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STUDY ON FORGING PROCESS OF VALVE BASED ON RESPONSE SURFACE METHOD

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This article takes the 21 - 4N engine valve as the research object and studies the effects of die forging temperature (1 000 - 1 180 °C), die forging speed (0,15 - 200 mm / s) and friction coefficient (0,1 - 0,5) on die forging results. First, a finite element model (FEM) of the valve blank and die is established using Creo; next, the valve forging process is simulated using Deform - 3D; then, the response surface analysis method is used to analyze and discuss the results of die forging, and to optimize the process parameters with valve product damage as the optimization goal, and determine the best process parameters for 21 - 4N engine valve forging; finally, the obtained parameters are verified through experiments, and the experimental results and prediction results have a good consistency.

Key words: die forging process, engine valve, 21 - 4N, FEM, surface

INTRODUCTION

5Cr21Mn9Ni4N (21 - 4N) has good oxidation resistance, good high temperature mechanical properties and chemical stability, good tensile strength and yield strength It is widely used in Manufacturing of various engine valves [1].

The valve forming process is complicated. Generally, dozens of procedures such as extrusion / electric upsetting, die forging, machining, and finishing are required from the blank to the finished product, and the technical requirements for each procedure are quite high. In 2 002, Zhang et al. [2] of Guangdong University of Technology used MAFAP finite element software to simulate the final forging process of valve blanks, and analyzed the distribution of stress, strain field, metal flow and die force field during the forming process of the blank. And the metal deformation mechanism in the final forging was obtained. In 2 011, Zhu et al. [3] of Wuhan University of Science and Technology studied the microstructure changes of nickel 80A alloy valve during upsetting and closed die forging by optical microscopy, X - ray diffraction (XRD), transmission electron microscopy (TEM) and finite element model (FEM). In 2 017, Fan et al. [4] of University of South China used OM, SEM, and EDS methods to experimentally study the 85Cr18Mo2V intake valve with an electric crack on the head and used the finite element software to simulate the electric upsetting process of 85Cr-18Mo2V intake valve.

This paper uses the Deform finite element analysis software to simulate the 21 - 4N valve die forging process, and analyzes the simulation results through the Design - Expert software to obtain the optimal process parameters of 21 - 4N valve die forging.

ESTABLISHMENT OF FINITE ELEMENT MODEL

In the actual forming of the valve, the “garlic head” is the main deformation part. Its deformation form is mainly axial compression and radial extension. At the same time, factors such as the heat exchange and the die material between the forging and the surrounding environment, the forging and the die must also be considered. In order to ensure the consistency between the simulation process and the actual production, the research makes the following assumptions on the valve forging process:

1) In the finite element simulation, the upper and lower dies are defined as rigid bodies. It is assumed that the mold does not deform and wear, which is consistent with the actual die forging.

2) In die forging, permanent plastic deformation is the main purpose, and the elastic deformability generated during the deformation process is very small compared to plastic deformation, which can be assumed to be ignored during analysis. Therefore, 21 - 4N is defined as a plastic body model in the finite element simulation of valve die forging.

3) In the finite element simulation of die forging, the upper and lower molds are set to be regular and symmetrical rigid bodies, the forgings are set to be symmetrical

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plastic bodies, and it is assumed that the stress and deformation of the forgings are also distributed symmetrically.

In valve die forging, the setting of boundary conditions is very important for the simulation results of die forging. Table 1 shows the thermal boundary conditions and some other parameter settings for 21 - 4N valve die forging in this study.

Table 1 **Deform simulation 21 - 4N die forging process parameters Settings**

Parameter	Valve	Unit
Temperature	1 060, 1 120, 1 180	°C
Velocity	50, 75, 100, 125, 150	mm / s
Friction	0,1, 0,2, 0,3, 0,4, 0,5	–
Temperature of die	200	°C
Billet material	21 - 4N	–
Die material	AISI - H - 13	–
Temperature of environment	20	°C
Heat transfer coefficient	0,02	N / s / mm / °C
Heat exchange coefficient between blank and die	1	N / s / mm / °C
Blank mesh size ratio	3	–
Heat transfer coefficient between blank and die	11	N / s / mm / °C
Minimum mesh size	0,3	–
Grid number	91 680	–

CROCKROFT - LATHAM INJURY GUIDELINES

In this paper, the damage in the mold forging process is studied in accordance with the normalized Crockroft - Latham (C - L) guideline [5], which determines that the first stretch main stress is the main cause of fracture. When determining the strain rate and die-forge temperature as a certain value, when the first stretch master stress reaches the threshold of damage along the integral value of the strain path, the material breaks, and the conditions for which the material breaks are considered to be shown in Equation (1). Because the form of the criterion is simple, it is easy to embed into finite element software, so it is widely used in the finite element simulation of volume forming.

$$W = \int_0^{\bar{\varepsilon}} \max(\sigma_1, 0)\, \mathrm{d}\,\bar{\varepsilon} \geq W_c \qquad (1)$$

In the equation:

σ_1 – Maximum main stress;

W_c – The critical value of fracture strain integral energy W;

$\bar{\varepsilon}$ – Equivalent plastic strain;

The die forging process simulation is done by Deform. The model is mainly composed of three parts, the top die, the bottom die and the sample. Position the imported blank and die, as shown in Figure 1.

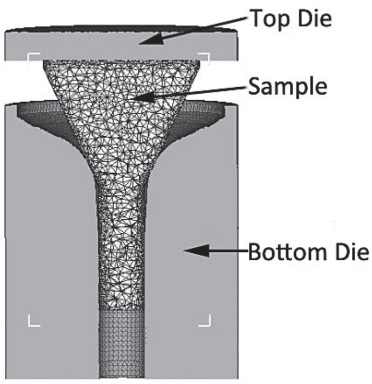


Figure 1 Die forging finite element model of 21 - 4N valve

OPTIMIZATION OF DIE FORGING PROCESS PARAMETERS OPTIMIZE THE DESIGN OF OBJECTIVE DETERMINATION AND SIMULATION EXPERIMENTS

This study uses Design - Expert.V8.0.6 multi - objective parameter optimization software to establish a response surface model of 21 - 4N engine valve damage with die forging forming parameters (die forging temperature, die forging speed, friction coefficient), The center combination test design is used to determine the corresponding surface simulation experiment scheme, and the analysis of the valve forging damage in the simulation results with the changes in the process parameters to optimize the process parameters to make qualified valve products.

Design - Expert.V8.0.6 is used to design the simulation experiment scheme, and a three - factor, three - level design scheme is selected. The three process parameters are divided into forging temperature T, forging speed V, and friction coefficient f. According to the method of design of the central experiment, 17 sets of simulation experiments are designed. Table 2 gives the conditions and results of 17 sets of simulation experiments.

RESPONSE SURFACE MODEL AND ANALYSIS OF FORGING DAMAGE

According to the simulation results of the above 17 sets of simulations, Design - Expert is used for regression analysis of the maximum damage of forgings, and a second polynomial fit is used to obtain the response surface model of forging damage as shown in Equation (2)

$$\begin{aligned} y_1 = {} & 302,6\,996 - 0,5\,417\,x_1 - 0,03\,048\,x_2 \\ & + 7,2\,515\,x_3 + 1,3\,347\times10^{-5}\,x_1\,x_2 \\ & - 0,01896\,x_1\,x_3 - 0,03\,770\,x_2\,x_2 \\ & + 2,4\,410\times10^{-4}\,x_1^2 + 1,6\,232\times10^{-4}\,x_2^2 \\ & + 41,2\,186\,x_3^2 \end{aligned} \qquad (2)$$

In the equation:

x_1 - Die-forge temperature;

x_2 - Die-forge speed;

x_3 - Friction factor.

Table 3 is a variance analysis of the damage response surface equation for 21 - 4N valve forgings. Among them, the larger the F value, the more significant the response surface model established. The smaller the P value, the more significant the effect of the parameters on the simulation results. As it can be seen from the table, the F value of the model is 52,87, which indicates that the response surface model established in this study is significant. The value of P is less than 0,0 001, indicating that in this model, the three process parameters of forging

Table 2 **Simulation experiment scheme and calculation results**

Number	T / °C	V / mm / s	f	Damage	σ / MPa	ε
1	1 180	150	0,3	2,60	599	35,17
2	1 120	150	0,1	1,93	578	9,34
3	1 180	75,08	0,5	4,58	523	21,37
4	1 120	75,08	0,3	0,61	560	15,19
5	1 060	0,15	0,3	2,32	1 326	8,90
6	1 060	150	0,3	2,23	748	73,63
7	1 120	75,08	0,3	0,61	560	15,19
8	1 120	75,08	0,3	0,61	560	15,19
9	1 060	75,08	0,1	1,24	675	16,06
10	1 120	0,15	0,1	1,57	1 400	297,9
11	1 120	150	0,5	3,64	538	41,34
12	1 120	75,08	0,3	0,61	560	15,19
13	1 180	0,15	0,3	2,45	1 555	12,05
14	1 120	0,15	0,5	5,54	1 336	40,56
15	1 180	75,08	0,1	1,54	576	17,15
16	1 120	75,08	0,3	0,81	562	15,19
17	1 060	75,08	0,5	5,19	667	20,16

temperature, forging speed and friction coefficient have significant effects on the damage of the forging, and the coupling effect between the three parameters also has damage to the forging significantly affected.

Figure 2 shows the linear relationship between the calculated value of the forging simulation and the predicted value of the response surface model. It can be seen from the figure that the model has a good degree of fitting and the fitting error is very small, indicating that the established response surface model can reflect well Correlation between predicted and experimental values. The signal - to - noise ratio of the model is 21,500, which is significantly greater than 3, indicating that the established damage response surface model of the forging has sufficient resolution, and further proves that the Equation (2) is reasonable to describe the die forging damage of the 21 - 4N engine valve.

Figure 3 shows the response surface of damage of valve forging with variation of die forging temperature, die forging speed and friction coefficient. As can be seen from the figure, among the three parameters, when one parameter is determined, the other two parameters change within a given range, the damage of valve forgings tends to decrease first and then increase; when the friction coefficient is 0,2, the die forging speed is 71,32 mm / s, and the die forging temperature is 1 115,51 °C, the damage of the valve forging reaches the minimum value of 0,222 513; but the different is when the friction coefficient determined, the variations in the damage of valve forgings is bigger, close to the maximum at the boundaries of the parameter range (Figure 3 (a)), and when the forging temperature or die forging speed must be damage to the valve forging rapidly increases with the increase of the coefficient of friction, the friction coefficient was 0,5 in the maximum (Figure 3 (b, c)); In the friction coefficient is 0,2, the damage of the valve forging in the forging temperature of 1 060 °C, at the rate of 0,15 mm / s die forging and die forging temperature of 1 060 °C, the rate of 150 mm / s die forging, die forging temperature of 1 180 °C, at the rate of 0,15 mm/s die forging and die forging temperature of 1 180 °C, the rate of 150 mm / s die forging, the damage were similar, are close to the maximum friction coefficient of 0,2 damage, and in die forging temperature or die forging speed, also have the same phenomenon, this indicates that there is an interaction between die forging temperature, die forging speed and friction coefficient.

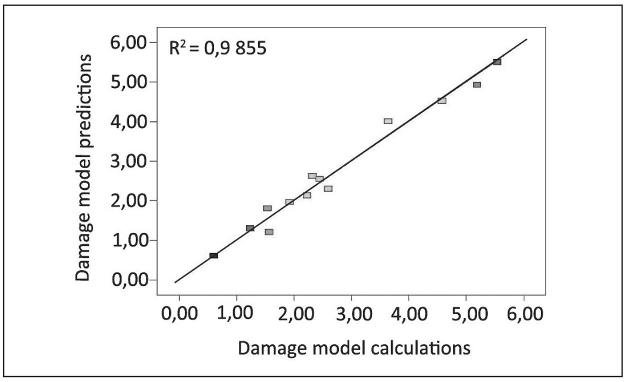


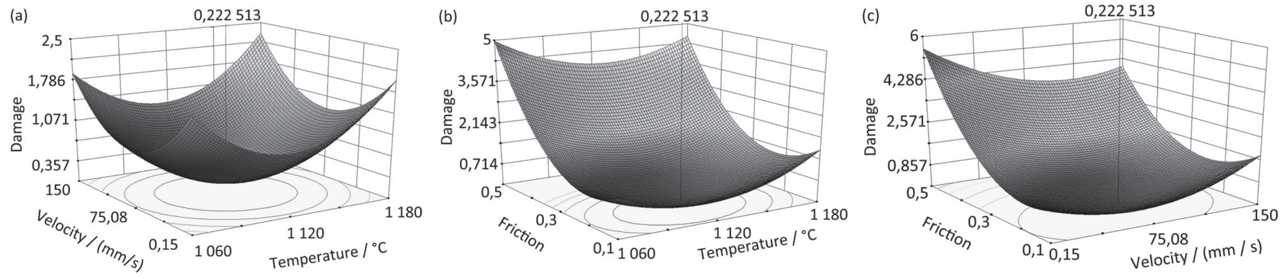
Figure 2 The comparison between simulation calculation value and prediction value.

VALIDATION ANALYSIS OF OPTIMIZATION RESULTS

In order to verify the reliability of the best process parameters obtained in the previous section, the best die forging process parameters of the obtained 21-4N engine valve were input into Deform to repeat the simulation of valve die forging. The damage distribution diagram of valve forgings as shown in Figure 4 (a) and the damage change diagram of valve forgings over time as shown in Figure 4 (b) are obtained.

Table 3 **Analysis of damage response surface equation of valve forgings of 21 - 4N**

Source of variation	Quadratic sum	Freedom	Mean square	F	P	
Model	41,91	9	4,66	52,87	< 0,0 001	Significant
x_1	4,512E-003	1	4,512E-003	0,051	0,8 274	–
X_2	0,27	1	0,27	3,11	0,1 212	–
x_3	20,07	1	20,07	227,83	< 0,0 001	–
$x_1 x_2$	0,014	1	0,014	0,16	0,6 980	–
$x_1 x_3$	0,21	1	0,21	2,35	0,1 691	–
$x_2 x_3$	1,28	1	1,28	14,50	0,0 066	–
$(x_1)^2$	3,25	1	3,25	36,92	0,0 005	–
$(x_2)^2$	3,50	1	3,50	39,70	0,0 004	–
$(x_3)^2$	11,45	1	11,45	129,96	<0,0 001	–



(a) f = 0,2 (b) 71,32 mm / s (c) T = 1 115,51 °C

Figure 3 Response surface of valve forging damage changing with forming parameters.

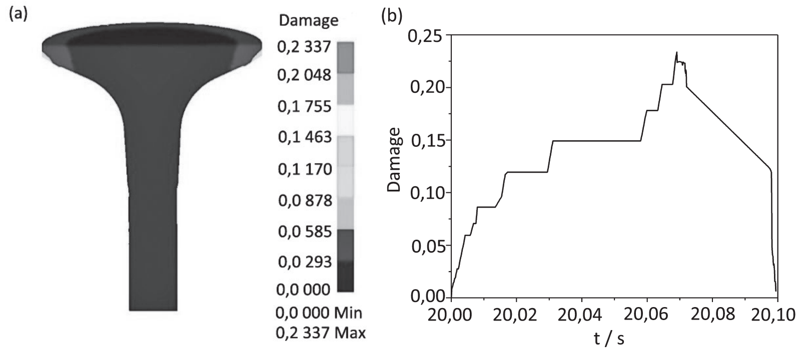


Figure 4 Damage distribution of valve forgings under optimum process parameters.

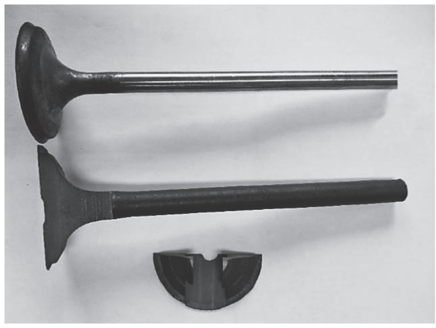


Figure 5 The 21 - 4N valve products obtained by die forging with the above parameters.

As can be seen from Figure 4, keep the damage of valve forging is below 0,24. After the completion of die forging, only the damage at the edge of the end is below 0,06. The damage of other parts is 0, indicating that the obtained valve blank is qualified; As can be seen from Figure 4 (b), from the beginning of die forging to the end, the damage of valve forging first increases to a certain value, then decreases to a maximum value of 0,23 377.

EXPERIMENTAL VERIFICATION

In order to verify whether the obtained parameters can be applied to the actual production, the process parameters obtained above were used to carry out the die forging of the 21-4N engine valve (Figure 5). Through measurement and observation, the valve size obtained is basically the same as that of the standard parts, and no forming defects are observed, indicating that the optimum technological parameters determined are reasonable.

CONCLUSION

1) The response surface was used to analyze the change law of forging damage with die forging temperature, die forging speed and friction coefficient, and it was found that there was an interaction between die forging temperature, die forging speed and friction coefficient.

2) The optimal process parameters of 21 - 4N engine valve forging are obtained: the die forging temperature is 1 115,51 °C, the die forging speed is 71,32 mm / s, and the friction coefficient is 0,2. Using the process parameters, the simulation of the forging process was performed again. The simulation results are basically consistent with the prediction results of the response surface, indicating that the prediction results are reasonable. Finally, the process parameters are verified through experiments and qualified valve forgings are obtained, which confirmed the reliability of the obtained process parameters.

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Compliance with ethical standard

The authors declare no conflict of interest.

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Note: The responsible translator for English language is J W Dong-North China University of Science and Technology, China