Int J Adv Manuf Technol (2017) 90:3129–3135
DOI 10.1007/s00170-016-9635-8

ORIGINAL ARTICLE

# Numerical optimization on hot forging process of connecting rods based on RSA with experimental verification

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Received: 9 May 2016 / Accepted: 17 October 2016 / Published online: 29 October 2016


**Abstract** A new method of optimization on the hot forging tools for connecting rods was developed in this paper by combining response surface analysis (RSA) with finite element method (FEM). The central composite design (CCD) was prepared with three experimental factors and two optimal targets. The experimental factors which are extracted from design dimensions of the hot forging tool involve cavity center distance, cavity rotation angle, and flash thickness. The targets comprise the maximum forming load and tool wear depth, both of which can be obtained from finite element simulations of hot forging processes. Response surface analysis was implemented to establish the relationships between the targets and the factors. According to the simulation results, the S-type region between die cavities that was dominated by three factors has a significant impact on the metal flowing and forming defects during the hot forging process. The steel billet and forging tools were dimensionally redesigned based on the optimal combination of experimental factors. Practice forging and physical experiments were performed to verify the simulation results, and good agreement between experimental value and simulation value was obtained.

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**Keywords** Connecting rods · Hot forging · CCD · RSA · FEM · Numerical optimization

## 1 Introduction

Connecting rods play the role of converting the reciprocating linear motion of piston into the rotary motion of a crankshaft. Automobile connecting rods are conventionally manufactured by hot forging. However, the competition from other production methods such as powder-forged connecting rods and sinter connecting rods has changed the dominant position of conventional forged rods in the automobile market [1]. Hence, the hot forging industry has to seek to reverse the situation. The effective ways to contend that impact lie in the production of components: increasing productivity and reducing costs, while also considering the ecological issue and energy consumption. For instance, possessing an advanced production line is a pre-requisite to improve the competitiveness of hot-forged connecting rod production [2].

Although hot-forged connecting rods have been occupying the dominant position in the connecting rod market for its excellent product quality, reasonable production cost, and mature technology, the emergence of new technologies has brought tremendous room for improvement to the forging industry, such as computer simulation technology [3, 4]. The application of finite element (FE) simulation in the forging industry has been becoming more sophisticated in recent years. A wealth of forging simulation software and programs provided by software developers and research institutions was used to simulate the metal forming processes [3, 5, 6]. Numerical simulation technology provides a powerful tool to investigate the metal flow, forging defects, and tool life for the forging industry. Satish et al. [7] used the software DEFORM for FE simulation of front axle beam forging to minimize the billet mass and other design parameters. Zhang et al. [8] researched the upsetting process of the 42CrMo billet by means of the software DEFORM-3D to execute the forming defects analyzed. Gronostajski et al. [9] presented the simulation of precision forging process of a gear wheel to find that the longer the tool surface contacts the forging material, the easier the surface region wears. This provides a guide to the design optimization of the forging processes and tools.

A series of studies on connecting rods have been conducted to cut down the material consumption and number of experimental tryouts by using the finite element method (FEM). Takemasu and fellows [10] were concerned about what the pre-form optimization of flashless forged connecting rods is. Bariani and Bruschi [11] used the software FORGE for modeling the forging and post-forging cooling of C70S6 connecting rods to find the factors causing production loss by means of coupling numerical and experimental techniques. Grass et al. [12] researched the hot forming processes of stretch-rolled connecting rods to reveal the impact of the deformation history on the local microstructure and mechanical properties. Above all, with FE simulation, the number of experimental tryouts is significantly reduced and material utilization is improved.

Despite of the wide application of FE simulation, a common problem encountered by designers is that the number of simulations cannot be increased indefinitely. In particular, the numerical simulation of large and complex components is quite time consuming. Additionally, the appropriate strategy should also be taken in order to give better insight into the influence of various design parameters and process parameters on the quality of forging and tool wear. For the prediction of tool life, Hatzenbichler and Buchmayr [13] optimized the preform for closed die forging to reduce the material costs and tool wear by means of point tracking in numerical simulation. Systematically, Behrens [14] presented a modeling approach for die wear calculation and verified it based on an industrial process for the hot forging of a driveshaft. Moreover, FEM and an integrated program were utilized to study the important factors, such as cooling conditions and stresses, in professional wear process [15, 16]. These provide important references for the study in this paper. For automobile connecting rods, the hot forging tool with a style of two cavities was developed to increase the productivity. However, there is no effective method to optimize the design parameters of the forging tool. The influence of the geometric parameters of the hot forging die on the forming load, forging defects, and tool wear still remains unknown.

In this paper, an approach for optimization design of connecting rod forging die is presented by coupling response surface analysis (RSA) with FEM. An experiment schedule has been established based on central composite design (CCD) where three geometric factors (cavity center distance, cavity rotation angle, and flash thickness) have been proposed in order to identify and optimize the structure of hot forging die. Two targets, the maximum forming load and tool wear depth, have been identified to give insight on the effect of the geometric factors on the simulation results. As an important part of this study, RSA has been constructed to reveal the nonlinear relationship between the targets and the factors. Finally, an optimal combination of the design factors has been selected to redesign the forging billet and die which were used in the subsequent practice forging to verify the simulation results.

## 2 Experimental procedure

### 2.1 Hot forging processes

According to industrial practice, the technological processes of hot forging connecting rods include blanking, medium frequency heating, pre-forging 1, pre-forging 2, final forging, and controlled cooling. The main processes of metal forming have a significant influence on the quality of products and tool life. Hence, this study was particularly focused on the forging processes. Hereafter, the forging process, tool, and billet were designed as shown in Fig. 1.

Comparing the three pairs of forging dies, one of their common characteristics is the layout of the two cavities. To quantify the common characteristics of dies, three dimensions are extracted from the dimensions of dies (Fig. 2): the cavity center distances ($|OE|$ and $|OF|$), the cavity rotation angles ($\angle BAD$ and $\angle ABC$), and flash thickness. They are selected here to conduct the optimization of connecting rod forging die.

Moreover, the length of the billet was defined by $|AB|$ in this study. Hereafter, the diameter of the billet was determined by the volumes of connecting rod forgings and flash, both of which are generally constants. Hence, the design of the billet is also related to the cavity center distance and the cavity rotation angle.

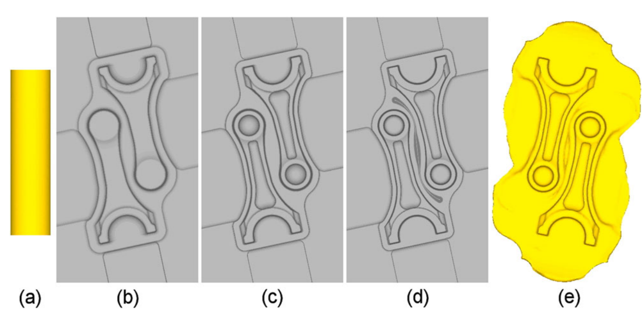


**Fig. 1** Design of the hot forging processes and the two-cavity forging dies for the connecting rods: **a** billet, **b** top die of pre-forging 1, **c** top die of pre-forging 2, **d** top die of final forging, and **e** forgings

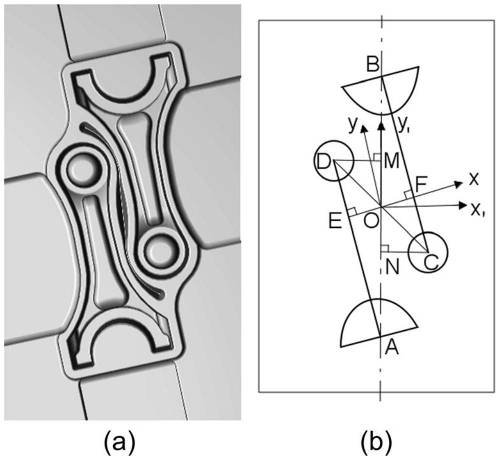


**Fig. 2** **a** Final forging die for connecting rods and **b** the structure of forging dies, where *O* is the center of die; *A*, *B*, *C* and *D* is the center of connecting rod's ends; *XOY* is die coordinate system and $X_1OY_1$ is cavity coordinate system

### 2.2 Optimization model

The flowchart of the optimization method is shown in Fig. 3.

With the three factors of design dimensions (cavity rotation angle $\alpha$, cavity center distance *d*, flash thickness *h*), an experimental program was prepared based on CCD, where the levels of factors *A*, *B*, and *C* are $30 < \alpha < 32$, $10 < d < 13$, and $4 < h < 6.5$, respectively. Forging tools were designed according to the experimental program and used to execute the simulation under the same conditions, and data collection was performed to establish the sample space. The targets as a function of the three factors were calculated by RSA, and the accuracy of the function was analyzed. Finally, the nonlinear algorithm is used to search optimum results.

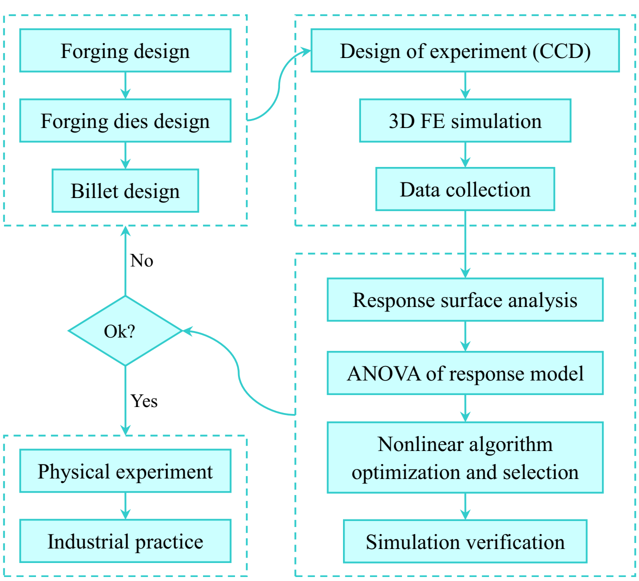


**Fig. 3** The flowchart of the optimization method

The optimal model can be summarized as the following equation set:

$$\begin{cases} \text{Variable} : A, B, C \\ \text{Min} \;\; R1 = \text{Max}\left|\sum_{i=1}^{m} f_{Zi}\right| \\ \text{Min} \quad R2 = \text{Max}\left|\int K\frac{P^a \cdot v^b}{H^c}dt\right|, (a = b = 1, K = 2, H = 50) \\ A'_{\max} \leq 270^{\circ} \\ 30 \leq A \leq 32 \\ 10 \leq B \leq 13 \\ 4 \leq C \leq 6.5 \end{cases} \quad (1)$$

where *A*, *B*, and *C* are the three design factors; *R*1 is the maximum forming load and *R*2 is the maximum tool wear depth; $f_z$ is the forming load of the element *i* and *m* is the number of elements; *a*, *b*, and *K* are the constants, since there are $a = b = 1$ and $K = 2$ for tool steels; the hardness of die material *H* is 50; *P* is the normal pressure on the surface of forging die and *v* is the material flow velocity on the surface of die in the tangential direction; *dt* is the time increment; and $A'_{\max}$ is the maximum folding angle.

In the nonlinear algorithm, the equation set (1) is solved by interpolation according to the limiting conditions until a desired level combination of factors is obtained. The billet and forging dies were redesigned by introducing the optimal geometrical parameters into the design aspects of forging dies.

### 2.3 Simulation procedure

The FE simulations were conducted by using the software DEFORM-3D. The material of workpiece is the nonquenched and tempered steel SVDH20S1, and the die is steel H13. The finite element number of workpiece and die is 65,160 and 35,100, respectively (Fig. 4). Boundary conditions of FE simulation were set as follows: ambient temperature of 20 °C, forging temperature of 1220 °C, die temperature of 180 °C, thermal conductivity (billet-die) of $1.1 \times 10^4$ W/m$^2$ k, thermal conductivity (billet-environment) of 200 W/m$^2$ k, and friction factor (shear friction model) of 0.3. The mechanical press in this study has a forming ability of 2500 t, a slide stroke of 400 mm, a stroke frequency of 70 min$^{-1}$, and a rod length of 1500 mm. The simulations were completed with the displacement step of 0.5 mm.

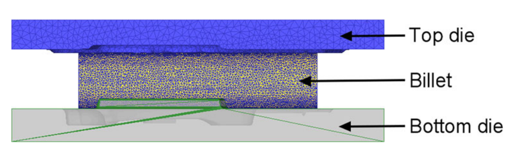


**Fig. 4** Finite element model of pre-forging 1 for connecting rods

Fig. 5 Top die of the pre-forging process for connecting rods

### 2.4 Industrial application

The final work in this study was the verification of the simulation results by the hot forging process in practice. By using the redesigned forging tools and billet, the forged connecting rod was processed in the industrial product line. The morphology of the pre-forging tool is shown in Fig. 5.

## 3 Results and discussion

### 3.1 S-type region between cavities

All of the CCD experiments were simulated on the software DEFORM-3D. The effective strain contour showing that an S-type region (along the arrow) exhibits the highest strain value between the cavities is given in Fig. 6. When the cavities are filled during every forging process, the massive flash at both ends of the S-type region implies that the S-type region plays a role as a metal flowing channel to release the redundant material until the pressing stroke finishes.

Meanwhile, the S-type region on the die surface has excessively contacted with the high velocity metal flow leading to material loss or wear, as described in [9]. The accelerated wear phenomenon can be observed in the practical forging die, as given in Fig. 5. An S-type gutter with depth of 10 mm was designed on the surface of the die to deposit the excessive material and to control the metal flowing velocity, as shown in Fig. 2a.

An oversized S-type region can lead to a rapid rise in forging load, and a too small S-type region can lead to insufficient structural strength of the mold. Since the shape and volume of the S-type region are dominated by the cavity rotation angle, the cavity center distance, and the flash thickness, the three dimensions were investigated afterward with the targets of maximum forging load and tool wear depth to improve tool life.

### 3.2 Establishment of RSA models

The CCD experiment results are given in Table 1. The first target $T1$ is the maximum forming load which was collected in the first pre-forging. The second target $T2$ is the maximum tool wear depth which is obtained in the final forging.

Regression analysis was conducted via the least square method to determine the polynomial coefficients of the response surface model. The function of responses $R1$ (maximum forming load) and $R2$ (the maximum tool wear depth) are given in expressions (2) and (3), respectively.

$$R1 = 35.497 + 35.497A - 0.411B + 0.593C + 0.199A^2 + 0.223B^2 + 0.549C^2 + 0.009AB - 0.551AC - 0.252BC + 1.009ABC - 0.006A^2B - 0.576A^2C + 0.323AB^2 \quad (2)$$

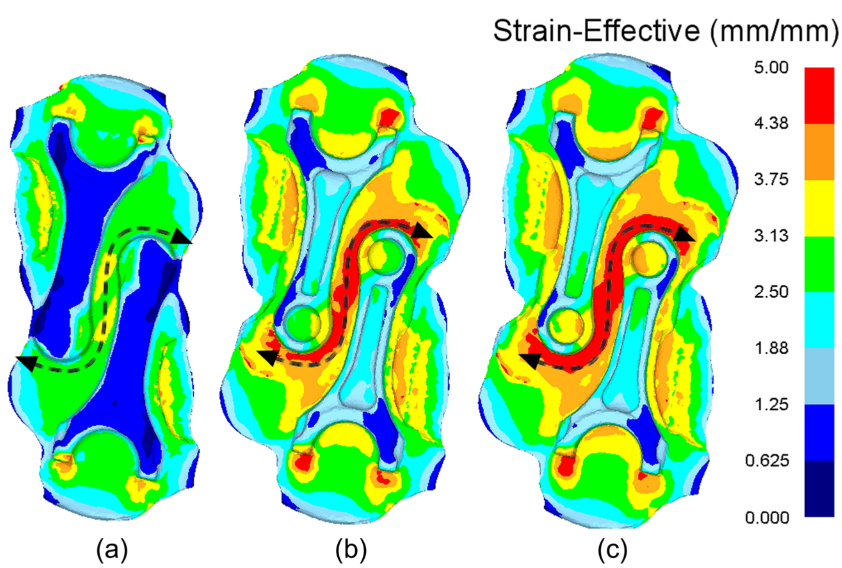


Fig. 6 Effective strain of hot forging sequence: **a** pre-forging 1, **b** pre-forging 2, and **c** final forging

**Table 1** Design plan and its numerical experimental results

| No. | *A* | *B* | *C* | *T*1 | *T*2 |
|---|---|---|---|---|---|
| 1 | 32 | 10 | 4 | 1450 | 0.0371 |
| 2 | 31 | 11.5 | 5.25 | 1210 | 0.0388 |
| 3 | 31 | 8.977311 | 5.25 | 1360 | 0.0636 |
| 4 | 32 | 13 | 6.5 | 1310 | 0.0402 |
| 5 | 32 | 10 | 6.5 | 1260 | 0.0385 |
| 6 | 31 | 11.5 | 3.147759 | 1304 | 0.0453 |
| 7 | 30 | 10 | 6.5 | 1500 | 0.0514 |
| 8 | 31 | 11.5 | 5.25 | 1290 | 0.0407 |
| 9 | 31 | 14.02269 | 5.25 | 1260 | 0.0351 |
| 10 | 30 | 13 | 6.5 | 1250 | 0.0374 |
| 11 | 30 | 13 | 4 | 1350 | 0.0385 |
| 12 | 30 | 10 | 4 | 1230 | 0.0378 |
| 13 | 31 | 11.5 | 5.25 | 1290 | 0.0568 |
| 14 | 32.68179 | 11.5 | 5.25 | 1260 | 0.037 |
| 15 | 31 | 11.5 | 5.25 | 1230 | 0.0464 |
| 16 | 31 | 11.5 | 5.25 | 1280 | 0.0389 |
| 17 | 31 | 11.5 | 7.352241 | 1452 | 0.03489 |
| 18 | 29.31821 | 11.5 | 5.25 | 1350 | 0.03478 |
| 19 | 32 | 13 | 4 | 1278 | 0.03649 |

$$R2 = 0.210 + 0.002A - 0.019B - 0.008C - 0.008A^2 + 0.003B^2 - 0.004C^2 + 0.004AB - 0.002AC - 0.004BC + 0.005ABC + 0.016A^2B + 0.013A^2C - 0.006AB^2 \quad (3)$$

The comparison of the prediction value calculated from the response functions and the real value from the FE simulation are given in Fig. 7. Good agreement between the prediction and the simulation results was observed clearly. Moreover, ANOVA of the two response functions (2) and (3) suggested that in the two cases, correlation coefficients and correction coefficients are larger than 0.93, SNR is larger than 10, and prediction accuracy is higher than 93 %. This implies the high validity and reliability of the two response functions.

The response surface of the response values *R*1 and *R*2 are illustrated in Fig.8. Curvatures of response surface reflect the weight of the factors to the response values. It is obvious that the curvatures of surfaces in Fig. 8a–c are larger than the curvatures of surfaces in Fig. 8d–f. What we can conclude is that the influence of the factors *A*, *B*, and *C* on *R*1 is greater than *R*2. Moreover, the influences of the factors are $C > B > A$ for *R*1 and $B > C > A$ for *R*2.

### 3.3 Nonlinear optimization results

In the conditions of no folding defects, a set of 16 combinations was obtained by using the nonlinear algorithm (Table 2). The desirability in each optimal solution is higher than 0.824. The combination of factors in case no. 6 was selected as the terminal design parameters to redesign the billet and forging tools for industrial application.

### 3.4 Tool redesign and application

The length of the billet is determined by the distance |*AB*| in Fig. 2. Hence, with the cavity center distance ($d$ = 30.76 mm) and cavity rotation angle ($\alpha$ = 13.00°), we obtain the length and the diameter of the billet as 275.80 and 68.53 mm, respectively. Meanwhile, flash thickness for pre-forging 1, pre-forging 2, and final forging is 5.8, 5.0, and 4.5 mm, respectively. The depth of the S-type flash gutter on the surface of final forging dies is 10 mm. Forging tools were redesigned for FE simulation and industrial application. Forged connecting rods were obtained with excellent mechanical properties,

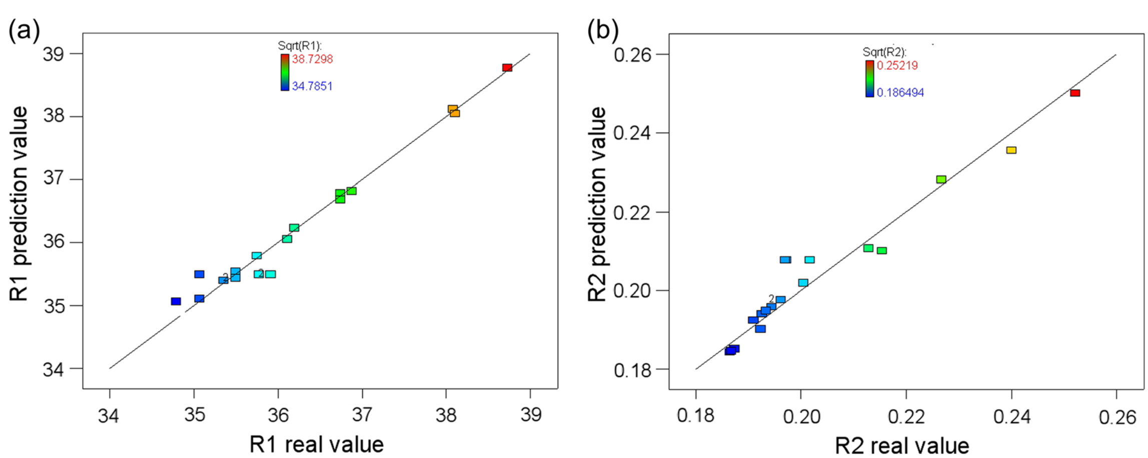


**Fig. 7** Prediction and the real value of the maximum forming load (*R*1) and tool wear depth (*R*2)

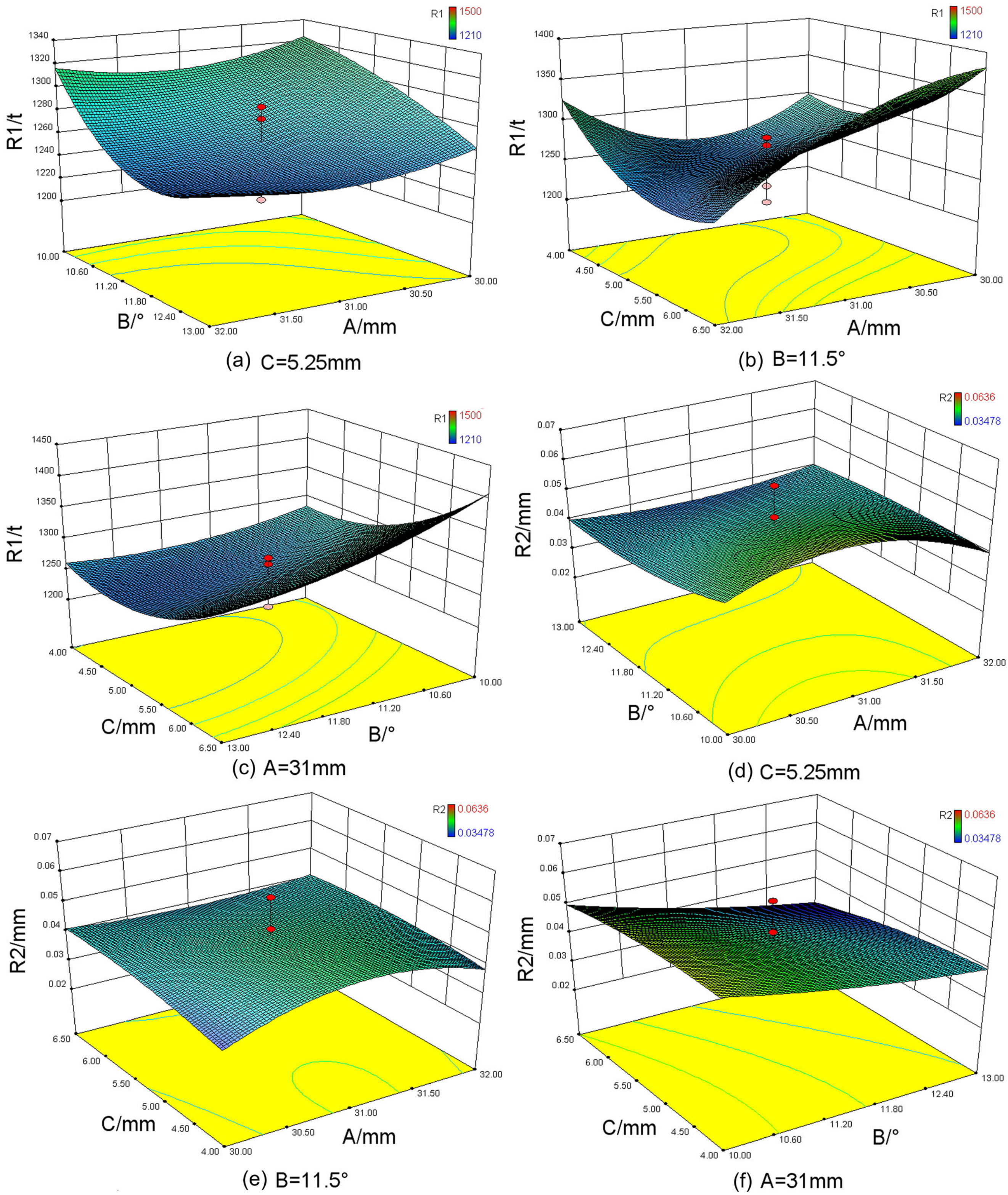


**Fig. 8** RSA of the maximum forming load (*R1*) and tool wear depth (*R2*) as a function of factors: the cavity center distance (*A*), the cavity rotation angle (*B*), and flash thickness (*C*)

better weight, and dimension accuracy, as shown in Fig. 9. In practice, data collection from the product line shows that both the average maximum forming load of 1270 t and the average maximum wear depth of 0.04 mm come from the pre-forging process after 1000 pressing.

**Table 2** Optimization results of nonlinear algorithm

| No. | *A* | *B* | *C* | *R*1 | *R*2 | Desirability |
|---|---|---|---|---|---|---|
| 1 | 30.00 | 10.00 | 5.00 | 1232.91 | 0.0383756 | 0.897835 |
| 2 | 30.78 | 13.00 | 5.78 | 1261.31 | 0.0353984 | 0.897437 |
| 3 | 30.77 | 13.00 | 5.79 | 1261.59 | 0.0353655 | 0.897433 |
| 4 | 30.77 | 13.00 | 5.80 | 1262.24 | 0.0352891 | 0.897421 |
| 5 | 30.76 | 13.00 | 5.82 | 1262.66 | 0.0352414 | 0.897392 |
| 6 | 30.76 | 13.00 | 5.83 | 1263.25 | 0.0351725 | 0.897358 |
| 7 | 30.99 | 13.00 | 5.53 | 1253.92 | 0.0363901 | 0.895074 |
| 8 | 31.05 | 13.00 | 5.64 | 1258.35 | 0.0359581 | 0.89399 |
| 9 | 30.01 | 10.00 | 5.00 | 1232.9 | 0.0386038 | 0.893779 |
| 10 | 31.13 | 13.00 | 5.61 | 1257.91 | 0.0361846 | 0.891136 |
| 11 | 32.00 | 10.54 | 6.50 | 1249.03 | 0.0400542 | 0.84086 |
| 12 | 32.00 | 10.63 | 6.50 | 1247.74 | 0.0401911 | 0.840563 |
| 13 | 32.00 | 11.43 | 5.95 | 1239.01 | 0.0416832 | 0.827286 |
| 14 | 32.00 | 11.36 | 5.87 | 1239.31 | 0.0416892 | 0.826688 |
| 15 | 32.00 | 11.89 | 5.51 | 1239.78 | 0.0417525 | 0.824752 |
| 16 | 32.00 | 11.80 | 5.58 | 1239.28 | 0.0417958 | 0.824727 |

## 4 Conclusion

In this paper, the design optimization of the forging tools of connecting rods was conducted by coupling RSA and nonlinear algorithm. In detail, the CCD experimental table was carried out via FE simulation. The following conclusions can be summarized:

1. The dimensions of flash thickness, cavity rotation angle, and cavity center distance dominate the shape of the S-type region on the two-cavity forging die of connecting rods and have significant influence on tool life.
2. The RSA suggests that the influence of the three factors on the maximum forming load is greater than the influence on the maximum tool wear depth. Meanwhile, flash thickness is the most important factor for forming load and tool wear, followed by the cavity rotation angle and the cavity center distance.
3. RSA models with high accuracy have been obtained via small sample space of CCD. A set of optimal solution was obtained with the nonlinear algorithm.
4. The optimal parameter combination was employed to redesign the billet and the forging tools for industrial practice. Good correspondence between the simulational and practical results was received.

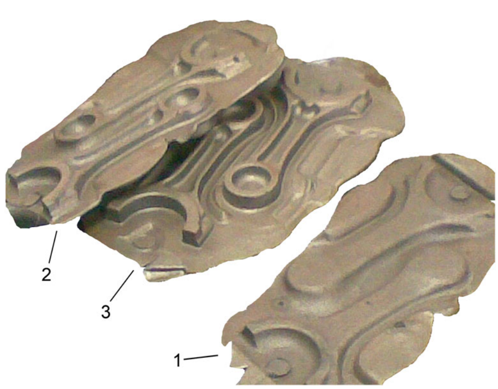


**Fig. 9** Product of forged connecting rods in the processes: *1* the first pre-forging, *2* the second pre-forging, and *3* final forging

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