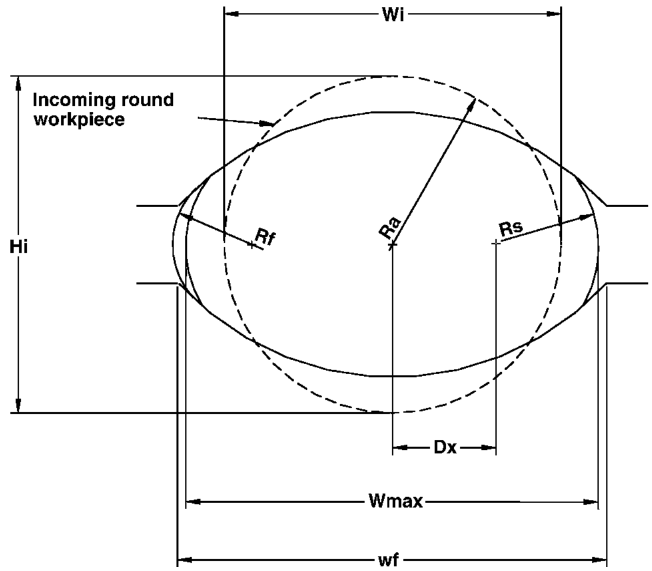

Fig. 2 Geometrical parameters for the radius of curvature in the analytical formula

The variables W_i and H_i, respectively, are the maximum width and the maximum height of incoming workpiece. A_0 is the area of incoming round workpiece, and γ is a correction coefficient that is dependent on pass type. The value of this coefficient is selected in the range of 0.8-1.1. In particular, for the four passes (oval-square, oval-round, square diamond, and diamond-diamond), the optimum value is equal to 0.83.

Figure 1 illustrates the parameters present in the formula for the two passes considered in this work: round-oval and round-flat oval.

Once the maximum spread is calculated, the Shinokura and Takai model is used to calculate the surface profile and cross-sectional area of the outgoing workpiece. It computes the radius of the surface profile of workpiece at the roll throat (R_S), as the linear interpolation of the radius of curvature of the incoming workpiece (R_a) and the radius of curvature of the caliber (R_f). R_S can then be calculated by the following formula:

$$R_S = R_a W_t + R_f (1 - W_t) \text{ and } D_x = \frac{W_{max}}{2} - R_S$$

where

$$W_i = \frac{W_f - W_{max}}{W_f - W_i} \qquad \text{(Eq 2)}$$

W_f is the width of the caliber, W_i is the width of the incoming workpiece, and W_{max} is the maximum spread of the outgoing workpiece. Figure 2 illustrates the geometrical parameters used in the formula for the round-flat oval pass.

3. Experimental Materials and Data

As reported above, two passes of an industrial process were performed, and the results were examined for this research: a round-oval pass and a round-flat oval pass. These passes are used in two different process sequences to produce concrete rebar with different diameters. In particular, the first roll-processing sequence (round-oval pass) is used to produce a bar 20 mm in diameter with the bar under consideration coming from the 14th pass in a sequence of 17 passes. The second roll-processing sequence (round-flat oval pass) is used to produce a bar 30 mm in diameter. In this case, the pass examined is the 11th in the sequence of 12 passes. After each pass, twist guides are installed to rotate the workpiece by 90° before the next pass. The cast iron rolls used for the rolling operations are 315 mm in diameter. The rolling speeds were, respectively, 4 m/s for the round-oval pass and 4.5 m/s for the round-flat oval pass. The incoming workpieces were 95 m long and 31.5 mm in diameter (sectional area equal to 780 mm^2) for the round-oval pass and 65 m long and 39 mm in diameter (sectional area equal to 1195 mm^2) for the round-flat oval pass. Caliber dimensions for the round-oval pass and round-flat oval pass are shown in Fig. 3 and 4.

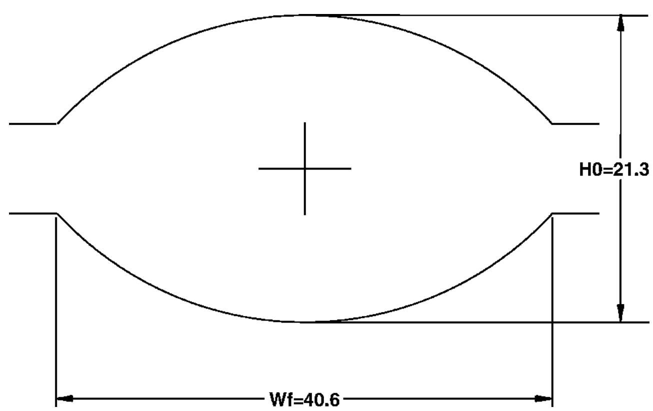

Fig. 3 Roll geometries for round-oval pass

The rolled rod material was low-carbon steel (0.2% C). A box-type furnace was used to heat up the billet to 1400 °C. During workpiece rolling, the process temperature was mea-

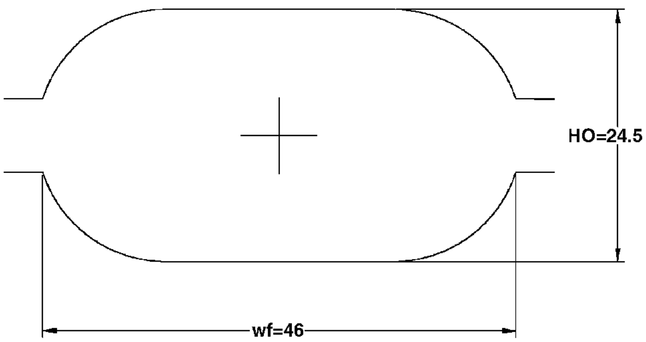

Fig. 4 Roll geometries for round-flat oval pass

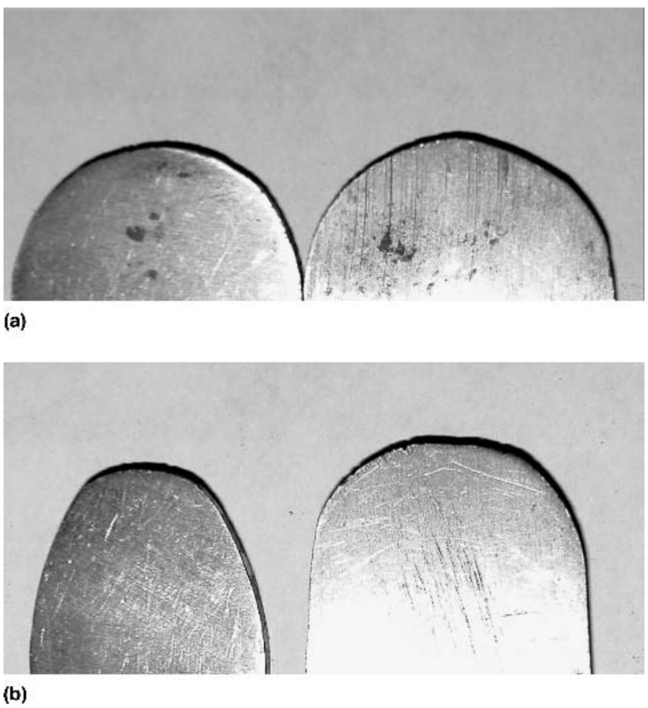

Fig. 5 Cross sections of the work-pieces before and after rolling

sured by an optical pyrometer. The geometrical characteristics of the workpieces were determined before and after each pass by cooling the workpieces in air. The outgoing workpieces were characterized, respectively, by the cross-sectional area of rod, 626 mm^2, and λ (i.e., the incoming workpiece cross-sectional area to outgoing workpiece cross-sectional area ratio), 1.2460, for the round-oval pass, and a cross-sectional area of 959 mm^2 and λ of 1.2458 for the round-flat oval pass. In Fig. 5, photographs of the cross sections of the work-pieces before and after rolling are shown. Table 1 contains the experimental data for the two roll passes under investigation in this research and described above.

4. Analytical and FE Model Results

The application of the formula for the round-oval pass has been used in different studies (Ref 3, 4); however, no control has been carried out for the round-flat-oval pass. Therefore, the same parameters, shown in the following figures, have been

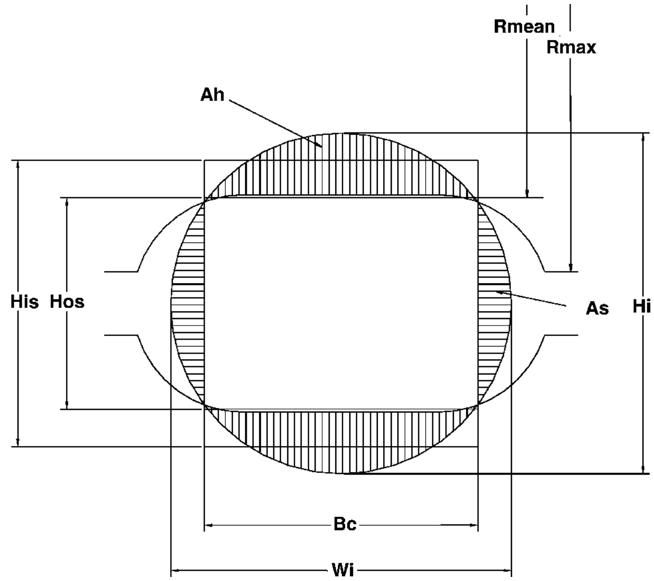

Fig. 6 Geometrical parameters for the maximum spread (round-oval) in the analytical formula

Table 1 Experimental data for roll passes of workpieces

Property	Round-oval	Round-flat oval
Temperature, °C	1,200	1,200
Maximum spread, mm	35.4	43.5
Radius of curvature	13.19	14.42
Outgoing workpiece area	626	959
λ	1.2460	1.2458

used to calculate the spread and the radius of curvature for this pass (i.e., round-flat oval pass). The value of the correction coefficient γ adopted for the two passes is 0.83. The results obtained from Eq 1 and 2 for the round-oval and round-flat oval passes (Fig. 6 and 7) are reported in Table 2.

For FE analysis, the Marc Autoforge program was used. To simulate the rolling process, a 3D system with a symmetry surface was adopted. The material used in the analysis is C22 steel. A rigid plane element puts the workpiece in contact with the roll. The surface of the rolls is treated as a rigid body. The contact table has been compiled by evaluating the Coulomb coefficient at the groove/workpiece interface by the formula (Ref 10):

$$F = (1.05 - 0.0005T)K_1$$

where T is the temperature (°C). Considering the velocity of the process, a coefficient K_1 must be considered when determining the friction coefficient. The value of this coefficient is 0.75 for the round-oval pass and 0.8 for the round-flat oval (Ref 10). Using these values, the coefficient of friction for the passes are, respectively, 0.33 and 0.34. It has been assumed the rolling process is isothermal at 1200 °C. A quasistatic analysis was conducted using these variables. In Fig. 8 the schematic diagram of the FE model for the round-flat oval passes is shown. In Fig. 9 and 10, examples of the FE analysis are shown.

The measures of the spread and radius were determined by

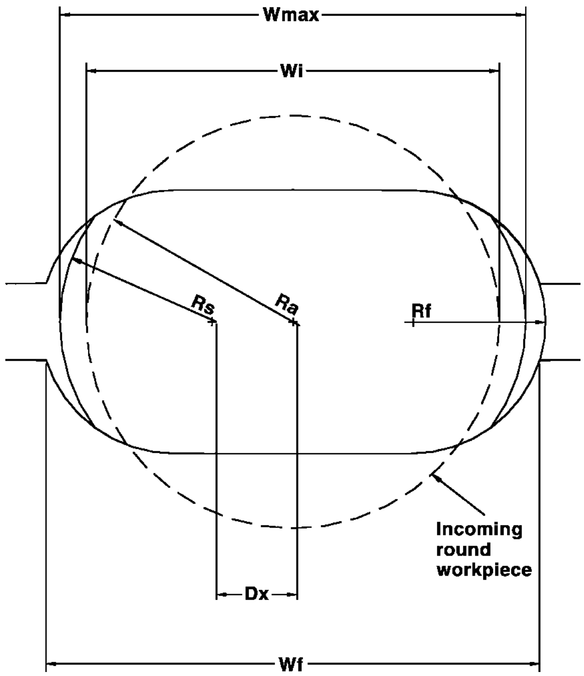

Fig. 7 Geometrical parameters for the maximum spread (round-flat oval) in the analytical formula

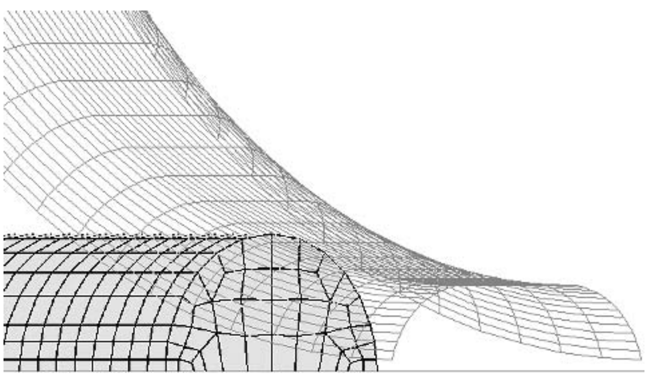

Fig. 8 Schematic diagram of FE model for round-flat oval pass

Table 2 Analytical model results

Property	Round-oval	Round-flat oval
Maximum spread, mm	35.6	44.2
Radius of curvature, mm	13.10	13.7

considering the lateral nodes of the elements placed in the workpiece central zone to avoid edge effects, which are manifest in the beginning and ending section. The spread and radius values were estimated using an average of seven measurements. In particular, to calculate the spread value, the distance between the workpiece nodes lying on the midplane was used. The radius was calculated as the inverse of the curvature of the curve passing through the three lateral nodes of the same workpiece section. The maximum spread and the radius of curvature measured in these analyses are reported in Table 3.

In the Fig. 11 and 12, the surface profiles predicted by Shinokura-Takai formulae and FE analysis are compared with

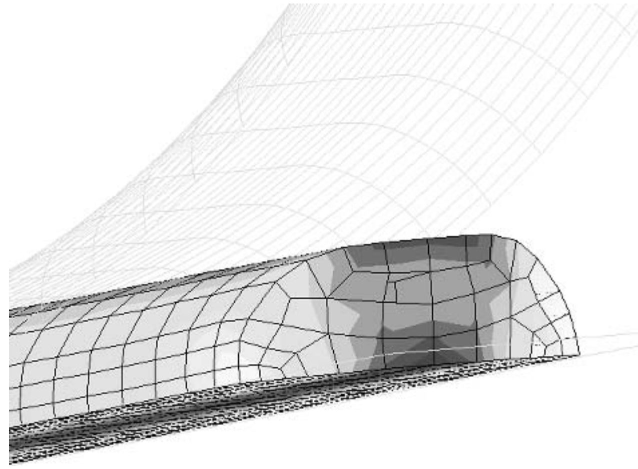

Fig. 9 FE analyses for round-flat oval pass

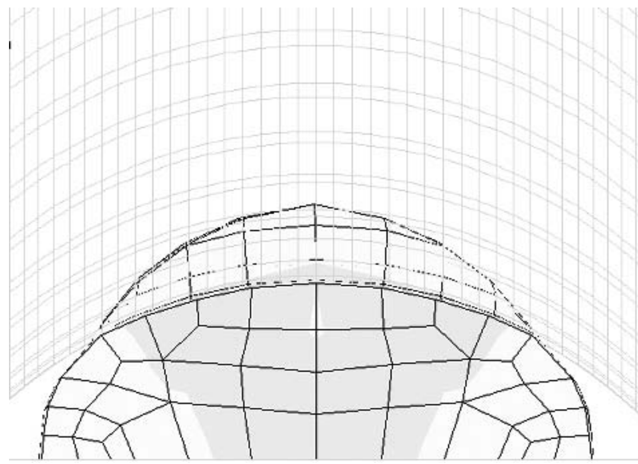

Fig. 10 Cross-sectional area in the FE analysis for round-oval pass

Table 3 FE model results

Property	Round-oval	Round-flat oval
Maximum spread, mm	35.2	44.8
Radius of curvature, mm	12.70	14.10

those experimentally obtained. It is noticed that the FE model and analytical values for the maximum spread and radius of curvature are very close to those of the experimental values, with an error less than 1%.

5. Conclusions

The maximum spread and radius of curvature of the workpiece were analyzed using experimental data, a preexisting analytical model, and a FE model for two different rolling passes: a round-oval pass and a round-flat oval pass. The results obtained in this work have shown that the analytical model can be used for the round-flat oval pass, and that FE modeling gives good values of the spread and radius of curvature for both passes. The difference in absolute percentage between the experimental data and the results of the analytical

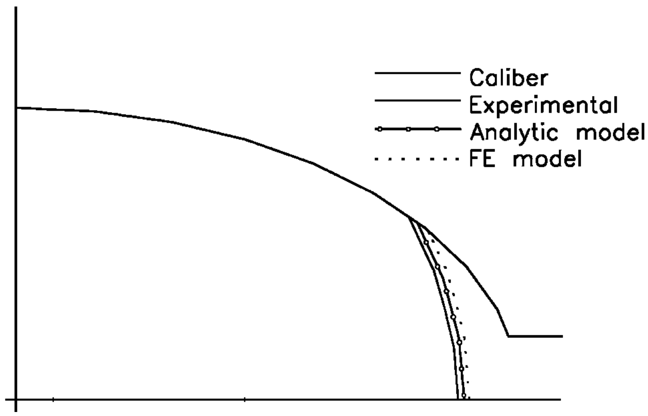

Fig. 11 Comparison of analytic model, FE model, and experimental data in round-oval pass

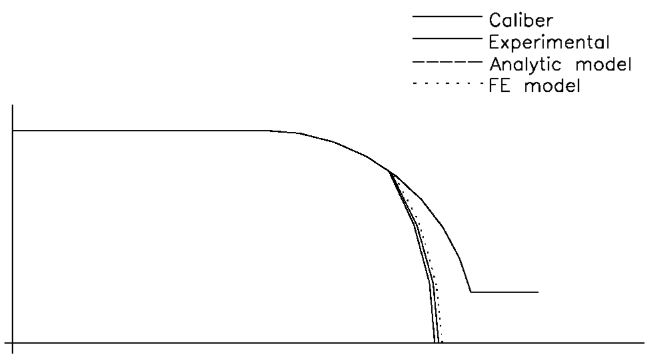

Fig. 12 Comparison of analytic model, FE model, and experimental data in round-flat oval pass

and FE models is reported in Table 4. This work emphasizes there are no differences between the incoming workpiece cross-sectional area and outgoing workpiece cross-sectional area ratio for the round-oval pass and the round-flat oval pass. For this reason, it is preferable to use flat-oval calibers, which are characterized by a greater simplicity of regeneration than the oval ones.

Table 4 Difference in experimental data and models

Model	Round-oval	Round-flat oval
Analytical	0.9%	0.5%
FE	0.3%	0.7%

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