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Die design in the complex shape drawing of cross roller guide to improve the dimensional accuracy

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Abstract

A drawing process allows for a smooth and clean surface, metal savings, low cost tooling, and closely controlled dimensions to be obtained in long products that have constant cross-sections. Recently, rods having irregular sections more complex than a rectangle or ellipse are necessary to produce mechanical parts. A cross roller guide is one of the parts produced by complex cold-shaped drawing. A cross roller guide has a linear bearing system that rolls along a guide way. A cross roller guide is one of the most important components in terms of equipment because the quality of the linear rail influences the precision linear motion. Therefore, the final dimensional accuracy of the linear rail in cold-shaped drawing is very important. The aim of this study is the optimization of the optimal die angles to improve the dimensional accuracy and straightness of the final product using design of experiment, FE-simulation, and the Taguchi method. Based on the analytical results, experiments for real industrial products have also been implemented to verify the results. From the experimental results, it was possible to improve the dimensional accuracy and straightness of final product.

Keywords: Complex shaped drawing; Cross roller guide; Die angle; Optimization

1. Introduction

Wire and rod drawing is widely used in metal-forming processes to obtain products such as rods, wires, and tubes. This process allows for a smooth and clean surface, metal savings, low cost tooling, and closely controlled dimensions to be obtained in long products that have constant cross-sections. The stress condition in the deformation zone for this process is a combination of tensile and compressive stresses. Recently, rods having irregular sections more complex than a rectangle or ellipse are necessary to produce automotive components, construction of rail-ways, components of firearms and transformers, springs with high stiffness, etc. Therefore, there has been increasing interest in the complex shaped drawing process and die design [1].

The cross roller guide, a linear motion guide, is an important and effective machine element in terms of its ability for high-precision positioning, automation and energy saving. Cross roller guides have a linear bearing system that rolls along a guide way. This rail way is usually shaped in a way that helps the bearing grip it.

Cross roller guides are an indispensable component of mechanical and electronic systems in a wide variety of industries, such as machine tools, industrial robots, electronic devices, precision instruments, semiconductors and LCD manufacturing equipment.

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Cross roller guides are one of the most important components in terms of equipment because the quality of the linear rail influences the precision linear motion. For long rails used in the cross roller guide, high dimensional accuracy as well as a complicated cross-sectional shape and small bending and torsion is pursued. In order to produce a sound cross roller guide having a complicated cross-sectional shape, highly precise material processing technology is indispensable. As a fabrication method of the cross roller guide, drawing by means of cutting and shaped drawing is considered, but the latter is superior from the viewpoint of processing time and waste of material [2-5].

The final dimensional accuracy of the linear rail in cold-shaped drawing is very important. In the cold drawing process, the rod is under the tensile state through the die; thus, it is not easy to meet the required dimensional accuracy [6]. An important characteristic of complex shaped cold drawing, unlike wire drawing, is the dimensional accuracy of the cross-section and the straightness after drawing. The quality of the final drawn product depends on the process parameters such as material properties, die reduction, and die angle. Therefore, it is essential to determine the proper process parameters.

The aim of this study is the optimization of the die angles to improve the dimensional accuracy and straightness of a cross roller guide which is fabricated from a round bar through two-stage drawing. Fig. 1 shows the photo of the cross roller guide. In order to achieve our aims, design of experiment, 3D FE-simulation, and Taguchi method were used. Based on the analytical results, experiments for real industrial product has also been implemented to verify the analytical result. From the experimental results, it was possible to improve the dimensional accuracy and straightness of the final product.

2. Process conditions and fe-simulation of a cross roller guide

2.1 Process conditions

The cross-sectional shape of the cross roller guide is shown in Fig. 2. As shown in Fig. 2, cross roller guides of a predetermined shape are fabricated from a round bar by two-stage shaped drawing. The diameter of the initial round material is 29.0 mm. The die reductions are 24.0 % and 22.0 % at each stage. The bearing length is 8.0 mm. The friction factor (m) between the material and die is 0.1, which is the result of the friction test with phosphate. The drawing speed is 200.0 mm/s at all stages. These process conditions are summarized in Table 1. For the initial material used in this study, AISI4137 steel, the stress-strain curve for the FE-simulation, which has been obtained by the tensile test, is given in Eq. (1):

$$\bar{\sigma} = 1640 \cdot \bar{\varepsilon}^{0.14} \text{ [MPa]} \quad (1)$$

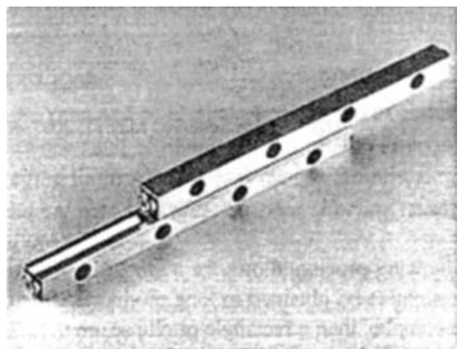


Fig. 1. Photo of the cross roller guide.

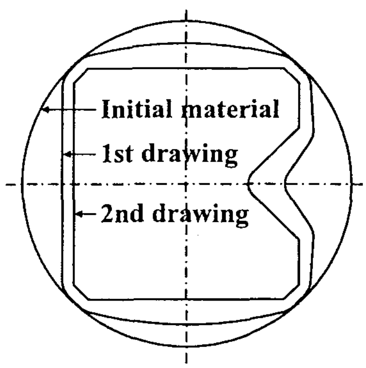
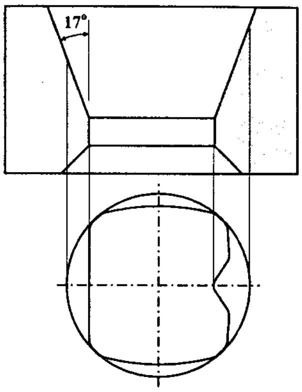


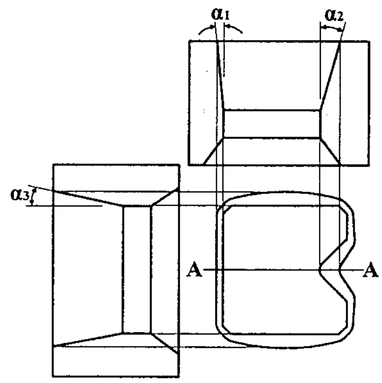
Fig. 2. Cross-sectional shape of a cross roller guide at each stage.

Table 1. Process conditions of the shaped drawing process.

Pass No.	1	2
Die reduction(%)	22.0	24.0
Total reduction(%)	22.0	41.0
Bearing length(mm)	8.0	8.0
Friction factor(m)	0.1	0.1
Drawing speed(mm/s)	200.0	200.0

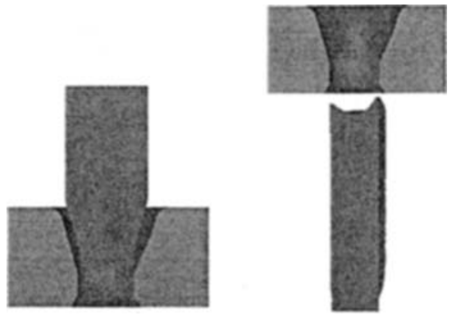


(a) First stage

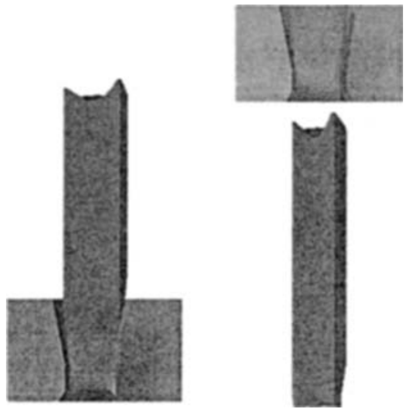


(b) Second stage

Fig. 3. Die shapes for the cross roller guide.



(a) First drawing



(d) Second drawing

Fig. 4. FE-simulation sequence of the two stages shaped drawing.

2.2 Design parameter and FE-simulation

There are many process parameters in the drawing process such as die reduction, die angle, drawing speed, and bearing length. In this study, the die angles of the second stage were chosen for the design parameters. In addition, the drawing parameters of the first stage were fixed because the second drawing stage had more influence on the quality of the final product than the first stage. Fig. 3 shows the die shapes and the design parameters. As shown in Fig. 3(b), the cross roller guide is symmetrical in section A-A. Because of the cross-sectional shape, there are three die angles (α_1, α_2, α_3). After the first drawing, the influence of three angles of the second stage on dimensional accuracy and straightness were evaluated by FE-simulation. Considering the symmetric cross-sectional shape, the 1/2 section was simulated. Fig. 4 shows the simulation sequence. The FE-simulation was carried out by the commercial S/W DEFORM-3D.

2.3 Decision of objective function

The aim of this study is the determination of the optimum second die angles to improve the dimensional accuracy and straightness of the cross roller guide. Two different objective functions are chosen in this study. One is the unfilled rate ($U.R$), which can evaluate the dimensional accuracy, and is expressed by the Eq. (2):

$$U.R = \left(A_{opt} - A_f\right) \Big/ A_{opt} \times 100 \quad [\%] \tag{2}$$

where A_{opt} is the area of the second die (189.97 mm^2), and A_f is the area of the final drawn product. A lower value for the unfilled rate means better dimensional accuracy.

The other function, which can evaluate straightness, is the least-square deviation between the average value and the actual measured value of the sampling position on the final drawn product. It is expressed by

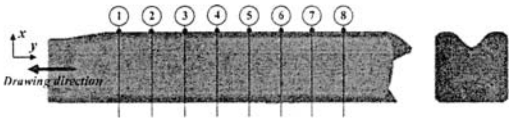


Fig. 5. Measured positions for the evaluation of straightness.

Table 2. Design parameters and levels in a shaped drawing process.

Parameters	Level 1	Level 2	Level 3
α_1(°)	7	9	11
α_2(°)	7	9	11
α_3(°)	8	10	12

the following Eq. (3):

$$S = \sqrt{\left\{ \sum_{k=1}^{n} (x_k - \bar{x})^2 \right\} / n} \quad (3)$$

where n is the number of the sampling position, x_k is the coordinate value of the position k, and $\bar{x}$ is the average coordinate of the sampling positions. Also, a lower value of S means better straightness of the final drawn product. Fig. 5 shows the sampling positions for the evaluation of straightness.

3. Determination of the optimal die angles

The Taguchi method is one of the most well known and widely applied robust design methods [7, 8]. The Taguchi method has created the S/N (signal to noise) ratio which is a measurement of the parameters. There are several S/N ratios available depending on the types of characteristics; lower is best (LB), nominal is best (NB), or higher is best (HB). The S/N ratio for LB characteristics related to this study is calculated as follows [9]:

$$S/N = -10 \cdot \log\left[\frac{1}{n} \sum_{i=1}^{n} y_{ij}^2 \right] \quad (4)$$

where n is the repetition number of simulation under the same design parameter conditions, y indicates the obtained results, and subscripts i and j indicate the number of design parameters arranged in the Taguchi orthogonal array.

As shown in Table 2, three design parameters, each with three levels, were specified for the shaped drawing. Accordingly, the experimental trials were arranged in an $L_9(3^3)$ Taguchi orthogonal array.

4. Results and discussion

4.1 Optimal die angles to improve the dimensional accuracy

Table 3. Orthogonal array and S/N ratios to improve dimensional accuracy.

Experiment No.	α_1(°)	α_2(°)	α_3(°)	Unfilled rate(%)	S/N ratio
1	7	7	8	1.209	-1.40258
2	7	9	10	1.436	-4.02589
3	7	11	12	2.521	-7.54263
4	9	7	10	1.082	-1.66580
5	9	9	12	1.437	-3.41906
6	9	11	8	1.108	-1.39383
7	11	7	12	1.930	-5.45890
8	11	9	8	0.921	-0.81948
9	11	11	10	1.412	-2.86725

Table 4. Parameter response for dimensional accuracy.

Parameter	α_1	α_2	α_3
Level 1	-4.324	-2.843	-1.205
Level 2	-2.160	-2.755	-2.854
Level 3	-3.049	-3.935	-5.474
Effects	2.163	1.180	4.268
Rank	2	3	1

The unfilled rate obtained from FE-simulation corresponding to the orthogonal array and the results transformed into the S/N ratios are summarized in Table 3.

Table 4 presents the parameter response data for the S/N ratio. In accordance with the principles of the Taguchi method, an assumption is made that a higher S/N ratio indicates an improved dimensional accuracy. Therefore, Table 4 shows that for the shaped drawing, the optimal design parameter settings are as follows; α_1 of 9°, α_2 of 9°, and α_3 of 8°. The result of the optimal design parameters indicating the maximum S/N ratio was verified by FE-simulation. The unfilled rate was 0.892, which was the lowest. The simulation result, which minimizes the unfilled rate, is transformed into an S/N ratio, with a value of 0.23457. Fig. 6 shows the cross-sectional shape of the cross roller guide according to the design parameters.

4.2 Optimal die angles to improve the straightness

Using the same orthogonal array (Table 3), the influence of the design parameter on straightness was evaluated. The least square deviation, which was obtained from the FE-simulation corresponding to the orthogonal array as well as the results transformed

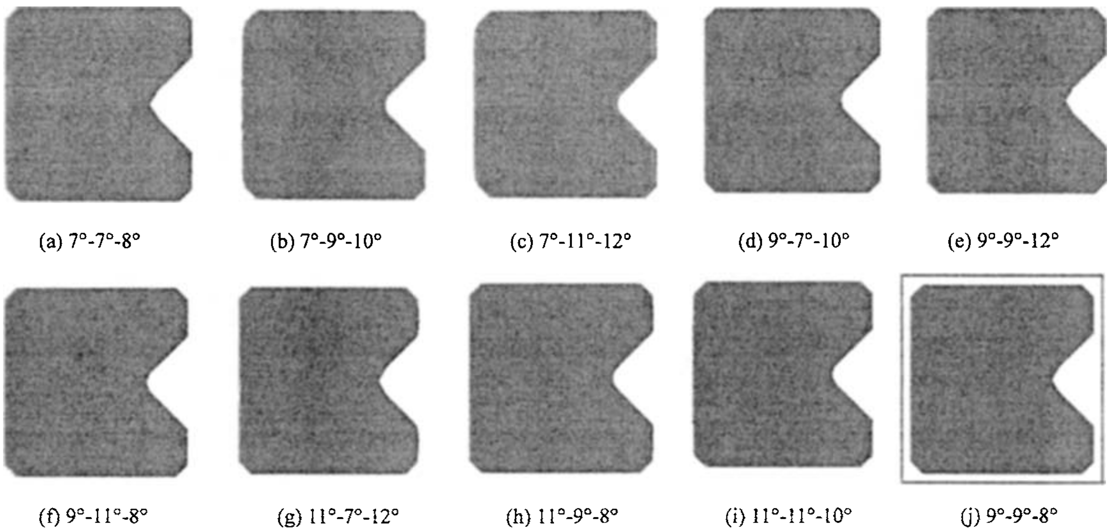


Fig. 6. Comparison of the cross-sectional shape.

into the S/N ratios are summarized in Table 5.

Table 6 shows the parameter response data for the S/N ratio. As shown in Fig. 8, the optimal design parameter settings for the improvement of straightness are as follows; α_1 of 9°, α_2 of 7°, and α_3 of 8°. The result of the optimal design parameters indicating the maximum S/N ratio was verified by the FE-simulation. From the FE-simulation for the optimal parameters, the value of S is 0.01418. The simulation result, which minimizes the least-square deviation for the evaluation of straightness, is transformed into an S/N ratio, with a value of 37.8938.

Table 5. Orthogonal array and S/N ratios to improve straightness.

Experiment No.	α_1(°)	α_2(°)	α_3(°)	S	S/N ratio
1	7	7	8	0.02015	33.9145
2	7	9	10	0.09891	20.0952
3	7	11	12	0.18011	14.8892
4	9	7	10	0.02227	33.0456
5	9	9	12	0.02234	33.0183
6	9	11	8	0.03419	29.3220
7	11	7	12	0.04324	27.2823
8	11	9	8	0.01954	34.1815
9	11	11	10	0.02390	32.4320

Table 6. Parameter response for straightness.

Parameter	α_1	α_2	α_3
Level 1	23.17	30.28	32.16
Level 2	30.75	27.70	27.11
Level 3	29.03	24.97	23.68
Effects	7.59	5.30	8.48
Rank	2	3	1

Fig. 7 shows the x-coordinate value at the sampling positions (see Fig. 3). As shown in Fig. 7, when the die angles are the optimum value, the straightness is the best.

Fig. 8 shows the distribution of velocity in the deformation zone according to the die angles. In Fig. 8, the distribution of velocity depends on the die angles. It can be seen that the distribution of velocity for the optimum die angles is more uniform than that of the other cases. Moreover, the inclination of material at the die inlet displays outstanding differences when compared to each other. The results of the inclination are the same as those of the distribution of velocity. When the die angles are the optimum value, the inclination indicates the minimum value.

In this study, two different objective functions, which are considered as minimum unfilled rate and minimum least-square deviation for straightness, have been chosen for minimization. In addition, the optimal die angles required to satisfy the objective function have been determined.

Table 7 shows the dimensional accuracy and straightness for the two sets of die angles. The case 1, α_1=9°, α_2=7°, α_3=8°, is better than the case 2, α_1=9°, α_2=9°, α_3=8°, considering these two objective functions concurrently. Therefore, case 1 has been considered to have the optimized die angles for the improvement of dimensional accuracy and straightness.

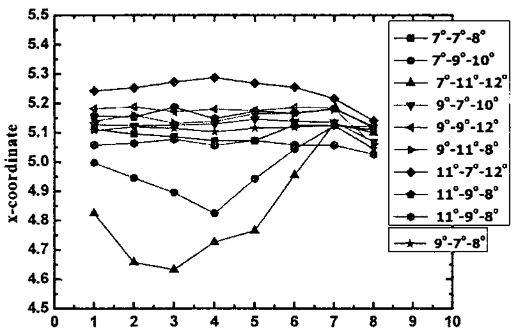


Fig. 7. X-coordinate value at the sampling positions.

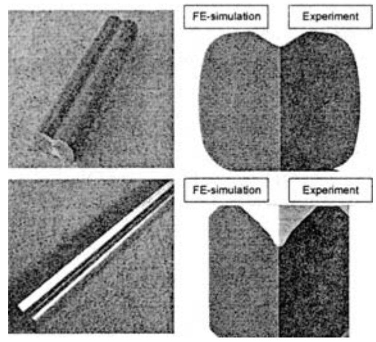
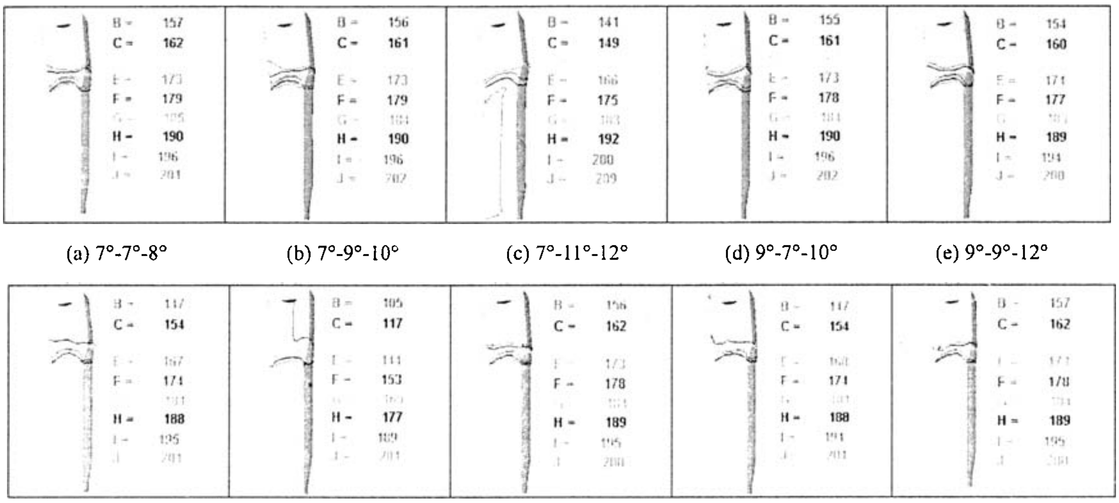


Fig. 9. Comparison of a cross-section between an FE-simulation and experiment.



(a) 7°-7°-8° (b) 7°-9°-10° (c) 7°-11°-12° (d) 9°-7°-10° (e) 9°-9°-12°

(f) 9°-11°-8° (g) 11°-7°-12° (h) 11°-9°-8° (i) 11°-11°-10° (j) 9°-9°-8°

Fig. 8. Distribution of velocity according to the die angles.

Table 7. The unfilled rate and the least-square deviation of the optimized die angles.

Case	α_1(°)	α_2(°)	α_3(°)	U.R	S	Remark
1	9	7	8	1.074	0.01418	best straightness
2	9	9	8	1.072	0.01875	best dimensional accuracy

5. Shaped drawing experiment

In order to verify the result of analysis, shaped drawing experiments using real industrial cold drawing machines have been performed for the selected optimum die angles. Fig. 9 shows the drawn product and the comparison of cross-sectional shape between the FE-simulation and experiment at each stage in the case of the optimum die angles. In Fig. 9, the result of the analysis is in good agreement with the result of the experiment.

6. Conclusions

In this study, the influence of die angles on the dimensional accuracy and straightness of the final drawn product have been investigated in the complex shaped drawing process to produce a cross roller guide. The dimensional accuracy and straightness have been varied according to the die angles. The Taguchi method and FE-simulation were implemented to improve dimensional accuracy and straightness. In a two-stage shaped drawing process to produce a cross roller guide, the die angles (α_1, α_2, α_3) of the second stage have been optimized using the Taguchi method and FE-simulation. The optimum combination of die angles were α_1 = 9°, α_2= 7°, and α_3 = 8°. In order to verify the results of the optimum combination of die angles, shaped drawing experiments were performed and the result was in good agreement with the result of the analysis. Through this investigation, we have clearly demonstrated that the results of the present study are capable of providing reasonable information for the design of optimum die angles to improve the quality of the final drawn product in the complex shape drawing process.

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