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Roll design method using virtual flow line for multi-stage profile rolling process †

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Abstract

The roll profile in the multi-stage profile rolling process for manufacturing shaped wires influences product quality and dimensional accuracy significantly. Because the multi-stage profile rolling process is affected by many variables, such as elongation, rolling reduction, and width spread in a complex manner, many difficulties are involved in roll design. The roll profile design is predominantly conducted using finite element analysis (FEA). In this paper, a design method using virtual flow line, which is a roll profile design method in the multi-stage profile rolling process, is proposed. This design method employs a cross-section of the three-dimensional (3D) profile as the roll profile with a virtual flow line, thereby enabling roll profile design without performing FEA. To validate the design method, roll profiles were designed by applying the design method to the profiles of 12 products typically manufactured industrially using the profile rolling process, and FEA was conducted. The results indicate that the proposed method not only ensures higher dimensional accuracy than the conventional method but also assigns a higher strain rate.

Keywords: Roll profile; Rolling process; Shaped wires; Virtual line flow; Finite element analysis

1. Introduction

The multi-stage profile rolling process refers to a process in which products are manufactured whose cross-sectional profile is complex, such as angle bar, H-beam, or I-beam [1-3]. It is highly important to choose an appropriate process design considering material formability, reduction in cross section, and productivity. However, as the strain in the profile rolling process incurs elongation and width spread in the longitudinal direction, many difficulties are involved with roll profile design.

For drawing and extrusion processes to manufacture shaped wires, Kim et al. [4] proposed a virtual die design method in which a virtual die is created and the cross section is used as a roll profile in the intermediate pass. Yang et al. [5] proposed an extrusion die design method that uses the B-spline curved surface and scalar field theory for roll profile design. However, because these design methods do not consider width spread, they are difficult to apply to roll profile design in the profile rolling process.

For the profile rolling process, finite element analysis (FEA) is typically used to design roll profiles [6]. Kim et al. [7, 8] proposed a roll profile design method that uses electric field analysis (EFA). Their design method employs equipotential line the analysis result after performing EFA through inputting different voltages to final and initial profiles, respectively as an intermediate roll profile. However, their roll profile design method could be time-consuming owing to EFA and validation analysis.

To overcome these problems, this paper proposes a roll profile design method that utilizes a vertical slab method [9] in order to design a roll profile more efficiently than existing roll profile design methods. In this study, a roll profile was designed for 12 types of cross-sectional profiles manufactured via the rolling process to verify the validity of the proposed design method, and FEA is conducted.

2. Roll design method

2.1 Roll design using virtual flow line

Roll profile design using virtual flow line in this study is a design method to obtain the roll profile of intermediate pass during the multi-stage profile rolling process. The proposed roll profile design configures a 3D profile consisting of virtual flow lines and the cross-sectional profile of final products and initial material, thereby using the cross section as a roll profile. The sequence of the roll profile design method is as follows:

[Step 1] Uniform material strain is induced by matching the cross-section centroids between the initial material and the final product, as shown in Fig. 1, and width spread of the material is induced by connecting a tangent line to the external

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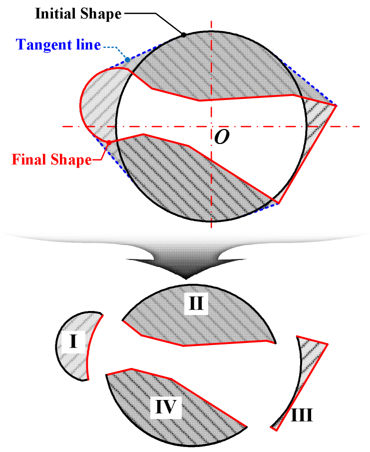


Fig. 1. Region divided for determination of virtual flow line [steps 1, 2].

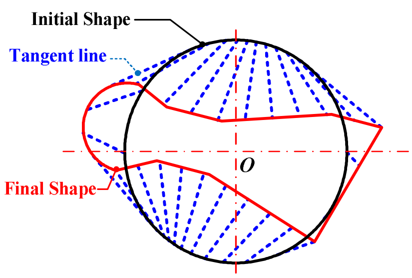


Fig. 2. Generation of virtual flow line for 3D model [step 3].

angle. As the rolling process progresses, width spread occurs owing to rolling reduction in the material. Thus, profiles whose left and right sides are asymmetrical are rotated around the centroid to make the width the largest prior to applying the design method.

[Step 2] The region is divided based on the centroid and tangent line, as shown in Fig. 1, to consider material flow due to width spread in the left and right directions and rolling reduction in the upper and lower directions. The cross section of the final product is divided into detailed sub-regions, with the same distance inside the divided four regions.

For the case of that the centroid of the final product is outside of the profile, the design method cannot be applied.

[Step 3] The area ratio of the cross section between the initial material and the final product inside the divided region is calculated as shown in Fig. 2, and a virtual flow line is determined to have the same area ratio inside the detailed sub-region in a single region.

[Step 4] The 3D profile of the virtual flow line determined at the four regions is configured as shown in Fig. 3. The cross section of the 3D profile that satisfies the target cross-sectional reduction ratio is then taken and used as a roll profile for each pass.

2.2 Virtual flow line

The virtual flow line used in this study is produced via application of the vertical slab method. The vertical slab method is a method that divides billet and roll profile into uniform slabs and designs a roll profile through prediction of the width spread of materials using an elongation coefficient [9]. The method induces material flow by making the area ratio of the cross section in a single region between the initial material and the final product and the area ratio of the detailed sub-regions the same. The cross-sectional area (O_A) of the initial material is determined from the final cross-sectional area (F_A) that is equally spaced in the width direction (x-axis) by assigning the same area ratio in the four detailed sub-regions, as shown in Fig. 4. The area ratio of each region can be expressed by the following equation:

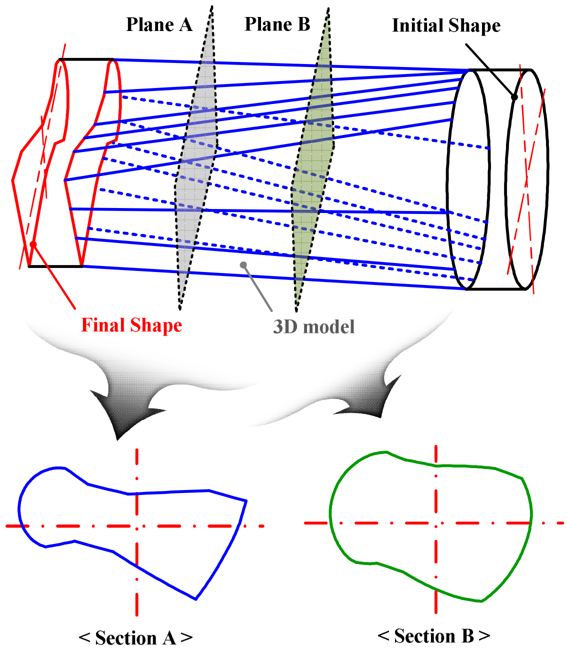


Fig. 3. Generation of 3D model for determination of cross-sectional shape of roll of each pass.

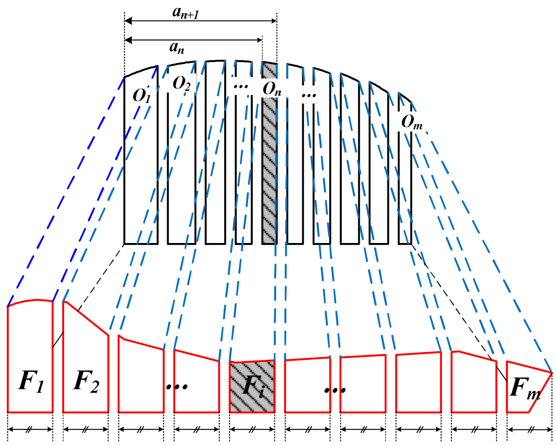


Fig. 4. Schematic illustration for determination of virtual flow lines.

$$\frac{F_A}{O_A} = \frac{F_n}{O_n} \tag{1}$$

where F_n refers to the area of the n-th detailed sub-region in the final product's cross section, and O_n refers to the area of the n-th detailed sub-region in the initial material's cross section. The area of the n-th detailed sub-region of the initial material can be expressed by the following equation:

$$\begin{aligned} O_n &= \int_{a_n}^{a_{n+1}} \sqrt{r^2 - x^2}\, dx \\ &= r^2[(\frac{1}{2}\theta_{n+1} + \frac{1}{4}\sin 2\theta_{n+1}) - (\frac{1}{2}\theta_n + \frac{1}{4}\sin 2\theta_n)] \end{aligned} \tag{2}$$

$$\theta_n = \sin^{-1}\left(\frac{a_n}{r}\right), \theta_{n+1} = \sin^{-1}\left(\frac{a_{n+1}}{r}\right) \tag{3}$$

where r refers to the radius of the initial material.

The vertical flow line is determined by calculating the width of the n-th detailed sub-region in the initial material's cross section that satisfies the area in Eq. (1) and the area of the initial material's cross section in Eq. (2), as shown in Fig. 4. The detailed sub-regions of the calculated initial material and the final product's cross sections show that each of the area ratios is distributed uniformly, as shown in Fig. 4.

2.3 Pass schedule

In this study, an equal-load pass schedule was used to make the loads in all passes the same as the criterion that determined the roll profile of the intermediate pass. The equal-load pass schedule predicted the roll force of each pass using Eq. (4), as defined by Geleji [10]. The equivalent rectangles technique is used to convert the roll profile's cross section to the same value as the area of the rectangle to apply Eq. (4) for the profile rolling process [11]. When the equivalent rectangles technique is applied in the profile rolling process, the difference between the actual and the theory of the contact area occurs. To correct this, a compensation coefficient, which is the square of the perimeter of the actual roll profile and the roll profile where the equivalent rectangles technique was applied is used as presented in Eq. (5).

$$P = k_m b l_d = k_{fm}(1 + cf\frac{l_d}{h_m}\sqrt[4]{v_r}) \tag{4}$$

$$c = \frac{5.5h_m}{a \cdot l_d} + 0.075 \cdot (\frac{a \cdot l_d}{h_m} - 1),\ a = \frac{p_r^2}{p_e^2} \tag{5}$$

where P is the roll force, k_m the mean strain resistance, k_{fm} the mean strain strength, l_d the projected contact length, h_m the mean height, v_r the peripheral speed, f the frictional coefficient, a the correction coefficient, P_r the circumference of the original roll profile, and P_e the circumference of the roll profile to which the equivalent rectangles technique was applied.

Table 1. Pass schedule for the fork bar shape and roll forces predicted.

Pass no.	1	2	3	4	Total	Avg.
Roll force predicted (kN)	396.0	386.4	383.9	377.0	-	385.8
Reduction in area (%)	16.1	9.9	9.1	8.6	37.2	-

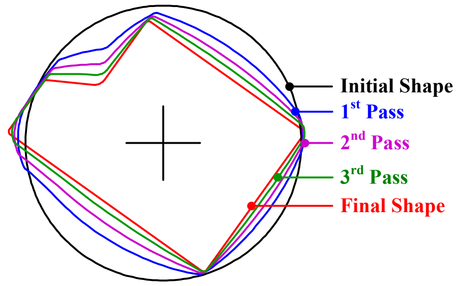


Fig. 5. Cross-sectional shape of the roll of each pass for the fork bar shape.

Fig. 5 and Table 1 present the equal-load pass schedule and design results obtained using the roll force calculation equation of the fork bar profile. The roll force of each pass was calculated as 385.8 kN on average. The total reduction in area was 37.2 % and the reduction in area at each pass was 16.1 %, 9.9 %, 9.1 % and 8.6 %.

3. Application of design method

3.1 Range of application

The roll profile design method proposed in this study aims to improve the filling rate of products whose shape is complex. Thus, the proposed design method was validated by applying the it to 12 types of products manufactured through the profile rolling process at industrial sites. Fig. 6 summarizes the cross-sectional profiles of the product through profile numbers and dimensions and the cross-sectional areas of the 12 types of profiles. The result in which the roll profile design method was applied to the product profile in Fig. 6 is shown in Fig. 7. The total reduction rate of the cross section was in the range 42 % to 44 %. For nos. 1, 3, 10, 11 and 12 profiles where the diameter of the initial material exceeded the profile of the final product, the total reduction rate of the cross section was set to 37.2, 19.8, 53.4, 32.2 and 35.2 %, respectively.

FEA was conducted with the conditions presented in Table 2 to verify the filling rate of the materials with regard to the roll profile designed in Fig. 7 in order to verify the validity of the roll profile design method proposed in this study. In FEA, FCC iron-carbon alloy initially containing 0.35 wt% C was applied, and a total of four passes were conducted at the following conditions: 300 mm roll diameter, 10 RPM initial roll circumferential speed, and 0.12 frictional coefficient. Furthermore, the commercial software DEFORM-3D Ver. 11.0, was used in the FEA.

Table 2. Process variables for FE-simulation.

Process conditions	Value
Material	0.35 wt% C
	$\sigma = 1869.38 \cdot \varepsilon^{0.28}$
Initial wire diameter (mm)	15
Roll diameter (mm)	300
Number of pass	4
Initial roll speed (rpm)	10
Friction coefficient (μ)	0.12

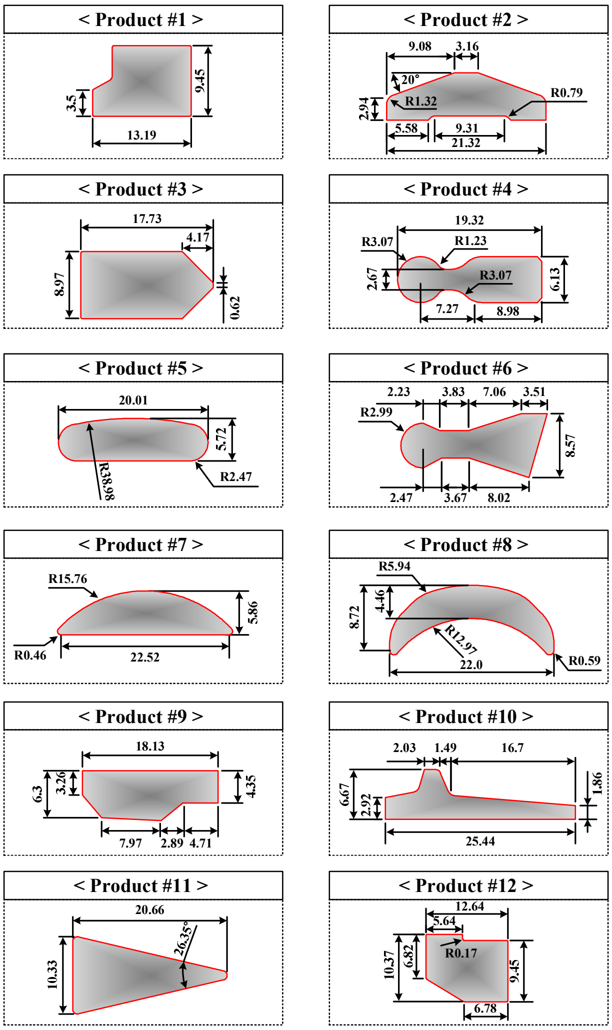


Fig. 6. Cross-sectional shape of the final product for application in the proposed roll design method.

3.2 Results of application

The unfilling rate (UR) was evaluated on the basis of the cross section of the final pass as the analysis result. The UR was calculated using the cross-sectional area of the analysis result and the target [12].

Of the 12 profiles that were evaluated, the profiles in Fig. 8 satisfied the final cross-sectional profile below 1 % of UR, which proved the validity of the design method. The other seven types showed a large UR, which can be largely divided into two categories: width spread deficiency and eccentricity of material.

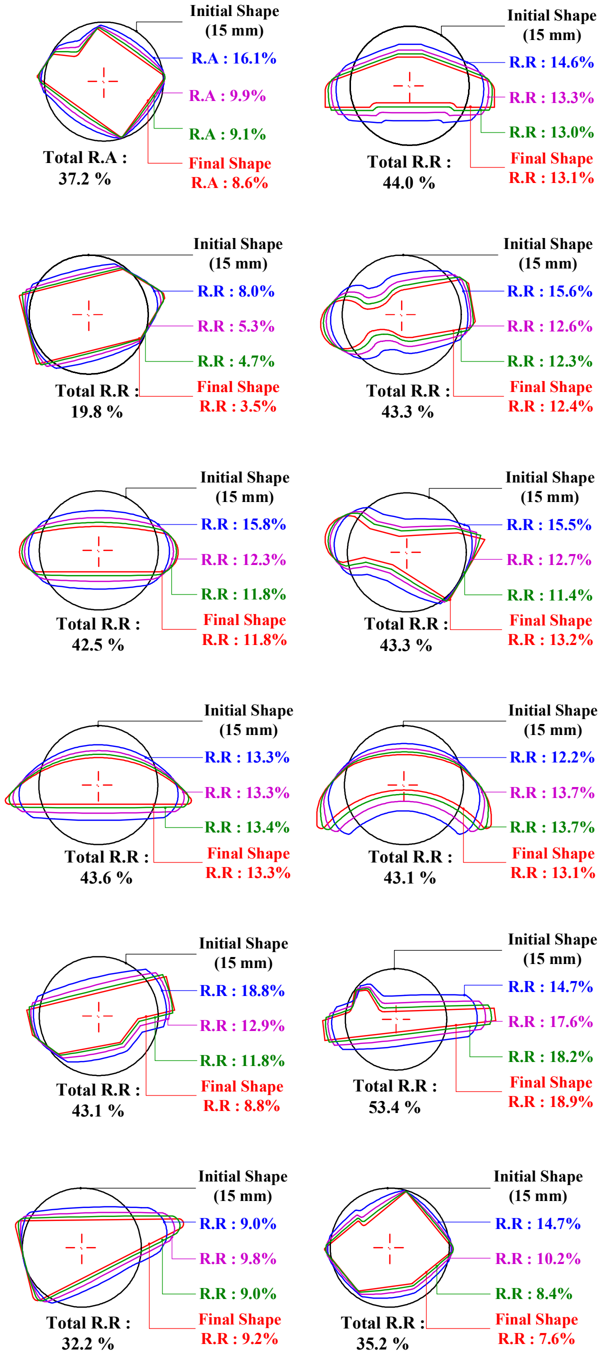


Fig. 7. Roll of each shape and analysis results.

As shown in Fig. 9, the results of FEM indicate that the width spread is insufficient for nos. 2, 5, 7, 8 and 10 products. Furthermore, as shown in Fig. 10, the results further indicate that the eccentricity of material occurred for nos. 3 and 11 products. Owing to the eccentricity of the material as the pass progressed, the quantity of over-filling and unfilling increased.

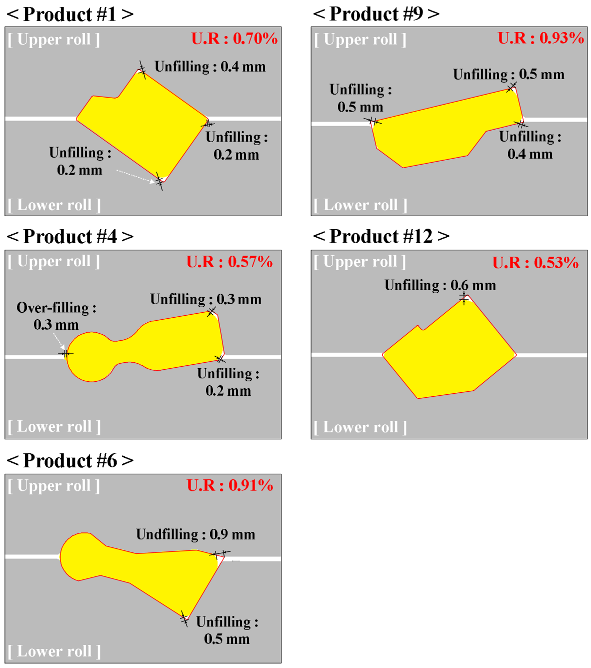


Fig. 8. Profiles satisfying the final cross-sectional shape from the results of FEM.

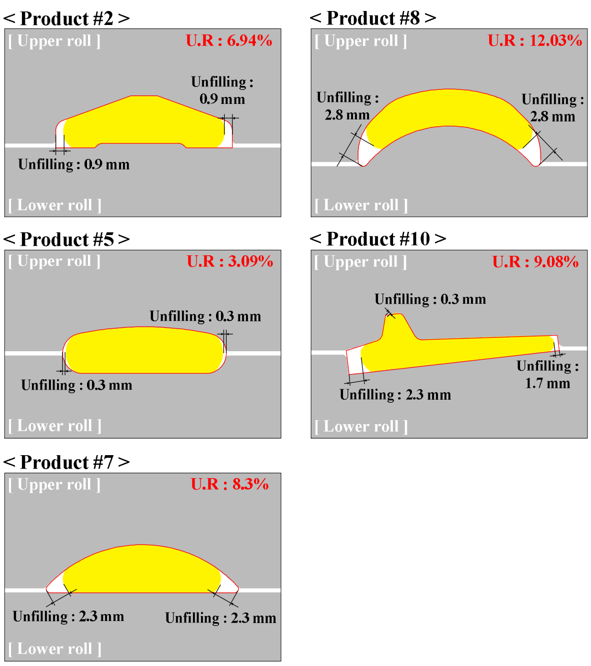


Fig. 9. Profiles showing the width spread deficiency from the results of FEM.

Therefore, in order to apply the design method proposed in this paper, it is necessary that the characteristics of the product shape be defined.

3.3 Discussion

To confirm the limits of design method, the metal flows were compared for nos. 1 and 8 products.

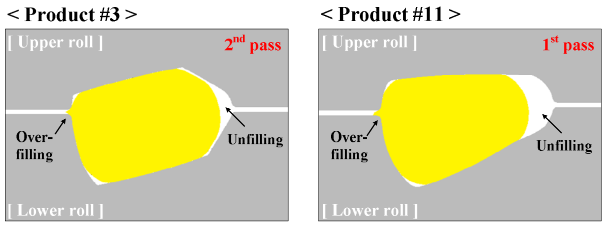


Fig. 10. Profiles in which the eccentricity of the material occurs from the results of FEM.

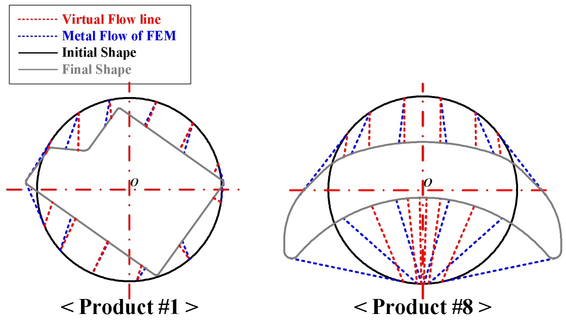


Fig. 11. Comparison with the virtual flow line and the metal flow of FEM.

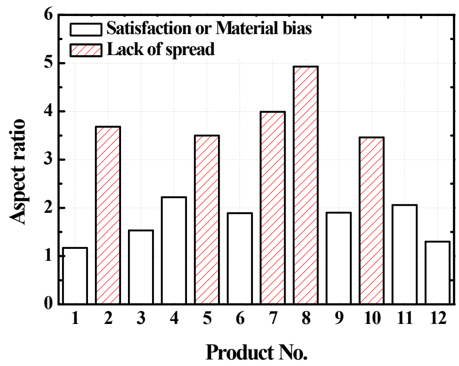


Fig. 12. Aspect ratio for cross-sectional shape of products.

The virtual flow line by the roll profile design method proposed in this study and metal flow earned from results of FEM were compared in Fig. 11. From the results of FEM, the metal flow was indicated as line with two points from initial billet to final product.

Fig. 11 shows the metal flow and virtual flow line of no. 1 product, having the UR of 0.7 %, is similar. However, flow lines of No. 8 product, having the UR of 12.03 %, are not similar.

In addition, the application results of the roll profile design method proposed in this study showed that width spread was deficient in the case of a high aspect ratio—the ratio of the maximum width of the product profile to the maximum height—as shown in Fig. 12. As shown in Fig. 13, the force applied to the roll profile in the x direction can be defined using Eq. (6) by utilizing the slope and length at the area where the material is contacted depending on the shape of the

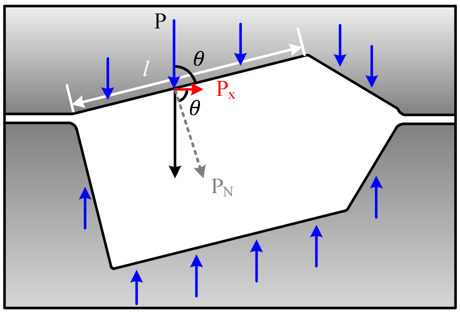


Fig. 13. Schematic illustration for calculation of off-center factor.

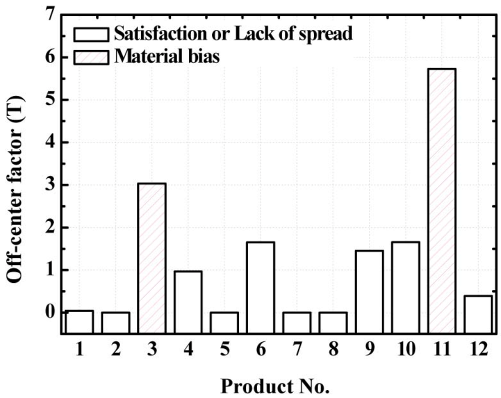


Fig. 14. Off-center factor for cross-sectional shape of products.

roll profile.

$$P_{xn} = l \times P \sin\theta \cos\theta \quad (6)$$

where P_{xn} is the force at the slope surface in the x direction, l the length of the slope surface, and P the vertical load. Here, a roll separating the force due to the roll force was assumed to be applied evenly on the material.

Based on the force in the x direction defined in Eq. (6), the off-center factor (T) was defined as follows to perform the evaluation of material eccentricity:

$$T = \sum_{n=1}^{i} P_{xn} / P. \quad (7)$$

The roll profiles obtained using the design method proposed in this study and the existing design method using EFA were compared, and a significant difference subsequently revealed particularly in the two regions shown in Fig. 15. For region A, in which the rolling reduction was locally large, as shown in Fig. 15, the rolling reduction in the roll profile designed with the virtual flow line became smaller as the pass progressed. In contrast, the rolling reduction in the profile designed with EFA remained virtually the same as the pass progressed. For region B in relation to the width spread in the roll profile designed with the virtual flow line, the distance in the width

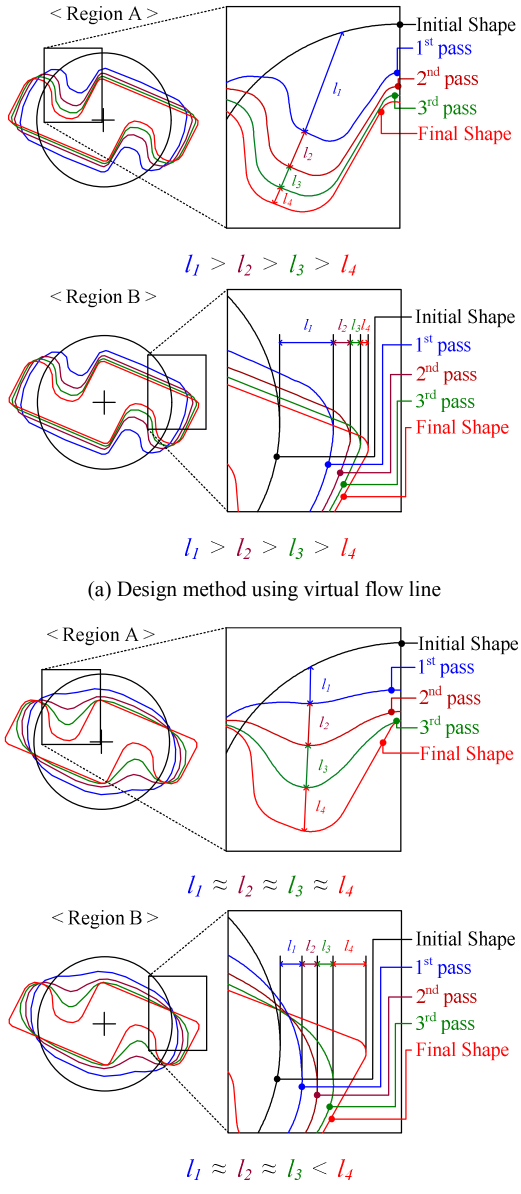


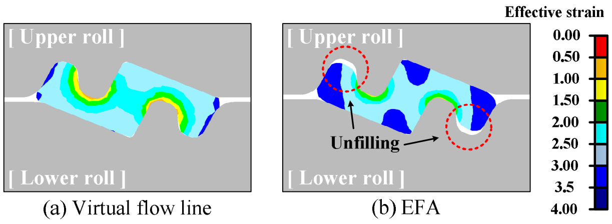
Fig. 15. Comparison of the roll profile for the design methods using virtual flow line and EFA.

direction gradually decreased as the pass progressed, in contrast with region A. As in the case of region A, the roll profile designed with EFA maintained a constant distance.

The FEA of the designed roll profile was conducted as shown in Fig. 15, with the result shown in Fig. 16 obtained. As shown in Fig. 16(a), the design method using the virtual flow line can assign a higher strain rate than the design method using EFA in Fig. 16(b), in which the maximum effective strain values are 3.5 and 2.0, respectively. As shown in Table 3, the URs of the final profile according to the design method are 0.4 and 4.3 %, respectively. It was indicated that the design method proposed in this study using a virtual flow line has a low UR than design method using EFA.

Table 3. UR for design method per pass.

Pass no.		1	2	3	4
UR (%)	Virtual flow line	1.8	1.5	0.1	0.4
	EFA	0.5	0.6	0.3	4.3



(a) Virtual flow line (b) EFA

Fig. 16. Comparison of design methods through results of FEM for S shaped wire.

4. Conclusions

In this paper, a roll design method for multi-stage profile rolling using virtual flow line was proposed. An equal-load pass schedule was designed for 12 types of profiles manufactured with the rolling process and FEA was conducted. The following conclusions can be drawn.

(1) The results of FEA for application of the proposed design method using virtual flow line showed that five of the 12 types of profiles satisfied a 1 % or lower UR.

(2) The features of five types predicted to have insufficient width spread and two types predicted to have material eccentricity were defined as aspect ratio and off-center factor, respectively.

(3) The product shape with high aspect ratio and high off-center factor is limited to apply the design method proposed. Also, the design method cannot be applied to the case of that the centroid of the final product is outside of the profile.

(4) Compared to the existing design method, the proposed design method using a virtual flow line not only ensures higher dimensional accuracy but also assigns a higher strain rate.

Acknowledgments

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