Parameter optimization in hot precision forging process of synchronizer ring based on grey relational analysis and response surface method

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Abstract

In this work, the hot precision forging process was proposed to manufacture the synchronizer ring made of H Mn64–8–5–1.5 alloy, and the forming process parameters were optimized. The true stress-strain data of H Mn64–8–5–1.5 alloy were obtained through the isothermal compression test. Then, the finite element model of the hot precision forging process of the synchronizer ring was built, and two schemes of the forming process were analyzed and compared. To solve the problems during the hot precision forging process of synchronizer ring, i.e. forging defects, low material utilization and large forming load, a multi-objective optimization method based on grey relational analysis (GRA) and response surface method (RSM) were introduced to optimize the process parameters. As a result, a set of optimal process parameters was determined through the model calculating. Numerical simulation and experiment were carried out to verify the optimal scheme, which was set up based on the obtained optimal process parameters. The results of experimental and numerical simulation have good consistency. The results show that the optimal scheme can ensure product quality, enhance material utilization and reduce forming load.

1. Introduction

As an important part of synchronizer, synchronizer ring directly affects the smoothness and flexibility of shifting in the process of vehicle driving. H Mn64–8–5–1.5 alloy, as a developed and mature complex wear-resistant brass alloy, has high mechanical properties, corrosion resistance, and process properties [1–3]. Thereby it has become one of the main materials in the manufacture of synchronizer rings.

Up to now, the compound process of hot precision forging and machining is widely used to produce the synchronizer ring. The precision forging process is a prerequisite for high-quality machining of synchronizer ring. Considerable research works are concentrated on the process of hot precision forging and die design of synchronizer rings. Xue et al [4] investigated the effects of blank shape, initial forging temperature and blank wall thickness on the hot forging forging forming quality of synchronizer ring. Ashhab et al [5] applied an artificial neural network to establish the mapping relationship between geometrical parameters of the synchronizer ring and the total equivalent plastic strain, contact ratio and forming force in the drawing-extrusion forming process of the synchronizer ring. This model is useful for the selection of process design parameters to obtain desired product properties. Zhao et al [6] investigated the relationship between the die temperature and die lifetime by using numerical simulation in the hot precision forging process. They found that the initial billet temperature, forging speed and lubrication conditions can significantly affect the lifetime of hot precision forging die. Liang et al [7] established a constitutive model of HNi55–7–4–2 alloy based on the Hansel-spittel model and applied the model
to simulate the hot precision forging of a synchronizer ring. The metal flow law and the forging defects in the two process schemes were analyzed and compared, and the simulation results were well consistent with the experimental results. Wu et al \[8\] proposed a hot forging process of a bimetal gear fabricated by two metals of steel and aluminum alloy, which can significantly reduce the weight of gear.

The present research for the hot precision forging of synchronizer rings mainly focuses on the forming process, die design, especially, the effect of process parameters on the forming quality. While, more attention should be paid to the forming quality, material utilization and forming load in the actual production. To improve the forging forming quality of the synchronizer ring, it is necessary to investigate how to optimize the process parameters. In the current work, an investigation was completed for a research gap-filling through implementing the multi-objective optimization of forging defects, cavity filling, material utilization and forming load which was affected by hot precision forging process parameters.

Grey relational analysis (GRA) is a quantitative method to analyze the correlation degree of various factors in the grey system, which has been extensively applied in many engineering fields, such as electrical discharge machining \[9–11\], laser beam machining \[12–14\], precision milling and grinding \[15, 16\], mechanism design \[17, 18\]. GRA is widely adopted to judge the correlation between multi-factors and multi-objective \[19, 20\]. In GRA, the complex multiple response optimization can be simplified into the optimization of a single response grey relational grade (GRD).

In this work, to avoid the forging defects of the synchronizer ring, ensure the cavity filling, improve the material utilization and reduce the maximum forming load, the multi-objective optimization was transformed into a single objective optimization problem of GRD based on GRA and entropy method (EM). Then the second–order prediction model between GRD and main process parameters was established using the response surface method (RSM). The influences of process parameters on the objectives were analyzed, and a set of optimal hot precision forging process parameters was obtained through the optimization process. Finally, numerical simulation and a confirmation experiment were carried out to verify the optimal forging scheme which was set up based on the obtained optimal process parameters.

### 2. Material property test

The synchronizer ring utilized in this investigation is produced by Luzhou Changjiang Machinery Co., Ltd, Luzhou, China. The ring material is HMn64–8–5–1.5 manganese brass alloy, which is widely used in the manufacture of car synchronizer rings. The chemical composition of as-extruded HMn64–8–5–1.5 alloy is given in the Table 1.

| Element | Cu | Mn | Al | Si | Fe | Pb | Zn |
|---------|----|----|----|----|----|----|----|
| Mass fraction (wt%) | 64 | 8  | 5  | 1.5| 0.8| 0.4| Bal. |

Figure 1. Optical microstructure of as-extruded HMn64–8–5–1.5 alloy.
in Table 1. Figure 1 shows the optical microstructure of the alloy at room temperature. It can be seen that the matrix is β phase and the Mn5Si3 strengthening phase is dispersedly distributed.

The high-temperature rheological behavior of as-extruded HMn64−8−5−1.5 alloy was tested in this work, to develop the hot precision forging process scheme and carry out the finite element simulation. The specimens were machined into Φ8 × 12 mm cylinders using a low-speed wire-cutting electrical discharge machining method. The isothermal compression tests were conducted on a thermal simulator (Gleeble-3500, Dynamic Systems Inc., New York, NY, USA). Graphite lubricant was coated on both ends of the specimens to mitigate the influence of friction on the experimental results. The specimens were heated to 600 °C, 650 °C, 700 °C, 750 °C and 800 °C, respectively. The strain rates were defined as 0.01, 0.1, 1 and 10 s⁻¹, respectively. The true strain of the specimens was set as 0.9. A total of 20 groups of experiments were carried out. The specimens before and after the test are displayed in Figure 2.

Figure 3 illustrates the true stress-strain curves of HMn64−8−5−1.5 alloy under various deformation conditions. It can be seen that the deformation strain rate, deformation temperature and strain have essential effects on the true flow stress of HMn64−8−5−1.5. The curves show that the true stress increases with the increasing strain rate and decreasing deformation temperature. This is because that working hardening is the dominant mechanism accompanying by the increasing strain during the initial deformation period, which leads to sharply increased stress. Then, the dynamic softening is significant with continually increasing strain. At a low strain rate (< 1 s⁻¹), the stress-strain curves are gradually steady with the increasing deformation strain, which shows obvious dynamic recovery. At high strain rate, the stress-strain curves gradually decrease with the increasing deformation strain, which shows obvious dynamic recrystallization.

3. Process design

3.1. Hot precision forging process

The synchronizer ring made of HMn64−8−5−1.5 alloy has the characteristics of typical gear ring components, as shown in Figure 4. There are 36 combing teeth distributed uniformly over the outer circumference of the ring. The module m is 2.25 mm, the pressure angle α is 20°, the addendum circle diameter Da is 87.95 mm, and the root circle diameter Df is 81.9 mm. There are 6 rectangular teeth and 9 oil grooves distributed uniformly over the inner circumference of the ring. Besides, the internal surface is a circular conical surface with a taper angle of 7.5°.

The manufacturing process flow of this synchronizer ring is as follows: smelting—continuous casting and rolling of copper α rod—hot extrusion of copper tube—sawing—medium-frequency induction heating—hot precision forging—machining. Among them, the forming of the combing teeth, rectangular teeth and convex keys are the most important technical difficulties in the hot precision forging process of the synchronizer ring. Since it is required to form the synchronizer ring by one-step forging and be filled without forging defects such as cracking and folding. Moreover, the billet size and forming load should be investigated to improve the material utilization and die lifetime.

Based on the previous experience, two hot precision forging process schemes were used for finite element simulation, analysis and comparing, as illustrated in Figure 5. In scheme 1, the billet was placed on the bottom of the bottom die and localized with the side face of the step. Billet size is as follows: the outer diameter D1 is 72 mm,
the inner diameter $d_1$ is 59.5 mm, and the height $h_1$ is 26 mm. In scheme 2, the billet was placed on the step plane of the bottom die and localized with the tooth profile of the bottom die. Billet size is as follows: the outer diameter $D_2$ is 80.6 mm, the inner diameter $d_2$ is 62.5 mm, and the height $h_2$ is 16.5 mm.

3.2. Finite element simulation

The 3D models of billet and die were created using the software UG 8.5, while the finite element simulations of the hot precision forging process were carried out on the DEFORM-3D platform. Due to the geometry symmetry, only $1/6$ structure needs to be modeled for numerical simulation. The billet was defined as plastic. The dies were defined as rigid since their elastic deformation is negligible in the forging process. The data from the isothermal compression test were imported to create the billet material model for the simulation. Table 2 lists the conditions and coefficients of the finite element simulation. The finite element model is shown in figure 6.
The metal flow was analyzed for the two process schemes through finite element simulation. Figure 7 shows the simulated hot precision forging process of the synchronizer ring in scheme 1, which can be mainly divided into three stages. In stage 1, the metal flowed axially to fill the rectangular teeth. Then, with the continuous press of the top die, the metal started to flow radially, as illustrated in figure 7(a). In stage 2, the metal was extruded to fill the teeth cavity along the radial direction, and the folding defects were observed in the inner wall of the billet, as shown in figure 7(b). In stage 3, with the top die moving down to the specified stroke, the cavities of teeth and outer ring wall were filled well. The filling mainly depended on the radial metal flow. However, when the oil grooves were formed, the folding defects would occur because the metal was converged, as displayed in figure 7(c). The simulation results of scheme 1 shows that obvious folding defects occurred at the oil grooves and the inner wall of the ring.

The hot precision forging process of scheme 2 can be also divided into three stages, as shown in figure 8. In stage 1, the top die inserted into the inner bore of the billet, the metal gradually filled the outer ring wall cavity along the axial direction. At the same time, due to the extrusion of the top die, the metal flowed radially to fill the

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**Table 2.** Finite element simulation conditions and coefficients.

| Conditions and coefficients | Values       |
|-----------------------------|--------------|
| The initial temperature of the billet (°C) | 700          |
| The initial temperature of the die (°C)   | 250          |
| Mesh type                    | Tetrahedron  |
| Mesh number                  | 100000       |
| Type of mesh density         | Relative     |
| Friction type                | Shear        |
| Friction factor              | 0.25         |
| Heat transfer coefficient (N/s/mm/°C)    | 5            |

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teeth cavity, as displayed in figure 8(a). In stage 2, the cavities of the oil groove and teeth were gradually filled. The bottom metal flowed radially to form rectangular teeth. Meanwhile, the extra metal formed the inner and outer flash, as illustrated in figure 8(b). In stage 3, as shown in figure 8(c), with the top die moving down constantly to the specified stroke, the extra metal flowed out to form large flashes in outer and inner parts. The simulation
results of scheme 2 show that the folding defects were only observed at the inner flash. It can be concluded that, compared with the process of scheme 1, scheme 2 is more appropriate for the synchronizer ring forging. Even so, a couple of problems of scheme 2 need to be overcome, i.e. the large inner and outer flashes and the low material utilization. As a result, the process parameters for scheme 2 need to be optimized.

4. Process parameter optimization

4.1. Determination of design variables

According to the simulation results illustrated in the previous section, the billet was placed on the step plane of the bottom die and localized with the tooth profile of the bottom die (scheme 2). Therefore, the inner diameter and height of the billet would have a significant effect on the forming process of the synchronizer ring. Besides, it can be seen from figure 3, the flow stress is positively related to the strain rate and negatively related to the deformation temperature. Thus, the initial forging temperature of the billet and the pressing speed also directly affected the hot forging process. Therefore, four factors named the inner diameter of billet $d$, the height of billet $h$, the initial temperature of billet $T$ and the pressing speed $v$, were selected as design variables in the current work. As given in table 3, 5 levels of each factor were determined by considering the pipe of inner diameter, the

![Figure 8. Numerical simulation of process scheme 2: (a) Stage 1; (b) Stage 2; and (c) Stage 3.](image)
weight of the synchronizer ring, the forging temperature range of HMn64–8–5–1.5 alloy and the capacity of actual forging equipment.

The reasonability of the determining process parameters of the hot precision forging can be validated based on four aspects: forging defects, cavity filling, material utilization and maximum forming load, which affects the hot forging quality of the synchronizer ring directly. The forging defects and cavity filling \( \alpha \) is represented by non-dimension parameters \( \alpha' \) and \( \beta' \), where \( \alpha' \) for forging defects or under-filling, and \( \beta' \) for no defect and full-filled. The material utilization can be expressed through the volume of external flash \( \beta \) and the volume of internal flash \( \gamma \). Based on the forging drawing of the synchronizer ring, the contour line of the forging part was extracted and stretched into the cut plane. As illustrated in figure 9, the size of the external and internal flashes was obtained through the Boolean operation between the cut plane and the simulation results. The maximum forming load \( \delta \) was measured during the forming process of the synchronizer ring.

4.2. Design and implement of experiments
The inner diameter \( d \), the height \( h \), the initial forging temperature \( T \), and the pressing speed \( v \) were selected as independent variables. The forging defects and cavity filling \( \alpha \), the volume of outer flash \( \beta \), the volume of internal flash \( \gamma \), and the maximum forming load \( \delta \) were used as the dependent variables. Then, the central composite design (CCD) with 4 factors and 5 levels was applied for 31 experiments. The experimental schemes and measurement results were summarized in table 4.

4.3. Grey relational analysis (GRA)
GRA has significant advantages in analyzing the relationship between multi-factor and multi-objective, which is widely used in solving multi-objective optimization response problems [21]. In the current work, it is utilized to optimize the process parameters of the hot precision forging of a synchronizer ring. The operation procedure for GRA was proposed with the following four steps (see figure 10 for the flow chart).
Step 1: Data pre-processing. To avoid the effect of various units and to reduce the variability, data pre-processing are normally required. In this work, the response of forging defects and cavity filling $\alpha$ is the ‘0’ or ‘1’ with the ‘1’ for the desired effect of the forging: no defects and full-filled. As a dimensionless quantity, the original response $\alpha$ does not need to be normalized. The other responses named the volume of external flash $\beta$, the volume of internal flash $\gamma$, the maximum forming load $\delta$, with ‘low is better’ as their characteristic, can be normalized as follows:

$$x_i^*(k) = \frac{\max x_i(k) - x_i(k)}{\max x_i(k) - \min x_i(k)}$$

(1)

where $x_i(k)$ and $x_i^*(k)$ denotes the original sequences and the sequences after data pre-processing, respectively. max $x_i(k)$ is the maximum value of sequence $x_i(k)$, min $x_i(k)$ is the minimum value of sequence $x_i(k)$, $k = 1, 2, \ldots, n$, while $I = 1, 2, \ldots, m$. $n$ is the number of responses, and $m$ is the number of experiments. In this study, $m = 31$ with $n = 4$.

Step 2: Calculation of grey relational coefficient (GRC) [22–24]. The GRC is determined to describe the relationship between ideal and actual normalized experimental data. The GRC $\xi$ can be expressed as:

$$\xi(x_i^*(k), x_0^*(k)) = \frac{\min_{i, k} |x_i^*(k) - x_0^*(k)| + \rho \max_{i, k} |x_i^*(k) - x_0^*(k)|}{|x_i^*(k) - x_0^*(k)| + \rho \max_{i, k} |x_i^*(k) - x_0^*(k)|}$$

(2)

where $x_0^*(k)$ denotes the ideal sequence. $|x_i^*(k) - x_0^*(k)|$ is the difference of absolute value between $x_i^*(k)$ and $x_0^*(k)$. $\min_{i, k} |x_i^*(k) - x_0^*(k)|$ is the smallest value of $|x_i^*(k) - x_0^*(k)|$, $\max_{i, k} |x_i^*(k) - x_0^*(k)|$ is the largest value of $|x_i^*(k) - x_0^*(k)|$, $\rho$ is the distinguishing coefficient, which is defined in the range $0 \leq \rho \leq 1$. Generally, the $\rho$ is set at 0.5.

### Table 4. Experimental design and measurement results.

| No. | Independent variables | Dependent variables |
|-----|-----------------------|---------------------|
|     | $T (^\circ C)$ | $v (\text{mm} \cdot \text{s}^{-1})$ | $d (\text{mm})$ | $h (\text{mm})$ | $\alpha$ | $\beta (\text{mm}^3)$ | $\gamma (\text{mm}^3)$ | $\delta (\text{kN})$ |
| 1   | 700 | 200 | 59 | 14 | 1 | 603.70 | 1764.35 | 789 |
| 2   | 650 | 250 | 63.5 | 15.5 | 1 | 1086.34 | 1094.09 | 968 |
| 3   | 750 | 150 | 63.5 | 15.5 | 1 | 1020.41 | 1194.37 | 718 |
| 4   | 650 | 250 | 60.5 | 15.5 | 1 | 788.45 | 1664.35 | 941 |
| 5   | 700 | 200 | 62 | 14 | 1 | 752.40 | 1268.70 | 749 |
| 6   | 650 | 250 | 60.5 | 12.5 | 1 | 349.38 | 1302.24 | 698 |
| 7   | 700 | 100 | 62 | 14 | 1 | 738.85 | 1313.06 | 721 |
| 8   | 750 | 250 | 63.5 | 15.5 | 1 | 1024.06 | 1184.87 | 808 |
| 9   | 750 | 150 | 60.5 | 12.5 | 1 | 387.14 | 1300.74 | 548 |
| 10  | 700 | 200 | 62 | 14 | 1 | 1578.78 | 1704.78 | 1180 |
| 11  | 700 | 300 | 62 | 14 | 1 | 753.11 | 1311.99 | 760 |
| 12  | 650 | 150 | 60.5 | 12.5 | 1 | 366.26 | 1301.97 | 685 |
| 13  | 750 | 250 | 60.5 | 15.5 | 1 | 807.05 | 1704.51 | 793 |
| 14  | 700 | 200 | 62 | 14 | 1 | 716.71 | 1331.05 | 725 |
| 15  | 750 | 150 | 60.5 | 15.5 | 1 | 813.86 | 1714.12 | 796 |
| 16  | 750 | 250 | 60.5 | 12.5 | 1 | 400.82 | 1307.56 | 582 |
| 17  | 700 | 200 | 65 | 14 | 0 | 791.21 | 590.27 | 702 |
| 18  | 800 | 200 | 62 | 14 | 1 | 690.61 | 1383.23 | 546 |
| 19  | 650 | 150 | 63.5 | 15.5 | 1 | 1069.0 | 1118.46 | 971 |
| 20  | 650 | 150 | 63.5 | 12.5 | 0 | 351.38 | 724.97 | 610 |
| 21  | 700 | 200 | 62 | 14 | 1 | 752.40 | 1268.70 | 749 |
| 22  | 700 | 200 | 62 | 14 | 1 | 716.71 | 1331.05 | 725 |
| 23  | 700 | 200 | 62 | 14 | 1 | 742.91 | 1315.17 | 751 |
| 24  | 700 | 200 | 62 | 14 | 1 | 742.91 | 1315.17 | 751 |
| 25  | 750 | 250 | 63.5 | 12.5 | 0 | 478.06 | 774.51 | 492 |
| 26  | 700 | 200 | 62 | 14 | 1 | 742.91 | 1315.17 | 751 |
| 27  | 750 | 150 | 63.5 | 12.5 | 0 | 515.09 | 741.57 | 457 |
| 28  | 650 | 150 | 60.5 | 15.5 | 1 | 795.73 | 1650.39 | 968 |
| 29  | 600 | 200 | 62 | 14 | 1 | 759.26 | 1268.95 | 899 |
| 30  | 650 | 250 | 63.5 | 12.5 | 0 | 342.08 | 706.55 | 664 |
| 31  | 700 | 200 | 62 | 11 | 0 | 199.98 | 836.75 | 492 |
Step 3: Calculation of response weight. Grey relational grade (GRG) is the weighted sum of GRC. The weight factor represents the importance of the responses. The entropy method (EM) is an objective weighting method [25]. Based on the GRC obtained in step 2, the weight factor of each response can be calculated through the EM.

The proportion $P_{ik}$ for the $k$th performance characteristic in the $i$th experiment can be determined as follows:

$$P_{ik} = \frac{\xi_{ik}}{\sum_{i=1}^{m} \xi_{ik}}$$

The matrix composed of specific gravity $P_{ik}$ is marked as $P$. The entropy $(H_k)$ of the $k$th index can be obtained through equation (4). The weight factor $(\omega_k)$ of the $k$th is determined by using equation (5).

Table 5 lists the calculation results of the entropy $H_k$ and weight factor $\omega_k$. It can be found that the response of forging defects and cavity filling $\alpha$ with the largest weight factor is the most influential index. Therefore, if the forging part is defective, the subsequent optimization is of little significance.

$$H_k = -\frac{1}{\ln m} \times \sum_{i=1}^{m} (P_{ik} \times \ln P_{ik})$$

$$\omega_k = \frac{1 - H_k}{\sum_{k=1}^{n} (1 - H_k)}$$

Step 4: GRG calculation. The GRG can be expressed as equation (6). The calculation results of GRC and GRG are summarized in table 6.

$$\phi(x_i^y, x_0^y) = \sum_{k=1}^{n} \omega_k \xi(x_i^y(k), x_0^y(k))$$

where, $\omega_k$ is the weight factor, obtained through the EM.

4.4. Response surface modeling and analysis

To implement the process parameter optimization for the hot precision forging of the synchronizer ring, the relationship between GRG and design variables was established by using the complete quadratic model of the response surface method (RSM). Using Minitab software, the relationship expression of the model was obtained, as shown in equation (7).

$$y = 0.67809 + 0.01453T$$
$$- 0.00281v - 0.02026d - 0.02041h$$
$$+ 0.0046T^2 - 0.01167d^2 - 0.001331h^2$$
$$- 0.00285Tv + 0.00329Td - 0.00534Th$$
$$+ 0.00235wh + 0.04111dh$$

where $y$ is the estimated value of GRG.

The comparison between the model prediction data and experimental ones is illustrated in figure 11. It can be seen that the model prediction data were in good agreement with the experiments accompanied by an average relative deviation of 0.62%. Figure 12 shows the residual diagram of the prediction model. It showed a random pattern of residuals on both sides of 0, which indicates that the prediction model fits the sample well. Table 7 lists the analysis of variance (ANOVA) for the GRG prediction model. The significance $P$-value of the model is 0.0001, less than 0.05, which means that the model is very significant. The $R$-Sq value of the established model is 97.27%, indicating a high fitting degree between the predicted and experimental results. The value of $R$-Sq(adj) is 95.45% and it is very close to that of the $R$-Sq, which indicates that the established model is reasonable and can accurately describe the experimental data. It can be concluded that the developed GRG prediction model can describe the response of GRG well to design variables with high reliability and fitting accuracy. Therefore, it is appropriate for subsequent multi-objective optimization.
4.5. Effect of design variables on responses

The main effect analysis was implemented to investigate the influence of forming process parameters on the GRC of the forging defects and cavity filling $\alpha$, the volume of outer flash $\beta$, the volume of inner flash $\gamma$ and the maximum forming load $\delta$, as shown in figure 13. Figure 13(a) displays the main effect plot of GRC for forging

![Figure 11. Comparison between the model prediction data and experimental results.](image)

Table 6. Calculation results of GRC and GRG.

| No. | $\alpha (k = 1)$ | $\beta (k = 2)$ | $\gamma (k = 3)$ | $\delta (k = 4)$ | $\phi$ |
|-----|-----------------|-----------------|-----------------|-----------------|-------|
| 1   | 0.5935          | 0.3333          | 0.5213          | 0.6485          |
| 2   | 0.3994          | 0.5381          | 0.4143          | 0.6514          |
| 3   | 0.4181          | 0.4928          | 0.5807          | 0.6752          |
| 4   | 0.5004          | 0.3534          | 0.4276          | 0.6195          |
| 5   | 0.5162          | 0.4639          | 0.5532          | 0.6783          |
| 6   | 0.7978          | 0.4519          | 0.6000          | 0.7322          |
| 7   | 0.5224          | 0.4482          | 0.5779          | 0.6799          |
| 8   | 0.4170          | 0.4968          | 0.5074          | 0.6615          |
| 9   | 0.7590          | 0.4524          | 0.7989          | 0.7655          |
| 10  | 0.3333          | 0.3450          | 0.3333          | 0.5699          |
| 11  | 0.5159          | 0.4485          | 0.5440          | 0.6721          |
| 12  | 0.7800          | 0.4520          | 0.6132          | 0.7318          |
| 13  | 0.4926          | 0.3451          | 0.5183          | 0.6340          |
| 14  | 0.5328          | 0.4421          | 0.5743          | 0.6792          |
| 15  | 0.4898          | 0.3431          | 0.5161          | 0.6326          |
| 16  | 0.7458          | 0.4501          | 0.7431          | 0.7314          |
| 17  | 0.3333          | 0.4992          | 1.0000          | 0.5960          | 0.6007 |
| 18  | 0.5457          | 0.4254          | 0.8024          | 0.7224          |
| 19  | 0.4041          | 0.5264          | 0.4129          | 0.6487          |
| 20  | 0.3333          | 0.6401          | 0.8134          | 0.7026          | 0.5938 |
| 21  | 0.5162          | 0.4639          | 0.5532          | 0.6783          |
| 22  | 0.5328          | 0.4421          | 0.5743          | 0.6792          |
| 23  | 0.5205          | 0.4475          | 0.5515          | 0.6741          |
| 24  | 0.5205          | 0.4475          | 0.5515          | 0.6741          |
| 25  | 0.3333          | 0.6794          | 0.7611          | 0.9117          | 0.6276 |
| 26  | 0.5205          | 0.4475          | 0.5515          | 0.6741          |
| 27  | 0.3333          | 0.6516          | 0.7951          | 1.0000          | 0.6501 |
| 28  | 0.4973          | 0.3564          | 0.4143          | 0.6172          |
| 29  | 0.5131          | 0.4638          | 0.4499          | 0.6571          |
| 30  | 0.3333          | 0.6327          | 0.8347          | 0.6359          | 0.5851 |
| 31  | 0.3333          | 1.0000          | 0.7043          | 0.9117          | 0.6662 |
defects and cavity filling $\alpha$. The inner diameter of billet $d$ and height of billet $h$ have the most significant influence on GRC. Where, $d$ is negatively correlated with GRC ($\alpha$), while $h$ is positively correlated. It can be explained that both $d$ and $h$ affect the volume of the billet directly. As $d$ increases and $h$ decreases, the volume of billet decreases, resulting in insufficient metal to fill the die cavity. The main effect diagram of GRC for outer flash volume $\beta$ is shown in figure 13(b). It can be observed that the $h$ has the greatest effect on GRC ($\beta$) with a negative correlation. A bigger value of $h$ means a larger billet volume. Therefore, more extra metal will flow out of the die cavity and form the outer flash easily. It resulted in a smaller GRC ($\beta$) value. As depicted in figure 13(c), the $d$ has the largest influence on GRC ($\gamma$) with positive correlation, followed by $h$ with negative correlation. However, if $d$ is too large and $h$ is too small, under-filling may occur in the forging part. Figure 13(d) illustrates the main effect diagram of GRC for the maximum forming load $\delta$. The flow stress of the material reduces with the increase of temperature, therefore GRC($\delta$) is positively correlated with the initial forging temperature $T$. The flow stress of material is positively correlated with the strain rate, while the deformation resistance rises with the increase of the pressing speed $v$. Consequently, $v$ is negatively correlated with GRC ($\delta$). With the increase of $d$ and the decrease of $h$, the number of internal and external flashes becomes small, because the contact area between the billet and die decreased. It causes the reduction of the maximum forming load and the increase of the GRC ($\delta$) correspondingly.

5. Confirmation simulation and experiment

The influence of various process parameters on different objectives is reflected by the change of GRG, therefore the multi-objectively optimization can be implemented based on the optimization of GRG. In the current work, the optimization procedure was conducted through the response optimizer in Minitab software. The larger the GRG is, the better the corresponding response values are. The constraint conditions of each variable are as follows: $59 \text{ mm} \leq d \leq 65 \text{ mm}$, $11 \text{ mm} \leq h \leq 17 \text{ mm}$, $650 \text{ °C} \leq T \leq 750 \text{ °C}$, and $100 \text{ mm} \cdot \text{s}^{-1} \leq v \leq 300 \text{ mm} \cdot \text{s}^{-1}$. The range of $T$ has been narrowed here. When $T$ closes to $600 \text{ °C}$, a brittle zone will appear. While, when $T$ exceeds $750 \text{ °C}$, the gain coarsening tends to be serious after forging. It will affect the mechanical properties of the forging part. Based on the optimization in the available design space, the optimal solution of GRD was determined to be 0.6895, and the optimal scheme for the process parameters was obtained as follows: $d$ was $63 \text{ mm}$, $h$ was $15 \text{ mm}$, $T$ was $720 \text{ °C}$ and $v$ was $100 \text{ mm} \cdot \text{s}^{-1}$.

| Table 7. ANOVA for the GRG prediction model. |
|-----------------|-----|-------------------|-------------------|------|------|
| Symbol          | DF  | Sum of squares    | Mean square       | F-value | P-value |
| Response model  | 12  | 0.062638          | 0.00522           | 53.44  | 0.0001 |
| Error           | 18  | 0.001758          | 0.000098          | —      | —      |
| Total           | 30  | 0.064397          | —                 | —      | —      |
| Standard deviation | R-Sq = 97.27% | R-Sq(adj) = 95.45% |

Figure 12. Residual diagram of the GRG prediction model.
The optimal process parameters were applied to numerical simulation to verify the optimal scheme. The results of the numerical simulation were displayed in figure 14. It can be observed that the forging part was filled and there was no folding defects occurred except the inner flash. The size of the inner flash is appropriate and uniform. The material utilization reaches 60.08%. The maximum forming load is 709 kN. Figure 14(b) shows the temperature distribution of the forging part. The highest temperature is 806 °C, appearing at the outer flash. While the lowest one is 713 °C, appearing in the ring body. The temperature distribution within the synchronizer ring is in a reasonable range of 710 °C–760 °C. As displayed in figure 14(c), the deformation of each part of the synchronizer ring is relatively uniform. The deformation of rectangular teeth is the smallest and the outer flash is the largest. The simulation results show that the forging part can achieve the production requirements based on the proposed optimal process parameters.

In the actual experiment, the hot extruded tube (figure 15(a)) was sawed for blanking (figure 15(b)). The billet after blanking was preheated in a heating furnace (figure 15(c)) and hot forged on CNC electric screw press (figure 15(d)). The preheating temperature of the die is in the range of 250–300 °C and the dies were lubricated by spayed graphite. The forging part (figures 15(e) and (f)) was air-cooled to room temperature. The
confirmation experiment shows that the maximum forming load is 780 kN, the thickness of the outer flash is about 1.3 mm. The experiment results are well consistent with the numerical simulation, with a maximum error of 9.1%. Therefore, the proposed precision forging process is verified.

The difference of forming load between simulation and experiment could be mainly caused by the accuracy of the material model, the control of actual billet temperature, and the control of forming equipment speed. In addition, the dimensional deviation of billet, the deviation of the die manufacturing and installation, and the control of the actual forming stroke may also cause the difference between the simulation and experiment results. In conclusion, the optimal scheme obtained from the optimization of hot precision forging process parameters based on GRA and RSM can ensure that the product can achieve the design requirements. It means there are no forging defects occurred, the dies are filled, the material utilization is significantly improved, and the forming load is effectively reduced during the hot precision forging process of the synchronizer ring.

6. Conclusions

In this work, the hot precision forging process of the synchronizer ring was analyzed through numerical simulation. The process parameters were optimized based on the GRA and RSM. Several important results of the investigation were summarized as follows:

(1) The true stress-strain curves of HMn64–8–5–1.5 alloy were obtained through a hot-compression test at the temperature range of 600°C–800°C and a constant strain rate of 0.01–10s⁻¹. The curves show that the flow stress of HMn64–8–5–1.5 alloy has a nonlinear relationship with deformation temperature, strain rate and strain. Meanwhile, the flow stress is positively related to the strain rate and negatively correlated with deformation temperature.
(2) Folding defects have occurred at the inner wall of the ring and the oil grooves during the numerical simulation of forging process scheme 1. While the defects appeared at the inner flash in scheme 2. Therefore, the precision forging process of scheme 2 is better than that of scheme 1.

(3) Through combining the EM and GRA, the RSM was used to develop the GRG prediction model, with the initial temperature of billet \( T \), the pressing speed \( v \), the inner diameter of billet \( d \), and the height of billet \( h \) as the design variables, as well as the forging defects and filling \( \alpha \), the outer flash volume \( \beta \), the inner flash volume \( \gamma \), and the maximum forming load \( \delta \) as the optimization objectives variables. The ANOVA result shows that the prediction model has good statistical adequacy and prediction accuracy.

(4) The determining optimal process parameters are as follows: \( d = 63 \text{ mm} \), \( h = 15 \text{ mm} \), \( T = 720 \degree \text{C} \) and \( v = 100 \text{ mm} \cdot \text{s}^{-1} \). After optimization, the forging part is filled well and no folding defects occur. The size of the inner flash is appropriate and uniform. Meanwhile, the material utilization is significantly improved, and the forming load is effectively reduced.

(5) The numerical simulation results are consistent with the experiments accompanied by a maximum error of 9.1%. It verifies the proposed precision forging process based on obtaining optimal process parameters. The procedure proposed in this work can be applied to other similar industrial processes to obtain optimum design values.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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