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Numerical Modeling of Roller Leveler for Thick Plate Leveling

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To ensure quality of the steel structures used in the shipbuilding and construction industry, the thick plate market increasingly demands for more flatness and higher residual stress. Diminishing slit camber caused by residual stress and incorrect flatness due to aging effect has recently emerged as important quality issues. In the current study, we proposed a new numerical model for a two-dimensional roller leveler which calculates the curvature and moment of the material depending on the intermesh. This curvature was used to calculate the stress and strain values of the material along the thickness direction. Correction factors were also introduced to correct the location of the contact point that changes when the relationship between the intermesh and curvature was assumed as three-point bending of a concentrated load at the plate center. The result from this numerical model and that of the finite element analysis were compared to verify the effectiveness of this model.

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1. Introduction

With the automation in the manufacturing of steel structures used in the shipbuilding and construction industry, the thick plate market increasingly demands for more flatness and higher residual stress to ensure quality of steel plates compared with that before. Diminishing slit camber caused by residual stress and incorrect flatness due to aging effect has recently emerged as important quality issues.

However, study on the leveling theory of the steel-making process is still in its basic stage compared with that on other processes such as rolling. The reason is that both elastic and plastic deformation need to be considered, and various complicated analysis conditions are required to build a numerical model of a precise leveler because the asymmetrically arranged numerous rolls could make contact with the materials inside the leveler. The existing numerical models of a roller leveler are presented in the representative studies of Soda,[1] Araki,[2] Matoba et al.,[3] and Ye et al..[4] Soda and Araki explained the relationship between the location of the rolls and deformation, whereas Matoba et al and Ye et al derived the relationship between the roll intermesh and curvature. In particular, Soda[1] directly integrated the deflection equation of plate based on the equilibrium equation of force and bending moment, and Araki[2] analyzed the effect of placement of the rolls and the amount of indentation on the curvature by obtaining the profile of the material. In order to simplify the calculation, the contact surface pressure of the roll and the material is assumed as a concentrated load, and limited to the case of two-dimensional leveling in which the plate having the initial curvature distribution in the longitudinal direction is flattened by repeated bending. Matoba[3] proposed a numerical model that determines the change of load, curvature and roll through the numerical analysis of the leveling load caused by repetitive bending of the plate and the change of position of the roll by this load. Ye[4] proposed a model that predicts the residual stress in a short time assuming that the plane strain and the stress distribution in the thickness direction is assumed to be 0 because the long analysis time is not practically applied in predicting the residual stress of the plate in the roller leveling process. As an analytical study, Park et al.[5] proposed the program for elastic-plastic analysis of sheet such as spring back and contact problem between sheet and rolls in roller leveler, to remove the blanking bow and deviation of curvature of a thin steel sheet. Smith[6] studied the effect of the number of leveling rolls on the mechanism of straightening, to remove the residual curvature of the material induced by the leveler. And Cai et al.[7] studied the methods to design the major process parameters of continuous roll forming (CRF) and to predict the longitudinal deformations caused by

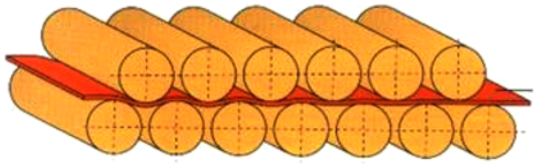

Fig. 1 Roller leveler

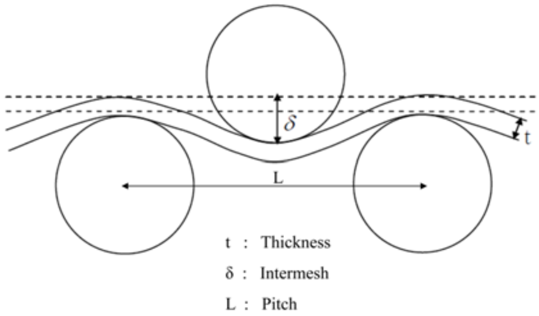

Fig. 2 Intermesh, thickness and pitch in roller leveler

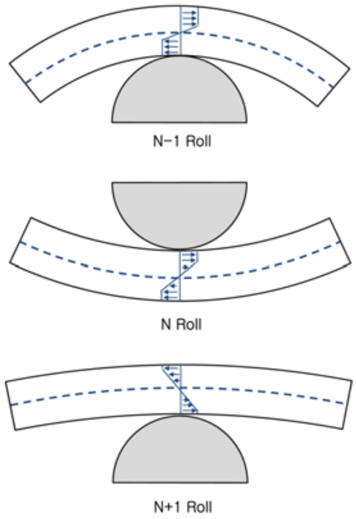

Fig. 3 Radius of curvature and stress distribution

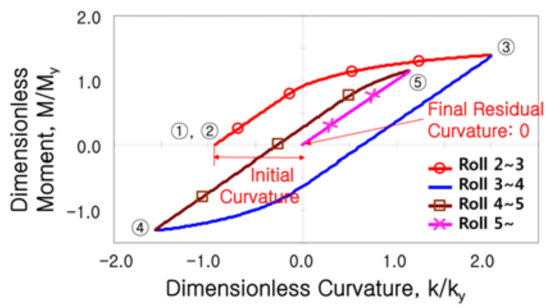

Fig. 4 Moment and curvature

roll gap. On the other hand, an experimental study has been conducted about the leveling strain for sheets with different thickness and materials, and showed approximation formula for relation between leveling condition and deformation by Hibino.[8] As an initial work of this study, the relationship between initial residual curvature and final residual curvature has been studied with a numerical model for cold roller leveler by Lee et al..[9]

In the current study, the model of Matoba et al.[3] and Ye et al.[4] obtained from the bending theory of a plate, which allows simple calculation, was applied to propose a new numerical model for a two-dimensional (2D) roller leveler. For this new model, the curvature and moment of the material were calculated depending on the intermesh, and this curvature was used to calculate the stress and strain values of the material along the thickness direction. Correction factors were also introduced to correct the location of the contact point that changes when the relationship between the intermesh and curvature was assumed as three-point bending of a concentrated load at the plate center. The result from this numerical model and that of the finite element analysis (FEA)[10-13] were compared to verify the effectiveness of this model. The relationship between the initial and final residual curvatures for different intermeshes was also examined to propose the optimal method in order to set up the intermesh.

2. Numerical Model of a Roller Leveler

2.1 Leveling theory

Fig. 1 shows a roller leveler consisting of many rolls continually laid out in a zigzag pattern at the top and bottom. By passing the plate through the rolls arranged in a zigzag shape, flattening is accomplished by repeated bending. Fig. 2 shows that the intermesh that determines the indentation force of the roll is set to its maximum at the front roll and to successively decrease as the plate moves to the next rolls, with considering thickness and pitch. Finally, as shown in Fig 3, the radius of curvature of the plate gradually increases. Consequently, its plastic deformation along the thickness direction decreases, and its residual curvature and residual stress are minimized.

Fig. 4 shows the relationship between the curvature and moment, where M, M_y, k, and K_y are the moment, yield moment, curvature, and yield curvature of the plate, respectively. The circled numbers (①, ② ···) indicate the number of each roll. After the plate was rolled through rolls 1 and 2, the initial curvature (bending of the plate) remaining on the plate showed the maximum curvature and maximum plastic deformation at roll 3. As the plate moved through rolls 4 and 5 and onward, less curvature and plastic deformation occurred. At the final roll, the curvature was reduced once again so that the plate underwent bending deformation only at the elastic zone. To let this condition happen, the roll intermesh was set up, and the final residual curvature was set to zero. If sufficient curvature (plastic deformation) were established at roll 3, the plate would have the same curvature at roll 3 regardless of its initial curvature dimension, and the initial bending of the plate would be corrected by the intermesh that yielded a final residual curvature of zero.

Fig. 5 shows the stress distribution along the thickness direction. Plate thickness t and distance from the neutral plane x are shown in Fig. 5(a). Fig. 5(b) shows the stress distribution that occurred when the plate touched the roll. The circled numbers (①, ②···) represent the number of each roll that touched the plate. Fig. 5(c) shows the residual stress

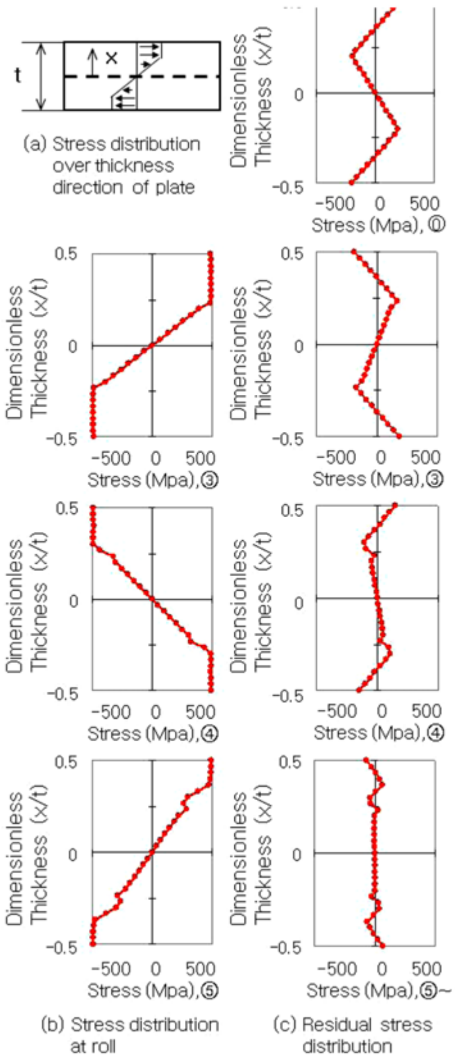

Fig. 5 Stress distribution along thickness direction

distribution when the bending moment becomes zero after the plate passed through the circled number (①, ②···) rolls. The y-axis in Figs. 5(b) and (c) represents the thickness up to the point under stress, which is dimensionless (x/t). The plate would bend when it is cut for processing if the residual stress inside the plate is uneven, although the curvature of the plate is zero. This characteristic is called diminishing slit camber. Fig. 5(b) shows that the initial stress of the material caused maximum plastic deformation and even stress distribution at roll 3 and created less plastic deformation after rolls 4 and 5. As the plastic deformation decreased, as shown in Fig. 5(b), the residual stress shown in Fig. 5(c) was also evenly distributed along the thickness direction. Therefore, the roller leveler caused sufficient plastic deformation at roll 3, which, when repeatedly applied, gradually reduced the bending of the plate. This process not only flattened the plate regardless of its initial residual curvature (or residual stress) but also evenly distributed the stress along the thickness direction in the plate.

2.2 Relationship between intermesh and curvature

The roller leveler, which is composed of three rolls, can be simplified as a three-point bending problem in which a load is applied to the center

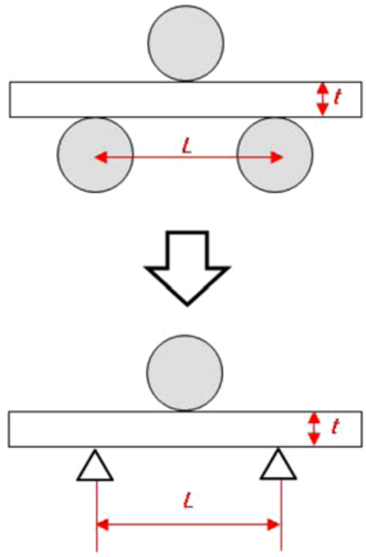

Fig. 6 Roller leveler with three rolls

of the plate to determine the relationship between the intermesh and curvature, as shown in Fig 6. If the roller leveler has n rolls, for example, we can consider that this type of roller leveler under three-point bending is laid out in series. Thus, assuming that the plate is affected by three-point bending, the relationship between the intermesh and curvature from the third to the (n−2)th roll can be expressed by the following equation:[3,4,9]

$$k_i = (-1)^{i-1}\frac{24}{L^2}\delta_i \tag{1}$$

where δ_i is the intermesh at roll i, k_i is the curvature of the material at roll i, and L is the pitch between two rolls (see Figs. 2 and 6). The curvature and moment have a positive (+) sign when the top is convex, also they have a negative sign (-) when it is concave. The curvatures at roll 1 and roll n were assumed to be zero, i.e.,

$$k_1 = k_n = 0 \tag{2}$$

The relationship between the intermesh and curvature at roll 2 and roll (n−1) is expressed as follows:[4]

$$k_2 = -\frac{1}{2}\left\{\frac{\delta_2}{\frac{L^2}{8}-\frac{L^2}{24}\left(1+\frac{M_1}{M_2}\right)}+\frac{24\delta_2}{L^2}\right\} \tag{3}$$

$$k_{n-1} = -\frac{18}{L^2}\delta_{n-1} \tag{4}$$

where M_i is the moment applied to the plate at roll i.

The relationship between the intermesh and curvature in Eq. (1) was derived under the assumption that the plate contacted the uppermost part of the roll. However, the plate did not actually touch the exact center of the roll of the roller leveler, as shown in Fig. 7. In particular, when the roll intermesh was large, the error of the curvature increased at the latter rolls [roll 4 through roll (n−2)]. Accordingly, correction factors were adopted for Eq. (1) to correct the varying contact point as expressed below. Here, α_i is the plastic deformation ratio of the material section at roll i (see Fig. 8). Coefficients A and B are determined from

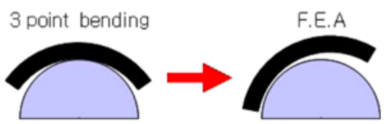

Fig. 7 Contact point on the roll

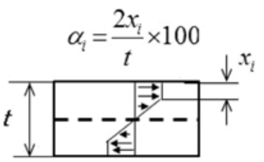

Fig. 8 Plastic deformation ratio

each leveler.

$$k_i = (-1)^{i-1}\frac{24}{L^2}\delta_i\lambda_i \tag{5}$$

$$\lambda_i = e^A \times \alpha_i^B \tag{6}$$

$$k_{n-1} = -\frac{18}{L^2}(\delta_{n-2}+\delta_{n-1}) \tag{7}$$

Because the intermesh at roll (n−1) generally has a value of zero or lower, the curvature of the plate at roll (n−1) was affected by the intermeshes at both rolls (n−1) and (n−2). Therefore, Eq. (4), which expresses the relationship between the intermesh and curvature at roll (n−1), was modified into Eq. (7).

The moment of the plate was caused by the bending at each roll of the roller leveler. If the bending were removed to make the moment equal to zero, the curvature of the material under this condition is called residual curvature. k'_i, a residual curvature at roll i after modification, can be expressed as follows:[8]

$$k'_i = k_i - \frac{M_i}{M_y}k_y \tag{8}$$

where k_y and M_y are the yield curvature and yield moment, respectively. Accordingly, k'_n, which is the final residual curvature, is expressed as follows:

$$k'_n = \frac{M_n}{M_y}k_y \tag{9}$$

where M_n is the moment applied to the material at roll n.

2.3 Stress and moment

The material was assumed to undergo pure bending to obtain the stress and strain values along its thickness direction at the roller leveler, which means that a section perpendicular to a neutral plane is always straight and perpendicular even after deformation. The material between two contact points on the rolls was divided into m small segments again to obtain the curvature between them. $k_{i,k}$, which is the curvature at node k between rolls i and (i+1), is expressed as follows:[9]

$$k_{i,k} = k_{i,k-1} + \Delta k_k = k_i + \sum_{j=1}^{k}\Delta k_j \tag{10}$$

where Δk_k is the curvature increment at node k. The same value of Δk_k was applied in the calculations in this study.

The strain increment in the rolling direction can be obtained at node k from the curvature increment and height z from the neutral plane as follows:

$$\Delta\varepsilon_{k,z} = z\Delta k_k \tag{11}$$

where $\Delta\varepsilon_{k,z}$ denotes the strain increment in the rolling direction at node k and height z, which is the distance from the neutral plane along the thickness direction.

The material is assumed to have perfect plasticity. Accordingly, $\Delta\sigma_{k,z}$, which is the stress increment in the rolling direction at node k and height z, can be expressed as follows:

$$\begin{aligned} &if \quad \sigma_{k,z}\Delta\varepsilon_{k,z} > 0 \\ &\qquad \Delta\sigma_{k,z} = E\Delta\varepsilon_{k,z} \quad where \ |\sigma_{k,z}| < \sigma_y \\ &\qquad \Delta\sigma_{k,z} = 0 \quad where \ \sigma_y \le |\sigma_{k,z}| \\ &else \quad \Delta\sigma_{k,z} = E\Delta\varepsilon_{k,z} \end{aligned} \tag{12}$$

where $\sigma_{k,z}$, σ_y, and E denote the stress in the rolling direction at node k and height z, yield stress, and elastic modulus of the material, respectively.

$\sigma_{k,z}$ and M_k, which are the stress and moment at node k, respectively, can be calculated as follows:

$$\sigma_{k,z} = \sigma_{k-1,z} + \Delta\sigma_{k,z} \tag{13}$$

$$M_k = \int_{-\frac{t}{2}}^{\frac{t}{2}}\sigma_{k,z}z\,dA \tag{14}$$

where t is the plate thickness and dA is the surface area where $\sigma_{k,z}$ was applied.

We assume here that the moment applied to the material has a maximum value at the contact point on each roll and linearly changes between the contact points. Under this assumption, $x_{i,k}$, which is the coordinate in the rolling direction at node k between rolls i and (i+1), can be expressed as follows:

$$x_{i,k} = x_i + \frac{L}{2}\left(\frac{M_k - M_i}{M_{i+1} - M_i}\right) \tag{15}$$

where x_i is the coordinate of the material along the rolling direction at the contact point with roll i and M_i is the moment applied on the material at the contact point with roll i.

3. Verification of the Numerical Model

Marc, which is a commercial program that allows relatively simple analysis of contact problems, was applied using plane strain and an implicit method to verify the leveler model. The material used for the analysis was assumed to have a perfect plastic body, and its mechanical properties are shown in Table 1. The plate thickness was 18 mm, and the diameter and pitch of the roll of the leveler were 360 mm and 390 mm, respectively. The arrangement of the rolls and intermesh is shown in Fig. 9.

Fig. 10 shows the contact point of the roll and the material obtained from FEA. The contact point on the roll is located slightly before its

Table 1 Material constants of the plate

Yield stress	Elastic modulus	Poisson's ratio	Coefficient of friction
490 MPa	210 GPa	0.3	0.3

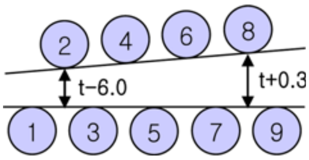

Fig. 9 Roll number and intermesh

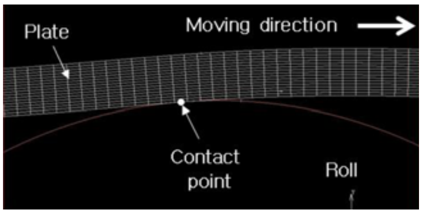

Fig. 10 Contact point on the roll

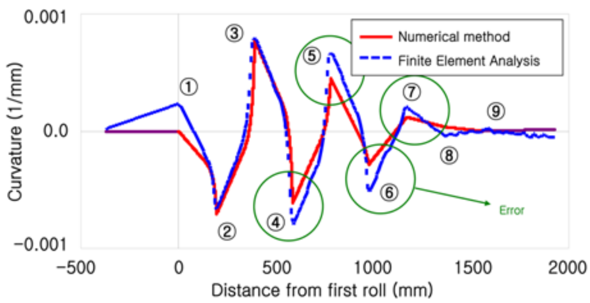

Fig. 11 Curvature of the plate (without correction factor)

peak along the motion direction of the material.

Fig. 11 shows the changes in the curvatures from the numerical analysis and FEA without any correction factor applied. The curvature showed differences between roll 1 and the rolls following roll 4. The curvatures at rolls 1 and 9 were different because the curvatures were assumed to be zero at these locations by the numerical model. The difference in the curvature after roll 4 was attributed to the error resulting from the deviation of the contact point of the plate and the roll from its peak.

4. Determination of the Coefficient of Correction factor

Numerical analysis and FEA were performed by varying the maximum plastic deformation ratio (plastic deformation ratio at roll 3) from 5% to 85% to determine coefficients A and B in Eq. (6). Fig. 12 shows the varying curvature ratio obtained from FEA and the numerical analysis according to the change in the maximum plastic strain for rolls 4 through 7. As the plate moved from one roll to the next, the maximum plastic strain became larger, and the error of curvature increased. A regression equation was used to calculate coefficients A and B using the relationship between the maximum plastic strain and curvature, as listed in Table 2.

Table 2 Coefficients of correction factor

	Roll 4	Roll 5	Roll 6	Roll 7
A	6×10^{-9}	9×10^{-9}	13×10^{-9}	20×10^{-9}
B	4.1	4.1	4.1	4.1

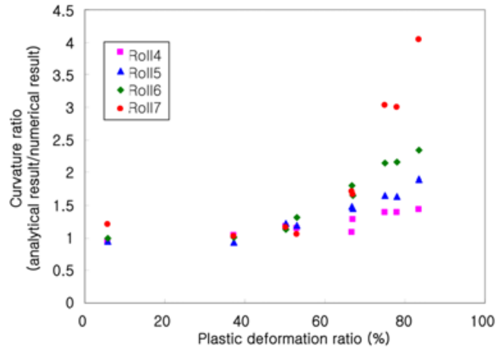

Fig. 12 Curvature ratio

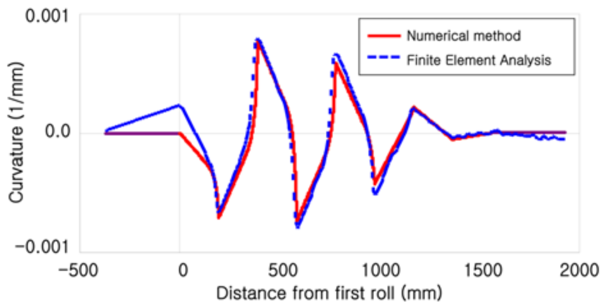

Fig. 13 Curvature of the plate (with correction factor)

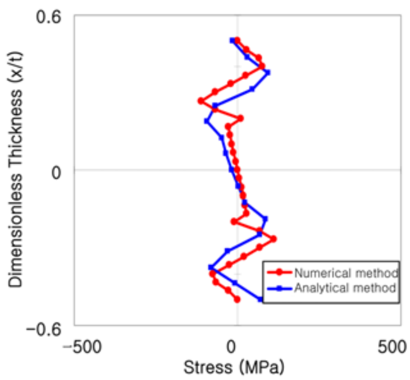

Fig. 14 Distribution of residual stress

Fig. 13 shows the comparison of the curvatures of the plate obtained from the numerical analysis and from FEA with the application of a correction factor under the same conditions shown in Fig. 11. We found that the results from the numerical analysis and FEA were almost the same.

Fig. 14 shows the final residual stress along the thickness direction. The results of FEA and the numerical analysis were found to almost match.

5. Concluding Remarks

This study proposed a new 2D numerical modeling that corrected the varying contact points by applying different correction factors to reduce the curvature error of the existing roller leveler model. The relationship between the stress and moment based on the bending theory of plate was formulated, and the analysis result of the proposed model was also compared with the FEA result to obtain the correction factor coefficients. We found that the two results matched based on the changes in the plate residual stress distribution along the thickness direction and the contact point on the roll is located slightly before its peak along the motion direction. Also we examined the relationship between the initial and final residual curvatures for different intermeshes. The varying curvature ratio from FEA and the numerical analysis according to the change in the maximum plastic strain for rolls are obtained. As a result, the error of curvature is increased by the larger maximum plastic strain. We expect that further studies will examine the derivation of the optimal leveling conditions to minimize the residual stress at single and multi-pass leveling using the model proposed in this study.

REFERENCES

1. Soda, C., “A Study on Plate Leveling (1st Report),” J. Mech. Lab., Vol. 15, No. 4, pp. 310-348, 1961. (in Japanese)
2. Araki, J., “An Analysis of Longitudinal Profile of Material in Straightening,” Seisan-kenkyu (J. Inst. Indust. Sci., Univ. Tokyo), Vol. 24, No. 7, pp. 267-270, 1972. (in Japanese)
3. Matoba, T., Ataka, M., and Jimma, T., “Calculation Method of Roller Leveling Conditions for Steel Plates,” Journal of the Japan Society for Technology of Plasticity, Vol. 36, No. 418, pp. 1306-1311, 1995. (in Japanese)
4. Ye, H. and Hwang, S., “Prediction of the Residual Stress for a Steel Plate after Roller Leveling-Part I: Development of the Model,” Transactions of Materials Processing, Vol. 22, No. 1, pp. 5-10, 2013.
5. Park, K.-C. and Hwang, S.-M., “Development of a Finite Element Analysis Program for Roller Leveling and Application for Removing Blanking Bow Defects of Thin Steel Sheet,” ISIJ International, Vol. 42, No. 9, pp. 990-999, 2002.
6. Smith, R. P., “The Effect of the Number of Leveling Rolls on the Straightening Process,” Iron & Steel Technology, Vol. 4, No. 8, pp. 57-68, 2007.
7. Cai, Z.-Y., Li, L.-L., Wang, M., and Li, M.-Z., “Process Design and Longitudinal Deformation Prediction in Continuous Sheet Metal Roll Forming for Three-Dimensional Surface,” Int. J. Precis. Eng. Manuf., Vol. 15, No. 9, pp. 1889-1895, 2014.
8. Hibino, F., “The Practical Formula for Leveling Strain in a Roller Leveler,” Journal of the Japan Society for Technology of Plasticity, Vol. 31, No. 349, pp. 208-212, 1990.
9. Lee, J.-B., Kwon, H.-C., and Lee, S.-J., “Research on Optimal Leveling Conditions of Roller Leveler in Thick Plate Mill,” Proc. of the Korean Society for Technology of Plasticity Conference, pp. 93-96, 2009.
10. Bathe, K. J., “Finite Element Procedures,” Prentice-Hall, 1996.
11. Vafaeesefat, A. and Khanahmadlu, M., “Comparison of the Numerical and Experimental Results of the Sheet Metal Flange Forming Based on Shell-Elements Types,” Int. J. Precis. Eng. Manuf., Vol. 12, No. 5, pp. 857-863, 2011.
12. Liu, K., Liu, Y., and Yang, H., “Experimental and Fe Simulation Study on Cross-Section Distortion of Rectangular Tube under Multi-Die Constraints in Rotary Draw Bending Process,” Int. J. Precis. Eng. Manuf., Vol. 15, No. 4, pp. 633-641, 2014.
13. Fang, G., Gao, W.-R., and Zhang, X.-G., “Finite Element Simulation and Experiment Verification of Rolling Forming for the Truck Wheel Rim,” Int. J. Precis. Eng. Manuf., Vol. 16, No. 7, pp. 1509-1515, 2015.