

Analytical Model to Predict the Free Surface Profile of Outgoing Material in Oval-to-round Pass Rolling when Cross-section of Incoming Material is not Circular and Roll Gap Changes

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(Received on May 24, 2022; accepted on September 7, 2022; J-STAGE Advance published date: October 24, 2022)

There is a strong demand for the development of an analytical model that is necessary to quickly perform the roll pass design of hot rod (or bar) rolling process. In line with this, this study proposes an analytical model that predicts the free surface profile (FSP) of outgoing material in oval-to-round pass rolling sequence even when the cross-section of incoming material is not circular and roll gap changes. The separation angle and point were calculated by interpolating the intersection angle and the groove angle. FSP passing through the maximum spread of outgoing material and the separation point is calculated based on a weighting function depending on the geometry of incoming cross-section and roll groove. The performance of the proposed model was verified by finite element analysis that simulated 10-pass continuous bar rolling process. FSPs predicted by the analytical model and those by FE simulation were in good agreement. In addition, the proposed analytical model was applied to other 4-pass continuous rolling. It has been shown that it is possible to quickly calculate the amount of roll gap adjustment in each pass that improves the roundness of the material (from 83.57 to 98.65) in the final pass without the time-consuming FE analysis.

KEY WORDS: analytical model; free surface profile prediction; roll gap variation; groove rolling.

1. Introduction

Rod (or bar) are produced by passing the square billet (rolled square section for rolling into various long steel products) through a number of stands arranged in a tandem. Each stand has two work rolls with grooves machined into a specific shape. Two (upper and lower) grooves form a profile when we look at them in the rolling direction. This profile is almost similar to the cross-sectional shape of the material rolled in each stand and is also called as a pass in the production site. As the material is rolled continuously in each pass, the cross-sectional area of the material decreases and its shape changes.

In modern rod (or bar) rolling mills, a pair of rolling sequences such as box-to-box pass, oval-to-round pass (or vice versa), square-to-diamond pass (or vice versa), and diamond-to-diamond pass are line up repeatedly to produce rod (or bar). Selection of subsequent pair of the rolling sequence and design of the roll groove (shape and dimensions) in each pass is called roll pass design or pass

schedule design.

Roll pass designers commonly select oval-to-round pass rolling sequence because of good rollability and product quality. Here, rollability refers to the ability of a rolling mill to manufacture the product without surface defect on the material at a desired rolling speed. Due to the relatively uniform reduction in area in each pass, the oval-to-round pass guarantees a stable rolling that allows the material to enter smoothly the roll grooves, compared with other types of rolling sequences. In every pass, the material elongates in the rolling direction and at the same time spreads perpendicular to the rolling direction. Therefore, roll pass designers have been eager to predict the maximum spread of the outgoing material and its free surface profile of outgoing material section which does not contact the roll groove in each pass.

Shinokura and Takai¹⁾ performed pilot hot rolling test with four types of rolling sequence (square-to-oval pass, oval-to-round pass, square-to-diamond pass, and diamond-to-diamond pass) using plain carbon steel as specimens. Based on the rolling test data, they proposed a formula predicting the maximum spread of the outgoing material. This formula was very practical in the four types of rolling sequence.

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Lee *et al.*²⁻⁵⁾ proposed an analytical model to predict the free surface profile (hereafter FSP) of the outgoing material in oval-to-round (or vice versa) pass rolling sequence. They utilized the formula developed by Shinokura and Takai¹⁾ and calculated FSP of the outgoing material by linear interpolation between the corner radius of the groove and the radius of curvature of the incoming material section. They assumed that the cross-sectional shape of material incoming to oval groove was a circle at all instances. In the actual rod (or bar) rolling process, however, the cross-section profile of material entering to oval groove is not a circle. In addition, variations in roll gap (height of roll groove) were not considered to predict FSP of the outgoing material. Therefore, Lee's model²⁻⁵⁾ has limited practical applications.

Meanwhile, several expert systems⁶⁻⁹⁾ using artificial neural network coupled with finite element analysis were also developed to overcome the weaknesses of the analytical models (which operate only under limited rolling conditions). However, due to the complexity of this system, a large error in FSP prediction occurs and the computation time is too large as the number of passes increases.

This study proposes an analytical model for predicting FSP of outgoing material in oval-to-round pass (or vice versa) rolling sequence even when the cross section of material entering the oval pass is not a circle and the roll gap in the oval and round grooves changes. For each roll groove, a point where the incoming material section and the roll groove intersect is computed and corresponding intersection angle is found. Then, the angle where outgoing material section begins to separate from the roll groove is computed by nonlinear interpolation between the intersection angle and the groove angle which had been decided when designing the roll groove. FSP passing through the maximum spread of outgoing material and the separation point is calculated based on a weighting function depending on the geometry of incoming cross-section and roll groove. In case that cross-section of material entering the oval groove is not a circle, its cross section is approximated into an artificial circle and then FSP of outgoing material in the oval pass is computed.

2. Analytical Model for Predicting the Maximum Spread and FSP of Outgoing Material

Proposed analytical model is applicable for the oval-to-round pass (or vice versa) rolling sequence that are arranged repeatedly in the horizontal stand and vertical stand as shown in Fig. 1. This arrangement does not require the rolled material to turn 90° after the oval or round pass rolling. In this study, “oval pass” and “round pass” mean the situation that the material is rolled between the oval roll grooves and the round roll grooves, respectively.

2.1. Round-to-Oval Pass Rolling

The process of calculating the maximum spread, $W_{\max}$, FSP and cross-sectional area of the material rolled in the round-to-oval pass will be described step by step. First, non-circular cross section (NCCS) of material entering the oval pass is approximated into a complete circle on the basis of its cross-sectional area. In subsections (b) and (c), the geometry including roll gap change (height of roll groove) in the oval pass is described. In subsection (d), $W_{\max}$ is then

calculated based on the roll groove geometry and reduction in area during rolling. Finally, FSP in the oval pass is determined by interpolating the intersection angles and the groove angle based on the geometry of incoming cross-section and roll groove. The unique point of this study is that FSP can be calculated using the intersection angles and the groove angle, and a weighting function depending on $W_{\max}$ and reduction in area during rolling.

(a) Geometry of the Material Cross Section Entering the Oval Pass

In actual rod (or bar) rolling, material whose cross section is not circular usually enters the oval roll groove. **Figure 2** shows the material's non-circular cross section (hereinafter referred to as NCCS) which is about to be rolled in oval pass. For convenience, the first quadrant of NCCS is shown. NCCS consists of two profiles and a line. i) a profile formed by material's spread in the previous pass, ii) a profile formed by material in contact with the roll groove in the previous pass, and iii) a straight line connecting the ends of the two profiles.

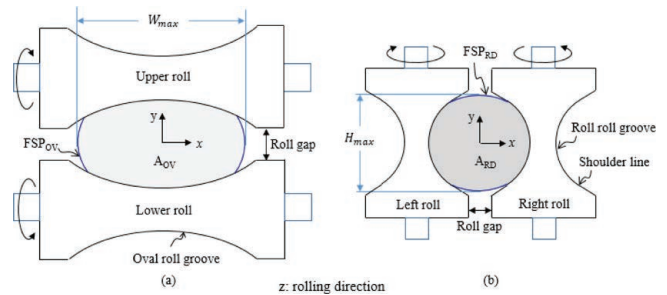


Fig. 1. Schematic of round-to-oval pass (or vice versa) rolling sequence (a) A pair of oval roll grooves is placed horizontally. (b) A pair of round roll grooves is placed vertically. A_{OV} and A_{RD} refer to the cross-sectional area of the material leaving the oval and round roll groove, respectively. FSP_{OV} and FSP_{RD} (marked in blue) stands for the free surface profile (not in contact with the roll) of the outgoing material, respectively. For convenience, the (work) roll diameter was drawn with a much reduced than the actual one. (Online version in color.)

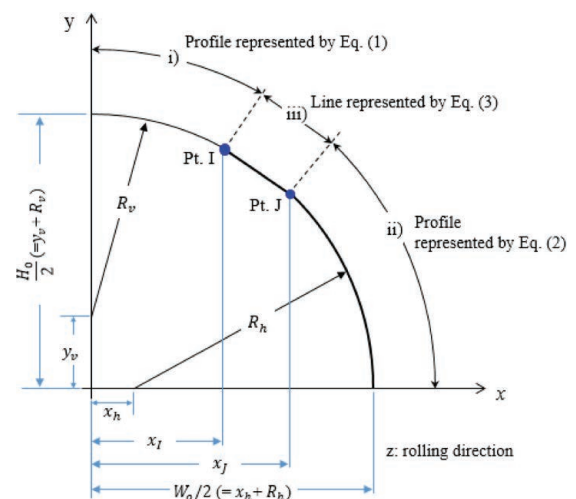


Fig. 2. Geometry of material's NCCS (non-circular cross section) entering the oval roll groove in the first quadrant. The NCCS is consists of two profiles and a line. R_v and R_h stand for the radius of curvature of the two profiles i) and ii), respectively. (Online version in color.)

For the first profile i): $x^2 + (y - y_v)^2 = R_v^2$ (1)

For the second profile ii): $(x - x_h)^2 + y^2 = R_h^2$ (2)

For the line iii): $(y_I - y_J)x - (x_I - x_J)y = x_J y_I - x_I y_J$... (3)

(b) Geometry of the Oval Roll Groove

Figure 3 illustrates a schematic of the oval (roll) groove viewed from the rolling direction (z-axis) and the formulas required for drafting the oval groove when the roll gap, i.e., groove height is changed.

Width of roll groove: $W_g = 2\sqrt{R_g^2 - (y_g + G_d/2)^2}$... (4)

where $y_g = R_g + (\delta - H_g)/2$

Profile of roll groove: $x^2 + \{y + y_g - (G - G_d)/2\}^2 = R_g^2$... (5)

where $G = G_d + \delta$

R_g , G , and H_g stand for radius of curvature, roll gap, and groove height. The (roll) groove angle is decided when the roll groove is designed. A change in roll gap is equivalent to a change in groove height. G denotes the actual roll gap set for rolling in production floor and G_d is the roll gap when the oval roll groove is designed. δ represents the amount of roll gap adjusted by an operator in the production floor. If δ is positive, G increases, and if δ is negative, G decreases.

(c) Change in Roll Gap (Height of Roll Groove) in Oval Pass

Figure 4 illustrates the geometry of the oval roll groove when a material with NCCS enters. Pt. B stands for the point where the upper oval roll groove and NCCS intersect. As G increases, H_g also increases (or vice versa). If we change the roll gap arbitrarily, the upper oval roll groove may be positioned as shown below.

Case 1) Upper oval roll groove (marked in red) is located somewhere on the profile (i). This case corresponds to skin pass rolling with exceedingly small reduction in area.

Case 2) Upper oval roll groove is located somewhere on the line (iii). This case results in a slightly increased reduc-

tion in area. This case applies when controlling the cross-sectional shape of the material in the finishing rolling mill.

Case 3) Upper oval roll groove is located somewhere on the profile (ii). This case corresponds to normal rolling condition because it gives a substantial reduction in area at the oval pass.

(d) Maximum Spread of Material Cross-section Leaving the Oval Roll Groove

Shinokura and Takai¹⁾ presented the empirical formula (Eq. (6)) that predicts the maximum spread W_{max} of outgoing material section based on the incoming material cross sectional shape and geometry of roll groove.

$$W_{max} = W_o + \gamma \times A_p / A_o \times W_o / (2W_o + H_o) \times \sqrt{D_{avg} A_p / x_B} \quad \dots \dots \dots (6)$$

where $A_p =$

$$4 \left[\int_0^{x_I} Eq.(1) dx + \int_{x_I}^{x_J} Eq.(3) dx + \int_{x_J}^{x_B} Eq.(2) dx - \int_0^{x_B} Eq.(5) dx \right] \quad \dots \dots \dots (7)$$

γ indicates a correction coefficient reflecting the geometry of roll groove, and 0.83 was used. A_o and A_p denote the material's cross-sectional area before rolling and the one reduced during rolling. W_o , A_p , H_o , and x_B are described in Fig. 4. D_{avg} is the average diameter of the oval roll and is used to compute the effective (equivalent) rolling speed in the oval pass. The method of calculating D_{avg} is described in detail in Ref.⁵⁾

The reliability of Eq. (6) is guaranteed if the cross-sectional shape of the material entering oval roll groove is a circle. In actual rolling, however, the material entering the oval groove does not have a circular cross section but has a NCCS as shown in Fig. 2. Hence, this study approximates NCCS into circular cross section based on its cross-sectional area and then uses Eq. (6) to compute W_{max} .

In **Fig. 5**, NCCS of material (marked with green dashed line) entering the oval groove is approximated into a circular section (marked in black dashed line). The coordinates of the intersection point F are as follows.

$$x_F = \sqrt{R_F^2 - y_F^2} \text{ and } y_F = \left[R_g^2 - R_F^2 - \{y_g - (G - G_d)/2\}^2 \right] / (2y_g - G + G_d) \quad \dots \dots (8)$$

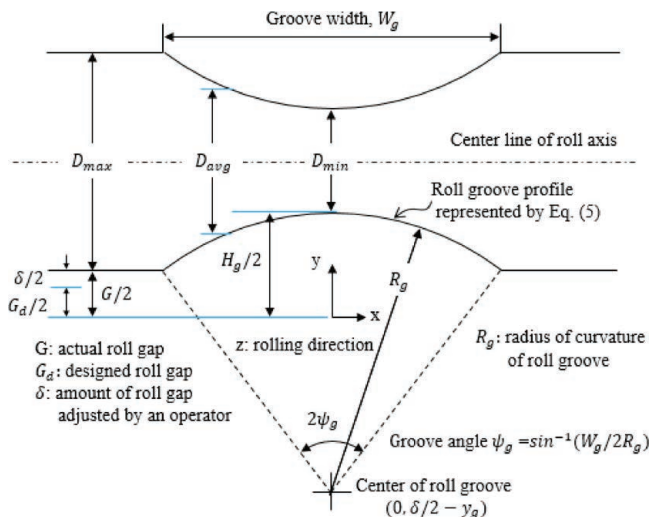


Fig. 3. Geometry of an oval roll groove, roll diameters, definition of roll gaps and groove angle. (Online version in color.)

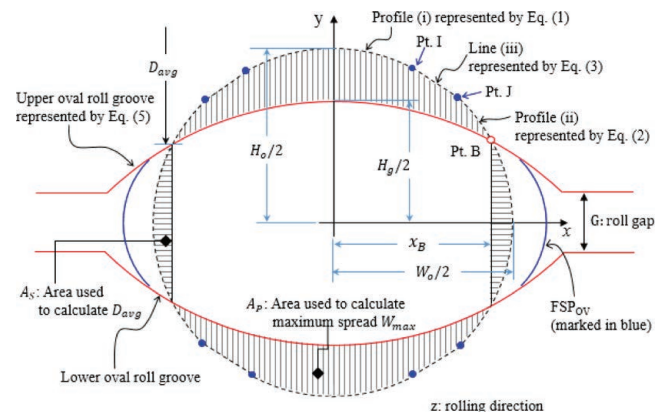


Fig. 4. Geometry of the oval roll groove, FSPOV and intersection when a material with NCCS (indicated by dashed lines) enters the oval roll groove. (Online version in color.)

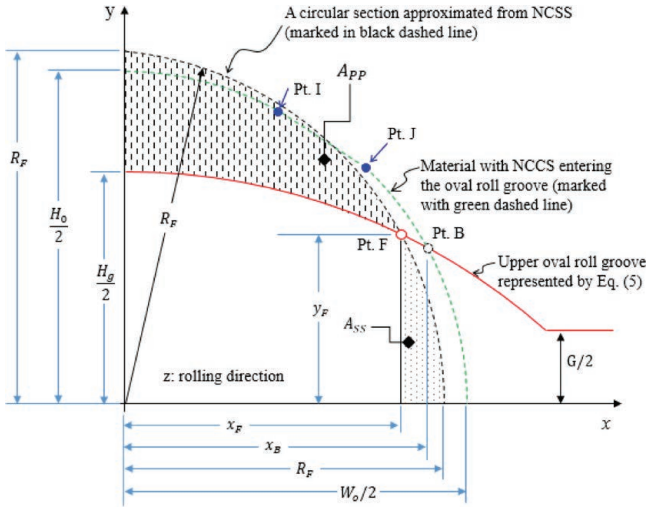


Fig. 5. Approximation of NCSS into a circular cross section based on cross sectional area of NCSS. (Online version in color.)

R_F is the radius of the circular cross section approximated from NCSS. In case that NCSS enters the oval roll groove, the intersection point is B. With this area approximation, a correction coefficient ρ has been added to Eq. (6) as follows.

$$\rho = A_p / A_{pp} \quad (9)$$

where $A_{pp} = 4 \left[\int_0^{x_F} (R_F^2 - x^2)^{1/2} dx - \int_0^{x_F} \text{Eq. (5)} dx \right] \dots$

As the cross section of the material entering the oval groove is closer to the circular cross section, ρ is closer to 1. Using Eq. (6) and R_F , the formula for predicting the maximum spread of the outgoing material is modified in the form below.

$$W_{max} = 2R_F + \rho \times \gamma \times A_{pp} / (3\pi R_F^2) \times \sqrt{D_{avg} A_{pp} / x_B}$$

$$\text{where } D_{avg} = D_{min} + H_0 - (\pi R_F^2 - A_{pp} - A_{ss}) / (2x_F) \text{ and}$$

$$A_{ss} = 4 \int_{x_F}^{R_F} (R_F^2 - x^2)^{1/2} dx \quad \dots \dots \dots (10)$$

(e) FSP_{OV} and Cross-sectional Area of Outgoing Material in Oval Pass

Once W_{max} is found, FSP_{OV} and cross-sectional area of material leaving the oval roll groove A_{OV} can be calculated. **Figure 6** shows the oval roll groove, cross section of the material entering the oval groove (indicated by black dashed lines), and FSP_{OV} (marked in blue) of the outgoing material. R_m stands for the radius of curvature of FSP_{OV}. Pt. F denotes a point where the oval roll groove intersects with the incoming circular section. Pt. T indicates a point at which outgoing material cross section begins to separate from the oval roll groove. The coordinates of the intersection point T are expressed as follows

$$x_T = R_g \sin \theta_T \text{ and } y_T = R_g \cos \theta_T - y_g + (G - G_d) / 2 \dots (11)$$

In this study, θ_T and θ_F are called separation angle and intersection angle, respectively. θ_T should be located between θ_B and ψ_g as the material inside the oval groove elongates and spreads during rolling. In this light, the separation angle ϕ_T required for predicting FSP in the oval pass is obtained by interpolating intersection angle θ_F and groove angle ψ_g in

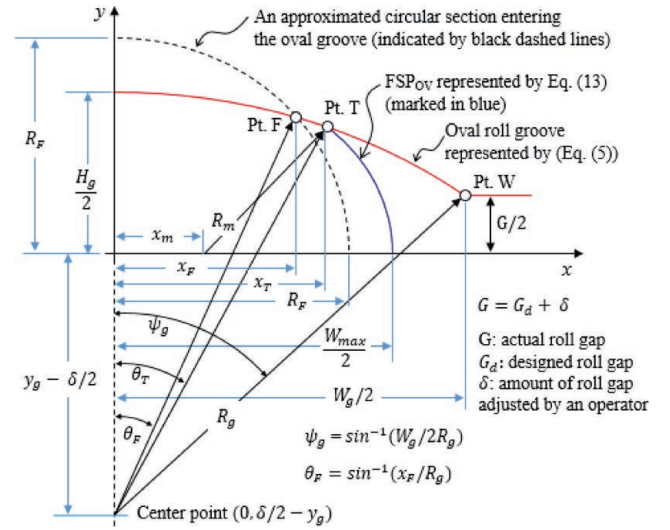


Fig. 6. Geometry of oval roll groove, intersection angle θ_F , separation angle θ_T , and groove angle ψ_g in the first quadrant to calculate FSP (marked in blue) of the outgoing material. (Online version in color.)

the form below

$$\theta_T = \sqrt{\alpha} \theta_F + (1 - \sqrt{\alpha}) \psi_g$$

where $\alpha = (W_g - W_{max}) / (W_g - 2R_F)$ and $\dots \dots \dots (12)$

$$\theta_F = \sin^{-1}(x_F / R_g) \text{ and}$$

$$\psi_g = \sin^{-1}(W_g / 2R_g)$$

The ratio α is a weighting function dependent on the geometry of incoming material section and roll groove. ψ_g is the groove angle and determined amid designing the oval roll groove.

FSP_{OV} is assumed to have a circular shape to keep the strain energy of material during rolling to the lowest. Therefore, FSP_{OV} is equal to the shape of a circle with a radius of curvature, R_m and is expressed by the following equation.

$$(x - x_m)^2 + y^2 = R_m^2$$

where $R_m = \frac{W_{max}}{2} - x_m$ and,

$$x_m = \left[\frac{W_{max}^2 - 4R_g^2 - 4(2y_g - \delta)^2 + 4R_g(2y_g - \delta) \cos \theta_T}{4W_{max} - 8R_g \sin \theta_T} \right] / \dots \dots \dots (13)$$

FSP_{OV} passes through coordinate $(W_{max}/2, 0)$ and pt. T. Subsequently, the cross-sectional area of the outgoing material A_{OV} (See Fig. 1) can be calculated as follows.

$$A_{OV} = 4 \left[\int_0^{x_T} \text{Eq. (5)} dx + \int_{x_T}^{W_{max}/2} \text{Eq. (13)} dx \right] \dots \dots \dots (14)$$

2.2. Oval-to-Round Pass Rolling

W_{max} , FSP and cross-sectional area of the material rolled in the oval-to-round pass are calculated through a process similar to that performed in the round-to-oval pass rolling.

(a) Geometry of the Material Cross Section Entering the Round Roll Groove

The material cross section entering the round roll groove

has an oval shape as shown in **Fig. 7**. The oval shape consists of two profiles. i) a profile formed by material in contact with the roll groove in the earlier pass. ii) a profile formed by material's spread in the earlier pass. Pt K denotes an intersection of the two profiles.

$$\text{For the first profile i): } x^2 + (y + y_v)^2 = R_v^2 \dots\dots (15)$$

$$\text{For the second profile ii): } (x - x_h)^2 + y^2 = R_h^2 \dots (16)$$

(b) Geometry of the Round Roll Groove

Figure 8 illustrates the geometry of a round roll groove, definition of roll gap and groove angle. When designing a round roll groove, a designer draws a shoulder line near the roll gap based on the angle ϕ_N .

$$\text{Circle: } (x - \delta/2)^2 + y^2 = R_g^2 \text{ for } \phi < \phi_N, \dots\dots (17)$$

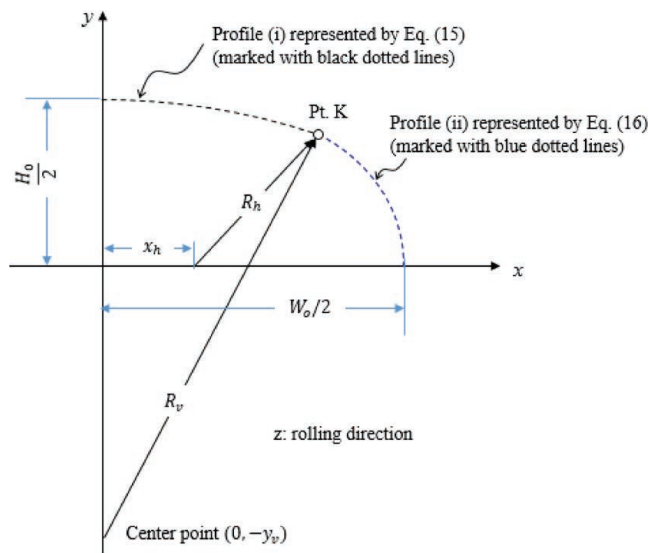


Fig. 7. A material cross section entering the round roll groove. It consists of two profiles. The first quadrant of the section is shown for convenience. H_o and W_o corresponds to the height and maximum spread of material rolled out of the oval roll groove. (Online version in color.)

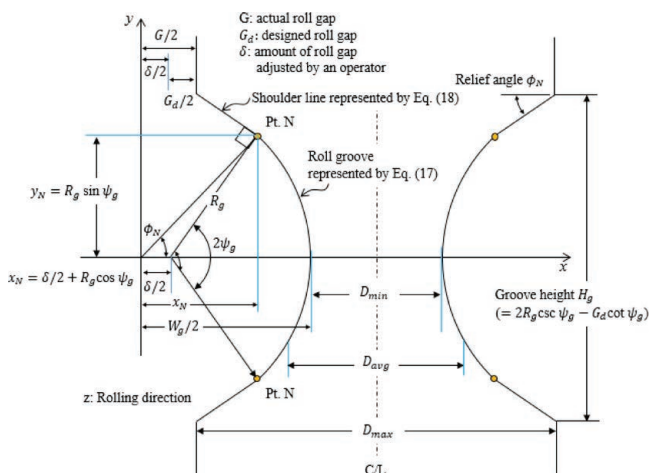


Fig. 8. Geometry of a round roll groove, definition of roll gaps, relief angle, shoulder line and groove height. (Online version in color.)

$$\text{Shoulder line: } y = (\delta/2 - x) \cot \psi_g + R_g \csc \psi_g \text{ for } \phi \geq \phi_N, \\ \text{where } \phi_N = \tan^{-1} [R_g \sin \psi_g / (\delta/2 + R_g \cos \psi_g)]. \dots\dots (18)$$

Therefore, the entire shape of the round roll groove is not a circle when viewed from the rolling direction (z direction). For this reason, the round groove is sometimes called “false” round groove.

(c) Change in Roll Gap (Height of Round Roll Groove) in Round Pass

In round pass, the roll gap must not be adjusted so that the cross-section of the incoming material intersects the shoulder line. (Fig. 8). Otherwise, the material spreads too much, causing “overfill” where the material also meets the shoulder line of the roll groove. This overfill leads to serious product defects when rolled in the next pass. For this reason, the cross section of incoming material is always positioned on the circular profile of the round roll groove and therefore multiple cases do not occur as in the sub-section(c) of Section 2-1.

(d) Maximum Spread of Material Cross Section Leaving the Round Roll Groove

Figure 9 illustrates the geometry of the round roll groove, FSP_{RD}, and intersections when material with oval cross section enters the round roll groove. Like the maximum spread W_{max} of the outgoing material in the oval pass, the maximum spread H_{max} of the outgoing material in the round pass can be calculated by the following equation.

$$H_{max} = H_o + \gamma \times A_p / A_o \times H_o / (2H_o + W_o) \times \sqrt{D_{avg} A_p / y_B} \dots\dots (19)$$

γ indicates a correction coefficient reflecting the roll groove, and 0.76 was used. A_o and A_p denote the material's cross-sectional area before rolling and the one reduced during rolling. W_o , A_p , H_o , and x_B are described in Fig. 9. D_{avg} is an average diameter of the roll defined at the intersection between the incoming material cross-section and the geometry of round roll groove, and obtained by the following equation.

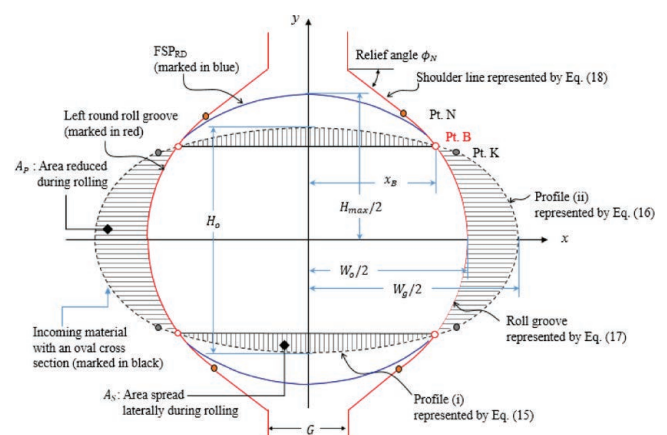


Fig. 9. Geometry of the round roll groove, FSP_{RD} and intersecting points when a material with oval cross section enters the round roll groove. (Online version in color.)

$$D_{avg} = D_{min} + W_g - (A_o - A_p - A_s) / (2y_B)$$

where

$$\begin{aligned} A_p &= 4 \left[\int_{x_B}^{x_K} Eq.(15) dx + \int_{x_K}^{W_o/2} Eq.(16) dx - \int_{x_B}^{W_o/2} Eq.(17) dx \right] \\ A_o &= 4 \left[\int_0^{x_K} Eq.(15) dx + \int_{x_K}^{W_o/2} Eq.(16) dx \right] \\ A_s &= 4 \left[\int_0^{x_B} Eq.(15) dx - x_B y_B \right] \end{aligned} \quad \dots\dots\dots (20)$$

(e) FSP_{RD} and A_{RD} (Cross-sectional Area of Outgoing Material) in Round Pass

Figure 10 illustrates the geometry of round roll groove, intersection angle, separation angle, and groove angle and FSP_{RD} of the outgoing material in one quadrant. As in the oval pass, the separation angle ϕ_T needed for predicting FSP in the round pass is obtained by interpolating intersection angle ϕ_B and edge angle ϕ_E as follows

$$\phi_T = \sqrt{\alpha} \phi_B + (1 - \sqrt{\alpha}) \phi_E$$

where $\alpha = (H_g - H_{max}) / (H_g - H_o)$ and $\dots (21)$

$$\phi_B = \tan^{-1}(y_B / x_B) \text{ and } \phi_E = \tan^{-1}(H_g / G).$$

The x-coordinate of the pt. T depends on ϕ_T as follows.

$$x_T = (\delta / 2 \times \cot \psi_g + R_g \csc \psi_g) / (\tan \phi_T + \cot \psi_g) \text{ for } \phi_T < \phi_N \quad \dots\dots\dots (22)$$

$$\begin{aligned} x_T &= \left[\delta \tan \phi_T + \sqrt{4R_g^2 (\tan^2 \phi_T + 1) - \delta^2} \right] / \\ &\quad \{2(\tan^2 \phi_T + 1)\} \text{ for } \phi_T \geq \phi_N \end{aligned} \quad \dots\dots (23)$$

The y-coordinate of the pt. T is then $x_T \tan \phi_T$.

Similarly in the oval pass, FSP_{RD} of the material during rolling in round pass may have a circular shape to keep its strain energy to the lowest. Therefore, FSP_{RD} is a circle with a radius of curvature R_m passing through $H_{max}/2$ and pt. T as shown in Eq. (24).

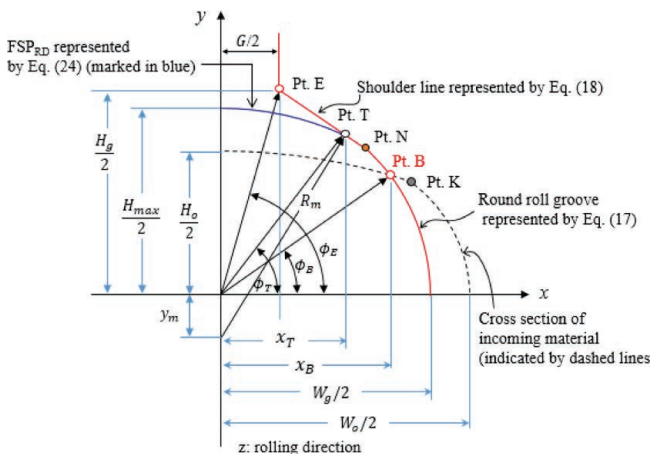


Fig. 10. Geometry of round roll groove, intersection angle, separation angle, and groove angle in the first quadrant to calculate FSP_{RD} (marked in blue) of the outgoing material. (Online version in color.)

$$\begin{aligned} x^2 + (y + y_m)^2 &= R_m^2 \\ \text{where, } R_m &= H_{max} / 2 - y_m, \text{ and } \dots (24) \\ y_m &= [4y_T^2 + 4x_T^2 - H_{max}^2] / \{4(H_{max} - 2y_T)\} \end{aligned}$$

Cross-sectional area of the outgoing material A_{RD} (See Fig. 1) can be calculated as follows.

$$A_{RD} = \left[\int_0^{x_T} Eq.(24) dx + \int_{x_T}^{W_{max}/2} Eq.(17) dx \right] \text{ for } \phi_T < \phi_N \quad \dots (25)$$

$$\begin{aligned} A_{RD} &= \left[\int_0^{x_T} Eq.(24) dx + \int_{x_T}^{x_N} Eq.(18) dx + \int_{x_N}^{W_{max}/2} Eq.(17) dx \right] \\ &\text{for } \phi_T \geq \phi_N \end{aligned} \quad \dots\dots\dots (26)$$

2.3. Calculation Process

The process of calculating those angles (intersection, separation, and roll groove), the points (I, J, F, B, F, T, and W), FSP and cross-sectional area of outgoing material in the oval-to-round (or vice versa) rolling sequence is described in **Fig. 11** in the form of a flow chart.

3. Results and Discussion

3.1. Verification of the Analytical Model Proposed in This Study

The proposed analytical model was applied to a round-to-oval pass rolling to check the usefulness of FSP prediction based on the interpolation of the intersection and roll groove angles. **Figure 12(a)** shows the geometry of oval roll groove and incoming material. The incoming cross-section is a circle with a diameter of 101.5 mm. The material used in this study is 0.15% plain carbon steel (S15C). **Figure 12(b)** shows the FSPs and separation points predicted by Lee's model,⁵⁾ the analytical model proposed in this study, and FEM. Although the maximum spread predicted by the analytical models is slightly different from that predicted by FEM, the separation point calculated by the proposed analytical model matches well with those by FEM, compared with that predicted by Lee's model.⁵⁾ The proposed analytical model about 2% higher accuracy in predicting the separation point directly affecting FSP than the analytical model proposed by Lee.⁵⁾ Hence, it can be inferred that proposed analytical model can be applicable to continuous oval-to-round (or vice versa) pass rolling sequence.

3.2. Application to 10-pass Continuous Rolling without Roll Gap Changed

Figure 13 shows the shapes and dimensions of roll grooves used for 10-pass rolling continuous rolling. The diameter of the material section entering the first pass is 101.5 mm. The diameter of the material section rolled out in the last pass was designed to be 23.24 mm. The reduction ratios in area of the material (cross) section for each pass are in the range of 18–30%. The reduction ratio in each pass is designed to decrease as the pass number increases. The reduction ratio in the last pass is designed to be 18% to secure the roundness of the final product. Roundness is defined as the ratio of height to width of the outgoing material section in each pass. The relief angles θ_N designed for

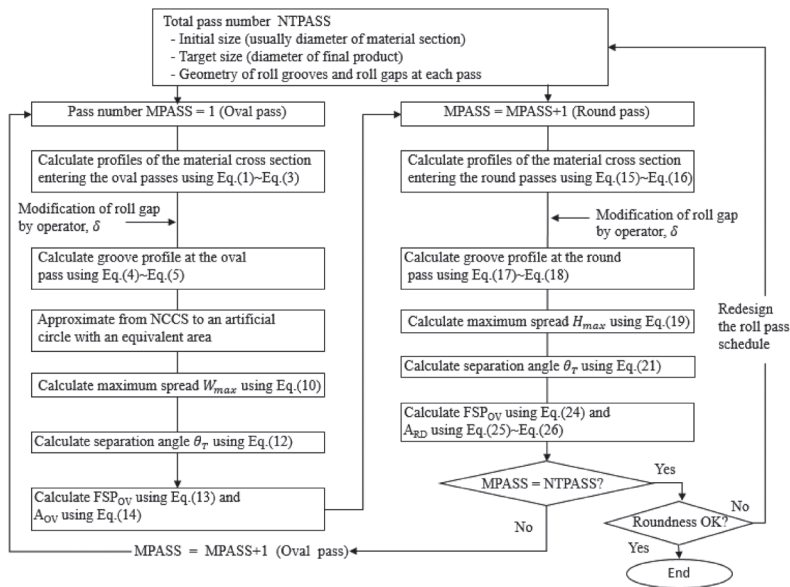


Fig. 11. A flow chart to compute FSP and cross-sectional area of outgoing material in oval-to-round (or vice versa) rolling sequence.

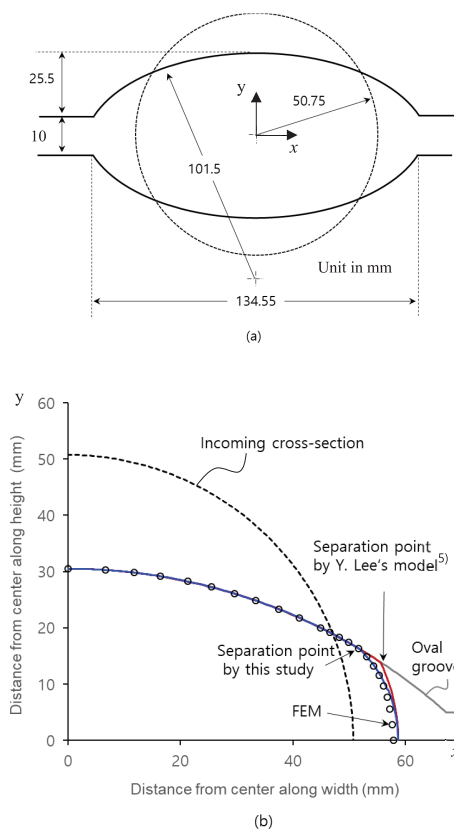


Fig. 12. (a) Geometry of roll groove and incoming material with a diameter of 101.5 mm in the round-to-oval pass rolling (b) Comparison of FSPs of outgoing material predicted by the analytical model proposed in this study and FEM rolling. (Online version in color.)

round roll grooves are in the range of 23–35°.

Figure 14 shows the FSPs of outgoing material section predicted by the analytical model proposed in this study and FEM. The shape of the material section entering the oval passes (No. 3, 5, 7, and 9) excluding No. 1 pass is not a circular cross section but NCCS (non-circular cross section). Nevertheless, the predicted FSPs of material section leaving

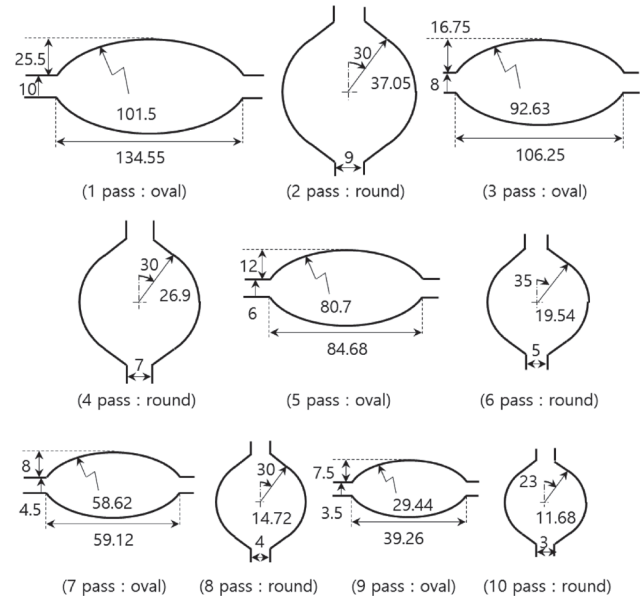


Fig. 13. Shapes and dimensions of roll grooves used for the prediction of FSP of outgoing material in the 10-pass continuous rolling.

the oval passes agree well with the FE simulation results. This means that the approximation (from NCCS to circular cross section) method suggested in this study is working.

In the round passes (No. 2, 4, 6, 8, and 10), the calculated separation points are close to those predicted by FEM and error ($= (\text{analytical model} - \text{FEM}) / \text{analytical model} \times 100 (\%)$) is only in the range of 0.3–1%. In the case of the last pass, the difference between the material cross sectional area predicted by the analytical model and the one by FEM is merely 0.015% (See Fig. 14), demonstrating the satisfactory performance of the proposed analytical model.

3.3. Application to 4-pass Continuous Rolling with Roll Gap Changed

The proposed analytical model proposed was also applied to four-pass continuous rolling sequence to show the ability

of predicting the roundness of the material section in the final pass by changing the roll gaps. **Figure 15** shows the shapes and dimensions of roll grooves of the four-pass continuous rolling sequence. Diameter of the material entering No. 1 pass is also 101.5 mm. The shapes and dimensions

of roll grooves of No. 2 and 3 passes are the same with No. 2 and 3 passes for 10-pass continuous rolling sequence addressed in Fig. 13 but roll gaps in No. 2 and 3 passes are different. In addition, the dimension of round roll groove in No. 4 pass is different.

Figure 16 shows that FSPs of outgoing material and separation points predicted by the proposed analytical model are in good agreement with those by FEM for all passes. Good applicability of the proposed analysis model was also confirmed for the four-pass rolling sequence in which the roll groove dimension and roll gaps were changed. However, the roundness of outgoing material in the last pass is 83.57, which implies that the roundness is quite low. Difference between the maximum height and width of the outgoing material section in the last pass is 10.2 mm.

We have changed roll gaps of No. 1–3 passes in the four-

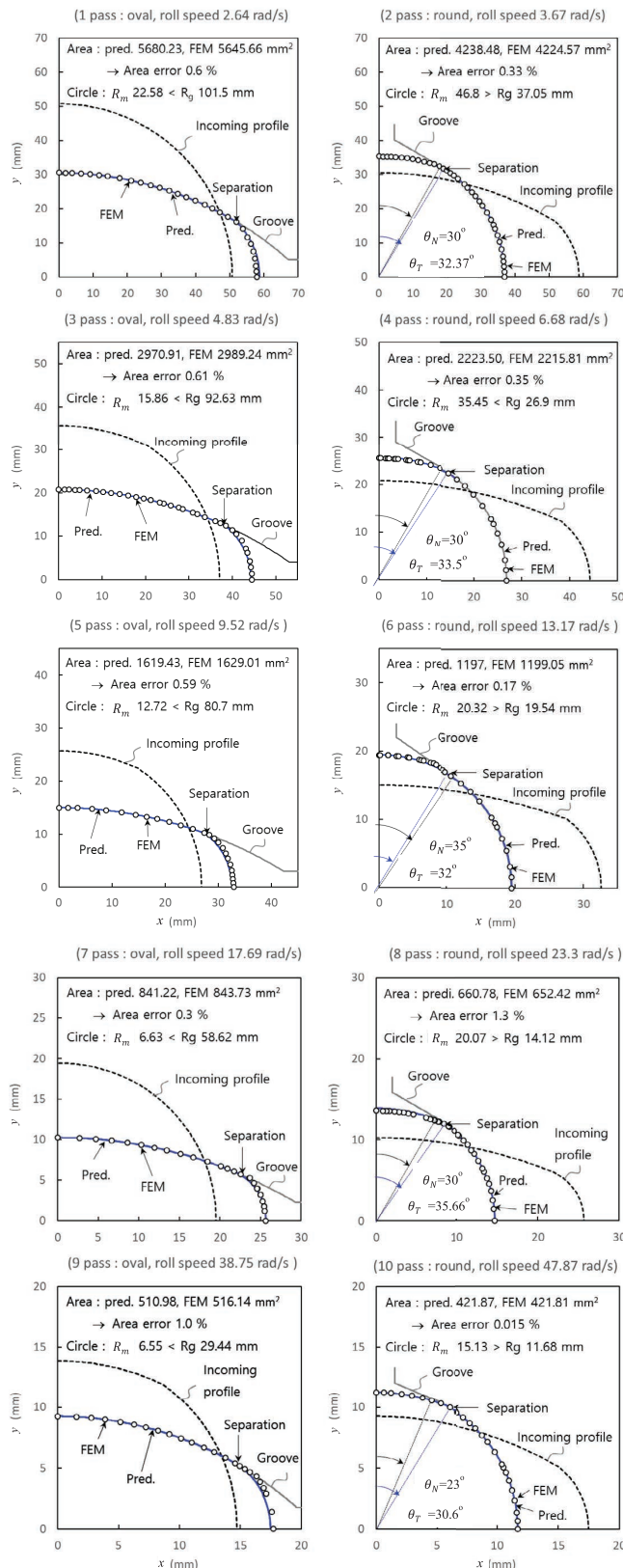


Fig. 14. FSPs of outgoing materials predicted by the analytical model proposed in this study and FEM when the reference roll gaps were used in the ten-pass continuous rolling. $\theta_N = 90 - \phi_N$ and $\theta_T = 90 - \phi_T$. (Online version in color.)

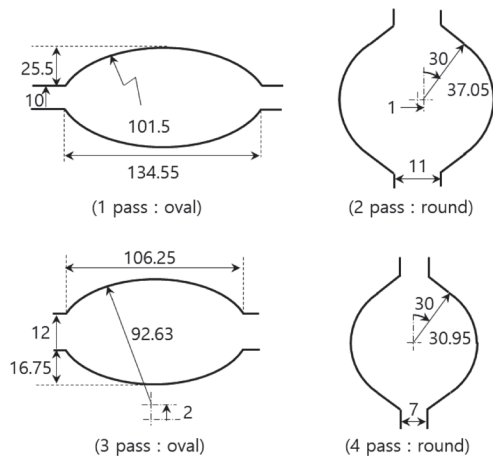


Fig. 15. Shapes and dimensions of roll grooves used for predicting FSP of outgoing material in the four-pass continuous rolling.

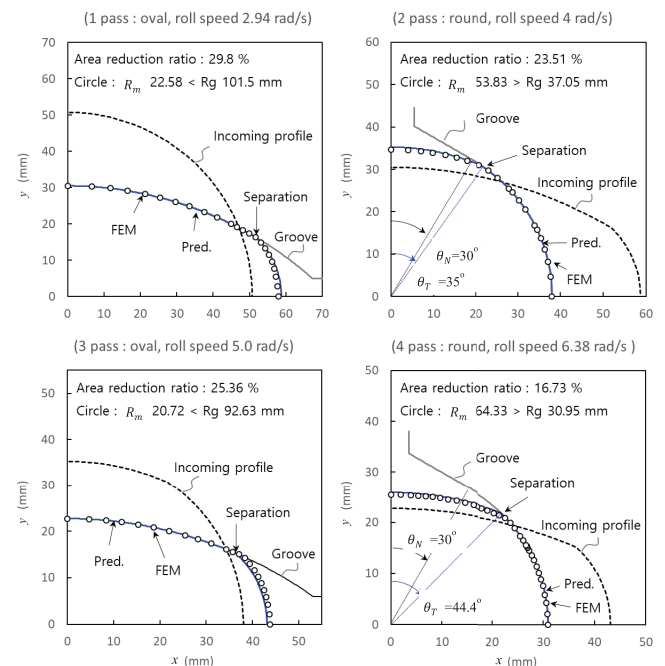


Fig. 16. FSPs of outgoing materials predicted by the analytical model proposed in this study and FEM when the roll gaps in the 2nd and 3rd pass in the 4-pass continuous rolling were increased. (Online version in color.)

pass rolling sequence to improve the roundness of the outgoing material section in the final pass. **Table 1** shows the results (reduction ratio in cross sectional area and roundness of outgoing material at each pass) when roll gaps in the No. 1–3 passes are changed. The roundness in the last (No. 4) pass was significantly improved by increasing the roll gaps. This is because the amount of decrease in reduction ratio in area at the passes (No. 1, 2, and 3) led to an increase in the reduction in area at the last pass. Consequently, the roundness of the material section in the last pass increased from 83.57 to 98.65 due to the increased reduction ratio of 4.7% in No. 4 pass. Roundness of 98.65 is a sufficient value for roundness of large-diameter bar product.

Figure 17 shows FSPs of outgoing material section for No. 2 and 4 pass when roll gaps in the passes (except for the 4th pass) are increased. Input (change in roll gap) and

subsequent results (reduction ratio in area and roundness of outgoing material section) at each pass are summarized in Table 1. It should be mentioned that “without mod.” on the left in Fig. 17 indicates that FSPs of the outgoing material for the 2nd and 4th pass in Fig. 16 are just enlarged for convenience. On the other hand, “with mod.” on the right in Fig. 17 means that FSPs of the outgoing material when roll gaps were changed (See Table 1). It is observed that increase in roll gap notably reduces the separation angle (from 35° to 31.1° for 2nd pass and from 44.4° to 28° for 4th pass) and the radius of curvature R_m of FSP (from 53.85 mm to 45.15 mm for 2nd pass and from 64.33 mm to 43.39 mm for 4th pass). This reduction directly leads to improved roundness of the material section leaving the last pass. It is deduced that it is possible to quickly calculate the amount of roll gap adjustment in each pass that improves the roundness of the material in the final pass without the time-consuming FE analysis.

Table 1. Summary of change in roll gap, reduction ratio in area, and roundness of outgoing material cross section at each pass when the analytical model proposed in this study was applied to four-pass rolling sequence.

Rolling sequences	1st pass: oval	2nd pass: round	3rd pass: oval	4th pass: round
Roll gap (mm)	10 → 15	11 → 15	12 → 19	7
Reduction ratio in area (%)	29.8 → 24.45	23.5 → 21.9	25.36 → 20.22	16.73 → 21.43
Roundness	–	92.7 → 94.1	–	83.6 → 98.65

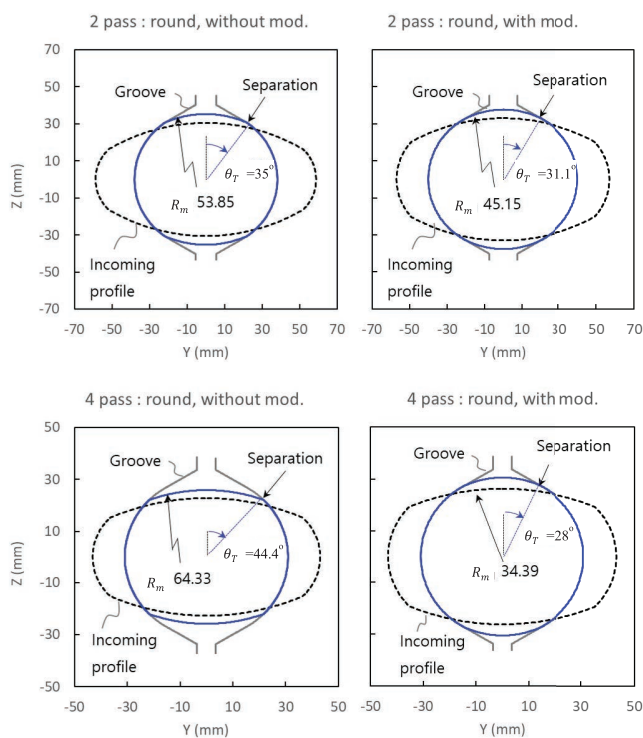


Fig. 17. Comparison of FSPs of outgoing material predicted by the analytic model proposed in this study when the roll gaps in the passes (except 4th pass) in Fig. 15 were increased. The values of increased roll gaps are shown in Table 1. (Online version in color.)

4. Conclusions

In this study, we proposed an analytical model for the prediction of free surface profile (FSP) of outgoing material in the round-to-oval (or vice versa) pass rolling sequence even when the cross section of incoming material is not circular and roll gap changes. The separation angle coupled with FSP was predicted by interpolating the intersection angle and the groove angle nonlinearly. The performance of the proposed analytical model was verified by comparison of FSPs and separation angles predicted by the proposed analytical model and those predicted by FE analysis for single pass, four-pass, and ten-pass rolling sequences. The conclusions are as follows. (1) It is reasonable to approximate the incoming NCCS (non-circular cross section) to a circular cross section based on its cross-sectional area to predict FSP. (2) Using the analytical model presented in this study, even engineers with little experience in the roll-pass design can quickly compute the roll groove height, *i.e.*, the amount of roll gap adjustment in each pass that improve the roundness of the final product.

Conflict of Interest

The authors do not have any conflicts of interest to declare.

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