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Design of intermediate die shape of multistage profile drawing for linear motion guide †

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Abstract

The design of an intermediate die shape is very important in multistage profile drawing. In this study, two design methods for the intermediate die shape of a multistage profile drawing for producing a linear motion guide (LM) guide is proposed. One is the electric field analysis method using the equipotential lines generated by electric field analysis, and the other is the virtual die method using a virtual drawing die constructed from the initial material and the final product shape. In order to design the intermediate die shapes of a multistage profile drawing for producing LM guide, the proposed design methods are applied, and then FE analysis and profile drawing experiment are performed. As a result, based on the measurement of dimensional accuracy, it can be known that the intermediate die shape can be designed effectively.

Keywords: Multistage profile drawing; Linear motion guide; Intermediate die; Electric filed analysis; Virtual die method

1. Introduction

A linear motion (LM) guide is an important and effective machine part in a linear motion system because the high precision positioning, automation, and energy savings are depends on the qualities of the LM guide [1]. LM guides are widely used in general machines, industrial robots, machine tools, electric devices, and semiconductor manufacturing devices. As shown in Fig. 1, a linear motion guide is a long rail with a constant irregular cross-sectional shape. Because the precision of a linear motion system depends mainly on a linear motion guide, high dimensional accuracy with small amounts of bending and torsion are required. LM guide is manufactured using the multistage profile drawing process. Profile drawing is the most effective method to fabricate profiles with irregular constant cross-sectional shapes. This process allows excellent surface finishes and closely controlled dimensions to be obtained in long products [2]. Moreover, unlike alternative machining processes, this process minimizes the waste of material and improves mechanical properties by strain-hardening [3]. However, the advantages are often reduced because of the high cost of drawing dies and the labor-intensive task of process design. In multistage profile drawing, it is essential to design the proper intermediate die shape in order to produce a sound product.

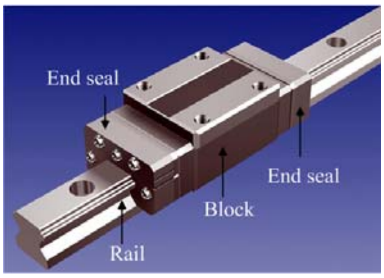

Fig. 1. Photo of LM guide.

Several studies have been carried out about the profile drawing process [2-13]. Until now, studies of the design of intermediate die shapes for multistage profile drawing have not been sufficient, and the design of the intermediate die shape has been done in an intuitive way based upon the experience of industrial experts.

In this study, two methods are proposed in order to design the intermediate die shape of a multistage profile drawing for producing a LM guide: the electric field analysis method, and the virtual die method. The designed intermediate die shapes based on the proposed methods are compared with an actual operation die shape designed by industrial experts. Finally, the proposed design methods are verified by FE analysis and multistage profile drawing experiments, and in order to evaluate

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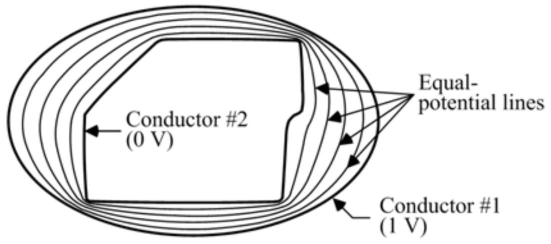


Fig. 2. Electric field analysis.

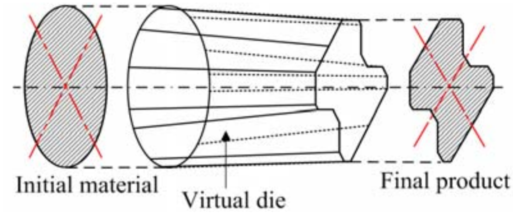


Fig. 3. Construction of a virtual die.

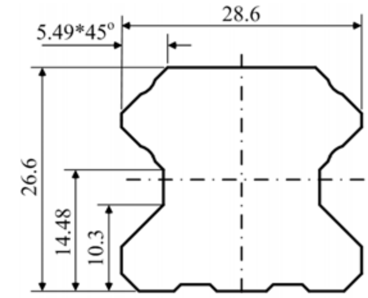


Fig. 4. Cross sectional shape of LM guide (unit: mm).

the dimensional accuracy of the final products, the unfilled areas of the final products are measured by 3D surface profiler.

2. Intermediate die shape design methods

2.1 Electri field analysis method

Yang et al. proposed the electric field theory approach to determine a preform shape in the axisymmetric hot forging process [14]. In this study, electric field analysis was applied to design the intermediate die shape of a multistage profile drawing. As shown in Fig. 2, electric field is generated between two conductors when different currents are applied to each conductor. Then, several equipotential lines with same voltage appear. In the previous study, the equipotential lines showed similar trends as the minimum work paths between two conductors [14]. Based on this tendency, the intermediate die shape is determined by using the equipotential lines between the initial and final product shape and the reduction ratio per pass. The design procedure by using electric field analysis is as follows:

Stage 1. Calculate the cross sectional area of the intermediate die based on the reduction ratio.
Stage 2. Perform the electric field analysis (Initial shape → 1 V, Final shape → 0 V).
Stage 3. Select the equal-potential line which has the same area using the calculated area in stage 1 from the result of the electric field analysis.
Stage 4. The selected equipotential line in stage 3 is set as the intermediate die shape.

2.2 Virtual die method

As shown in Fig. 3, a virtual die can be constructed by connecting the initial material shape and the final product shape. An arbitrary cross section can be obtained by cutting the constructed virtual die. In the virtual die method, the divided section is used to design the intermediate die shape. The procedure of the virtual die method is as follows:

Stage 1. Construct the first virtual die using the initial material shape and the final product shape.
Stage 2. Divide equally the first virtual die according to the pass number.
Stage 3. Calculate the scale factor (*SF*) of each pass that is calculated by the reduction ratio between the divided section in stage 2 and the final shape. The *SF* is calculated as follows:

$$SF = \sqrt{100/(100 - r_i)} \tag{1}$$

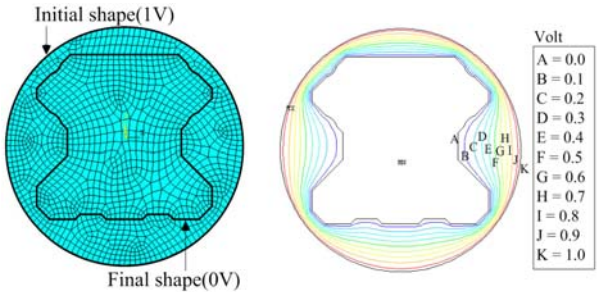
where r_i is the reduction between the divided section and the final shape. In the multistage profile drawing, the local reduction at the groove area should be higher than that of any other area (see Fig. 7).
Stage 4. Magnify the final shape using the calculated *SF* value of each pass. The second virtual die is constructed using the divided section in stage 2 and the magnified final shape.
Stage 5. Divide the second virtual die constructed in stage 4 in half, and select the divided section as the intermediate die shape. In stage 4~5, it is possible to increase the local reduction at groove area without a change of reduction ratio.

3. Intermediate die design of the profile drawing for LM guide

Fig. 4 shows the shape and dimension of the LM guide which is fabricated from an initially round material by three-pass profile drawing at an actual production site. The proposed design methods are applied to design the intermediate die shapes of the three-pass profile drawing to produce the LM guide.

3.1 Application of electric field analysis method

The diameter of the initial material is 38.5 mm in the actual operation. Therefore, the total reduction ratio is about 46.27%. The reduction ratio for each pass of the three-pass profile drawing was calculated using the following iso-reduction



(a) Initial model (b) Result of analysis

Fig. 5. Electric field analysis.

equation [15]:

$$r_{ave} = \left[1-\left(1-\frac{r_t}{100}\right)^{1/n}\right]\times 100 \quad [\%] \tag{2}$$

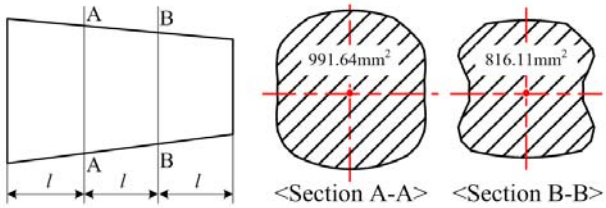
where r_{ave} is the average reduction ratio of an iso-reduction pass, r_t is the total reduction ratio, and n is the pass number. The calculated r_{ave} is 18.70%. Therefore, the areas of the first and the second stages are 946.24 mm^2 and 769.25 mm^2, respectively.

The electric field analysis is carried out using ANSYS V11. The initial model and the results of the analysis are shown in Fig. 5. From the analytical result and the calculated areas, the two equal-potential lines having the same areas as the first and the second stages are selected as the shapes of the intermediate die.

3.2 Application of the virtual die method

Fig. 6(a) shows the first virtual die constructed using the initial material shape and the final product shape. The first virtual die is divided equally into three parts according to the pass number of 3. The divided sections are shown in Fig. 6(b). The areas of the divided sections are 991.64 mm^2 and 816.11 mm^2. Therefore, the reduction ratio of the first stage is 14.82%, and the second stage is 17.70%. In the profile drawing, the local reduction at the groove area must be higher than the other area, as shown in Fig. 7 [16]. The LM guide has a deep groove on both side walls. It is impossible to use the divided sections of the first virtual die as the intermediate die shapes because of insufficient local reduction at groove areas. In order to increase the local reduction at the groove area under the same reduction ratio, the *SF* was introduced (Eq. (1)). In Eq. (1), the r_1 and r_2 of the first divided sections are 36.92% and 23.35%. Therefore, the *SF* values of the first divided sections (Fig. 6(b)) are 1.259 and 1.142, respectively.

In order to increase the local reduction at the groove area, the final product shape is magnified by using the *SF* values as shown in Fig. 8. Then, the second virtual dies of each stage are constructed using the first divided sections (Fig. 6(b)) and the magnified final shape (Fig. 8) like Fig. 3. Finally, the seco nd virtual dies are equally divided, and these divided sections



(a) 1st virtual die (b) Divided sections

Fig. 6. First virtual die and the divided sections.

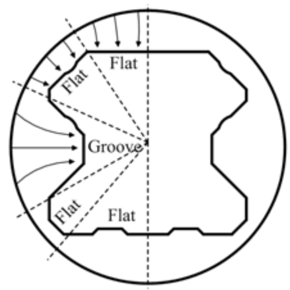


Fig. 7. Different local reduction.

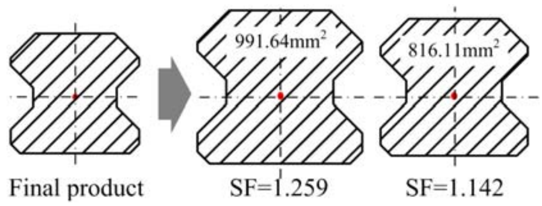


Fig. 8. Magnification of the final shape by using SF values.

are selected as the intermediate die shapes. Fig. 9 shows the divided sections of the second virtual dies. As shown in Fig. 9, it can be seen that the local reduction of the second virtual die is higher than that of the first virtual die at the groove area.

Fig. 10 shows the designed die shapes with the die shapes used at the actual production site. Although there is little difference in shape, the die shapes are similar to the shape used in actual operation. As shown in Fig. 10, when the electric field analysis method was applied, the local reduction at the groove area is higher than that of the actual operation in the first stage. This means the decrease in the unfilled area in the corner of the die because the higher local reduction at groove area promotes the filling of the corner of the drawing die. Table 1 shows the reduction ratios of the three cases.

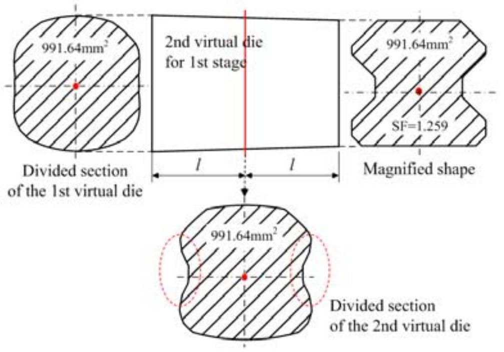
4. FE analysis and profile drawing experiment

4.1 FE analysis

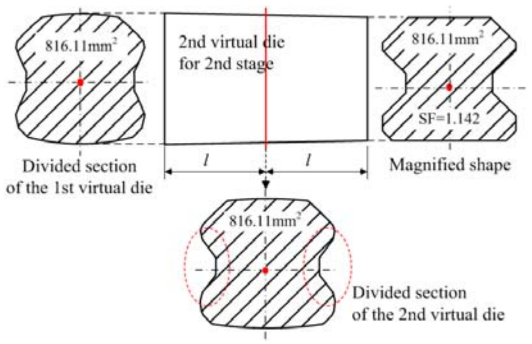
In order to verify the effectiveness of the proposed design methods, FE analysis is carried out. Considering the symmetric plane, a half-section has been analyzed using DEFORM-3D as shown in Fig. 11. The number of elements is about 74,400 and the minimum mesh size is about 0.6 mm. After the analysis, the unfilled area of the final product was measured to evaluate the dimensional accuracy. The flow stress curve of

Table 1. Comparison of the reduction ratios (%).

Method		Electric field	Virtual die	Actual operation
Stage No.	1	18.70	14.82	20.60
	2	18.70	17.70	15.98
	3	18.70	23.36	19.46

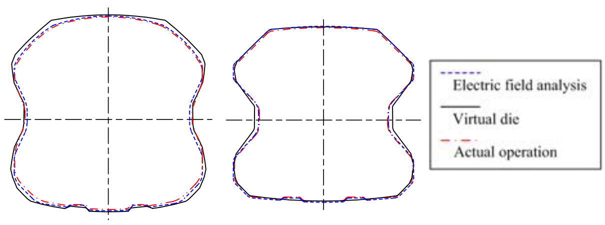


(a) 1st stage



(b) 2nd stage

Fig. 9. Divided section of the second virtual die.

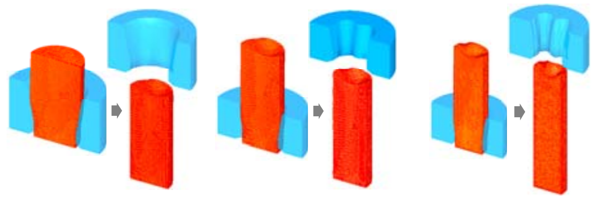


(a) 1st stage (b) 2nd stage

Fig. 10. Comparison of the intermediate die shape.

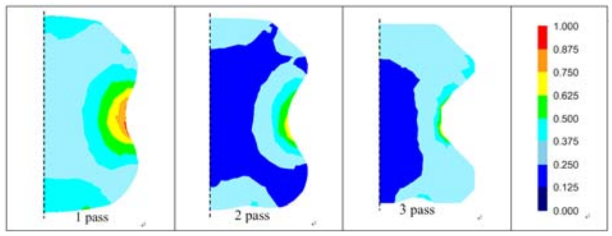
the initial AISI4137 material was obtained through the tensile test. The friction coefficient between the material and the drawing die was set to 0.1 considering the phosphate coating treatment of the material [17], and the drawing speed was 200 mm/s for all stages.

Fig. 12 shows the distribution of effective strain. At the actual operation, to prevent breakage and increase the formability of the drawn material, annealing was performed after every stage. As shown in Fig. 12, the strain for each pass had a similar value, about 0.2~1.0, due to the annealing after each stage. However, the strain in the vicinity of the groove area was

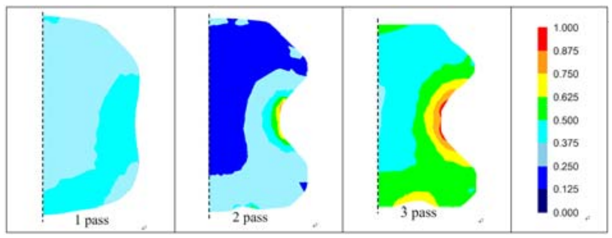


(a) 1st stage (b) 2nd stage (c) 3rd stage

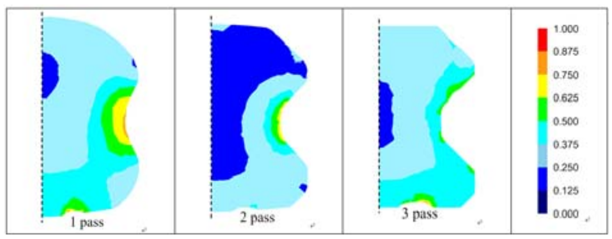
Fig. 11. FE analysis model of profile drawing.



(a) Electric field analysis



(b) Virtual die method



(c) Actual operation

Fig. 12. Distribution of effective strain.

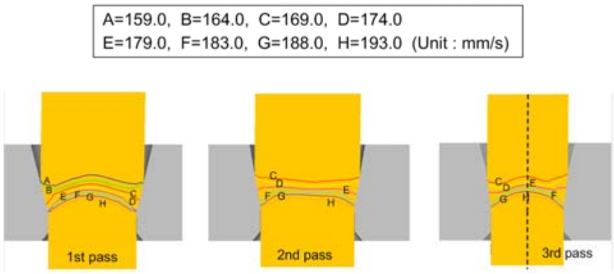
higher than that of the other area because of the higher local reduction.

Fig. 13 shows the distribution of velocity of the material in the deformation zone. As shown in Fig. 13, the proposed design methods results in a more uniform distribution of the velocity. As shown in Fig. 10(a), when the proposed design methods are applied, the reduction of the upper side is higher than that of the lower side as compared with the actual operation. This leads to the increase in contact length between the material and the die, and more uniform material flow in the deformation zone. As a result, the straightness of the final product has been improved [13].

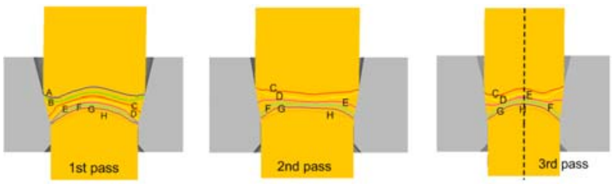
In the profile drawing of the LM guide, the dimensional accuracy of the final product is very important. Dimensional accuracy mainly depends on both the unfilled area of the cross sectional shape, and the torsion or bending of the material.

Table 2. Comparison of the unfilled area (FE analysis).

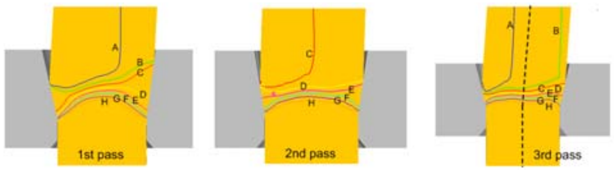
Design method	Electric field	Virtual die	Actual operation
Unfilled Area (mm^2)	1.507	3.171	6.761



(a) Electric field analysis



(b) Virtual die method



(c) Actual operation

Fig. 13. Distribution of velocity in the deformation zone.

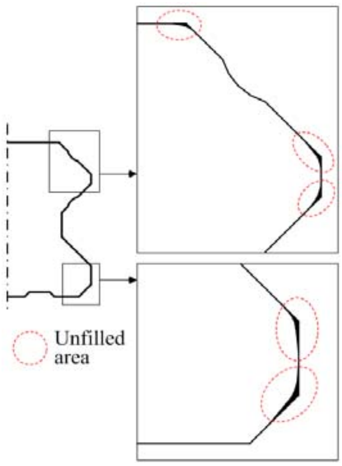


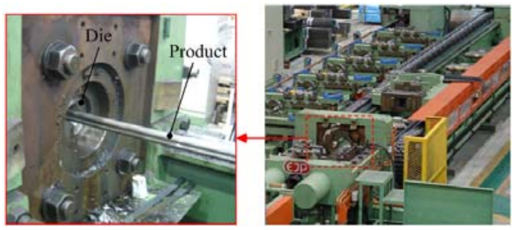
Fig. 14. The unfilled area of the final product.

Fig. 14 shows the FE analysis result for the unfilled area of the final product after the three-stage drawing. The unfilled area was measured in order to evaluate the dimensional accuracy of the final products.

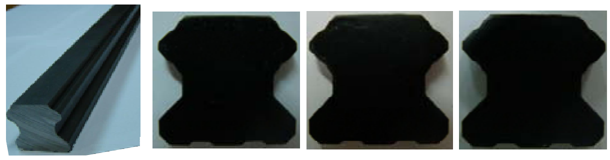
Table 2 shows the unfilled area of the final products. It can be known that the dimensional accuracy is improved when the proposed design methods are applied.

Table 3. Comparison of the unfilled area (experiment).

Design method	Electric field	Virtual die	Actual operation
Unfilled Area (mm^2)	0.250	0.488	0.826



(a) Cold drawing machine



LM guide Electric field Virtual die Actual operation

(b) Final product

Fig. 15. Profile drawing experiment.

4.2 Profile drawing experiment

A multistage profile drawing experiment was performed to verify the effectiveness of the proposed design methods. A cold drawing machine at the actual operation site was used for the experiment. The drawing machine, the final drawn products, and the cross section of the final products are shown in Fig. 15.

After the experiment, the unfilled areas of the final products were measured using a 3-D surface profiler. The measured results are summarized in Table 3. From comparison of the unfilled area between Table 2 and Table 3, although there is some difference between FE analysis and the drawing experiment because of the limited number and size of elements in the FE analysis, the results indicate almost the same tendency. This means that the dimensional accuracy of the final product can be improved when the proposed design methods are applied.

5. Conclusions

In this study, the electric field analysis method and the virtual die method are proposed to design the intermediate die shapes of the multistage profile drawing process. By using the proposed methods the intermediate die shapes are designed for producing a LM guide fabricated using a three-stage profile drawing in the actual operation site.

From the FE analysis result the unfilled area of the final product was measured to evaluate the dimensional accuracy of the final product. When the electric field and the virtual die method were applied, the unfilled area decreased by about

78% and 53% compared with that of the actual operation, respectively.

Finally, the result of FE analysis was verified through a profile drawing experiment performed using the actual drawing machine. Based on the experiment, when the electric field analysis and the virtual die method were applied, the unfilled areas decreased about 70% and 41%, respectively. The difference between FE analysis and the drawing experiment is due to the limited number and size of elements in the FE model. However, the results indicate almost the same tendency.

The design of the intermediate die shape is one of the most important tasks in multistage profile drawing. Previously, this design has been done in an intuitive way based upon the experience of industrial experts, which is expensive and time-consuming. The greatest advantages of the proposed design method is that it is possible to design the intermediate die shape of the profile drawing without excessive labor, reduce costs, and save time regardless of the geometric complexity. Therefore, the proposed methods can help die designers without sufficient practical experience, and can be applied to profile drawing for fabricating various profiles.

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