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Gear hot forging process robust design based on finite element method

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Abstract

During the hot forging process, the shaping property and forging quality will fluctuate because of die wear, manufacturing tolerance, dimensional variation caused by temperature and the different friction conditions, etc. In order to control this variation in performance and to optimize the process parameters, a robust design method is proposed in this paper, based on the finite element method for the hot forging process. During the robust design process, the Taguchi method is the basic robust theory. The finite element analysis is incorporated in order to simulate the hot forging process. In addition, in order to calculate the objective function value, an orthogonal design method is selected to arrange experiments and collect sample points. The ANOVA method is employed to analyze the relationships of the design parameters and design objectives and to find the best parameters. Finally, a case study for the gear hot forging process is conducted. With the objective to reduce the forging force and its variation, the robust design mathematical model is established. The optimal design parameters obtained from this study indicate that the forging force has been reduced and its variation has been controlled.

Keywords: Hot forging; Robust design; Numerical simulation; Taguchi method; Orthogonal design; Analysis of variance

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1. Introduction

The forging process, which is one of the foremost metal forming methods, can be defined as the process which gives the metal impact or pressure, forces the metal deformed in the dies. This method can improve the mechanical properties of the forging. In the forging process, the maximum forging force is very important for the final forging quality and the life span of dies. It is one of the most essential factors to consider when choosing forging equipment. For the same forging, if the maximum forging force can be reduced, small tonnage equipment can be used. This will assist the extension of the life span of dies, and reduce the cost of forging. Therefore, a small forging force is one objective that should be pursued in forging technology and the process of die design. However, in the actual forging process, many factors will affect forging force and cause it to vary, such as the wear of the die, manufacturing tolerance, dimensional change caused by temperature variation, and different friction conditions, etc. This variation should be controlled, or it will cause an unpredictable result. The methodology of the Taguchi robust design method [1-3] for the hot forging process is elaborated in detail in this paper, and a case study for gear hot forging process is conducted, the optimal design parameters are obtained, the forging force is reduced, and its variation is controlled.

2. Robust design steps for hot forging technology based on finite element method

The objective of the Taguchi robust design is to

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improve the quality of a product or process by not only striving to achieve performance targets, but also by minimizing performance variation [4, 5]. In robust design, parameters are classified using the following terminology:

- Control Factors (x). A designer can freely specify these parameters. These are equivalent to design variables in optimization.
- Noise Factors (z). These parameters are uncertain. They are either not under a designer's control, or their settings are difficult or expensive to control. Noise factors cause the response, y, to vary and lead to quality loss [6] (performance variation). Examples include system wear, variations in the operating environment, and economic uncertainties.
- Response (y). These parameters are dependent performance characteristics. Responses are the system outputs, and are functions of control and noise factors.

The focus in robust design is to reduce the variation of system performance responses caused by uncertainty of noise factor values, or to reduce system sensitivity [7, 8]. Solutions, which are system designs represented through settings of the control factors, are sought that minimize response variation in addition to achieving performance targets (mean, μ_y on target and minimized variance, σ_y^2).

Taguchi parameter design, an implementation of robust design, is built on the foundation of statistically designed experiments (DOE) [9-11]. In this approach, the evaluation of mean performance and performance variation is accomplished through a product array experimental design, constructed by “crossing” two arrays: a “control” array, designed in the control factors and a “noise” array, designed in the noise factors. This requires a large number of experiments to be conducted. However, since the hot forging process is a complex process, it becomes too difficult to carry out a large number of actual experiments. Finite element analysis is incorporated in order to simulate the hot forging process and to calculate the objective function value.

During the forging process, the main factors which cause shaping property and forging quality variation, and lead to quality loss, include die wear, manufacturing tolerance, dimensional change caused by different temperatures, and the variation of friction conditions. These factors are either not under a designer's control, or their settings are difficult or expensive to control. Consequently, they are selected as noise factors in the robust design. The control factors include the dimension parameters of the workpiece, the flash gutter and preform part. The designer can control these factors. The performance characteristics include forging force, deformation uniformity, and deformation damage.

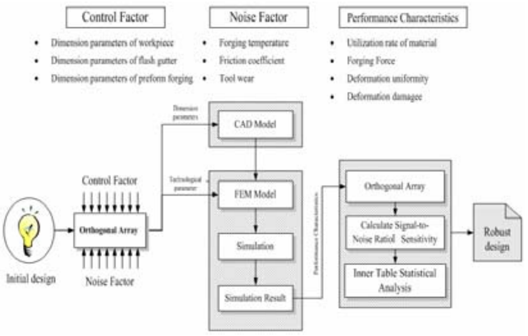


Fig. 1. Robust design steps for hot forging technology based on finite element method.

The hot forging process robust design based on numerical simulation is a reiteration process. During this process, the CAD software (SolidWorks) will be employed to change the dimension parameters of the dies and workpiece. Finite element analysis (DEFORM) is incorporated to simulate the hot forging process and to calculate the objective function. The robust design scheme for hot forging technology based on the finite element method is shown in Fig. 1. First, according to the idea of the design, design parameters are classified as control factors and noise factors, and then we design the inner table and outer table of the orthogonal experiment. Second, in the orthogonal experiment process, the API functions of SolidWorks are employed to change the geometric models of dies and preform forging. Third, these geometric models which have been modified will be imported into the DEFORM environment and other design parameters such as forging temperature and friction conditions can be written into the finite element model file. Subsequently, the simulation program will be called upon, and the objective function value is calculated based on the simulation result. In this way, the design of the experiment is implemented only once. After all the experiments have been conducted, the signal-to-noise ratio and loss function can be calculated according to the result of the orthogonal experiment design and the best design parameters are obtained.

3. Case study—robust design for gear hot forging process

3.1 The mathematic model of gear hot forging process robust design

A gear hot forging process is selected as a case study to illustrate the characteristics of the robust design method for the hot forging process. It is also selected to explain major steps of this method. The FEM software Deform-2D is used to simulate the gear hot forging process. A hot forging drawing of the gear is shown in Fig. 2. Because the gear forging is axisymmetric, half of the forging is selected for simulation. Dies and workpiece geometry are shown in Fig. 3.

According to factory experience, the initial H0/D0 ratio of the workpiece and the dimensions of the flash gutter bridge are important factors that significantly affect the forging force. Therefore, they are selected as control factors for the hot forging process robust design. Conversely, the forging temperature and friction coefficient also significantly influence the final forging quality. However, these factors are difficult to control in the hot forging process. Therefore, these two factors are selected as noise factors of the hot forging process robust design. In the actual forging process, the die dimensions will change due to wearing and different temperatures. Since this kind of variation is difficult to control, they are also selected as noise factors. The maximum forging force is selected as the performance characteristic of robust design, and it can be defined as the sum of the Z direction force of all the element nodes that have contact with the upper die. It is identified as below:

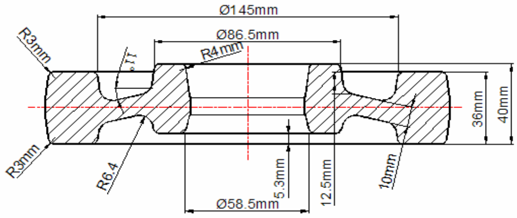


Fig. 2. Hot forging drawing of gear.

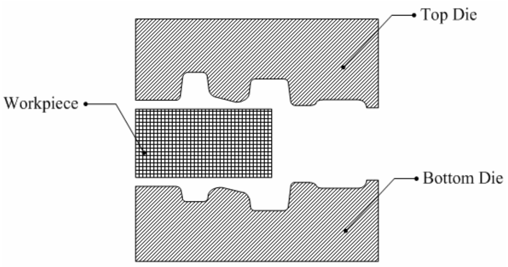


Fig. 3. Die & workpiece geometry.

$$F = \sum_{i=1}^{M} f_{iz} \tag{1}$$

Where f_{iz} is the Z direction force of the element node that is in contact with the upper die.

M is the total node number that is in contact with the upper die.

As stated above, the robust design mathematic model for gear hot forging technology is defined as in Fig. 4.

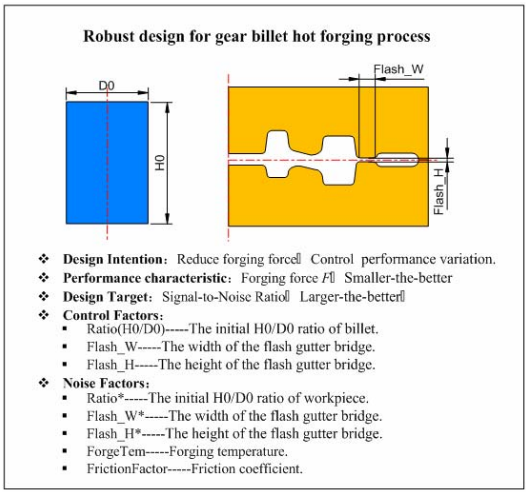
3.2 The initial design for gear hot forging process

The initial design is the first step of the Taguchi robust design. In this step, design experience and design knowledge are very important. The knowledge-based design method has been adopted in this paper for the initial design of the gear hot forging design process.

Table 1. Initial design of gear hot forging technology.

Design Parameter	Ratio	Flash_W (mm)	Flash_H (mm)	ForgeTem (℃)	FrictionFactor
Value	0.28	12	3	1000	0.3

Note：The material is 40Cr.
This part can be forged on a 3-tonnage hammer based on design experience



Robust design for gear billet hot forging process

- **Design Intention:** Reduce forging force， Control performance variation.
- **Performance characteristic:** Forging force F（Smaller-the-better
- **Design Target:** Signal-to-Noise Ratio（Larger-the-better）
- **Control Factors:**
  - Ratio(H0/D0)-----The initial H0/D0 ratio of billet.
  - Flash_W-----The width of the flash gutter bridge.
  - Flash_H-----The height of the flash gutter bridge.
- **Noise Factors:**
  - Ratio*-----The initial H0/D0 ratio of workpiece.
  - Flash_W*-----The width of the flash gutter bridge.
  - Flash_H*-----The height of the flash gutter bridge.
  - ForgeTem-----Forging temperature.
  - FrictionFactor-----Friction coefficient.

Fig. 4. Robust design mathematic model for gear hot forging technology.

In this way, the experience in this area that has been accumulated over a long period of time can be used in forging die and process design and can guide the designer in the design of the hot forging process and dies. The initial design of gear hot forging technology is shown in Table 1.

3.3 Robust design for gear hot forging process

Based on hot forging die and technology design experience, for the robust design for gear hot forging process, the initial H0/D0 ratio of the workpiece, the width of the flash gutter bridge (Flash_W), and the height of the flash gutter bridge (Flash_H) are selected as control factors. Each of these control factors has three levels, as shown in Table 2. The orthogonal table $L_9(3^4)$ is chosen to arrange the experiment, and is shown in Table 3.

There are five noise factors in the robust design for gear hot forging, including: the initial H0/D0 ratio of the workpiece (Ratio*), the width of the flash gutter bridge (Flash_W*), the height of the flash gutter bridge (Flash_H*), the forging temperature (ForgeTem), and the friction coefficient (friction factor). Because of wearing and the variation of temperature in the forging process, the first three factors will change. Based on the experience and the actual dimensions of these factors, this fluctuation can be controlled within the range of 5% of their dimensions. The detailed dimensions are shown below:

Ratio* : (Ratio ± 0.05), Flash_W* : (Flash_W ± 1.0), Flash_H* : (Flash_H ± 0.5)

Table 2. Control factor levels.

Factor Level	Ratio	Flash_W	Flash_H
1	0.2	8	2
2	1.0	12	4
3	1.8	16	6

Table 3. Experiment arrangement (inner table $L_9(3^4)$).

Factor Number	Ratio	Flash_W	Flash_H	e
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

The fluctuation range of the forging temperature and friction coefficient factors can be decided by the property of the material and by experience. Every factor has three levels and the noise factor levels and their actual data are shown in Tables 4, 5. According to scheme 1 of Table 5, the orthogonal table $L_{18}(3^7)$ is selected to arrange the experiment. The FEM soft

Table 4. Noise factor level.

Factor Level	Ratio*	Flash_W*	Flash_H*	Forge Tem	Friction Factor
1	Ratio-0.05	Flash_W-1.0	Flash_H-0.5	800	0.2
2	Ratio	Flash_W	Flash_H	1000	0.3
3	Ratio+0.05	Flash_W+1.0	Flash_H+0.5	1200	0.4

Table 5. Noise factor level (actual data).

Inner Table Scheme Number	Level	Noise factor				
		Ratio*	Flash_ W*	Flash_ H*	Forge- Tem	Friction- Factor
1	1	0.15	7	1.5	800	0.2
	2	0.2	8	2	1000	0.3
	3	0.25	9	2.5	1200	0.4
2	1	0.15	11	3.5	800	0.2
	2	0.2	12	4	1000	0.3
	3	0.25	13	4.5	1200	0.4
3	1	0.15	15	5.5	800	0.2
	2	0.2	16	6	1000	0.3
	3	0.25	17	6.5	1200	0.4
4	1	0.95	7	3.5	800	0.2
	2	1.0	8	4	1000	0.3
	3	1.05	9	4.5	1200	0.4
5	1	0.95	11	5.5	800	0.2
	2	1.0	12	6	1000	0.3
	3	1.05	13	6.5	1200	0.4
6	1	0.95	15	1.5	800	0.2
	2	1.0	16	2	1000	0.3
	3	1.05	17	2.5	1200	0.4
7	1	1.75	7	5.5	800	0.2
	2	1.8	8	6	1000	0.3
	3	1.85	9	6.5	1200	0.4
8	1	1.75	11	1.5	800	0.2
	2	1.8	12	2	1000	0.3
	3	1.85	13	2.5	1200	0.4
9	1	1.75	15	3.5	800	0.2
	2	1.8	16	4	1000	0.3
	3	1.85	17	4.5	1200	0.4

ware Deform-2D is used to simulate the gear hot forging process and to calculate the objective function. The calculation result of the orthogonal experiment is shown in Table 6. The calculation result of a further 8 schemes in the inner table (Table 5) can be obtained in the same way as in Table 6.

For each outer table, the signal-to-noise ratio can be calculated by using the "smaller-the-better" mathematical expression. For the first outer table (Table 6), the signal-to-noise ratio mathematical expression is shown below:

$$\eta = -10\lg\frac{1}{n}\sum_{i=1}^{n} y_i^2 = -10\lg[\frac{1}{18} \times (0.184^2 + 0.089^2 + \cdots + 0.510^2)] = 8.23(dB) \quad (2)$$

Table 6. Outer table of scheme 1 in inner table (L_{18} (3^7)).

Factor Number	Ratio	Flash_W	Flash_H	Forge-Tem	Friction-Factor	MaxLoad (10^8N)
1	1	1	1	1	1	0.184
2	1	2	2	2	2	0.089
3	1	3	3	3	3	0.328
4	2	1	1	2	2	0.198
5	2	2	2	3	3	0.738
6	2	3	3	1	1	0.488
7	3	1	2	1	3	0.516
8	3	2	3	2	1	0.197
9	3	3	1	3	2	0.400
10	1	1	3	3	2	0.238
11	1	2	1	1	3	0.552
12	1	3	2	2	1	0.022
13	2	1	2	3	1	0.342
14	2	2	3	1	2	0.487
15	2	3	1	2	3	0.221
16	3	1	3	2	3	0.207
17	3	2	1	3	1	0.450
18	3	3	2	1	2	0.510

Table 7. Inner table and signal-to-noise ratio.

Factor Number	Ratio	Flash_W	Flash_H	e	Signal-to-Noise Ratio (dB)
1	1	1	1	1	8.23
2	1	2	2	2	9.79
3	1	3	3	3	10.44
4	2	1	2	3	11.83
5	2	2	3	1	12.52
6	2	3	1	2	9.51
7	3	1	3	2	13.45
8	3	2	1	3	8.51
9	3	3	2	1	11.48
K1j K2j K3j	28.460 33.860 33.440	33.510 30.820 31.430	26.250 33.100 36.410	32.230 32.750 30.780	T=95.76 CT=1018.89 ST=25.94
Sj	6.015	1.326	17.900	0.695	

For the signal-to-noise ratio, another 8 outer tables can be calculated by using the same method, and the result is listed in Table 7.

Table 8. Analysis of variance table.

Source	Sum of Squares	df	Mean square	F	**Significance**
Ratio	6.015	2	3.008	8.657	Significant
Flash_W	1.326	2	0.663	1.908	Not significant
Flash_H	17.900	2	8.950	25.761	Highly significant
Error	0.695	2	0.347		
Total	25.94	8			

Note：F0.05 (2,2)=19, F0.1 (2,2)=9.00

Table 9. Optimal design of gear hot forging technology.

Design Parameter	Ratio	Flash_W (mm)	Flash_H (mm)
Value	1.0	8	6

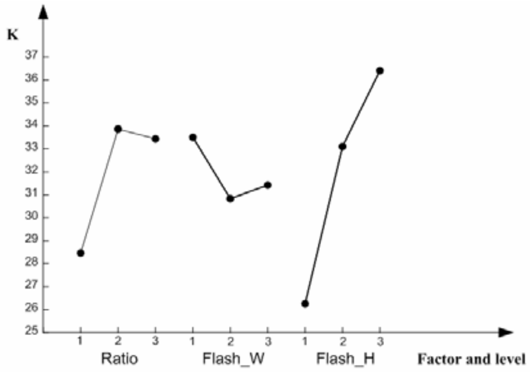


Fig. 5. Control factors influence scheme.

Based on the signal-to-noise ratio data of Table 7, the analysis of variance result is shown in Table 8. From Table 8, the sum deviation square of error column is only 0.695, which represents the lowest data. Therefore, the interaction of the control factors is very small. It can be seen that the initial H0/D0 ratio of workpiece is a significant factor, while the height of the flash gutter bridge (Flash_H) is the most significant factor, and the width of the flash gutter bridge (Flash_W) is the least important factor. From the data of Tables 7 and 8, the optimal design of gear hot forging technology can be obtained. For signal-to-noise ratio,high is better, so level 2 was chosen for the initial H0/D0 ratio, while level 3 was chosen for the Flash_H, and level 1 was chosen for the Flash_W. The optimal design for gear hot forging process is shown in Table 9. The control factor influence scheme is shown in Fig. 5. From this figure, the same conclusion can be obtained. The signal-to-noise ratio of the optimal design of the gear hot forging technology can be estimated below:

$$\begin{aligned}\hat{\eta} &= \overline{T} + (\overline{Ratio_2} - \overline{T}) + (\overline{\text{Flash\_H}_3} - \overline{T}) \\ &= \overline{Ratio_2} + \overline{\text{Flash\_H}_3} - \overline{T} \\ &= \frac{1}{3}\times 33.860 + \frac{1}{3}\times 36.410 - \frac{1}{9}\times 95.76 \\ &= 12.78(\text{dB})\end{aligned}$$

Note：symbol “¯” indicates “average”。

3.4 The improvement analysis of gear hot forging robust design

In order to compare the robust characteristics of the initial design with the robust characteristics of the optimal design, the design of experiments for initial design and final design have been implemented, as shown below. The control factors and their levels of initial design are shown in Table 10, and the experiment arrangement of the initial design is shown in Table 11. The control factors and their levels of optimal design are shown in Table 12; the experiment arrangement of optimal design is shown in Table 13.

Based on the data of Tables 11 and 13, the signal-to-noise ratio, the mean of MaxLoad and the standard deviation have been calculated. These are shown in Table 14. From Table 14, it can be seen that the signal-to-noise ratio has increased from 9.39 to 12.92, increasing about 37.6%, while the standard deviation has dropped from 0.140 to 0.122. This result indicates

Table 10. Factor levels of initial design.

Level	Experiment factor				
	Ratio	Flash_W	Flash_H	ForgeTem	FrictionFactor
1	0.23	11	2.5	800	0.2
2	0.28	12	3	1000	0.3
3	0.33	13	3.5	1200	0.4

Table 11. Experiment arrangement of initial design (L_{18} (3^7)).

Factor Number	Ratio	Flash_ W	Flash_ H	Forge- Tem	Friction- Factor	MaxLoad (10^8N)
1	1	1	1	1	1	0.500
2	1	2	2	2	2	0.203
3	1	3	3	3	3	0.209
4	2	1	1	2	2	0.195
5	2	2	2	3	3	0.249
6	2	3	3	1	1	0.469
7	3	1	2	1	3	0.494
8	3	2	3	2	1	0.172
9	3	3	1	3	2	0.317
10	1	1	3	3	2	0.182
11	1	2	1	1	3	0.538
12	1	3	2	2	1	0.193
13	2	1	2	3	1	0.201
14	2	2	3	1	2	0.474
15	2	3	1	2	3	0.226
16	3	1	3	2	3	0.205
17	3	2	1	3	1	0.264
18	3	3	2	1	2	0.505

Table 12. Factor level of optimal design.

Level	Experiment factor				
	Ratio	Flash_W	Flash_H	ForgeTem	FrictionFactor
1	0.95	7	5.5	800	0.2
2	1.0	8	6	1000	0.3
3	1.05	9	6.5	1200	0.4

Table 13. Experiment arrangement of optimal design (L_{18} (3^7)).

Factor Number	Ratio	Flash_ W	Flash_ H	Forge- Tem	Friction- Factor	MaxLoad (10^8N)
1	1	1	1	1	1	0.351
2	1	2	2	2	2	0.096
3	1	3	3	3	3	0.115
4	2	1	1	2	2	0.105
5	2	2	2	3	3	0.114
6	2	3	3	1	1	0.344
7	3	1	2	1	3	0.364
8	3	2	3	2	1	0.105
9	3	3	1	3	2	0.115
10	1	1	3	3	2	0.110
11	1	2	1	1	3	0.379
12	1	3	2	2	1	0.130
13	2	1	2	3	1	0.102
14	2	2	3	1	2	0.356
15	2	3	1	2	3	0.101
16	3	1	3	2	3	0.102
17	3	2	1	3	1	0.108
18	3	3	2	1	2	0.364

Table 14. Design scheme comparison.

Robust characteristic	Experiment scheme	
	Initial design	Optimal design
Signal-to-noise ratio (dB)	9.39	12.92
Maxload$_{mean}$ (10^8N)	0.311	0.192
Std.dev.	0.140	0.122

that the performance variation has been controlled effectively. At the same time, the mean of MaxLoad has dropped from 0.311×10^8N to 0.192×10^8N, decreasing about 38.3%. These results indicate that the MaxLoad of the forging process has been reduced effectively. Therefore, the robustness of the final design has been improved and the final design is optimal.

4. Summary

In the forging die and technology design area, there are several factors that need to be taken into consideration, such as the dimension tolerance in the die manufacture process, the wear on the tools in the forging process and the variation of dimensions caused by aspects such as a change in various temperatures. These noise factors cause performance variation in the final forging quality and life of the die. This kind of performance variation must be controlled. A robust design based on the Taguchi method and the finite element method has been implemented for the gear hot forging process, and a robust design mathematic model has been established. After actual computation, the optimal design has been attained, the performance variation has been controlled effectively, and the efficacy of the forging process robust design methodologies has been proven.

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