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Minimum additional material volume prediction for preform product by using abductive network and Taguchi method

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ABSTRACT

Purpose: To predict the minimum value of additional material volume for an acceptable preform product. To predict an acceptable preform product without shape defect such as unfilling in a closed-die forging operation.

Design/methodology/approach: In order to reduce the number of experiments, an orthogonal array from the Taguchi's experimental method will be utilized to design the process parameter combinations for database sets to promote the prediction precision. Also, in order to reduce the number of experiments to get the minimum additional material volume of preform, the abductive network is applied to synthesize the data sets obtained from the numerical simulation.

Findings: The minimum additional material volume can be determined as 7.6% for an acceptable preform product in conjunction with the billet settle position, E, of 11.8 mm and the aspect ratio of width to height, B/H, of 1.4.

Research limitations/implications: The Taguchi method can be used to narrow the ranges of process parameters for database sets which can promote the precision of abductive network to search for the the minimum additional material volume for an acceptable preform product. The abductive network is applied to synthesize the data sets obtained from the numerical simulation of the reduced ranges of the process parameters.

Practical implications: The combination of the abductive network and Taguchi method can be used as a reference and guidance for the development of searching the minimum or maximum value of one of the process parameters, accompanying by the other suitable parameters.

Originality/value: An assessment model of the closed-die forging process is developed using a neural network system and Taguchi method. Based on the developed neural network, the additional material volume of preform product, one of the forging process parameters can be minimum accompanying by the other suitable process parameters to get an acceptable product.

Keywords: Abductive network; Taguchi method; Finite element method; Preform design; Closed die forging

TECHNICAL PAPER

1. Introduction

Preform design is one of the most important aspects in metal forming process design. Defect-free metal flow and complete die filling can be achieved by a properly designed performing operation. Traditionally, the preform design is based on empirical or approximate analysis, requiring time consuming and expensive trial-and–error.

However, it is necessary to perform a lot of numerical simulations for obtaining a suitable range of the process parameters for producing an acceptable product on metal forming process. In order to reduce the number of finite element simulation, Lapovok et al. [1] proposed an apprach to optimising the design of preforms for metal working operations. G. Zhao et al. [2, 3] presented inverse die contact tracking method utilizing both the forward and inverse finite element method to design the preform shapes in forging process. Lee et al. [4] studied the formability estimation of deep drawing process by using Taguchi method. Poy et al. [5] proposed a new approach to optimal design of multi-stage metal forming processes with micro genetic algorithms. Lorenzo et al. [6] proposed an inverse approach for the design of the optimal preform shape in cold forging using a response function which links the set of parameters defined the perform shape with the fulfilment of the product design specifications. Lee et al. [7] proposed a modelling drilling process using the abductive network. Yang et al. [8] used the Taguchi method to design optimization for quality to find the optimal cutting parameters in turning operations. Ko et al [9, 10] described a new method of preform design in multi-stage metal forming processes considering workability limited by ductile fracture. Kim et al. [11] applied the artificial neural network in metal forming processes. Zhao et al. [12] used the FEM-based inverse die contact tracking method to design the preform shape for a representative plane-strain cross section of the track link block forging. Ohdar et al [13] proposed an artificial neural network approach for exploring the predition of powder metallurgy process parameters. The authors [14] established a prediction model for predicting the minimum wall thickness and the protrusion height on the T-shape tube hydroforming process, using the finite element method in conjunction with abductive network.

In this paper, the use of the abductive network in conjunction with Taguchi method is presented to predict the minimum additional material volume of preform billet for an acceptable product without shape defect such as unfilling in closed-die forging process.

2. Method of analysis

The finite element method has been applied to simulate the plastic flow of workpiece materials during the closed-die forging process. For the closed die forging process of a plastic deformation problem, the governing equations for the solution of the mechanics in plastic deformation for rigid-plastic and rigid-viscoplastic materials involve equilibrium equations, yield criterion, constitutive equations and compatibility conditions.

A commercial FE code DEFORM-2D Version 7.2 [15] is adopted to analyze the plastic deformation of the isothermal closed-die forging of a golf-head section.

In an abductive network, a complex system can be decomposed into smaller, simpler subsystems grouped into several layers using polynomial functional nodes. The polynomial network proposed by Ivakhnenko [16] is a group method of data handling (GMDH) techniques. These nodes evaluate the limited number of inputs by a polynomial function and generate an output to serve as an input to subsequent nodes of the next layer.

3. Problem statement

The schematic diagram of the isothermal closed-die forging for a golf-head part section is shown in Fig. 1. In this process, an upper die moves downwards toward a rectangular shape preform billet whilst the lower die is stationary, the preform billet is forged subsequently into a part section at temperature of 925°C. During the analyses, the upper and lower dies are assumed to be rigid, whereas the preform billet is assumed to be plastic. The flow stress of the billet material, Ti6Al4V, is $\bar{\sigma} = 72.70\bar{\varepsilon}^{0.0256}$ MPa at temperature of 925°C, and the constant shear friction factor, m, is assumed as 0.25 at the interface between the workpiece and die. The velocity of the upper die, V_d, is set as 10 mm/s downwards, and its stroke is set according to the flash height of the forging reached 2.0 mm. In this study, an acceptable preform product, the detail dimensions of the product are shown in Fig. 2, which should be with unfilled region volume less than 0.5 %.

In this analysis, a preform billet with a simple rectangular cross section is utilized and the billet geometrical parameters to be adjusted can be summarized as follows:

a) The settle position of the billet, E, is defined as a location distance from the right side of the left boss in lower die to the left margin of the billet as indicated in Fig. 1;
b) The aspect ratio, B/H, represents a ratio of the width to height;
c) The additional material volume, δ%, is defined as a percentage of the extra volume necessarily to compensate the flash loss to ensure die cavity filling. Therefore, $\delta\%=(V_o-V_p)/V_p$, V_o and V_p represent the preform billet and preform product volumes, respectively.

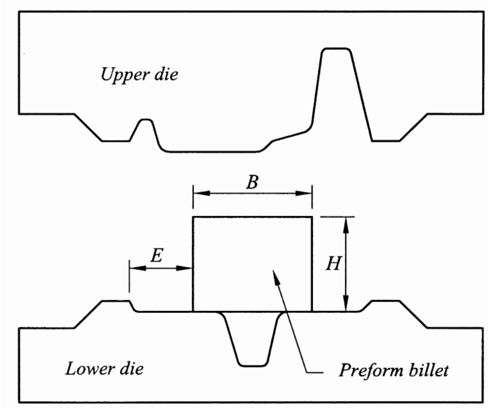


Fig. 1. The schematic diagram of the isothermal close-die forging of a golf-head part section

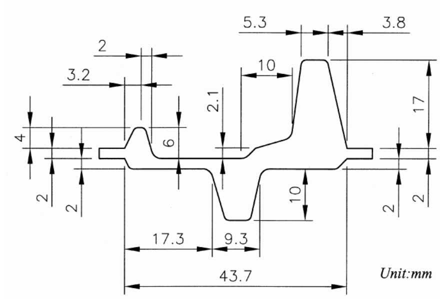


Fig. 2. The geometrical dimensions of a forged golf-head product

The process parameters are selected by varying the variable position E, the aspect ratio B/H and the additional material volume δ% of perform and they are set in the ranges of 10.5-12.5 mm, 1-1.4 and 5-15, respectively. Hence, there are three process variables and each one is set at three levels (Table 1).

The unfilled volume, U^*, is expressed as an insufficient volume amount to fill a complete preform product die cavity. For an acceptable product, the unfilled volume, U^* should be less than or equal to 0.5%.

4. Results and discussion

According to the orthogonal array of the Taguchi method, 9 simulations of forming condition sets are carried out in this study first. Table 2 shows the FEM simulation results of the unfilled volume percent, U^*, for various combinations of process parameters. The acceptable product has to be fit the unfilled volume requirement, i.e. $U^* \leqq 0.5\%$. For example, the formed product shown in Figure 3(b) is an acceptable product because of $U^* \leqq 0.5\%$, whereas that shown in Figure 3(a) is an unacceptable product because of $U^*>0.5\%$.

Table 3 shows the factor effects on each process parameter at different levels. The larger position E, the larger aspect ratio B/H and the larger additional material volume δ% of the perform billet, the smaller is the unfilled volume U^*. This distribution trend can be clarified from the results shown in Table 3.

Table 1.
Data sets of Taguchi method for various combinations of process parameters

Process parameter	Level 1	Level 2	Level 3
E	10.5	11.5	12.5
B/H	1.0	1.2	1.4
δ%	5	7.5	10

Table 2.
Data sets for various combinations of process parameters (Taguchi orthogonal array) and the FEM simulation results

No.	E	B/H	δ%	U%
1	10.5	1.0	5	8.11
2	10.5	1.2	10	2.37
3	10.5	1.4	15	0.35
4	11.5	1.0	10	1.75
5	11.5	1.2	15	0.34
6	11.5	1.4	5	2.69
7	12.5	1.0	15	0.35
8	12.5	1.2	5	1.75
9	12.5	1.4	10	0.61

Table 3.
The factor effect

Level	E	B/H	δ%
1	3.61	3.4	4.18
2	1.59	1.75	1.58
3	0.9	1.22	0.35
Effect	2.71	2.18	3.83

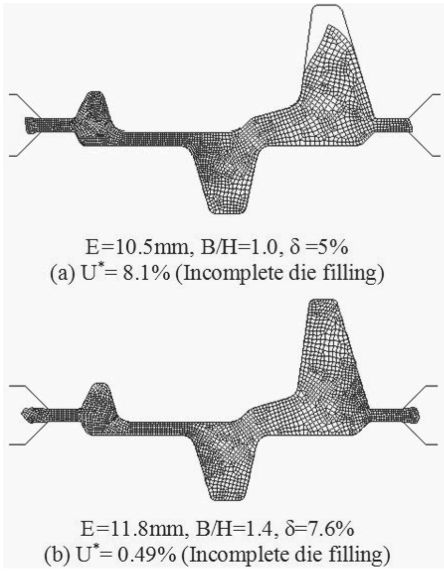


Fig. 3. Some sectional profiles of the forged product for various process parameter combinations; (a) unacceptable products, (b) an acceptable products

From the above analysis relative to the factor effects, the process parameter ranges may be furthermore narrowed, i.e. E from 10.5-12.5 to11.5-12.5, B/H from 1.0-1.4 to1.2-1.4 to build a database of process parameter combination, which can promote the precision for searching the minimum value of additional material volume comparing with the original settings of the process parameters. Therefore, 27(3×3×3) combinations of process parameters are chosen for the database sets shown in Table 4. From the numerical simulation results with the conditions shown in Table 4, a two-layer network shown in Fig. 4 is built for predicting the unfilled volume U^* from the above database sets.

The established network can be utilized to predict the minimum value of additional volume within a small region. By selecting a proper δ% with a small interval change of E or B/H as shown in Figure 5. A small region that satisfies the condition of

Table 4.
Data sets for various combinations of process parameters (narrowed range) and the FEM simulation results

No	E	B/H	δ%	U^*%	No	E	B/H	δ%	U^*%
1	11.5	1.2	5	3.49	15	12	1.3	10	0.35
2	11.5	1.2	7.5	2.02	16	12	1.4	5	2.19
3	11.5	1.2	10	0.84	17	12	1.4	7.5	0.64
4	11.5	1.3	5	3.15	18	12	1.4	10	0.34
5	11.5	1.3	7.5	1.50	19	12.5	1.2	5	2.11
6	11.5	1.3	10	0.35	20	12.5	1.2	7.5	1.76
7	11.5	1.4	5	2.69	21	12.5	1.2	10	0.44
8	11.5	1.4	7.5	1.26	22	12.5	1.3	5	2.27
9	11.5	1.4	10	0.34	23	12.5	1.3	7.5	1.16
10	12	1.2	5	2.39	24	12.5	1.3	10	1.10
11	12	1.2	7.5	1.10	25	12.5	1.4	5	1.97
12	12	1.2	10	0.36	26	12.5	1.4	7.5	1.20
13	12	1.3	5	1.89	27	12.5	1.4	10	0.60
14	12	1.3	7.5	0.79					

$U^* \leqq 0.5\%$ may be searched for. The minimum value of additional volume is 7.6% existing at B/H=1.4 and E around 11.8, as shown in Fig. 5(b). On the contrary, if δ% is selected as 7.5 the qualified product criterion, $U^* \leqq 0.5\%$, can not be attained regardless the variations of E and B/H as shown in Fig. 5(a).

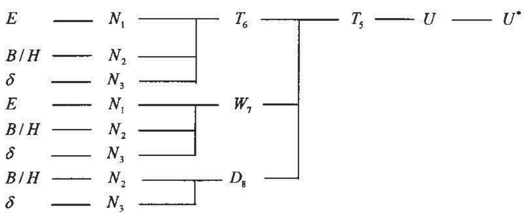
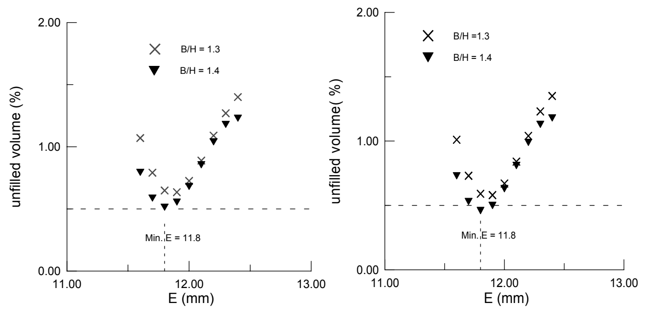


Fig. 4. Abductive network for predicting unfilled volume



(a) δ =7.5% (b) δ =7.6%

Fig. 5. The relationship among settle position, E, aspect ratio, B/H, and unfilled volume, U^*, at different additional material volumes of δ =7.5% and δ =7.6%

In order to validate the accuracy of the prediction model, the predicted result of the unfilled volume 0.46% are consistent with the FEM simulations result of unfilled volume 0.49%. Therefore, the developed networks have a reasonable accuracy for the modelling of isothermal closed-die forging process about the minimum value of the additional material volume for an acceptable product prediction.

5. Conclusions

In this paper, the use of the abductive network in conjunction with Taguchi method is presented to predict the minimum value of additional material volume for an acceptable preform product without shape defect such as unfilling in a closed-die forging operation. Different settle position of billet combining with various aspect ratios of width to height, and various additional material volumes of preforms are also accounted for as the process parameters in this study. A finite element method based code is utilized to investigate the material flow characteristics under various process parameter combinations. The Taguchi method can be used to narrow the ranges of process parameters for database sets which can promote the precision of abductive network to search for the minimum additional material volume for an acceptable preform product. The abductive network is then applied to synthesize the data sets obtained from the numerical simulation of the reduced range. A prediction model is established for predicting the minimum additional material volume, one of the process parameters, for producing an acceptable product.

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