3D preform design in forging process based on quasi-equipotential field and response surface methods

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Abstract

A new approach to optimize 3D preform shape in multi-step die forging based on Quasi-equipotential Field Method and Response Surface Method is proposed. Using the proposed method, the optimized preforging shape is determined in the hot forging of the pendulum mass. Based on the optimized preforging shape, the advisable blocking blank is constructed. The final perform design, including the advisable blocking blank and preforging shape, is completed. The desired pendulum mass forging without any defects and with smaller flash is obtained.

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Key words: Preform optimization design; Quasi-equipotential field method; Response surface method; Forging process

1. Introduction

Forging is one of primary material forming processes. Generally, one or more preform steps are necessary before the final forging step. Designs of the number of the preform step and preform shapes are fundamental and difficult for the design of forging processes and dies.

Up to now, many researchers paid more attentions to preform design and proposed many preform optimization design methods [1-4]. Lee et al. [5] presented a new approach to perform design in hot forging by using electric field method, also termed quasi-equipotential field method. The equipotential field between the initial and final shapes of different voltages can be used to simulate the minimum deforming paths between the undeformed shape
and the deformed shape. Meanwhile, the reasonable initial volume and potential value of the electric field is gotten by the artificial neural network. The preform designs of three types of typical axisymmetrical forgings are completed. Wang [6] employed the quasi-equipotential field method to design the proper preform for producing isothermal forged superalloy disks. The practical applications have shown the quasi-equipotential field method is an effective method of preform design in hot forging. However, it is still different for the perform design in multi-step forging of complex parts. Aiming at the two problems, a new approach to optimize 3D preform shape in multi-step forging is proposed and used to realize the preform optimization design of a pendulum mass forging.

The pendulum mass forging (Shown in Fig. 1) is a complex part used in construction machinery. The material of the complex part is 40Cr. Shown in Fig. 1, the dimension of the forging is 412 mm × 342 mm × 173.4 mm. The maximum area at A-side is 28.76 times of the minimum cross-sectional area at B-side. In practice, the forging is easy to generate underfill and lap defects shown as in Fig. 2.

2. Electrostatic field simulation and equipotential surface extraction

2.1. Electrostatic field simulation

During electrostatic field analysis, the initial shape is the outer contour of the cylinder billet with the dimension of φ220 × 124 mm (height/diameter ratio is 0.564.). The final shape is the outer contour of the finish forging. Based on the symmetry principle, half of the geometric model is taken as the researching objective. Ansys12.0 is employed to numerically analyze the electrostatic field. The material property is defined as the air and the relative dielectric constant is 1.0. The 10-node tetrahedral element Solid123 is selected when the discretization of the geometric model. 0V and 1V Voltages are applied to the outer contours of the finish forging and the enlarged billet, respectively. Fig. 3 shows the FEM model of electrostatic field analysis.

Fig. 4 gives the distribution contour of equipotential surfaces. Obviously, there are numerous equipotential surfaces with different electric potential values between outer contours of the finish forging and the enlarged billet. There is a minimum equipotential surface that can be extracted to regard as the optimized preforging shape among numerous equipotential surfaces.
2.2. Equipotential surface extraction

Taking the extraction of the equipotential surface with 0.01V potential value as an example, the width along the Y direction of the equipotential surface is about 178.2 mm. Equipotential lines that are parallel to the XZ coordinate plane and are within 0-178.2 mm are extracted. The interval is 10 mm, and then 19 equipotential lines are extracted. Based on the equipotential lines, equipotential surface and corresponding CAD model are obtained by means of the cross section curve lofting method of the UG NX software. The results are shown in Fig. 5.

Fig. 5. Equipotential surface extraction (potential value $\Phi = 0.10$ V): (a) Extracted equipotential lines   (b) Extracted equipotential surface and CAD model.

3. Preforging shape optimization based on Quasi-equipotential Field Method and Response surface analysis

3.1. Central composite design of experiment

Potential value $\Phi$ of equipotential surface and volume ratio $R_v$ between the pre-forging and finish forging are selected as optimization design variables. The lower and upper limits of $\Phi$ are 0.02V and 0.18V, respectively, and the optimization range of $R_v$ is 1.00-1.20.

The Central Composite Design method is used to complete the experimental design with two factors and five levels for the response surface analysis. Values of the experimental factor levels are shown in Table 1. Using the central composite experimental design method, 13 groups of experiments are arranged. According to the distribution of experimental points and experimental schedule, FEM simulation experiments are conducted. The experimental schedule is shown as Table 2. The forging filling rate $\xi$ [5] is taken as the response function $R_I$.

| Experimental factors | Level values |
|----------------------|--------------|
|                      | $-\alpha$    | -1 | 0 | 1 | $+\alpha$ |
| A $R_v$              | 1.00         | 1.03 | 1.10 | 1.17 | 1.20 |
| B $\Phi(v)$          | 0.02         | 0.043 | 0.10 | 0.157 | 0.18 |
3.2. Experiments based on FEM simulation

Firstly, extract five equipotential surfaces with different potential value \( \Phi \) listed in Table 1, CAD models of corresponding equipotential bodies can be obtained, and they can be used as preforging shape of the pendulum mass forging. After being enlarged according to the required volume ratio \( R_v \), five CAD models are saved in the form of *.stl and are imported into Deform3D software to simulate the final forging process of the pendulum mass. Subsequently, the forging filling rate \( \xi \) in different simulation experiments can be calculated by means of analyzing the shape different between the finish forging and the ideal forging.

3.3. Response surface analysis

Table 2 gives the calculation results of the forging filling rate \( \xi \) for different FEM simulation experiments. The 13 groups of the experimental data are regarded as sampling points of the response surface analysis, a second-order response surface regression model between the objective response \( \xi \) and design variables \( \Phi \) and \( R_v \) is established.

Table 2. Experiment schedule and calculation results.

| Experiment No | Factor A: \( R_v \) | Factor B: \( \Phi \) | Response R1: \( \xi \) |
|---------------|---------------------|---------------------|---------------------|
| 1             | 1.17                | 0.04                | 1.0706              |
| 2             | 1.00                | 0.10                | 0.9218              |
| 3             | 1.10                | 0.10                | 0.9886              |
| 4             | 1.03                | 0.16                | 0.9291              |
| 5             | 1.10                | 0.10                | 0.9886              |
| 6             | 1.20                | 0.10                | 1.0458              |
| 7             | 1.10                | 0.02                | 1.0273              |
| 8             | 1.10                | 0.10                | 0.9886              |
| 9             | 1.10                | 0.18                | 0.9697              |
| 10            | 1.17                | 0.16                | 1.0071              |
| 11            | 1.10                | 0.10                | 0.9886              |
| 12            | 1.03                | 0.04                | 0.9743              |
| 13            | 1.10                | 0.10                | 0.9886              |

\[
\xi = -0.0877 + 1.3348R_v + 0.4641\Phi - 1.1438R_v\Phi - 0.2738R_v^2 + 1.8691\Phi^2. \tag{1}
\]

The fitting degree of the regression model is 99.37\%. The standard deviation S is less than 0.0045. Thus, the regression model has higher prediction accuracy and can better describe the response of the objective function \( \xi \) to the design variables \( \Phi \) and \( R_v \). The results indicate the influence of the volume ratio \( R_v \) of the forging filling rate \( \xi \) is significantly larger than the other parameters.

3.4. Results and discussion

Taking 1.0 as the forging filling rate \( \xi \), the software Design-Expert provides 9 groups of best combinations of \( \Phi \) and \( R_v \) shown in Table 3. In order to fill the final forging die cavity at A-side, metals had better fill up the die cavity by means of upsetting mode in the course of the final forging step. Thus, it should make the A-side of the preforging contact the die cavity at the beginning of the final forging step so as to restrict the radial flow of metals and force metals fill the die cavity. The more appropriate equipotential value should less than 0.1 V.

According to the Table 3, the best combination of experimental factors is 0.074 V potential value and 1.10 initial volume ratio. Extracting the equipotential surface with 0.074 V potential value, the optimized preforging shape of the pendulum mass forging is shown as Fig. 6.
4. Design of blocking blank

4.1. Longitudinal and cross section curves method

Shown in Fig. 6, the preforging shape is split into two parts along the central plane (YZ coordinate plane) of the preforging die cavity, and the volume ratio between the part A and B is 1.944. Obviously, the volume difference between the part A and B of the preforging shape is still great. Therefore, a blocking step is necessary before the preforging step. A longitudinal- and cross-section curves method is introduced to design advisable blocking blank.

Supposing that blocking blank is a symmetric solidbody with the same cross-section, the longitudinal- and cross-section curves are designed according to certain rules, and then the two sets of curves are extruded as two solidbodies, respectively. The intersection of the two solidbodies is the blocking blank.

Table 3. The best combination of experimental factors in response surface analysis.

| No. | Factor A: $R_v$ | Factor B: $\Phi$ | Response $R_1$: $\xi$ | Satisfaction-degree |
|-----|----------------|-----------------|----------------------|---------------------|
| 1   | 1.07           | 0.04            | 1.00                 | 1.00                |
| 2   | 1.08           | 0.05            | 1.00                 | 1.00                |
| 3   | 1.09           | 0.060           | 1.00                 | 1.00                |
| 4   | 1.10           | 0.074           | 1.00                 | 1.00                |
| 5   | 1.11           | 0.088           | 1.00                 | 1.00                |
| 6   | 1.12           | 0.096           | 1.00                 | 1.00                |
| 7   | 1.13           | 0.116           | 1.00                 | 1.00                |
| 8   | 1.14           | 0.135           | 1.00                 | 1.00                |
| 9   | 1.15           | 0.15            | 1.00                 | 1.00                |

Fig. 6. Optimized preforging shape of pendulum mass forging (half).

4.2. Blocking blank design

In order to realize the reasonable dispensation of metals to solve the underfilling problem at A-side of the pendulum mass forgings, the volume ratio between the left and right parts for blocking blank should be similar to the preforging shape and is 1.944 or so. The designed curve sets of longitudinal- and cross-sections of the blocking blank are given in Fig. 7 and the corresponding solidbody is the blocking blank shown as in Fig. 8. The volume ratio between the left and right parts for the blocking blank is 1.938.

5. Result of preform optimization

Based on quasi-equipotential field method and response surface analysis, the final perform design of the pendulum mass forging is completed. The advisable forging process includes blocking, preforging and final forging steps. The initial blank is a $\Phi 216 \, \text{mm} \times 123 \, \text{mm}$ round bar.

According to the final perform design, the FEM simulation and practical experiment have been implemented. A 40000 kN friction screw press is employed in the preforging and final forging steps. Fig. 9 gives the FEM simulation and experimental results of the final forging step. Obviously, after two-step preforming that includes
blocking and preforging steps, the die cavity is fully filled up in the final forging. The desired pendulum mass part with good quality and without any defects is obtained.

Fig. 7. Designed longitudinal- and cross-section curve sets of the blocking blank: 1-blocking blank; 2-preforging die.

Fig. 8. CAD model of designed blocking blank (half).

Fig. 9. Simulation and experimental results of finish-forging: (a) filling result of simulation; (b) finish-forging.

6. Conclusions

A new method to optimize 3D preform shape in multi-step die forging is proposed. Firstly, optimum preforging shape is determined based on quasi-equipotential field method and response surface optimization. Secondly, longitudinal- and cross-section curves method is introduced to design advisable blocking blank in accordance with the optimized preforging shape. Using the proposed method, the preform optimization design for the hot forging of the pendulum mass is realized. The desired pendulum mass forging without any defects and with smaller flash is obtained. The proposed method is very effective for the preform design in forging process of complex parts.

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