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Study on the manufacturing process of precision linear guide rail through shape rolling and shape drawing †

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Abstract

Guide rails are one of the most important components in terms of equipment because the quality of the linear rail in-fluences on the precision linear motion. For long rails used in the guide rail, high dimensional accuracy as well as a cross-sectional shape is required. As a production method of guide rail, drawing process is mainly used. But, the shape rolling process is open used for the pre-process of the other metal forming process such as forging, extrusion, and shape drawing. The shape rolling process is one of the most effective processes which can make long products with constant irregular cross-sectional shape. Therefore, the tool shape is a very important process variable to obtain the required final product. The objective of this paper is the design of roll shape of the rolling process to produce the initial material with irregular cross sectional shape for shape drawing. Also, the die shape of the drawing process is determined to satisfy the dimensional accuracy of the final product. In this study, FE-analysis and artificial neural network (ANN) were applied to achieve the objective. Further, shape rolling and shape drawing experiments were performed to verify the result of FE-analysis. From results, it was possible to design the roll shape of shape rolling process effectively.

Keywords: At shape rolling; Shape drawing; Fe-simulation; Artificial neuron network; Tool shape design; Guide rail

1. Introduction

Guide rails are one of the most important components in terms of equipment because the quality of the linear rail influences on the precision linear motion. For long rails used in the guide rail, high dimensional accuracy as well as a cross-sectional shape is pursued. As a production method of the guide rail, drawing process is mainly used. An important characteristic of shape drawing is the dimensional accuracy of the cross-section after drawing.

For most of the shape drawn products commonly available round or square billet can be used as initial material shape. Complex products should, however, be pre-rolled to obtain initial shape for shape drawing. The shape rolling process is adequate for mass production of structures or machine parts with continuous shape. In shape rolling, billets are formed by different roll's geometric grooves, so the cross sections of the products are variable. The billet is gradually filled into the cavity of the roll as it passes through the roll gap. Deformation occurs on the constrained boundary and free surface sides, with non-uniform deformation behavior. The constrained boundary indicates the interface between the billet and the roll, and the roll pressure and friction exist on this boundary. On the free surface side, the bulge of billet may occur because of the billet is pressed down by the roll, and under this situation a complicated 3D shape rolling model is formed.

In recent years, there has been a growing need in the metal forming industry to improve not only dimensional accuracy, but also quality of products.

After Beynon[1], Wusatowski[2] and Chitkara[3] et al., design rules were determined empirically from production data. Because of the complexity of the process, however, process sequence design for new materials and complex geometries is not easy to carry out. Thus, several researchers [4-6] have used the finite element (FE) technique to analyze the process to reduce the number of modifications. Kennedy[7] and Montmitonnet[8] et al. have applied the numerical results obtained from such FE-simulations for process sequence design.

As mentioned above, shape drawing process can be classified to two kinds of processes according to the requirement of the pre-rolling process. One is direct shape drawing from initial material to final product. The other process type is the

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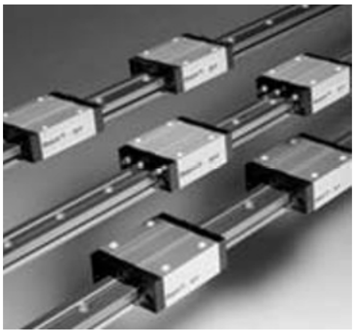


Fig. 1. Photo of the guide rail.

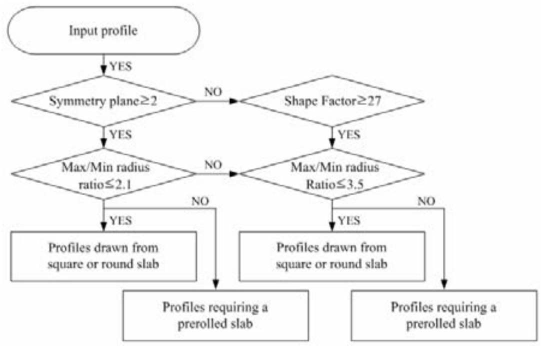


Fig. 2. Classification standard of shape drawing.

shape drawing with pre-rolled materials into complex cross sectional shapes. Therefore, to design shape drawing process, the process classification should be done first. The previous study is not enough to determine classification standard on shape drawing process. However, Lee et al. [9] suggested a classification standard of shape drawing process considering the shape difficulties of the final product; number of the symmetry planes, shape factor (SF), and radius ratio (R_{max}/R_{min}) of circumscribed circle (R_{max}) and inscribed circle (R_{min}).

In general, the tool shape design relies on empirical rules or the know-how of design engineers, requiring costly effort at the development stage. Therefore, many studies have been carried out, experimentally and numerically.

The objective of this paper is the design of the tool shape of the pre-rolling process to make irregular cross sectional shape through the successive shape drawing. Also, the die shape of the drawing process is determined to satisfy the dimensional accuracy of the final product. In this study, FE-analysis and ANN were applied to achieve the objective. And then, shape rolling and shape drawing experiments were performed to verify the result of FE-analysis. From results, it was possible to design the roll shape of shape rolling process effectively.

2. Process conditions in shape rolling

Fig. 1 shows the photo of the guide rail. Guide rails are mainly used to the equipment with linear motion. Therefore, the guide rail is required a cross-sectional shape with high accuracy. Fig. 2 shows the classification standard of shape drawing[9]. The applied final product shape is shown in Fig. 3.

Table 1. Chemical composition of billet.

Comp.	C	Mn	Si	Cr	P	S	Ni
Wt, %	0.03	2.0	1.0	17	0.045	0.03	13

Table 2. Process condition of rolling for FE-simulation.

Condition	Values
Material of billet	AISI 316L
Initial billet size	W92 x H30mm
Pass number of rolling	2 pass
Total reduction ratio	20%
Initial temperature	1050°C
Dimension of roll	304.8 mm
Rolling velocity	12.46 rad/s
Thermal conductivity	18.5 w/m°C

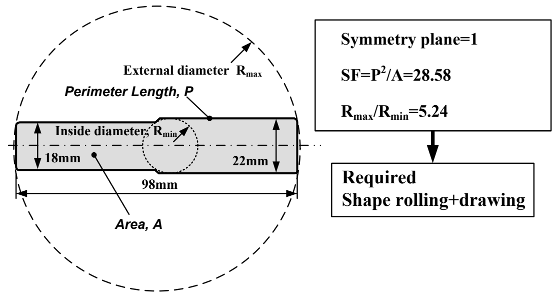


Fig. 3. Results of classification from final shape.

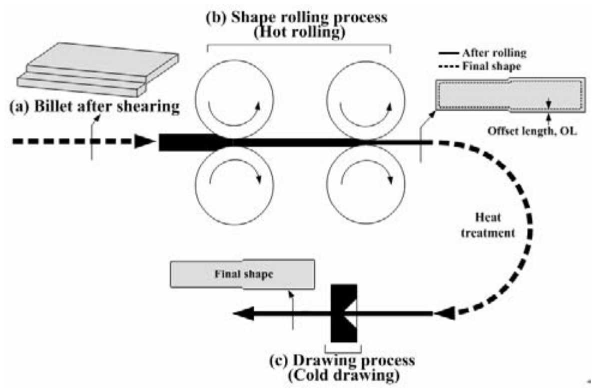


Fig. 4. Sequence for producing guide rail.

From the result of classification for the final product, the number of symmetric plane is 1, SF is 28.58, and the radius ratio is 5.24. Therefore, shape drawing with pre-rolling process is required to produce the final product.

Fig. 4 shows the process sequence for producing guide rail. In order to acquire the initial material of shape drawing, the rolling process is performed in a total of 2 pass. The main factor influenced on the shape of final product was the initial material of shape drawing. And the initial material of shape drawing and the final product are very closely related.

The used initial material is AISI 316L. And the roll material is used AISI H-13. The chemical composition of the AISI 316L is indicated in Table 1. Table 2 shows process condition

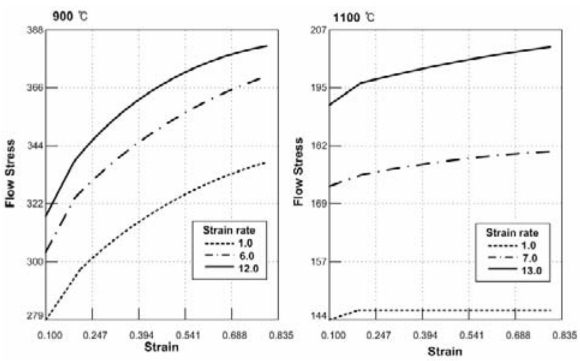
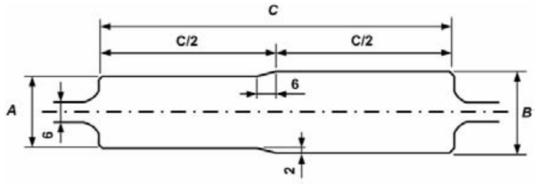
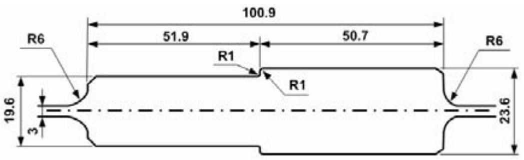


Fig. 5. Strain-stress curve of AISI 316L.



(a) 1st pass roll



(b) 2nd pass roll

Fig. 6. Geometries of rolls on shape rolling process.

of rolling for FE-simulation. The total reduction ratio is 20%. The initial temperature of billet is 1050°C. And, the diameter of roller is 304.8mm. The velocity of rolling is set up 12.46 rad/sec. The friction factor between roller and material is constantly set up 0.7 and the thermal conductivity is 18.5w/m °C.

Fig. 5 shows the flow stress curve of AISI 316L for FE-analysis evaluated by compression test. Fig. 6 shows the geometries of rolls for shape rolling process. The sectional shapes of material after rolling and before shape drawing have been consistent with each other. Therefore, the geometry of the 2nd pass roll has been fixed up in this process. Therefore, the geometry of the 1st pass roll has to be selected as the design parameters. As shown in Fig. 6(a), the lengths of A, B and C are the design parameters.

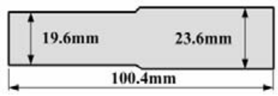
3. Results of FE-simulation on shape rolling process

In this paper, the technique using ANN has been proposed to find the combination of shape parameters of 1st pass roll having the initial material shape of shape drawing process after shape rolling process. The range of design parameters have been determined A (22, 23, 24mm), B (25, 26, 27mm) and C (98, 100, 102mm), respectively.

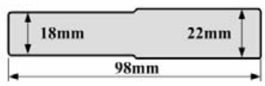
Fig. 7 shows the cross-sectional shapes after rolling and drawing processes. In order to maintain uniformed metal flow during drawing process, the initial cross-sectional shape for drawing process was determined by the industrial experts. The

Table 3. Comparison of width length according to geometry parameters.

Case	Geometry parameter (mm)			Length (mm)
	A	B	C	FEM
1	22	25	98	99.667
2	22	26	100	99.797
3	22	27	102	100.657
4	23	25	100	98.827
5	23	26	102	100.437
6	23	27	98	99.897
7	24	25	102	99.727
8	24	26	98	98.897
9	24	27	100	99.507



(a) Rolling



(b) Drawing

Fig. 7. Cross-sectional shapes after rolling and drawing process.

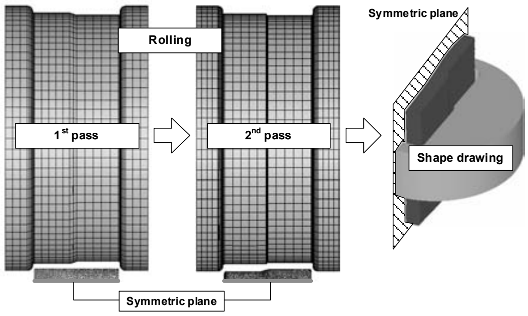


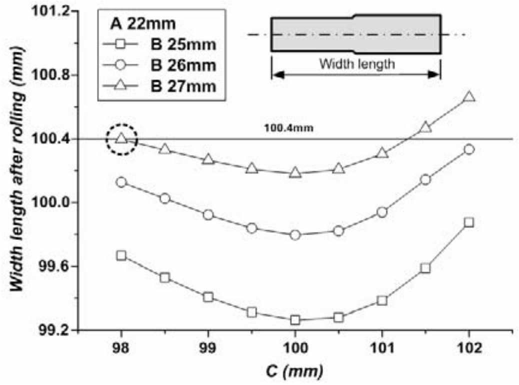
Fig. 8. FE-simulation models on rolling and drawing process.

target dimension of material after rolling process is shown in Fig. 7(a) considering the drawing process. Also, FE-simulation results have been compared with the initial shape of shape drawing, respectively.

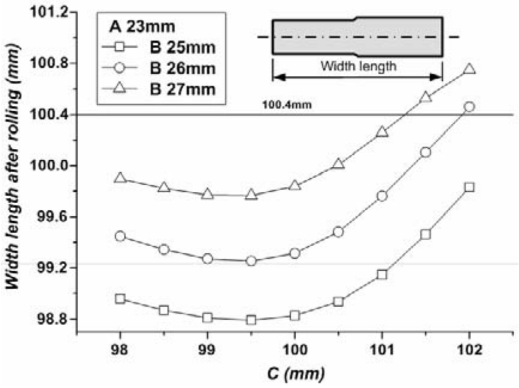
The FE-simulation models for rolling and drawing processes are shown in Fig. 8. Considering the symmetrical cross-section, 1/2 section was analyzed by using DEFORM-3D. Table 3 shows the comparison of width length according to geometry parameter. From the FE-simulation results, width length 100.437mm of case 5 (A=23mm, B=26mm and C=102mm) is most similar than target length (100.4mm).

To perform a shape drawing process, the width length of the initial material should adequately maintained target length in drawing process. When the width length was smaller or larger than the final product, it is easy to present the defects such as a folding and a dimension error, etc. after drawing process[10].

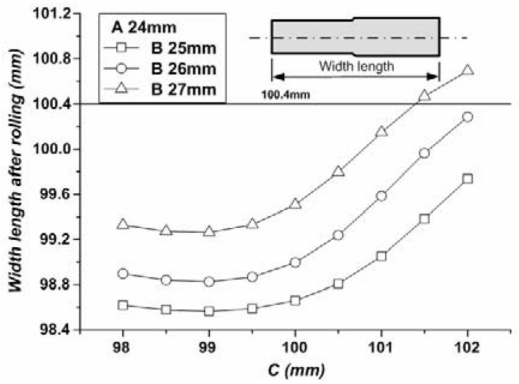
The combinations of design parameters and the width length are feed to the ANN as input and target data, respectively. After training from FE-simulation results, the satisfac tory combination of design parameter was acquired from trained ANN results. Prediction results of width length using



(a) A=22mm



(b) A=23mm



(c) A=24mm

Fig. 9. Prediction for results of width length using neural network.

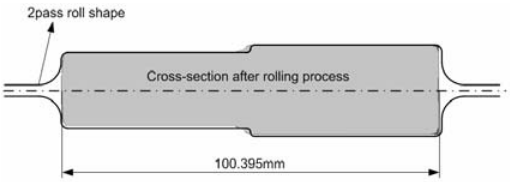


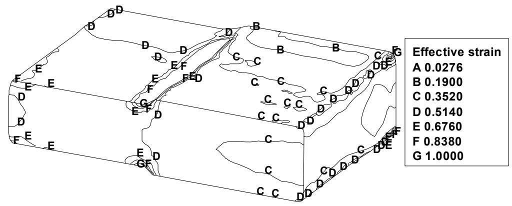
Fig. 10. Cross-section after rolling process.

ANN were shown in Fig. 9. From the predicted results by ANN, the combination of design parameters having a target length is selected as A=22mm, B=27mm and C=98mm.

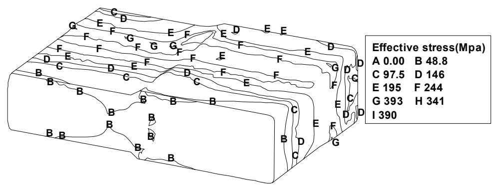
The selected combination of design parameters had been used in order to confirm the optimal selection using FE-simulation (Fig. 10). Table 4 shows comparison of ANN and FE-analysis. Predicted width length 100.39mm from ANN is very similar to the width length 100.395mm from FE-simulation result.

Table 4. Optimal geometry parameter.

Geometry parameter (mm)			ANN (mm)	FEM (mm)
A	B	C		
22	27	98	100.39	100.395



(a) Effective strain



(b) Effective stress

Fig. 11. Effective strain and stress on rolling process.

Fig. 11 shows distribution of effective strain and stress on rolling process. The effective strain values have been relatively large in the fillet and corner regions. And, the effective stress has been uniformly distributed in all regions. Also, we are confirmed that the material during shape rolling process has been rolled without defects such as a folding, etc.

4. Results of shape drawing process

To acquire an initial shape before drawing process, the optimal design parameter of roll had been determined by FE-simulation and ANN. The initial material of drawing process is deformed according to shape rolling process with the optimal design parameter. Fig. 12 shows the schematic of die shape in the drawing process. A reduction ratio is 12.8% in the drawing process. Table 5 shows the process condition of shape drawing process. The bearing length of drawing die is 8.0mm, friction factor is 0.1, die angles are 7, 8, 9 and 10°, and velocity of drawing is 200mm/sec, respectively. And FE-simulation is performed using a rolled material by drawing process.

Fig. 13 shows the comparison of filling between the acquired shape and the final product shape after drawing process. From the results, the unfilled region is mainly occurred at the corner part. And the unfilled regions with the half die angle of 8° and 9° are relatively small.

After FE analysis the unfilled rate (*UR*) of the cross section of the final product was investigated to evaluate the dimensional accuracy. The unfilled rate is calculated by Eq. (1)

Table 5. Process condition of shape drawing process.

Condition	Value
Bearing length (mm)	8.0
Friction factor, m	0.1
Half die angle (°)	7.0, 8.0, 9.0, 10.0
Drawing speed (mm/sec)	200
Flow stress (MPa)	$\bar{\sigma} = 509.5 + 1066.5 \cdot \bar{\varepsilon}$

Table 6. Comparison of the unfilled rate according the half die angle.

Half die angle (°)	$A_{Analysis}$ (mm^2)	A_{Final} (mm^2)	UR (%)
7	1954.503	1963.451	0.455733
8	1955.724		0.393521
9	1957.707		0.292531
10	1952.267		0.569569

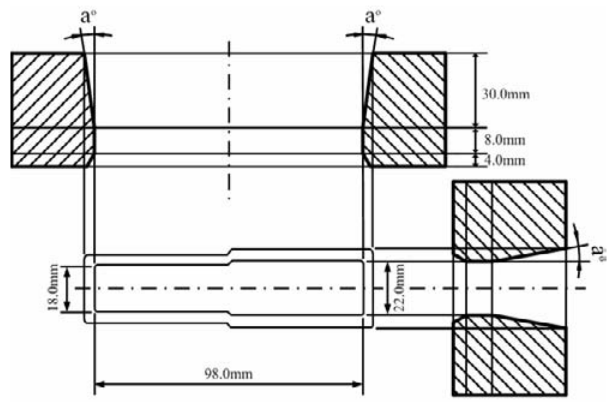


Fig. 12. Schematic of die shape in the drawing process.

$$UR = (A_{Final} - A_{Analysis}) / A_{Final} \times 100 \quad [\%] \tag{1}$$

where A_{Final} and $A_{Analysis}$ are the required cross sectional area of the final product and FE analysis result. A lower unfilled rate means better dimensional accuracy. The unfilled rates are summarized in Table 6. The unfilled rate with the half die angle of 9° is smallest than others. The result of ANN according to half die angle is shown in Fig. 14. From the ANN result, the minimum unfilled rate is 0.293 at half die angle of 8.9°. Therefore, the half die angle is selected as 8.9°.

Fig. 15 shows the cross-sectional shape of FE- simulation. From FE-simulation results, the material of drawing process is not only smoothly formed into final product without any defect, but also the width length after drawing process is presented 98.45mm.

As a result, the width length of the final product (98mm) is similar with FE-simulation result (98.45mm). The allowable tolerance of this product is less than ±1mm. Therefore, it is confirmed that the rolled material by the designed roll is satisfied with width length of final product after drawing process.

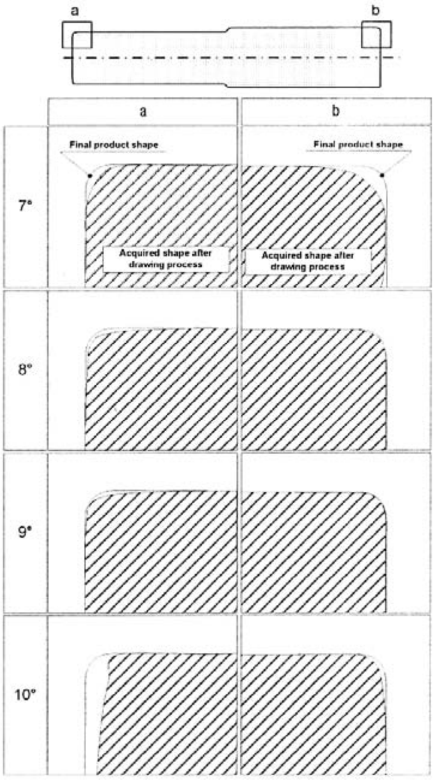


Fig. 13. Comparison of filling between the acquired shape and the final product shape after drawing process.

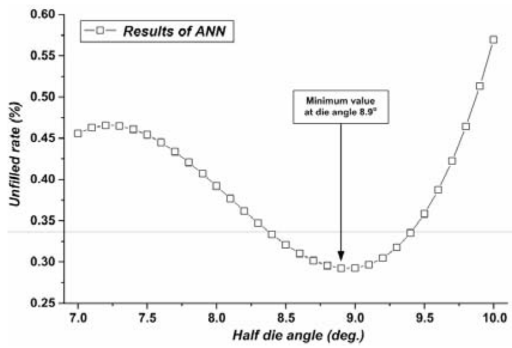


Fig. 14. Result of ANN according to half die angle.

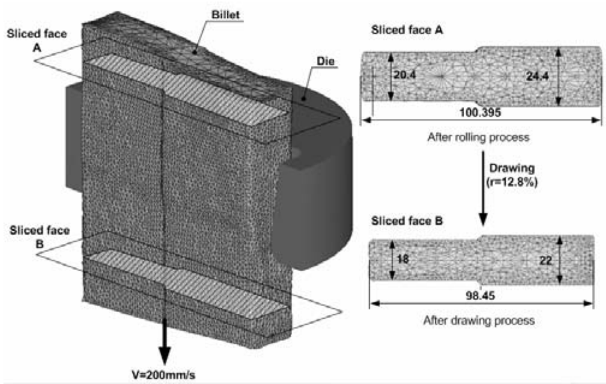


Fig. 15. FE-model of drawing process and cross section after rolling process.

5. Shape rolling and shape drawing experiments

Finally, shape rolling and shape drawing experiment were performed to verify the effectiveness of the proposed design of 1st pass roll. Fig. 16 shows die shape of rolling and drawing processes. The roller and drawing die for experiments had been manufactured based on the combination design parameters by ANN. The production of the final product by experiments is shown in Fig. 17. The surfaces of the product by experiments were not presented to any defect.

Fig. 18 shows the comparison of the cross-sectional shape between the results of FE-simulation and experiment. From the results, the cross-sectional of the experiment was very similar with that of FE-simulation. Also, the width length of experiment was measured as 98.2mm. Fig. 19 shows the strength analysis results of the drawing die. The maximum elastic deformation of die is occurred 0.089mm at y-direction during drawing process. The die material is WC, which has the compressive strength of 2683MPa. Because the maximum effective stress (921MPa) of die is smaller than die strength, the drawing die is safe during drawing process. Fig. 20 shows the measurement of final product considering elastic deformation of material and die. The elastic deformation of material and die is occurred the maximum 0.71mm at x-direction during drawing process. Because, the elastic deformation is occurred within allowance tolerance (±1mm) of this product, the elastic deformation of material and die can be neglected.

(a) Rolling for 1st pass (b) Drawing

Fig. 16. Die shapes of rolling and drawing.

Fig. 17. Production of the final product by experiment.

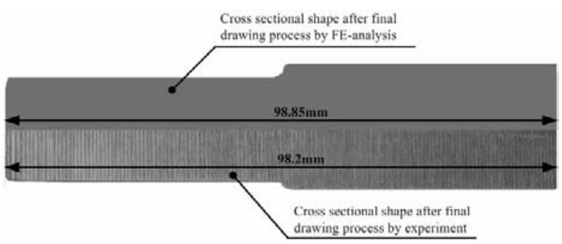
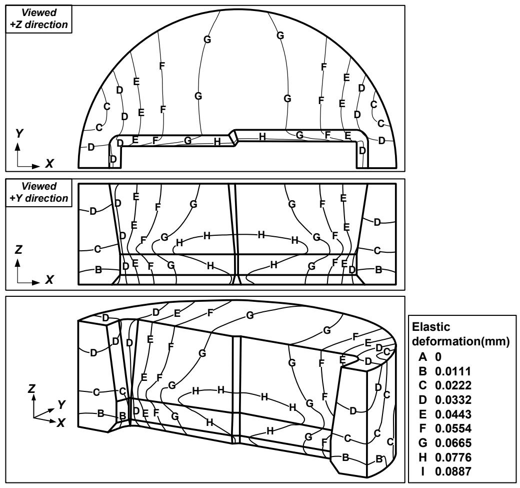


Fig. 18. Comparison of cross sectional shape between the results of FE-simulation and experiment.

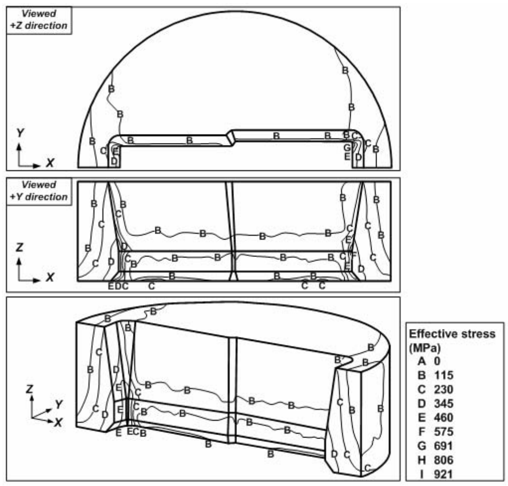
6. Conclusions

The shape drawing process was classified to shape drawing process and the shape drawing included pre-rolling process. In this paper, we carried out the design of roll shape of the pre-rolling process to produce the initial material with irregular cross sectional shape for shape drawing. Also, FE-simulation and ANN were applied to predict the profile of roll.

In the result of the classification standard for shape drawing, the profile of the final product has been presented that the number of symmetric planes is 1, the shape factor is 28.58, and R_{max}/R_{min} is 5.24. Hence, this product is necessary to



(a) Elastic deformation



(b) Effective stress

Fig. 19. Strength analysis results of the drawing die.

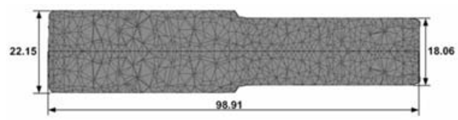


Fig. 20. Measurement of final product considering elastic deformation of material and die.

shape rolling process to acquire required shape. And the simulation is performed for each combination of design parameters according to the design of experiments.

From the FE-simulation results, width length 100.437mm of case 5 (A=23mm, B=26mm and C=102mm) is most similar than target length (100.4mm).

From the predicted results by ANN, the combination of design parameters having a target width length is selected as A=22mm, B=27mm and C=98mm. And the half die angle of the drawing die is selected as 8.9°. The predicted width length 100.39mm from ANN is very similar to the width length 100.395mm from FE-simulation result.

The shape rolling and drawing experiment were performed to verify the effectiveness of the proposed design of 1st pass roll. From the result, the cross-sectional of the experiment is very similar with that of FE-simulation. Also, the width length of experiment is satisfied with the dimensional accuracy of final product.

Acknowledgment

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