International Journal of the Korean Society of Precision Engineering, Vol 2, No. 1, April 2001.

Prediction Model of the Exit Cross Sectional Shape in Round-Oval-Round Pass Rolling

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ABSTRACT

A reliable analytic model that determines the exit cross sectional shape of a workpiece (material) in round-oval (or oval-round) pass sequence has been developed. The exit cross sectional shape of an outgoing workpiece is predicted by using the linear interpolation of the radius of curvature of an incoming workpiece and that of roll groove to the roll axis direction. The requirements placed on the choice of the weighting function were to ensure boundary conditions specified. The validity of the analytic model has been examined by hot rod rolling experiment with the roll gap and specimen size changed. The exit cross sectional shape and area of the workpiece predicted by the proposed analytic model were good agreement with those obtained experimentally. We found that the analytic model has not only simplicity and accuracy for practical usage but also save a large amount of computational time compared with finite element method.

Keywords : Rod rolling, exit cross sectional shape, surface profile, round pass, oval pass

1. Introduction

In continuous hot rod rolling process, materials are processed into rods with acceptable dimensional tolerance as they pass through the rolling stands, with the cross sectional shape (surface profile) of the material being progressively altered. To predict the surface profile of workpiece at a pass (stand), a number of numerical studies that simulate rod rolling have been presented on the basis of three-dimensional finite element analysis [1-5]. FEA is very effective in calculating the surface profile and the cross sectional area of workpiece but requires at least several hours to run a program for a single pass since three dimensional analysis is required in nature. Thus, considering computational time and complicated boundary conditions necessary in finite element method, the capability for predicting the surface profile of workpiece by an analytical method is highly desired.

Kemp [6] proposed a deformation model to calculate the surface profile of a workpiece in oval groove and round groove rolling, and compared with the experimentally determined surface profile. Kemp, however, did not specifically present the equations used for the prediction of surface profile

In this study, a new analytical model is proposed for the prediction of the surface profile of a workpiece for the oval-round (or round-oval) pass sequence, which is most widely used in the rod (or bar) mill. It is shown that the surface profile of a workpiece can be modeled when the maximum spread is known beforehand. Then, the surface profile of the exit cross section is computed by using information regarding the shape of the inlet cross-section and that of the roll groove. The validity of the surface profile model presented is examined by a series of the round-oval-round pass hot rolling experiment.

The dependency of the analytic model on the carbon contents of the plane carbons steels over the temperature range of 800 ~ 1100°C is investigated. The rolling temperature is in a range where rod (or bar) rolling is generally performed in present the rod (or bar) mill. In addition, to access the possibility of using the analytical model for predicting the exit cross section of non-ferrous materials and alloy steels in rod rolling, numerous experimental investigations for measuring the maximum spread of the materials were implemented in the University of Freiberg, Germany, where appropriate testing facilities are available and its results are presented.

2. Analytic model

The procedures for predicting the material profile of stress free surface at the exit of roll gap are described. The advantage of this model is that it does not require plasticity theory but need information about only geometric considerations.

2.1. Surface profile in oval-round pass rolling

Shinokura and Takai [7] carried out an experiment using a pilot hot rolling mill and developed the maximum spread formulae for a mild steel (JIS SS41) in four types of passes, including Square–Oval, Round–Oval, Square–Diamond and Diamond–Diamond. The idea behind their formulae was that the maximum spread of an outgoing (exit) workpiece could be expressed as a function of roll radius, the geometry of an incoming (inlet) workpiece, the area fraction between the incoming workpiece and the geometry of roll groove. Figures 1 and 2 illustrate the definition of area fraction and equivalent heights in round–oval and oval–round pass rolling, for example. The maximum spread, W_{max}, was then calculated as follows:

$$W_{max} = \gamma(1+W_1)\frac{R_{mean}(\overline{H}_1 - \overline{H}_0)}{W_1 + 0.5H_1}\cdot\frac{A_h}{A_0} \qquad (1)$$

where

$$\overline{H}_0 = \frac{A_0 - A_S - A_h}{B_C} \text{ and } \overline{H}_1 = \frac{A_0 - A_S}{B_C}. \qquad (2)$$

W_1 and H_1 are, respectively, the maximum width and the maximum height of an incoming workpiece (i.e., inlet cross section) and γ is correction coefficient dependent on pass type. This formula is of a very simple form and has only on a coefficient but can predict the maximum spread with practically accuracy. Shinokura and Takai[2] proposed that the common value of γ for all four passes was 0.83.

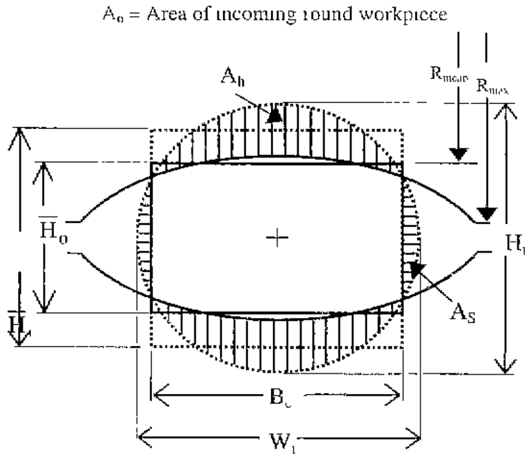


Fig. 1 Application of equivalent rectangle approximation into round-oval pass to calculate the effective height for workpiece and the area fraction between the incoming workpiece and the geometry of roll groove

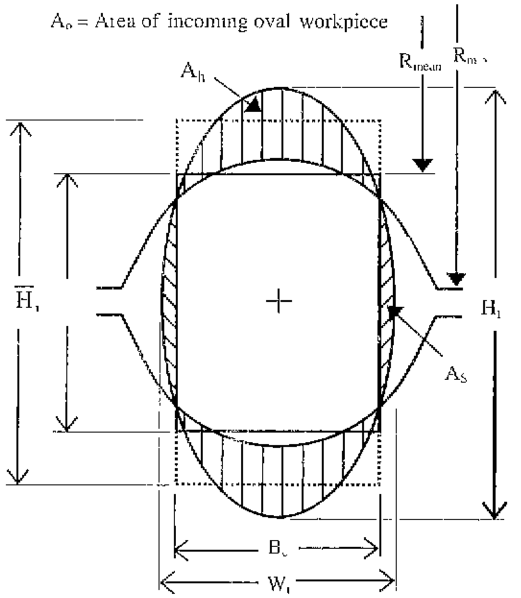


Fig 2 Application of equivalent rectangle approximation into oval-round pass to calculate the effective height for workpiece and the area fraction between the incoming workpiece and the geometry of roll groove

2.2. Surface profile in oval-round pass rolling

In oval-round pass, one of the possible surface profiles of workpiece is illustrated in Fig. 3. R_l is the radius of curvature of the inlet cross section, and R_g is the radius of the round groove. Assuming that W_{max}, the maximum spread does not exceed $2R_g$, the radius of the surface profile of the exit cross section, R_s, may be given by

$$R_s = R_l \cdot W_t + R_g \cdot (1 - W_t), \tag{3}$$

$$W_t = \frac{2 \cdot R_g - W_{max}}{2 \cdot R_g - W_l}. \tag{4}$$

W_t is a weighting function. W_l is the width of the inlet cross section, and W_{max} is the maximum spread of the exit cross section, which can be calculated by Shinokura and Takai's equation [7]. According to Eq. (3), R_s becomes R_l when W_{max}=W_l (no spread at all), and R_s becomes R_g when W_{max}=$2R_g$. It should be noted that Eq. (3) is valid under the condition that R_g=D_r+G/2.

Once R_s is determined, the contact point (C_x, C_y) can be obtained. The cross sectional area of the exit cross section may be calculated from

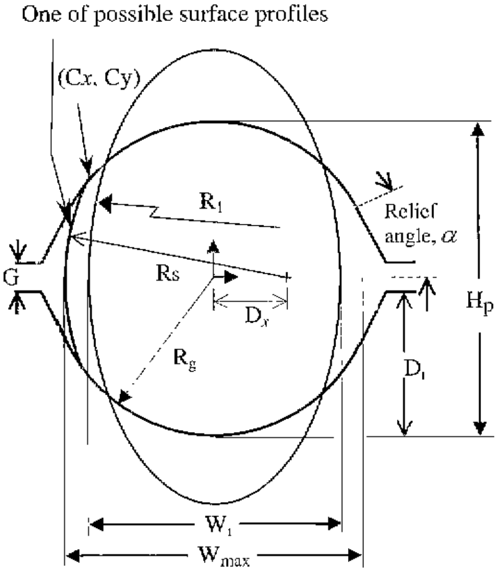


Fig 3 Geometrical designation of roll groove and the radius of surface profile, r_s, of a workpiece for an oval-round pass rolling. r_s on the right hand side is omitted for clarity.

$$A_{round} = 4\int_0^{Cx} (R_g^2 - x^2)^{1/2} dx - R_s^2(2\theta - \sin 2\theta), \tag{5}$$

where $\theta = \sin^{-1}(C_y / R_s)$.

It should be noted that the material is assumed to be incompressible during rolling and only geometric change was considered in the formulation. Thus, Eqs. (3~5) greatly simplifies the problem of obtaining the final rolled shape.

2.3. Surface profile in round-oval pass rolling

The geometrical designation of round-oval pass rolling is described in Fig. 4. R_a is the radius of curvature of the inlet cross section, R_s is the radius of curvature of the outlet cross section, and R_l is the radius of the roll groove. Assuming that W_{max} does not exceed W_f (the width of the roll groove area), an equation similar to Eq. (3) may be proposed for round-oval pass,

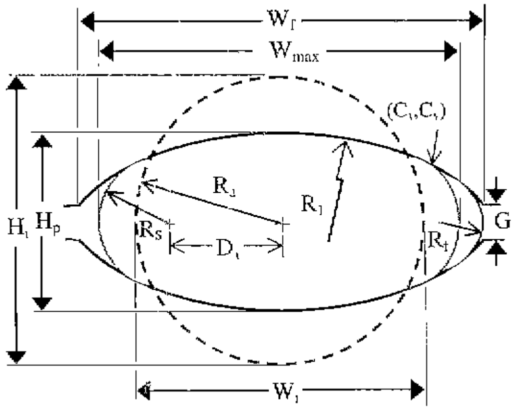


Fig. 4 Geometrical designation of roll groove and the radius of the surface profile, r_s, of a workpiece for a round-oval pass rolling.

as follows:

$$R_s = R_a \cdot W_t + R_f \ (1 - W_t), \tag{6}$$

$$W_t = \frac{W_l - W_{max}}{W_f - W_l}. \tag{7}$$

R_l is the radius to be achieved when W_{max}=W_f. R_f may be approximated by the radius of a circle which is located within the roll groove area and passing through the point (x=W_f/2, y=0), as shown in Fig. 4. Then, it may be shown that

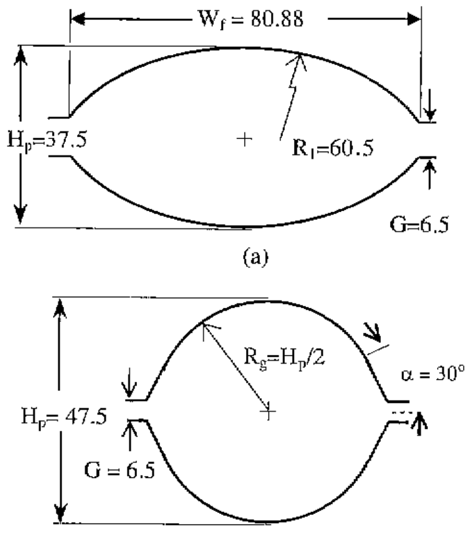
$$R_f = \frac{R_1 H_p - (W_f^2 + H_p^2)/4}{2R_1 - W_f}, \qquad (8)$$

where H_p is the thickness of the roll groove area. The derivation procedure for R_f is described in detail in Ref. [8]. Once R_s is determined, the contact point (C_x, C_y) can be obtained. The area of the exit cross section may be calculated from

$$A_{oval} = 4\left[\int_0^{Cx} (R_1^2 - x^2)^{1/2} dx - (R_1 - H_p/2)C_x + \frac{\pi}{4} R_s^2 - \int_0^{W_{max}/2 - C_x} (R_s^2 - x^2)^{1/2} dx\right] \qquad (9)$$

3. Experiment

Plain carbon steel with 0.1% carbon content was used in the experiments. The specimens were round bars with 60mm or 66mm in diameter and 300mm in length, which were machined from hot rolled square billets (160mm by 160mm). Prior to each pass, the specimens were soaked 30°C above the desired rolling temperature, which was 1000°C, for 60 minutes to ensure homogenous temperature distributions.



(a)

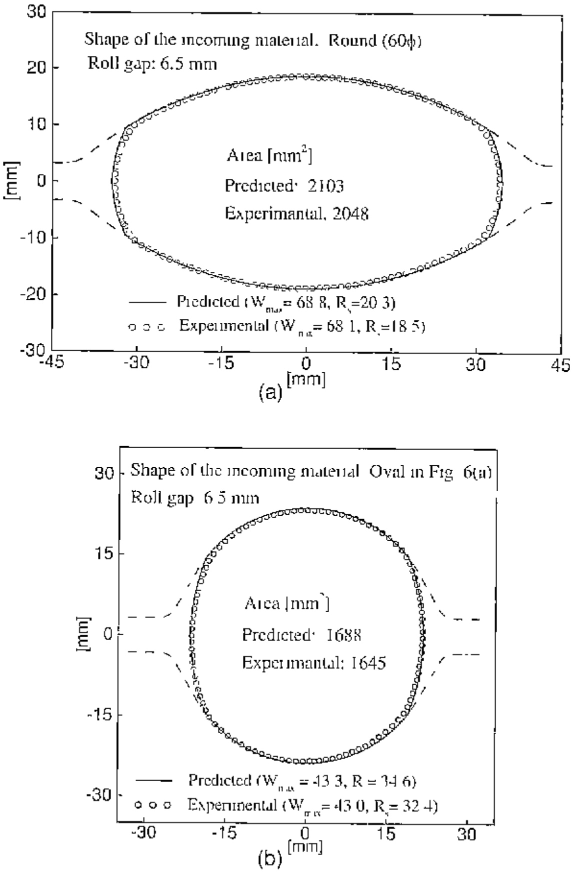
(b)

Fig. 5 Pass sequence designed for the hot rod rolling experiment. (a) oval pass and (b) round pass

As for the rolls, ductile cast iron rolls with the roll diameter of 310mm were used. Both the round grooved rolls and the oval grooved rolls were machined from these rolls. The rolling geometries for the round-oval pass (first pass) and the oval-round pass (second pass) are shown in Fig 5. The rolling speed was controlled to impose the constant roll speed of 34rpm during the tests. Tests were conducted without lubrication on the roll surface.

4. Results and Discussion

Fig. 6 shows the predicted and measured surface profiles of the exit cross section at the round-oval pass (a) and at the oval-round pass (b), when the diameter of the specimen was 60mm. Dotted lines represent the roll



(a)

(b)

Fig. 6 Predicted and measured surface profile of the workpiece when a bar with 60mm in diameter is rolled.

groove shape and solid lines the predicted surface profile of the exit cross section. The measured coordinate is shown by symbols (open circles) indicating every third data point, for clarity.

Excellent agreements were noted between predictions and measurements. As may be expected, the increase in the diameter of the specimen (from 60mm to 66mm) resulted in the increase in the maximum spread, especially in the round-oval pass. This aspect was illustrated in Fig. 7 Good agreements were observed again between the predicted surface profile and the measured one.

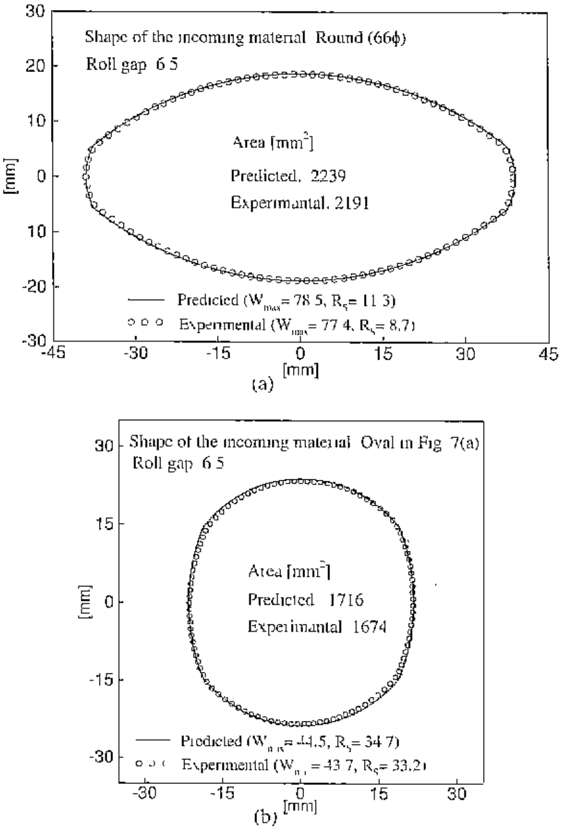


Fig. 7 Predicted and measured surface profile of the workpiece when a bar with 66mm in diameter

Fig. 8 shows the effect of the roll gap change on the area the exit cross section for both the round-oval pass and the oval-round pass. The differences between the predictions and measurements were in the range of 1.5 ~ 3.5%, which were acceptable, considering that the deviations in the dimensions of the products due to scaled off area oxidized by air cooling. The results indicated that the present model might be applied regardless of the roll gap size.

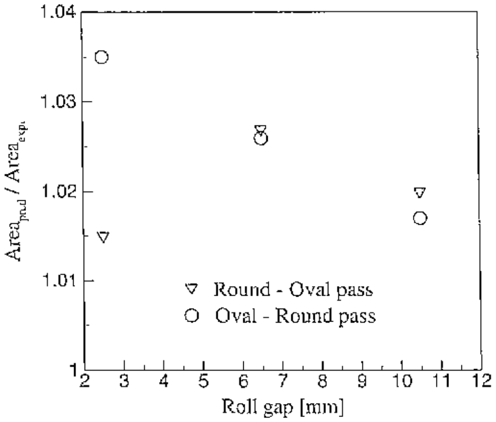


Fig. 8 Normalized cross sectional area. $area_{pred}$ = predicted area and $area_{expt}$ = measured area.

However, more study seems necessary to insure the validity of the model for diverse process conditions such as the effect of the material types and rolling temperature. Fig. 9 shows the effect of rolling temperature and carbon contents on the exit cross sectional area for oval-round (or round-oval) pass rolling sequence. Almost no influences are observed for the plain carbon steels as the rolling temperature changes. It also demonstrates that the dependency of the model on the carbon contents of the steels over the temperature range of 800 ~ 1100°C. The rolling temperature is in the range generally performed in present the rod (or bar) mill. The cross sectional area at each rolling temperature is divided by the one, which was rolled at the temperature of 1000°C. The results show that the cross sectional area is influenced slightly when the rolling temperature decreases to 800°C. In overall, the analytic model is considered to be insensitive the carbon contents of steel.

Fig. 10 illustrates the measured non-dimensional maximum spread at oval-round (or round-oval) pass rolling sequence for non-ferrous materials and alloy steels. Recall that the present study has demonstrated that the exit cross section can be predicted once the

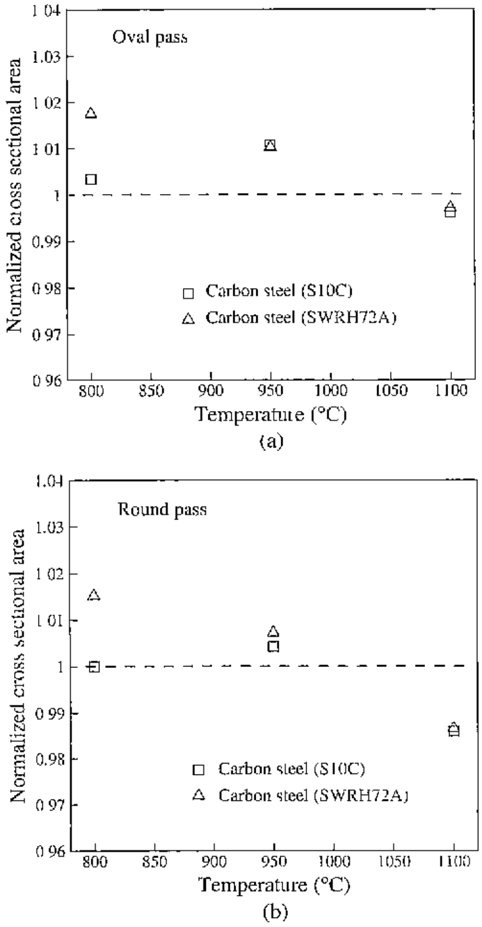


Fig. 9 The effect of rolling temperature and carbon contents on the exit cross sectional area for oval-round (or round-oval) pass rolling sequence.

maximum spread of the workpiece is known beforehand. This implies that the analytic model proposed in this study might be applied to the prediction of exit cross section of non-ferrous materials and alloy steels if we use the experimental data in Fig. 10, which was produced in The Institute for Metal forming at Technical University Bergakademie Freiberg, Germany.

It should be stressed that TU Bergakademie Freiberg is the only scientific institute in the world with its own continuous and high speedy rod (or bar) rolling mill. This was built in 1982 after industrial requirements for a special equipped laboratory mill to realise practice relevant rolling tests and other investigations. On the other side scientists and technologists required a plant to study material behaviour as to test future technologies. Thus by the combined efforts of industry, engineering and scientists in Universiy of Freiberg this unique rolling mill was built. Originally it combined the last four stands of a continuous rod rolling mill including water/air cooling and laying head and some extras.

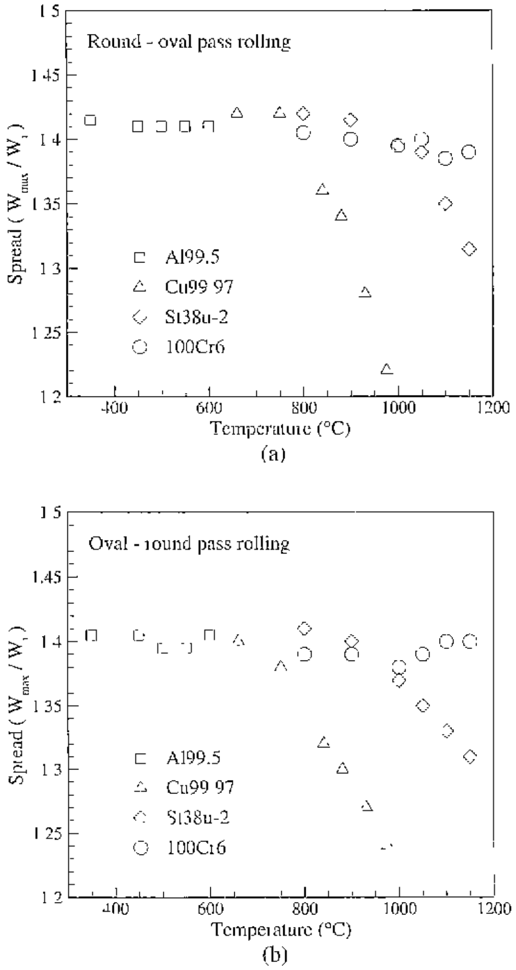


Fig. 10 Maximum spread of materials as a function of temperature for (a) round-oval pass and (b) oval-round pass rolling

From the beginning, main focus was given on technical/ technological projects suggested and paid by the industry. The other was to develop or to optimise new bar and rod rolling technologies. Many rolling tests also included investigations of material flow, power consumption etc. in rod rolling, as trials to study the effects of high speed rolling or longitudinal drags. In the last decade the main focus was laid more on the effects of thermo-mechanical rolling, on microstructure development and mechanical properties of the final rod products. National and international research projects allowed engineers not only from Europe but also from other continents to use the possibilities of this unique rod rolling mill.

The mill is being undergoing a reconstruction now. The technical equipment will be adapted to modern standard and the mill also upgraded for rolling of thin strips. Thus in the future the Institute for metal forming will not only be able to simulate continuous rolling of rods, but also of strips (1~5 × 80 × 60.000 mm) including their cooling, coiling and further treatment.

5. Conclusions

In this study, an analytical model for the prediction of the exit cross section (or surface profile) of a workpiece during round-oval-round pass sequence was proposed, and the validity of the model was examined by a series of hot rolling experiment. The conclusions may be summarized as follows:

1) The exit cross section of a workpiece predicted by the proposed analytical model is in good agreement with those obtained experimentally.

2) For the other material types, the exit cross section in oval-round (or round oval) pass rolling can be predicted if the maximum spread of the materials is known beforehand.

3) The analytical model may become a valuable tool for the on-line control and the initial pass schedule design for a continuous rod (or bar) rolling process.

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