Multi-objective preform optimization for spherical hinge mandrel based on response surface methodology

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Abstract: The multi-objective optimization was studied in application of response surface method and orthogonal design for a preform design of vehicle thrust rod spherical hinge mandrel. Firstly, taking deformation uniformity and mold filling completeness as objectives, then an orthogonal experiment was designed to acquire main factors which influence total deformation quality. The effects of two main factors were precisely predicted through MATLAB and the results were discussed by optimal graphics. Secondly, on basis of optimized results, a second-order response surface model was established through equant design. The model was designed for preform re-optimization taking lower forging load and mold maximum effective stress as objectives. In application of preform optimization method, the best polytechnic parameters were selected, and qualified products were produced.

Spherical hinge mandrel which serves in poor environment for long time is pivotal stressed member of vehicle thrust rod. And, medium carbon steels which have better integrated mechanical properties are often selected to the part, such as 40Cr, 42CrMo. The forging is vulnerable to macro-defects in the deformation, like fold, crack and gap. Meanwhile, it is easy to result in uneven deformation in different degrees due to forging section mutation. The application of preform optimization which effectively control and optimize forging quality, on one hand, ensures materials fill the mold cavity completely; on the other hand, enhance the uniformity of forging microstructure.

In the recent, many scholars at home and abroad have conducted a large aggregation of studies on preform optimization of forging process. Sedighi M and Tokmechi[1] developed a new algorithm for preform design of complex parts by combining parameters design with FVM (Finite Volume Method). In domestic, Zhao X H et al. [2] first utilized sensitivity analysis method to optimize the preform design in forging process taking net shape and higher forging deformation uniformity as objectives, and it turned out to be well-performed.

With great differences to the methods above, in 1951 Box and Wilson put forth RSM (Response Surface Methodology). As a result of its advantage in optimization of complex problem and possibility of being applied in volume forming field, Yang Y H [3] explored the application of RSM in optimization of volume forming and accomplished preform optimal design based on RSM.

On basis of previous studies, objective functions were established in this paper by combining orthogonal design with numerical simulation. Relations between response and design variable were described in prediction second-order model of RSM. Then, the paper conducted preform re-design in
aim on lowering finish-forging load and mold maximum effective stress. Eventually, multi-objective optimal problems of vehicle thrust rod spherical hinge mandrel were discussed.

Figure 1. Schematic drawing of spherical hinge mandrel forging.

1. Spherical hinge mandrel process route

“l” type thrust rod spherical hinge mandrel forging which made up of core, spindle and ball stud is shown in Figure 1, and different parts have various section shapes. In practical production, forgings of this kind are produced in method of closed die and open die forging. In consideration of cost, the process route discussed in this paper is designed in open die forging machine, and the whole steps are presented in Figure 2.

Figure 2. Process flow of spherical hinge mandrel.

2. Objective function

2.1. Forging mold-filling ratio P

The forging mold-filling objective function P is defined as follows [4]:

\[ P = \frac{A}{A_0} \]  

In formula: \( A \) means contact area between blank and mold cavity; \( A_0 \) means contact area the time materials totally fill mold cavity. \( P \) is a LTB (Larger-The-Better) objective function, and \( 0 \leq P \leq 1 \).

2.2. Deformation uniformity S

The objective function \( S \) of forging deformation uniformity is defined as follows [4]:

\[ S = \frac{\sum_{i=1}^{n} |\bar{\varepsilon}_i - \bar{\varepsilon}_{avg}|}{n \bar{\varepsilon}_{avg}} \]  

In formula: \( \bar{\varepsilon}_{avg} \) means forging entire element average effective strain; \( \varepsilon_i \) means effective strain of element \( i \); \( n \) means element number. \( S \) is a STB (Smaller-The-Better) objective function, and \( S > 0 \).
2.3. Integrated deformation function

In solution to problems of multi-objective optimization, linear weighting is one of simple and effective methods to construct integrated objective function. Integrated objective function is defined as follows:

\[ f = 0.7 \times (1 - P) + 0.3 \times S \] (3)

The reasons for selection of weighting coefficients which reflects mold-filling ratio and deformation uniformity as 0.7 and 0.3 respectively are based on following considerations: (1) In calculation of optimization and practical production, it is easy to realize completely filled forging compared to higher deformation uniformity; (2) Well-filled forging is essential requirement of forging deformation, and forging deformation uniformity is designed to be advanced in this premise as well as possible [4].

2.4. Design variable

In design of perform optimization, the shape of preform blank is generally described by B-spline. In order to avoid the emergence of more control points in spline in the description for complex shape, the forging is divided into two simple sections according to the forging shape shown in Figure 1. Geometry of 1/2 preform blank has been shown in Figure 3. Section 1 is a column, geometrical parameters are diameter and length, respectively written as \( D_1 \) and \( L_1 \); section 2 is a parallelepiped, geometrical parameters are length, width and height, respectively written as \( L_2 \), \( B \), and \( H \). A radius \( R \) is of transition between section 1 and section 2, and the default value of \( R \) is set to 5mm to reduce the numbers of parameters. In the premise of constant volume, the variables designed in this paper were normalized through proportional relation of geometrical parameters. The relations between selected design variables \( a, b, c, d \) and parameters which describe preform blank are \( a = V_1 / V \), \( b = L_1 / D \), \( c = B / D \), \( d = H / B \).

![Figure 3. Schematic drawing of preform blank geometric parameters.](image)

3. Design of experiments

3.1. Design and results of experiment

The design of experiments with four-factor, three-level orthogonal table and reference of approximate proportion of different geometrical parameters of finish-forging \( a = 0.45, b = 0.32, c = 0.64, d = 0.6 \), and the values of variables were designed larger to facilitate finish-forging deformation. As a result, the setting of factors and levels has been shown in table 1, experiment programs and results are shown in table 2. In order to reduce the time, the simulations were conducted with 1/8 of 3D model by Deform-3D software, and several relevant parameters of FEM simulation are shown in table 3.
Table 1. Factors and levels.

| Levels | Factors | a(V₁/V) | b(L₁/D) | c(B/D) | d(H/B) |
|--------|---------|---------|---------|--------|--------|
| 1      |         | 0.5     | 0.3     | 0.6    | 0.5    |
| 2      |         | 0.6     | 0.4     | 0.7    | 0.6    |
| 3      |         | 0.7     | 0.5     | 0.8    | 0.7    |

Table 2. Design program and results.

| Trial Number | a(V₁/V) | b(L₁/D) | c(B/D) | d(H/B) | P     | S     | f     |
|--------------|---------|---------|--------|--------|-------|-------|-------|
| 1            | 0.5     | 0.3     | 0.6    | 0.5    | 0.7908| 0.8229| 0.3933|
| 2            | 0.5     | 0.4     | 0.7    | 0.6    | 0.9462| 0.6475| 0.2319|
| 3            | 0.5     | 0.5     | 0.8    | 0.7    | 0.5455| 0.5974| 0.4974|
| 4            | 0.6     | 0.3     | 0.7    | 0.7    | 0.7464| 0.6407| 0.3697|
| 5            | 0.6     | 0.4     | 0.8    | 0.5    | 0.7970| 0.6212| 0.3285|
| 6            | 0.6     | 0.5     | 0.6    | 0.6    | 0.4820| 0.6885| 0.5692|
| 7            | 0.7     | 0.3     | 0.8    | 0.6    | 0.7034| 0.6128| 0.3915|
| 8            | 0.7     | 0.4     | 0.6    | 0.7    | 0.7789| 0.6578| 0.3521|
| 9            | 0.7     | 0.5     | 0.7    | 0.5    | 0.7651| 0.7124| 0.3782|

| K₁          | 0.374   | 0.385   | 0.438   | 0.367  |
| K₂          | 0.422   | 0.327   | 0.327   | 0.398  |
| K₃          | 0.374   | 0.482   | 0.406   | 0.406  |
| R           | 0.048   | 0.178   | 0.111   | 0.039  |

K₁, K₂, K₃ are values of each level, and R are ranges.

To filtrate key factors which influence quality assessment criteria, it is easy to find out R₃>R₂>R₁>R₄ in Figure 4, namely, L₁/D influences integrated deformation mostly while H/B least.

Figure 4. Influence of design variables.
5. RSM model
The response second-order prediction model optimization Figure is plotted by rstool tool in MATLAB language, shown in Figure5. From optimization Figure, the optimum of a \( \left( \frac{V_1}{V} \right) \) is 0.55, the optimum of b \( \left( \frac{L_1}{D} \right) \) is within limits of 0.35 to 0.4, the optimum of c \( \left( \frac{B}{D} \right) \) is within the limits of 0.7 to 0.75, the optimum of d \( \left( \frac{H}{D} \right) \) is 0.5.

To explore the influence of b \( \left( \frac{L_1}{D} \right) \), c \( \left( \frac{B}{D} \right) \) on finish-forging further, re-design of preform optimization of spherical hinge mandrel is in response of finish-forging load and mold maximum effective stress. The trials are designed on octagon equant factors which center on b of value 0.375 and c of value 0.725, the range of variable values: 0.35≤b≤0.4, 0.7≤c≤0.75. Nine trial points are selected in random to conduct numerical simulations, and variables are coded by formula (4), the results are shown in table 4.

\[
x_1 = \frac{b - 0.375}{2}, \quad x_2 = \frac{c - 0.725}{2}
\]

Table 4. Design program and experimental results of equant design.

| Trial Number | Trial Battery | Variable Code | Trial Result |
|--------------|---------------|---------------|-------------|
|               | \( b \)       | \( c \)       | \( x_1 \)   | \( x_2 \)   | Load P/KN | Mold Stress F/MPa |
| 1             | 0.357         | 0.743         | -0.018      | 0.018       | 1860      | 1190         |
| 2             | 0.375         | 0.707         | -0.018      | -0.018      | 2130      | 1240         |
| 3             | 0.393         | 0.743         | 0.018       | 0.018       | 2420      | 1370         |
| 4             | 0.393         | 0.707         | 0.018       | -0.018      | 2830      | 1530         |
| 5             | 0.375         | 0.725         | 0           | 0           | 1410      | 873          |
| 6             | 0.35          | 0.725         | -0.025      | 0           | 1870      | 1090         |
| 7             | 0.4           | 0.725         | 0.025       | 0           | 2510      | 1410         |
| 8             | 0.375         | 0.7           | 0           | -0.025      | 2550      | 1350         |
| 9             | 0.375         | 0.75          | 0           | 0.025       | 1890      | 1100         |
The above data are fitting by using Regress function in MATLAB, and correlation coefficient $r^2$, statistic $F$ and corresponding probability $p$ of $F$ shown in table 5.

| Response Surface Model | $r^2$ Correlation Coefficient | $F$ Statistic | $p$-value Probability($>F$) | Significance |
|------------------------|--------------------------------|---------------|----------------------------|--------------|
| $P$                    | 0.9787                         | 27.6093       | 0.0103                     | **           |
| $F$                    | 0.9515                         | 11.7805       | 0.0346                     | *            |

Second-order response surface models of finish-forging load and mold maximum effective stress are set up respectively as formula (5) and (6).

$$\begin{align*}
P &= 1400 + 15200x_1 - 11300x_2 + 131700x_1^2 + 136500x_2^2 - 10800x_1x_2 \\
F &= 600 + 1600x_1 - 8500x_2 + 254200x_1^2 + 214200x_2^2 - 438700x_1x_2
\end{align*}$$ (5) (6)

The second-order response surface contour maps concerning variable code of finish-forging load and mold maximum effective stress are plotted through MATLAB software, shown in Figure 6 (a), (b).

In multi-objective problems of optimization, it is unrealistic to meet the optimal solution simultaneously, so different objectives need some weight. Solving procedure in this paper is: firstly, different objectives are normalized; secondly, weight is assigned. In consideration of the significance of mold stress to mold longevity in forging process, $P$ is assigned a weight of 0.4; $F$ is assigned a weight of 0.6. Taking partial derivation of variable $x_1$ and $x_2$ to find the optimal solution, it is concluded that at variable code $x_1=0.017, x_2=0.026$, both finish-forging load and mold maximum effective stress reach optimums.

![Second-order response surface contour maps](image)

5. Program verification

Based on researches above, optimums of relevant design variables are determined to accomplish the objectives of completely mold-filling, uniform deformation, and lower finish-forging load and mold maximum effective stress. The preform blank is designed within technological parameters $a=0.55$, $b=0.358$, $c=0.75$, $d=0.5$, through conversion precise values of $D, L_1, B, H$ are acquired, respectively 70.82, 26.91, 53.12, 31.87. Through test verification, the qualified products were produced, shown in
Figure 7, the method of multi-objective preform optimization for spherical hinge mandrel was proved in practical production.

![Forging piece (No trimming)](image1) ![Final production](image2)

(a)Forging piece (No trimming)  (b) Final production

**Figure 7.** Produced spherical hinge mandrel.

6. Conclusions

1) Aimed at the situation of practical production and equipment available, a feasible technological process of spherical hinge mandrel was designed which set the foundation for preform optimization design.

2) Combined with mathematical and mechanical models, feasible objective functions were constructed to describe mold-filling capability and deformation uniformity. With weighting function, an objective function which feedback forging integrated deformation quality was created.

3) Two main factors which influence forging integrated deformation were sought in application of combination of orthogonal experiments with numerical simulation; they are \( L_1/D \) (length-diameter ratio of section 1) and \( B/D \) (ratio of width of section 2 to diameter of section 1). From the following MATLAB graph manipulation, more precise optimal Figure is generated, and the optimum or optimal ranges of different factors are also decided.

4) On above basis, response models are created by octagon equant design and the preform optimization which is aimed at lowering finish-forging load and mold maximum effective stress has achieved good performance. The feasibility of the preform design method is proved in application of numerical simulation and practical production.

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