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Design of Roll Profile in Shape Rolling by 3D-EFA

Sang-Jin Lee[1,*], Kyung-Hun Lee[2,*], Dae-Cheol Ko[3], Sang-Kon Lee[4], and Byung-Min Kim[5,#]

1 Precision Manufacturing System Division, Pusan National University, Busandaehak-ro 63beon-gil, Geumjeong-gu, Busan, 609-735, South Korea
2 PNU-IFAM Joint Research Center, Pusan National University, Busandaehak-ro 63beon-gil, Geumjeong-gu, Busan, 609-735, South Korea
3 Industrial Liaison Innovation Center, Pusan National University, Busandaehak-ro 63beon-gil, Geumjeong-gu, Busan, 609-735, South Korea
4 Ultimate Manufacturing Technology R&BD Group, Korea Institute of Industrial Technology, 302 Techno sunhwan-ro, Yuga-myeon, Dalseong-gun, Daegu, 711-880, South Korea
5 School of Mechanical Engineering, Pusan National University, Busandaehak-ro 63beon-gil, Geumjeong-gu, Busan, 609-735, South Korea
Corresponding Author / E-mail: bmkim@pusan.ac.kr, TEL: +82-51-510-3074, FAX: +82-51-581-3075
* Sang-Jin Lee and Kyung-Hun Lee contributed equally to this work

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The design of roll profile in shape rolling is important as a key role in improving product quality, such as dimensional accuracy, ensuring defect-free property and good mechanical properties. In this study, the design method using three dimensional electric field analysis (3D-EFA) is proposed to design intermediate roll profiles for the shape rolling. The shape of equi-potential lines as intermediate roll profiles could be generated between the initial shape and final shape by 3D-EFA. The intermediate roll profile for each pass is selected among a numerous equi-potential lines, and the effectiveness of the selected roll profiles is verified by FE-simulation. The over- or under-filling area is calculated from the result of FE-simulation, another equi-potential line is selected to compensate for the area of the error. The proposed method is applied to a shape like rear door hinge that is generally designed by the trial and error method to show the applicability of this method for various shapes. The lab-scale experiment is carried out with plasticine, and the results are within the allowable tolerance of ±0.5 mm. Therefore, the proposed method can be widely used to design roll profiles for complex shapes thereby reducing the design time.

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1. Introduction

Shape rolling is one of the rolling processes to manufacture long products with arbitrary cross-sectional shapes by passing rectangular or circular billets through various roll profiles. During shape rolling, the desired product shape is obtained through the plastic deformation that occurs between two rolls with parallel axes that revolve in opposite directions. The billet is deformed into the final product between the upper and lower roll, and the deformation behavior of the billet depends on the roll profile at each pass.[1]

Shape rolling has an advantage that products of uniform cross sections can be manufactured and applied in the machine parts of various shapes. And this process could obtain the products of the good mechanical properties with microstructures can be obtained due to the use of compressive deformation. The behavior of the material is affected by various factors in the rolling process. First, the rolling process is generally based on empirical rules from a large number of experiments at flat rolling. The increments in width and length of the billet during deformation are called spread and elongation, respectively. Calculating spread and elongation is important in determining the appropriate dimensions for the roll profile.[2] However, it is difficult to predict the increment amount because the spread and elongation depend on many factors, such as draught, temperature, rolling speed, initial shape of billet, steel type, ratio of billet diameter to roll diameter, condition of the roll, and metal surface. For shape rolling, it is more difficult to predict the spread and elongation due to the geometric factors, so roll profiles are designed by the trial and error method or experience of experts. The correct profile and good surface finish for the product are determined by the intermediate roll profile. Dimensional accuracy, minimum internal stress, and uniform strain distribution must be guaranteed for the final product.[1] However, it is difficult to predict the deformation behavior of the billet and to ensure the good product quality by the experience of experts. Furthermore, part shapes are becoming more complicated and the need of research is increasing.

Many investigators attempted to consider all these factors simultaneously to derive general formulas for spread. Siebel proposed a spread formula for flat rolling with a coefficient for the type of metal.[1] Wusatowski investigated the initial shape of billet and roll diameter to calculate a spread for mild steel for practical rolling temperature ranges and plain sections.[1] Saito et al. proposed general empirical formulas for various groove shapes as square-oval, square-diamond and round-oval through the experimental results from shape rolling.[3,4] Shinokura et al. proposed a new spread formula that is very simple and has only one coefficient, but it can predict the spread for every type of pass with high accuracy.[5] Lee et al. established a reliable analytical model that predicts the surface profile of the exit cross section of a billet in a round-oval pass. This model requires only the geometric information on the billet and roll profile, and the analytical model is based on the linear interpolation of the radius of curvature for an incoming billet and the roll profile.[6] The design of roll profile for an irregular angle bar using the modified butterfly method is introduced by Lee et al.[7] Prediction of the roll profile in shape rolling is a key role in improving the product quality, such as precise dimensions, ensuring defect-free properties and good mechanical properties.

Recently, the design method using electric field analysis (EFA) has been applied to the practical design of various products in industrial fields. This design method using equi-potential lines is physically meaningful, where the equi-potential lines have the similar trends as the minimum work paths when the material is being deformed.[8-11] Lee et al. introduced a new approach of design method to find an appropriate preform shape in axisymmetric hot forging by EFA. The preform shape is determined among the equi-potential lines obtained between the initial and final shape.[8] Lee et al. also proposed a design method for the intermediate die shape of a multistage profile drawing to produce a linear motion guide rail by EFA. The intermediate die shape is determined using the equi-potential lines as the die profile and the reduction ratio per pass.[9] Kim applied the design method using EFA to produce a steering spline shaft in shape drawing.[10] Lee et al. suggested a design method using 2D-EFA for multi-pass shape rolling.[11] However, this method includes modifying the shape of the selected equal-potential line and calculating the spread formula with equivalent thickness.

The objective of this study is to design the roll profile using three dimensional electric field analysis (3D-EFA) without modifying the shape. To design the roll profile, the shapes of equi-potential lines as intermediate roll profiles are generated between the initial and final shapes by 3D-EFA using the commercial software ANSYS with electric module. The equi-potential lines are selected by the reduction ratio in area, and FE-simulation is performed to verify the effectiveness of the selected intermediate roll profiles using the Deform-3D program. After FE-simulation, the over- or under-filling area is calculated and new equal-potential lines are selected with compensation for the area of the error if the dimensional error is over the allowable tolerance of ±0.5 mm.

The proposed design method is applied to the shape of a rear door hinge, which is typically designed by the trial and error method to show the applicability of the design method for various shapes. In addition, a lab-scale experiment is executed with a model material to verify the design method using 3D-EFA.

2. Design Method for the Roll Profile by 3D-EFA

2.1 Electric field analysis

Electric fields are governed by Maxwell's equation provided by Eq.

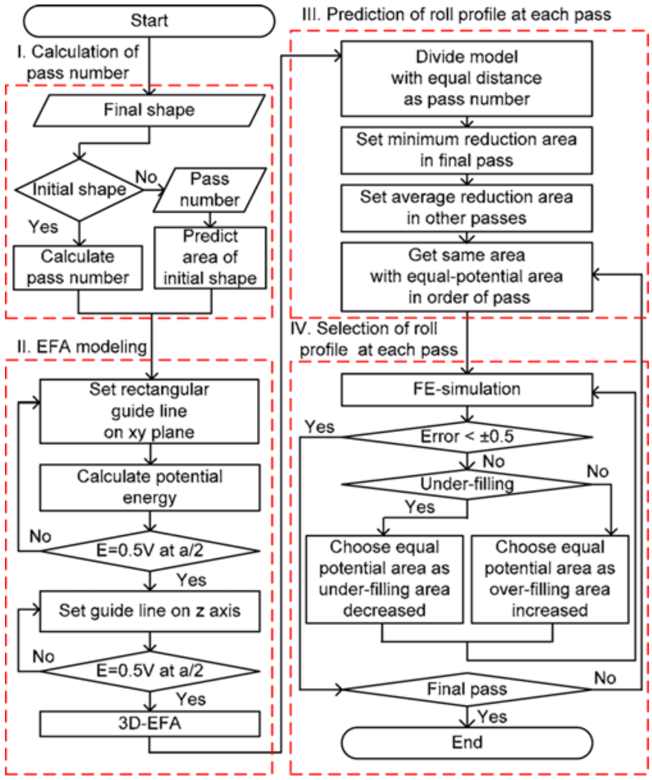


Fig. 1 Flowchart for roll profile design using 3D-EFA

(1) with no charges ($\rho = 0$) such as in a vacuum.

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{1}$$

where E, B, and t are the electric field intensity vector, magnetic flux density vector, and time, respectively. Conversely, an electrostatic field does not change with time, if there is no charge, and the governing equation is the Laplace equation given by Eq. (2), where Φ is the electric potential.

$$\nabla^2 \Phi = 0 \tag{2}$$

Electric fields are generated between two conductors with different voltages. The electric field is followed the Laplace equation and is constituted lines generated by the points of the same voltage. These are called as equi-potential lines. These equi-potential lines are infinite in number and they cannot fold each other, and the intermediate shapes are created with shape-features of the two conductors. In this paper, the equi-potential lines are used as the intermediate roll profile.

2.2 Design of roll profiles by 3D-EFA

The design method of roll profiles using equi-potential lines determined by 3D-EFA is physically meaningful, where the equi-potential lines have trends that are similar to the minimum work paths. Thus, one of design methods is proposed to predict the intermediate roll profiles, and this process of design is shown in Fig. 1.

Step 1 : Calculation of pass number

The pass number for the working environment and the area of the initial billet must be calculated from the desired final shape. In this work, a rectangular initial shape is used as the billet, and the pass

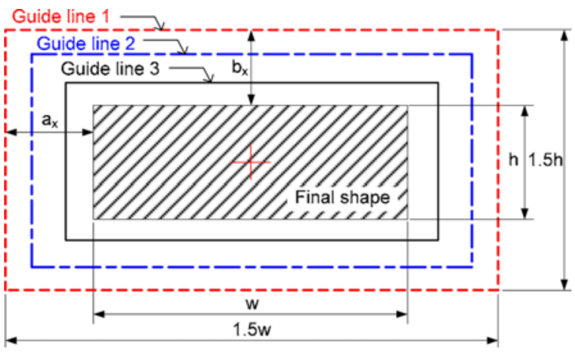


Fig. 2 Model for 2D-EFA

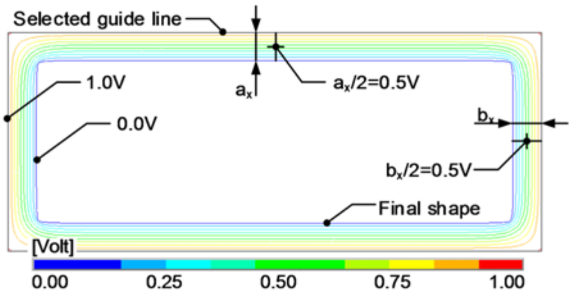
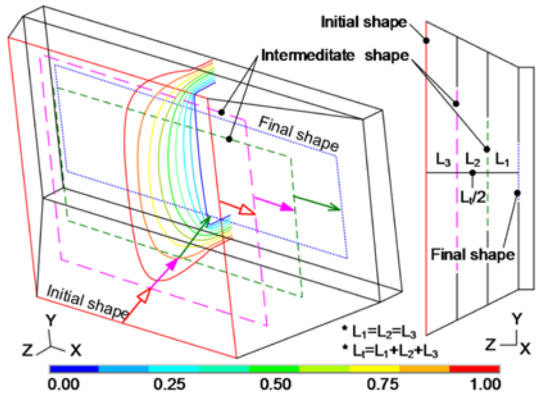
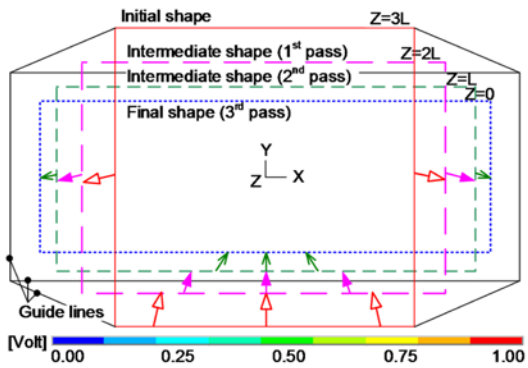


Fig. 3 Determining the guide line using 2D-EFA



(a) Model for 3D-EFA



(b) Equi-potential lines from 3D-EFA

Fig. 4 Model and results for 3D-EFA

number is calculated by Eq. (4).

$$N = \frac{\ln(A_f/A_i)}{\ln(1-e_m)} \quad (4)$$

where N, e_m, A_i, and A_f are the pass number, the mean reduction in area, and the cross-sectional area of the initial and final shapes, respectively.

Step 2 : EFA-modeling

3D-EFA is executed to find an intermediate roll profile at a minimum energy between the initial and final shape. The model for the electric field analysis defines two parameters: the guide line to connect the initial and final shapes in the Z-direction, and the distance between the initial and final shapes. The shape of the guide line is the same as the initial shape such as circle or rectangle. The initial size of the guide line is calculated by multiplying the width and height of final shape by 1.5 to make larger space for generating equi-potential lines, as shown in Fig. 2.

The guide line is found using 2D-EFA when there is an equal interval of potential difference between the extreme outer tips of the final shape and the guide line. This allows a minimum effect for the guide line and freely generates the equi-potential lines. The equal interval of potential difference is defined when the value of the voltage is between 0.5 and 0.55 at half the distance of a_x and b_x along the X and Y axis, as shown in Fig. 3.

The centroid of the initial shape must coincide with that of the final shape in the X and Y directions. The effect for the initial shape increases, if the distance between the initial and final shape gets larger in the Z-direction. Conversely, the effect for the final shape increases if the distance in Z-direction gets smaller. Therefore, the distance should be set up to get same effect of each shape in 3D-EFA. When the effect is same for both initial and final shapes, the interval of the potential difference becomes equal, and the value of the voltage becomes 0.5 at the middle of distance on the Z-axis. The intermediate roll profile at each pass can be generated by dividing the pass number because the potential difference is distributed in equal distances, as shown in Fig. 4.

Step 3 : Prediction of the roll profile at each pass

The reduction must be determined to obtain the roll profile at each pass. There is no rule for reduction and it varies according to the rolling mill. Therefore, equal reduction is used under the same performance of the rolling mills. However, the minimum reduction at the last pass is provided to improve the dimensional accuracy by minimizing the spread. Upon calculating the area reduction for each pass, the equi-potential lines are obtained and the 3D-EFA simulation model is divided in the Z-direction by the pass number, as shown in Fig. 4(a). The equi-potential lines corresponding to the reduction in area at each cross section are selected as the roll profile, as shown in Fig. 4(b).

Step 4 : Selection of the appropriate roll profile for each pass

FE-simulation is performed to confirm the validity of the design for cross section of the selected roll profile. After FE-simulation, the dimensional errors are checked, and if it is within allowable tolerance of ±0.5 mm, FE-simulation of the following pass proceeds. However, the selection of a new equal-potential line is required when over- and under-filling of the groove occurs during FE-simulation. For over- or under-filling, the area of error is added to or subtracted from the preselected equal-potential line. And then a new equal-potential line is selected, and FE-simulation is carried out with the new roll profile. The

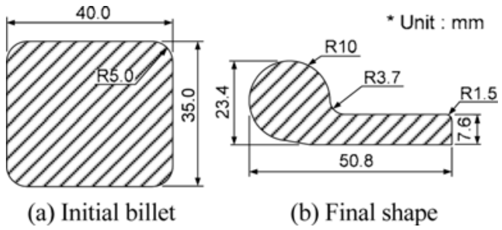


Fig. 5 Shapes and dimensions of the initial billet and final shape for the cross section of the rear door hinge

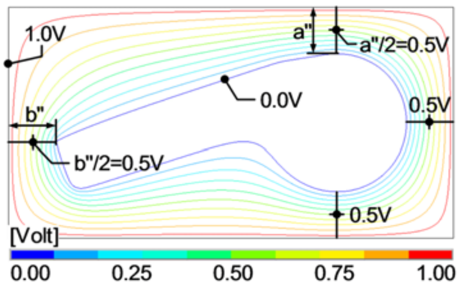


Fig. 6 Results of 2D-EFA for the rear door hinge

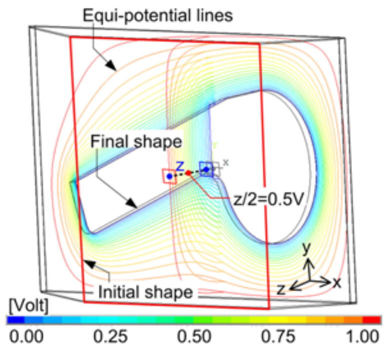


Fig. 7 Results of 3D-EFA for the rear door hinge

over- or under-filling can be reduced by the variation of the height and width of the roll profile according to an increase or decrease the area of the roll profile.

3. Application of Proposed Method for Rear Door Hinge

3.1 Design of the roll profile for a rear door hinge

The proposed design method is applied to the design of a roll profile for a rear door hinge, which is typically designed by the trial and error method. Fig. 5 shows the cross section of the initial billet and a final shape. The pass number for shape rolling of the rear door hinge is calculated by Eq. (4) as described in Step 1 of section 2.2. The final profile could be set with the apex upward or downward but the former is less likelihood of the scale and less cooling effect from cooling water. The location of the final profile has set with apex upward, as shown in Fig. 6.

According to Step 2, the size of the guide line, and the distance along the Z-axis between the initial and final shapes are calculated by 2D- and 3D-EFA, as shown in Figs. 6 and 7. Based on Step 3, the reduction in area has same amount (20.6%) at each pass except the last pass where it is 15% for the rear door hinge. The equi-potential lines are obtained by selecting the lines corresponding to the reduction in area at each pass. The equi-potential lines selected as the cross section of roll profile are presented in Fig. 8. Each intermediate roll profile is drawn using an AutoCAD program by AutoLISP from the XYZ-coordinates of the nodes. The shape of the initial billet is turned into final shape, as shown in Fig. 8(d).

Fig. 9 shows the 3D model of shape rolling for the FE-simulation and the conventional shape rolling process using four passes. The process conditions for shape rolling used in the FE-simulation are summarized in Table 1 and the strain-stress curve used in FE-simulation shows in Fig. 10.

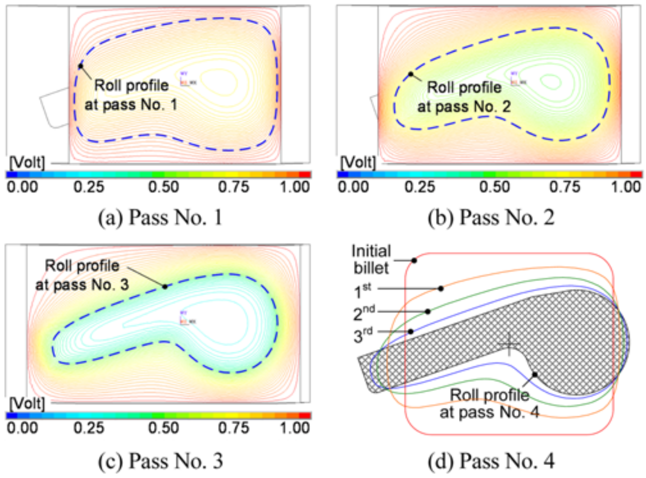


Fig. 8 Roll profile for each pass

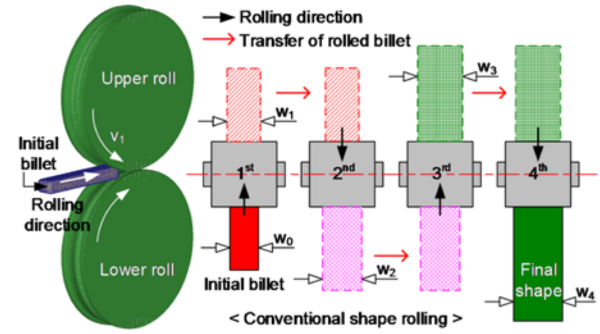


Fig. 9 Model for the FE-simulation

Table 1 Process condition for the FE-simulation

Process condition	Value
Material	SS400(ASTM A36)
Initial temperature of billet (°C)	1050
Size of billet (mm)	40 × 35
Roll speed (RPM)	100
Initial speed of billet (mm/s)	300
Coefficient of friction (μ)	0.35

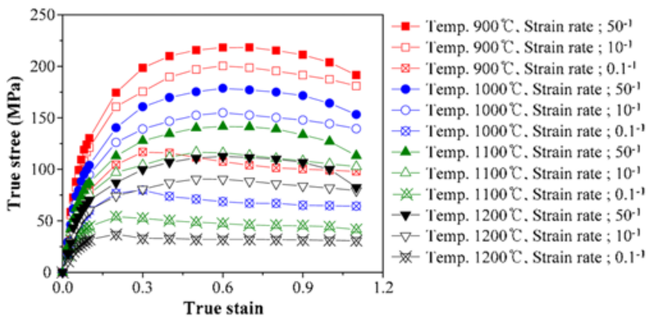


Fig. 10 Strain-Stress curve according to temperatures and strain rates

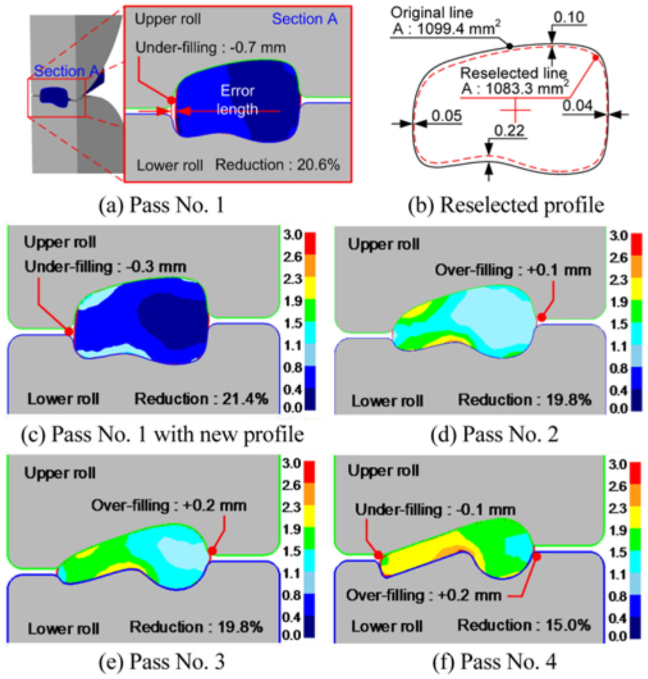


Fig. 11 Shape of the exit billet and the effective strain distribution in the roll pass designed by 3D-EFA

The FE-simulation for the rear door hinge for the shape rolling process is implemented using the commercial software DEFORM-3D. The dimensional errors are investigated and the appropriate roll profiles are reselected. Upon FE-simulation of the first pass, under-filling of -0.7 mm is observed, as shown in Fig. 11(a). The equi-potential line is reselected by subtracting the error area from the preselected line as in Step 4 of section 2.2. The reselected equi-potential line is used as the roll profile cross section and the FE-simulation is executed again for the first pass.

From Fig. 11(c), the maximum dimensional errors of the rear door hinge at pass No. 1 is -0.3 mm. The FE-simulations of the following passes are implemented and checked for maximum dimensional errors. Until final pass, slight over- and under-filling at the roll gap are observed, but the maximum dimensional errors are within the allowable tolerance of ±0.5 mm which is required tolerance of the product, as shown in Fig. 11(f). The effective stain at the inner corner is higher than at the other regions because this region has more pressure and deformation. The lowest effective stain occurred at the roll gap due to a lack of contact

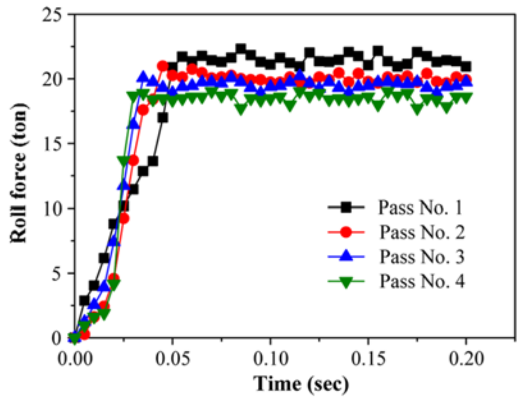


Fig. 12 Roll force by FE-simulation according to the pass number

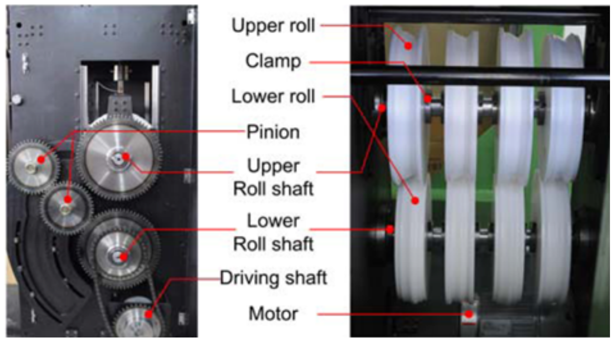


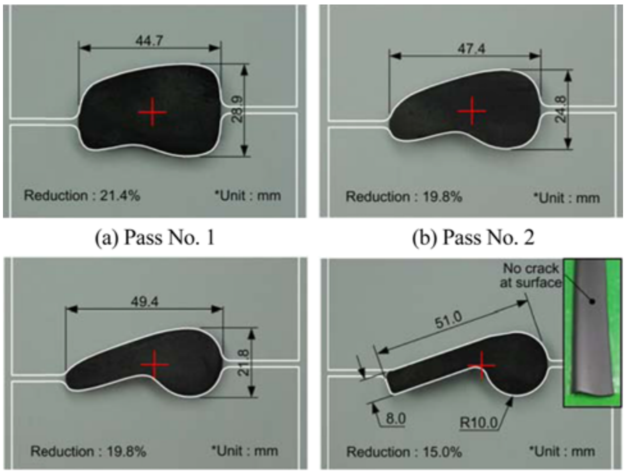
Fig. 13 Lab-scale equipment for shape rolling

between the billet and the rolls. The roll forces at each pass designed by 3D-EFA are shown in Fig. 12. The roll force increases quickly until the roll contacts the entire billet, and then the force becomes steady. The maximum roll force of 24 tons occurs at the first pass since the reduction ratio is higher, and the roll force is reduced at each pass. From the results of the FE-simulation, 3D-EFA is useful and effective for the design of roll profile from the aspects of effective strain distribution, dimensional error at the exit billet, and roll force.

3.2 Experimental verification of the proposed method

The designed roll profiles are verified by experiments with two 310 mm diameter rolling mills made from phenol resin. The lab-scale equipment for shape rolling is shown in Fig. 13, and the plasticine is used as the model material for the billet. This model material is made to achieve similarity of flow patterns to SS400 for shape rolling processes at high temperatures.[12] For this purpose, the cylinder and ring compression tests were completed with the model material using various strains and lubricants. The test results are in good agreement with the strain-rate sensitivity exponent and the coefficient of friction of SS400 at high temperatures. The size of the billet and the roll profile are the same as those in the FE-simulation except for the initial speed of the billet and the roll speed, which are altered due to the limitations of the equipment. The shape rolling experiments are performed five times for the rear door hinge.

Fig. 14 shows the cross section at each pass obtained from the experiment compared with the designed shape, where the white lines



(a) Pass No. 1 (b) Pass No. 2 (c) Pass No. 3 (d) Pass No. 4

Fig. 14 Results for the experiment with plasticine

indicate the designed shape. As the pass proceeds, the billet becomes thinner by rolling, and slight spreading occurs due to the friction at the interface, which restricts the material flow to the width direction. From the experimental results, slight under-filling at the roll gap of the rear door hinge is observed in pass No. 1 and slight over-filling is also observed in passes No. 2, 3, and 4, but they are within the allowable tolerance of ±0.5 mm. This is caused by the difference in the friction coefficient between the FE-simulation and the experiment. The exit billet shape at each pass agrees well with the designed shape and no cracks at the surface of billet are observed at each pass as shown in Fig. 14(d).

4. Conclusion

The design method using 3D-EFA is proposed to design the roll profile for shape rolling of an arbitrary shape. By applying the proposed design method to the shape rolling of a rear door hinge, following conclusions can be drawn.

(1) The roll profile of an arbitrary shape such as the rear door hinge has been designed by the proposed method using 3D-EFA. The existing design method could not be used to design a roll profile for the rear door hinge.

(2) From the FE-simulation for the rear door hinge, the design method with 3D-EFA was useful and effective based on the shape error of the rolled product, effective strain distribution, and roll force.

(3) In the shape rolling experiment for the rear door hinge, the maximum dimensional error at the final pass was within the allowable tolerance of ±0.5 mm. Some over- and under-filling at the roll gap was observed during the passes.

(4) From the FE-simulation and experimental results, the design method suggested in this study could be widely used to design roll profiles for arbitrary shapes in industrial fields.

ACKNOWLEDGEMENTS

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