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Design of Roll Profile for LM-Guide Block in Horizontal-Vertical Shape Rolling by 3D-EFA

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In this paper, the design method for intermediate rolls has been developed to manufacture a linear motion (LM) guide block in horizontal-vertical (H-V) shape rolling, based on the three-dimensional electric field analysis (3D-EFA). This design method can predict appropriate cross-sections of roll profile at each pass based on the initial and final shapes. 3D-EFA simulations are performed separately for the horizontal and vertical rolling passes to obtain roll profiles from equipotential lines. The roll profiles obtained based on 3D-EFA are simulated by the commercial program Deform 3D, and are the reselected by compensating for the area of the error from the equipotential lines. For convenience of field work and reducing strain concentration of the products, the roll profiles for the first and second passes are modified to be flat rolls because the roll profiles are almost rectangular. The effectiveness of the proposed design method is verified experimentally using AISI4120 steel for H-V shape rolling. From the experimental results, some over- and under-filling ate the roll gap are observed for the final pass. However the dimensional errors are within ±0.3 mm, and no cracking or shearing is observed. The proposed design method will improve the efficiency of the design process by reducing time and costs.

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1. Introduction

Horizontal-vertical (H-V) rolling is generally used to reduce and control the product with during hot bloom, slab and billet rough rolling. This process provides low distortion and void closure effects on the material.[1-3] The H-V rolling process can also be used for products with complex cross-section shapes at a finishing mill, because the side groove of the products can be formed using protrusive vertical rolls. Furthermore, the bloom, slab or billet are continuously formed using several stands. This continuous rolling process can deform the bloom or billet in at least two mill stands simultaneously. Simultaneous rolling is advantageous since mill stands can be set close together. With a short distance between the mill stands, a small temperature drop during shape rolling can reduce rolling loads, power consumption, and roll wear. Additionally, rolling with heavy draughts is possible because the billet is forced toward the next pass, thereby allowing greater angles of bite.[4] However, H-V shape rolling is complicated in terms of the roll profile design, roll speed determination, and roll positioning. It is also difficult to predict the deformation behavior of the material.

In the first approach for the spread of flat rolling, Siebel proposed a spread formula that is unrestricted by the side faces of the pass.[5] Tafel also suggested a spread formula with various rolling speeds to obtain better results.[6] Wusatowski investigated the effects of the rolling speed, temperature, chemical composition of the steel, type of rolls, and condition of the roll surface.[7] Micari applied a coupled thermal-mechanical analysis to hot plate rolling to evaluate the spread with several values of the width-to-thickness ratio.[8] Lahoti et al. developed a computer-aided design system to predict the metal flow and roll stress in plate rolling with mild-steel.[9] For shape rolling, Shinokura et al. experimentally investigated the spread phenomena for four types of passes, i.e., square-oval, round-oval, square-diamond, and diamond-diamond.[10] Shivpuri et al. applied a methodology based on an empirical procedure and finite element (FE) code to evaluate the existing roll passes and redesign the reduction for multi-pass shape rolling.[11] Kim et al. proposed a new steady-state process model for the prediction of the deformation behavior for a round bar formed from a square billet using shape rolling.[12] Mróz et al. verified the possibility of using FE-simulation for shape rolling of an unequal angle bar using an industrial test.[13]

Significant researches with respect to H-V shape rolling have been performed, both numerically and experimentally. Mori et al. established a method to simulate the three-dimensional deformation in plate rolling and edge rolling by assuming a friction coefficient.[14] Xiong et al. applied a coupling thermo-mechanical analysis to simulate V-H rolling for width reduction in the roughing stands of a hot strip mill using full three-dimensional rigid-plastic finite element method.[15,16] Chun et al. investigated the deformation of a slab with various width reductions using rigid-plastic finite-element analysis.[17] Mohammad et al. analyzed the sizing press and vertical roll processes to compare the quantity of existing defects in width reduction.[18] Yu et al. analyzed the stress distribution of the crack tip and, the influence of the vertical roll profile during multi-pass V-H rolling.[19,20] Ding et al. investigated the effect of the pre-vertical rolling temperature on the edge crack, microstructure, and mechanical properties of rolled AZ31B magnesium alloy sheets.[21] All these studies have focused on simple shape rolling like round and square bar and its plastic deformation behavior. It is difficult to apply to the actual production for lack of the research on intermediate roll design.

This study aimed to design roll profiles for H-V shape rolling using three-dimensional electric field analysis (3D-EFA) with a linear motion (LM) guide block as a case study. The design method using 3D-EFA can predict the cross-sectional roll profiles at each pass based on the initial and final shapes. The 3D-EFA simulations are performed separately for the horizontal and vertical rolling passes to obtain roll profiles using equipotential lines. The roll profiles obtained from 3D-EFA are simulated using the commercial program Deform 3D, and are then reselected based on compensating the error area using equipotential lines. The effectiveness of the proposed design method is verified experimentally with AISI 4120 steel for H-V shape rolling.

2. Overview of Design Method by 3D-EFA

2.1 Electric field analysis

An electric field is generated by electrically charged particle and time varying magnetic fields but an electrostatic field does not change with time. In free space, the governing equation is the Laplace equation given by Eq. (1), and it must equal zero since the charge density, ρ, is zero. The Laplace equation can be used to describe the behavior of the electric, gravitational, and fluid potentials, as well as the heat conduction.

$$\nabla^2\Phi = 0 \quad (1)$$

where ∇^2 is the Laplace operator and Φ is electric potential, respectively. An electric field is generated between two conductors with different voltages. In this field, lines constituting points with the same voltage are called equipotential lines. These equipotential lines have the shape features of the initial and product shapes, and they exhibit similar trends of minimum work paths. In this study, the design method using equipotential lines to determine the intermediate roll profiles is proposed.

2.2 Design of roll profiles for H-V rolling by 3D-EFA

In the design method by 3D-EFA, the cross-sectional roll profiles at each pass can be predicted base on the initial and final shapes. This proposed method can ensure the production of an appropriate profile

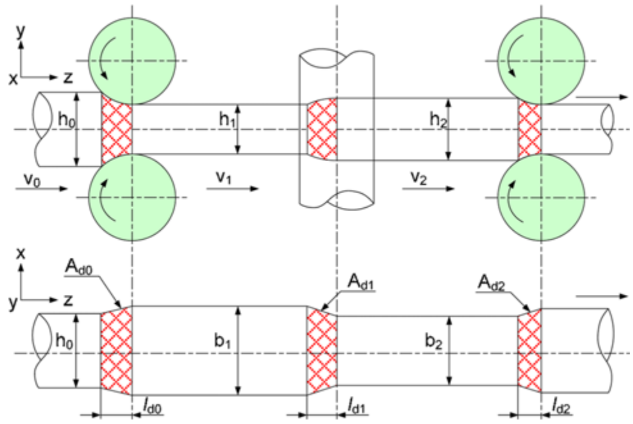


Fig. 1 Schematic illustration for horizontal-vertical rolling process

and decrease the time required to design roll profiles. Especially, the direction of the roll axis is alternatively changed in H-V rolling as shown in Fig. 1. The design procedure by 3D-EFA for H-V shape rolling follows five steps:

- Step 1: Calculation of pass number
- Step 2: Horizontal- and vertical EFA modeling
- Step 3: Roll profile design by 3D-EFA simulation
- Step 4: Selection of appropriate roll profile at each pass
- Step 5: Modification of roll profiles to flat rolls

3. Application of Proposed Method for LM-Guide Block

3.1 Calculation of pass number and setting the guide lines to design roll profiles for LM-guide block

In this section, the roll profile for an LM-guide block is designed by 3D-EFA for H-V shape rolling. First, the number of passes is determined to be five based on Eq. (2), as mentioned in Step 1 of section 2.2.

$$N = \frac{\ln(A_N/A_0)}{\ln(1-U_m)} \quad (2)$$

where N, U_m, A_0 and A_N are a total number of passes, mean reduction in area, and cross-sectional areas of initial billet and final product, respectively. A mean reduction in the area of 18% is used in this study because of the low draught in vertical rolling. The cross sections of the initial billet and final shape are shown in Fig. 2. For the 3D-EFA model, the guide line should be set to connect the initial and final shapes. The guide line is first calculated by multiplying the width and height of the final shape by 1.5, and is subsequently calculated iteratively using 2D-EFA. The iterations are continued until the electric potential is sufficiently close to 0.5V in the middle of the guide line and the final shape, in order to satisfy the equal-reduction of voltage between the guide line and final shape, as shown in Fig. 3.

Fig. 4 shows guide lines at each pass for the 3D-EFA modeling. The guide line at each pass is required to design roll profile when considering H-V shape rolling. In horizontal rolling, the width of guide lines are the same as the width of the guide line for the 5th pass, and the height gradually decreases from the initial billet to the final pass. The main reason is that the guide line leads in the direction of spreads,

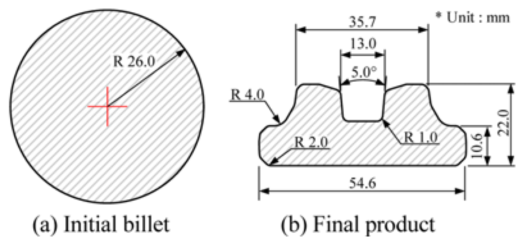


Fig. 2 Shapes and dimensions of initial billet and final product

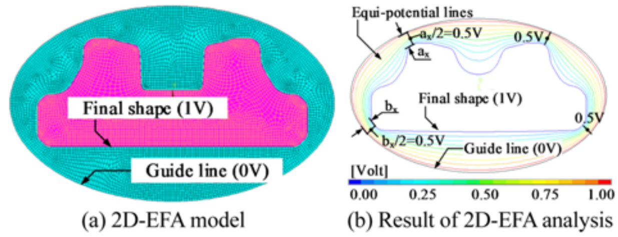


Fig. 3 Setting guide line by 2D-EFA

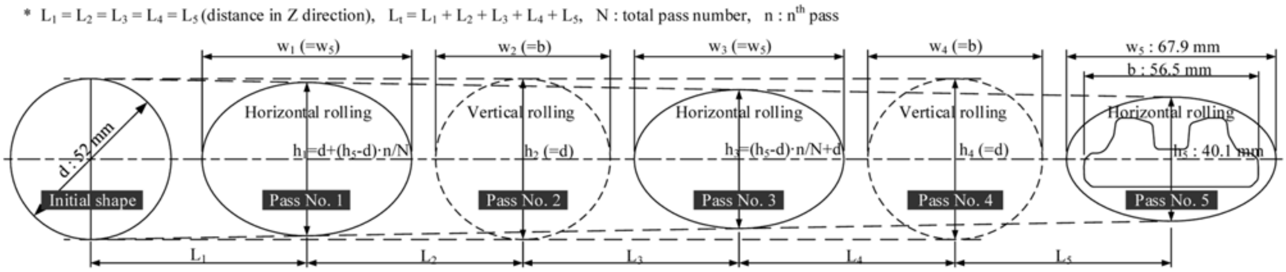


Fig. 4 Setting guide lines at each pass for 3D-EFA modeling

and determines a limitation of the spread. Accordingly, for the odd passes, the height of the billet decreases so the height of the guide line also decreases by Eq. (3) where h_n, d, n, N, and h_5 are a height of guide line for the n^{th} pass in horizontal rolling(i.e., 1^{st}, 3^{rd}, 5^{th} pass) , diameter of initial billet, pass number, total number of passes and height of guide line for final shape (See. Fig. 3(b)), respectively.

$$h_n = d + (h_s - d) \cdot n/N \tag{3}$$

In vertical rolling, the width and height of the guide line must be determined for the 3D-EFA model. The width of the guide line should be the same as the width of the final shape because the width of the billet should be slightly less than or equal to the width of the product at an even pass to produce a product with the required dimensions. The height of the guide line is set as the height of the billet because this is a limitation of maximum spread. In order to obtain the roll profiles at each pass, the 3D-EFA models for horizontal and vertical rolling are set as shown in Fig. 5. The guide lines in these models are arranged by pass order, where the model for horizontal rolling consists of the initial shape and guide line of the odd pass. The 3D-EFA model for vertical rolling includes the initial shape, the guide line for the even pass, and the final pass. Each section is located with an equal distance in the Z direction as shown in Fig. 4. The centroid of the initial shape must coincide with the final shape billet on the XY plane. The distance between the initial and final shapes can be found through iteration by 3D-EFA. The iterations are also continued until the electric potential becomes close to 0.5 V in the middle of the initial and final shapes. After the 3D-EFA modeling, different voltages are applied to the faces of the shape in the 3D-EFA model.

Namely, all the faces of the model are set at 0 V except the face of the final shape, which is set at 1 V. The FE-simulation is then performed for 3D-EFA, and the results are shown in Fig. 4. From the results of 3D-EFA, the equipotential lines are selected by the reduction of the area at each pass. The minimum reduction of the area for the vertical rolling pass is provided because the width of the final shape is larger than the initial billet. The final pass also used the minimum reduction of the area to improve the dimensional accuracy. Thus, the reduction of the area at each pass is initially assumed to be 27, 5, 27, 5 and 10.5% for the LM-guide block, and the selected shapes are shown in Fig. 6.

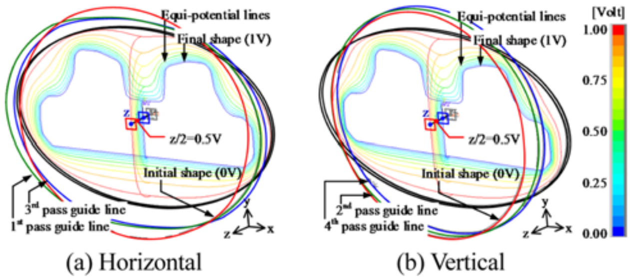


Fig. 5 3D-EFA results for H-V shape rolling process

The selected shapes are used as the roll profiles, and the working diameter is calculated to set the roll speed. The FE-simulation of shape rolling is proceeded to evaluate the suitability of the selected roll profiles. The processing conditions for the FE-simulation are presented in Table 1. After the FE-simulation, the dimensional error is checked, and if the error length exceeds ±0.5 mm, the area for over- and under-filling must be calculated. This area of error is then added to or subtracted from the area of the preselected shape. Using the recalculated area, a new roll profile is selected from the results of the 3D-EFA. Repeated FE-simulations and calculations will guarantee dimensional accuracy. The selected shapes are presented in Fig. 7, and the FE-simulation for shape rolling is executed continuously from the first to last pass.

In H-V shape rolling of the LM-guide block, slight over- and under-filling is observed at the roll gap, but the error allowance of ±0.5 mm is satisfied. The designed roll profile in the second pass is observed to be simple rectangular, so the roll profiles of the first and second passes

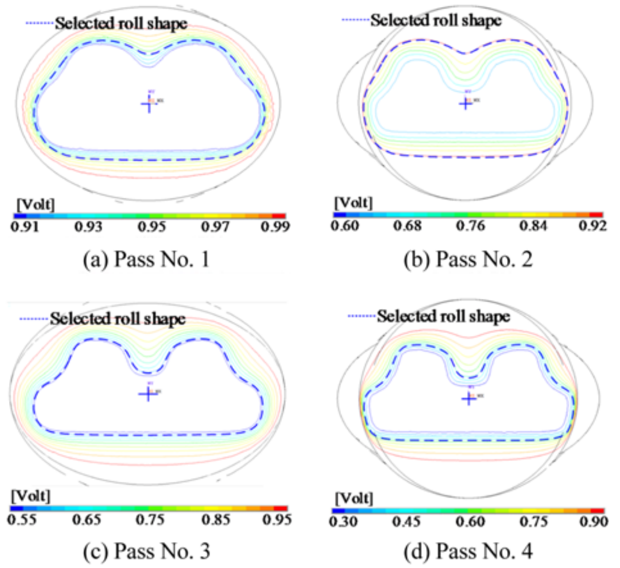


Fig. 6 Roll profiles at each pass from the equipotential lines

Table 1 Process conditions for the FE-simulation

Process condition	Value
Material	SCM 420 (AISI 4120)
Initial temperature of billet (°C)	1050
Size of billet (mm)	Ø52
Roll speed (RPM)	35, 51, 46.5, 70, 65.3 (in pass order)
Initial speed of billet (mm/s)	50
Coefficient of friction (μ)	0.36, 0.37, 0.37, 0.38, 0.39 (in pass order)

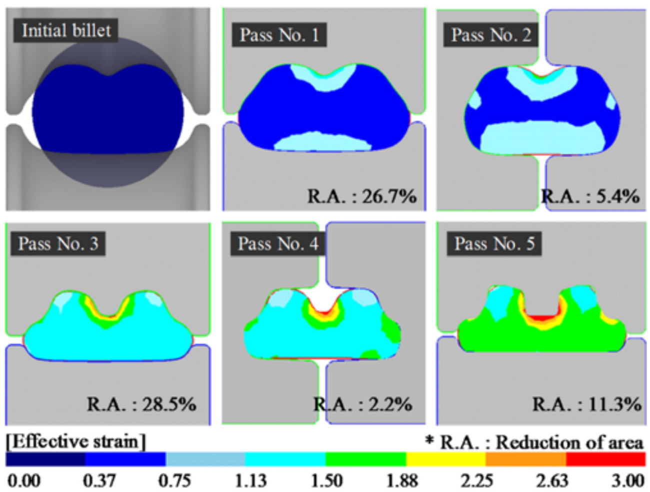


Fig. 7 Shapes of the rolled billets and effective strain distribution for the roll passes designed by 3D-EFA

are changed to flat rolls. By using a flat roll, low cost and minimal roll wear are achieved. Replacing the roll profile with a flat roll, the average heights of the shape in first and second passes are calculated, and the roll gaps are set by Shinokura's spread equation. The roll profiles are redesigned as flat rolls for the first and second pass, but

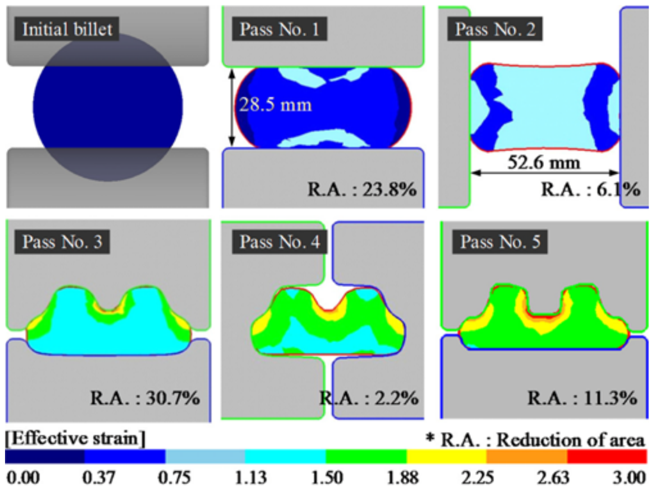


Fig. 8 Shapes of the rolled billets and effective strain distribution for the roll passes designed by 3D-EFA

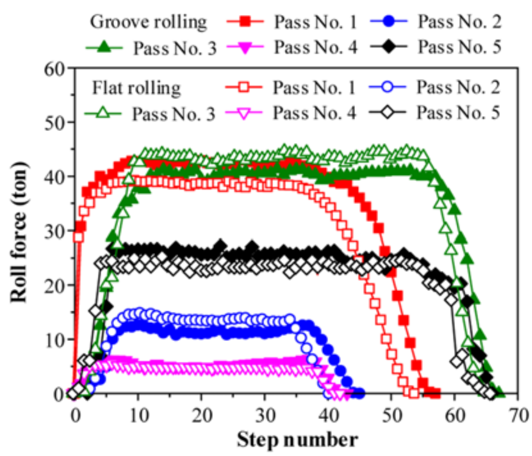


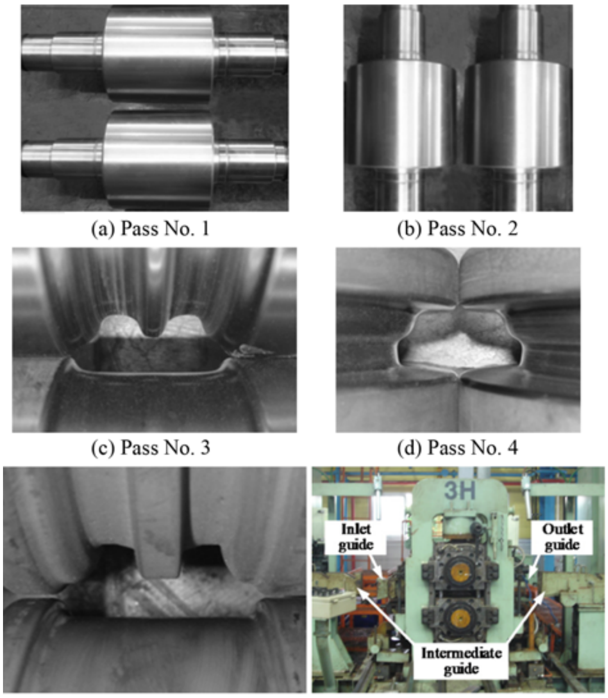
Fig. 9 Comparison of roll forces between the grooved and flat rolls by FE-simulation according to the pass number

passes number three to five apply the roll profiles shown in Fig. 8. The FE-simulation is performed with the redesigned roll profiles from the first to fifth pass. The maximum dimensional error of the LM-guide block at pass five is -0.25 mm, which is within the allowable tolerance of ±0.5 mm. There is a noticeable distinction between the high and low effective strain for the concave and convex portions of the block because the concave region has more reduction.

The roll forces of the grooved and flat roll at each pass are presented in Fig. 9. Both roll forces are similar because they have the same reduction of area. The roll force of vertical rolling is relatively lower than that of horizontal rolling. From the results of the FE-simulation, the proposed design method for H-V shape rolling is useful and effective for the design of roll profiles from the aspects of dimensional error, effective strain distribution, and roll force.

3.2 H-V shape rolling experiment

The designed roll profiles are verified by H-V shape rolling experiments for the five passes with roll barrels made from ductile



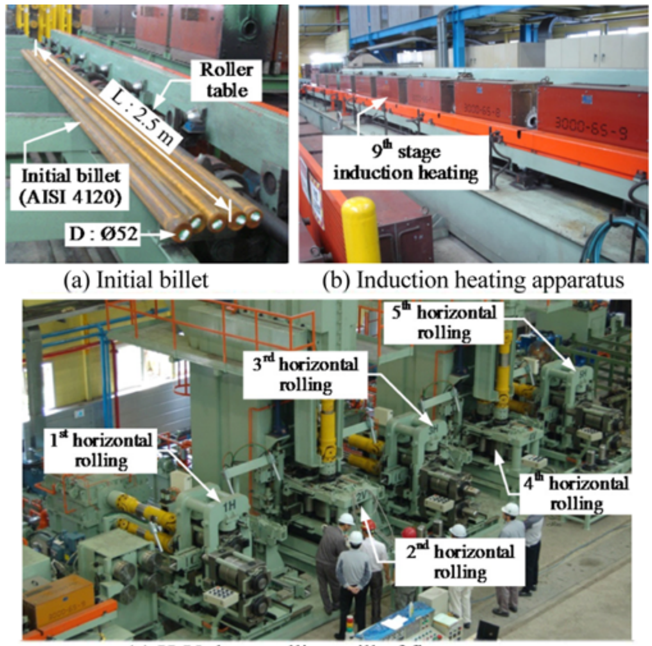
(a) Pass No. 1 (b) Pass No. 2
(c) Pass No. 3 (d) Pass No. 4
(e) Pass No. 5 (f) Setting of guides

Fig. 10 Roll barrels and guides for the LM-guide block

carbon iron (DCI). The manufactured roll barrels are shown in Fig. 10 and the roll profiles of the first and second pass are flat as described in Section 3.1. An initial billet of SCM 420 is used in this experiment, and the cross-sectional dimensions are measured after every pass. Fig. 10(f) shows the inlet, outlet, and intermediate guides for the good delivering the billet to the roll groove.

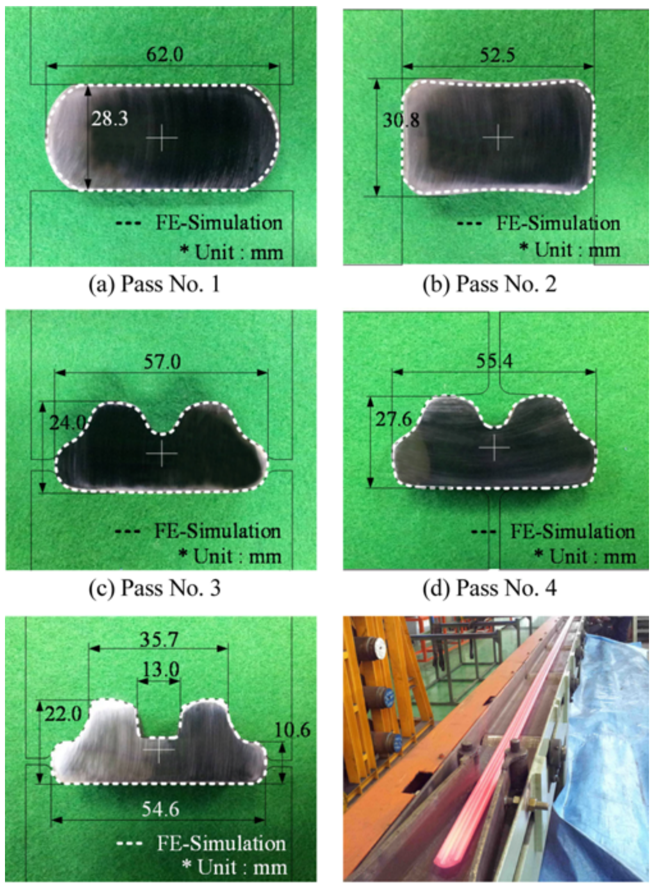
The diameter and length of the initial billet are Ø52 mm, and 2.5 m, respectively, as shown in Fig. 11(a). The initial billet is heated by induction heating with nine stages until 1130°C in Fig. 11(b). The heated billet is delivered to the inlet of the first pass roll when the temperature of the billet is 1050°C. The fabricated roll barrels are installed in the H-V shape rolling equipment as shown in Fig. 11(c). The speed of the initial billet is 0.5 m/s and the rolling speeds at each pass are continuously increased; however, the average roll diameter and draught are different, so the speeds of the rolls are 35, 51, 46.5, 70 and 65.3 rpm in pass order. The coefficient of friction depends on the rolling speed and temperature and varies according to the pass as presented in Table 1. The process conditions for H-V shape rolling are the same as those in the FE-simulation. The shape rolling experiments are performed ten times for the LM-guide block to determine the outlet billet shape at each pass.

Fig. 12 shows the cross-section of the billet at each pass obtained from the experiments compared with the designed shape, where the black lines are the designed roll shapes and the white dotted lines are the predicted outlet shape of the billet. Every pass has slight under- and over-filling at the roll gap and the top corner of the convex portion. However, the dimensional error at the final pass is within the allowable tolerance of ±0.5 mm as shown in Fig. 12(e). No cracking or shearing is observed as shown in Fig. 12(f). From the experimental results, the proposed design method using 3D-EFA is very effective for designing roll profiles for H-V shape rolling.



(a) Initial billet (b) Induction heating apparatus
(c) H-V shape rolling mill of five passes

Fig. 11 Equipment for H-V shape rolling



(a) Pass No. 1 (b) Pass No. 2
(c) Pass No. 3 (d) Pass No. 4
(e) Pass No. 5 (f) Final product

Fig. 12 Results from the experiment with AISI 4120 steel

4. Conclusion

A design method using 3D-EFA is proposed to design roll profiles for H-V shape rolling. From the application of the suggested design method for shape rolling of an LM-guide block, the following conclusions can be drawn.

(1) The roll profile of an arbitrary shape such as an LM-guide block has been designed by the proposed method using 3D-EFA for H-V shape rolling.

(2) In the FE-simulation for the LM-guide block, the results for the shape error of the rolled product, effective strain distribution, and roll force showed that the design method with 3D-EFA is useful and effective.

(3) In the shape rolling experiment for the LM-guide block, the maximum dimensional error at the final pass was within the allowable tolerance of ±0.5 mm, although some over- and under-filling at the roll gap and top corner of the convex area were observed during the passes.

(4) From the FE-simulation and experimental results, it can be concluded that the design method suggested in this study can be widely used to design roll profiles for H-V shape rolling in industrial fields.

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APPENDIX A. Principle for Determine the Number of Passes

The number of passes is closed related to the geometric conditions of the initial billet and final product, elongation, reduction in area, and the constant volume condition in the plastic deformation.

$$A_0 l_0 = A_1 l_1 \,,\;\; \lambda_1 = \frac{l_1}{l_0} \tag{1}$$

$$A_0 = A_1 \frac{l_1}{l_0} = A_1 \lambda_1 \tag{2}$$

$$A_1 = A_2 \lambda_2 \tag{3}$$

$$A_0 = A_2 \lambda_2 \lambda_1 \tag{4}$$

$$A_N = A_N \lambda_N \lambda_{N-1} \ldots \lambda_2 \lambda_1 \tag{5}$$

$$\lambda_1 \lambda_2 \ldots \lambda_{N-1} \lambda_N = \lambda_t = \frac{A_0}{A_N} \tag{6}$$

where A, l, and λ are a cross-sectional area, length and elongation coefficient, respectively. The subscript 0, 1, 2, N-1, N denote the number of stages in multi-stage shape rolling.

A mean elongation coefficient, λ_m is determined as:

$$(\lambda_m)^N = \lambda_t = \frac{A_0}{A_N} \tag{7}$$

$$\lambda_m = \sqrt[N]{\lambda_t} = \sqrt[N]{\frac{A_0}{A_N}} \tag{8}$$

A total number of passes can be expressed as:

$$N = \frac{\ln A_0 - \ln A_N}{\ln \lambda_m} = \frac{\ln \lambda_t}{\ln \lambda_m} \tag{9}$$

$$N = \frac{\ln(A_0/A_N)}{\ln \lambda_m} = \frac{\ln(A_N/A_0)}{\ln(1-U_m)} \tag{10}$$

where N, U_m, A_0 and A_n are a total number of passes, mean reduction in area, and cross-sectional areas of initial billet and final product, respectively.