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Research Article

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Microstructure homogeneity control of GH4706 superalloy turbine disc prepared by integral hot forming

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Abstract

Coarse mixed grains originating from strain-deficient regions during one-step integral hot forming compromise the properties of ultra-large GH4706 superalloy turbine disks. Different from conventional tuning methods centered on temperature and strain rate, this study proposes a homogeneity-oriented control strategy that incorporates an optimized pre-forging step, wherein die geometry is utilized as the primary regulation approach to redistribute the overall strain. This study combines multi-field, multi-scale finite element simulation with Taguchi experimental design and signal-to-noise ratio analysis to realize co-optimization of the overall average grain size (AVG) and its standard deviation (SD). A dual quantification framework integrating analysis of variance (ANOVA) and Sobol sensitivity analysis is adopted, in which the ANOVA contribution rates are validated by first-order Sobol indices calculated via Monte Carlo simulation. The results indicate that pre-forging die geometry is the dominant influencing factor, with a total contribution of 67.0% (concave radius: 36.4%, underfilling height: 21.3%, die angle: 9.3%), followed by strain rate with a contribution of 29.9%. By contrast, deformation temperature only contributes 3.1% within the pre-screened range of 1110–1140 °C. Accordingly, it is concluded that the geometric tolerance of pre-forging dies should be strictly controlled, while the deformation temperature window can be appropriately relaxed. Under the optimal parameter combination, the grain size at all 12 cross-section verification points is less than 40 μm, the standard deviation of grain size is less than 4 μm, and coarse mixed grains with a size exceeding 40 μm are substantially eliminated. Production verification conducted on a scaled forging with a diameter of 660 mm confirms that uniformly recrystallized microstructures are obtained at all six sampling positions, and the dynamic recrystallization (DRX) fraction at the hub end exceeds 70%. This study provides a validated and cost-effective design foundation for the full-scale integral hot forging of ultra-large turbine disks.

Keywords GH4706 alloy · Microstructure · Turbine disk · Multi-objective · Optimization · Homogeneity

1 Introduction

Ultra-large turbine disk forgings are key components of F-class heavy-duty gas turbines, and rank among the world's largest deformed superalloy disk forgings. Their large dimensions and complex structural characteristics impose severe technical

challenges on the melting, casting, cogging, and hot forging processes. For turbine disks with diameters exceeding 2-m, the forging of such ultra-large turbine disks has become a recognized extreme manufacturing challenge when evaluated against the global equipment capacity [1,2]. When production operates near the upper limit of existing equipment capacity, the microstructure and mechanical properties of turbine disk forgings tend to degrade as the disk size increases; the microstructure and properties deteriorate even further when approaching the equipment's load limit. Therefore, a major unresolved challenge is the multi-objective optimization of process parameters that accounts for equipment capacity, product microstructure, and manufacturing cost [3–5].

GH4706 alloy is developed on the basis of the composition of the widely recognized GH4169 alloy, which is a precipitation-strengthened Fe-Ni-based superalloy applied in high-temperature service environments [6,7]. The applicability of GH4706 alloy to the fabrication of ultra-large turbine disks is attributed to its excellent comprehensive properties [6–9]: low segregation tendency, favorable hot formability and outstanding mechanical properties. To regulate the microstructure homogeneity of GH4706 alloy turbine disks, it is necessary to predict, identify, and verify the optimal hot working process parameters. The conventional approach to this task relies on extensive trial-and-error experiments. However, for ultra-large nickel-based superalloy forgings, the production testing cost resulting from equipment energy consumption and raw material consumption is prohibitively high. Thus, a theoretical method that can directly identify the optimal parameter combination is required to balance and control the microstructure homogeneity, energy consumption, and material usage of ultra-large GH4706 alloy turbine disks. Previous studies have shown that combining finite element method (FEM) simulation with optimization techniques is highly effective for optimizing process parameters [10–12]. Finite element simulation can predict key outputs including forging load and microstructure distribution, while optimization techniques enable quantitative comparison of simulation results under different process conditions. In this way, efficient control of process parameters is realized, and the optimal parameter combination within a variable parameter range is obtained, thereby achieving effective control of the microstructure [13]. Compared with experimental methods, this approach greatly reduces costs. In recent years, the widely applied multi-objective optimization techniques for process parameters include the following [14–20]: Taguchi optimization, hot processing map optimization, Kriging optimization, genetic algorithm optimization, particle swarm optimization, among others. According to the literature, studies on the optimization of forging process parameters for ultra-large turbine disks remain relatively scarce. Trial production of an ultra-large GH4706 alloy turbine disk with a diameter exceeding 2000 mm has been completed via one-step integral hot forming on an 800 MN forging press [21]. Metallographic images of the local microstructure at the rim, web, and hub of the turbine disk after machining reveal the presence of coarse and mixed grains at the end faces of these regions. This indicates that the coarse and mixed microstructure formed during the integral hot forming stage is inherited in subsequent processes. Research has demonstrated that the mixed grain microstructure is mainly caused by a low recrystallization fraction [19]. Local coarse and mixed microstructures severely degrade the mechanical properties of turbine disks [19,20]. Although subsequent heat treatment can regulate the microstructure to a certain extent, the microstructure after hot forming serves as the foundation and a key factor determining the final performance of the turbine disk. Accordingly, solving the problem of local coarse and mixed grains and establishing a

method for controlling the microstructure homogeneity of integrally hot-formed turbine disk forgings are urgent issues to be resolved.

Based on prior multi-scale high-precision numerical simulation investigations [21], the present study proposes a regulation method for the microstructural homogeneity of integrally hot-formed forged turbine discs. The core of achieving microstructural uniformity regulation lies in introducing a pre-forging procedure and implementing geometric parameter optimization for the preform, which resolves the problem of insufficient local strain in the forged component. The optimized process parameter combination was obtained through numerical simulation and multi-objective optimization, and the optimal design for microstructure homogeneity in integral hot forming can be implemented in three steps: First, an orthogonal array of parameters to be optimized will be established within the optimized parameter range. Orthogonal simulation experiments will be performed using the established multi-field and multi-scale dynamic coupling model for GH4706 alloy. Second, based on the simulation results of multiple groups of process parameters, multi-objective optimization and analysis, including signal-to-noise ratio (SNR) calculation and variance analysis, will be carried out for multiple process parameters such as preform size, deformation temperature and strain rate, so as to realize the optimal design of preforming die geometry and overall hot forming process parameters. On this basis, quantitative analysis on the contribution degree and sensitivity of each process parameter will be completed. Third, industrial verification will be carried out to validate the effectiveness of the microstructure homogeneity control method for disk forgings. Considering the generality of the method, including the size effect, and the need for cost risk control, production verification using scaled-down forgings will be performed prior to the actual manufacturing verification of full-size ultra-large forgings.

2 Experiments and methods

2.1 Experimental materials and procedure

The alloy used in this study is wrought GH4706 alloy [6,7]. The nominal chemical composition of the GH4706 alloy adopted in this research is shown in Table 1. Isothermal compression tests were carried out on a computer-controlled hydraulic Gleeble-1500 thermal simulator. The specimens were machined by wire electrical discharge machining to 8 mm in diameter and 15 mm in height. To reduce the anisotropy of flow behavior, each specimen was heated to the deformation temperature at a heating rate of $10\text{ }^{\circ}\text{C}\cdot\text{s}^{-1}$ and held for 180 s. After compression to a true strain of 1.2, the specimens were immediately quenched in water, and the true stress–true strain curves were automatically recorded. Electron Back-Scattered Diffraction (EBSD) observations were performed on the central region of the sectioned specimens using a JSM 7800F scanning electron microscope. The EBSD samples were ground with silicon carbide abrasive papers up to 3000 grit, followed by electropolishing at 22 V for 20 s in an electrolyte consisting of 10% HClO_4 and 90% $\text{C}_2\text{H}_5\text{OH}$. The prepared specimens were stored in an alcohol solution. The central

position of each specimen was selected for observation, and the EBSD data were post-processed using the AZtecCrystal software package.

Table 1 Standard chemical compositions of GH4706 alloy (wt.%)

Alloy	C	Mn	Si	P	Mo	Ni	Cr	Fe	Al	Ti	B	Cu	Nb	Ta
GH4706	0.06	0.35	0.35	0.02	-	44	17.5	Bal.	0.4	2	0.006	0.3	3.3	0.05

2.2 Preliminary work

In this study, the Taguchi orthogonal experimental design method is adopted as the research framework, and finite element simulation is utilized to obtain simulation datasets including microstructure distribution and parameter field distribution. The SNR (SNR) method is applied to identify the optimal design scheme, and the analysis of variance (ANOVA) is employed to quantify the contribution rate of each factor [5,22]. First, an objective function for evaluating microstructure uniformity is constructed [12]. The multi-objective optimization of the turbine disk forging process is oriented toward realizing microstructure homogenization, which can be quantitatively characterized by two indicators, the overall average grain size (AVG) and the standard deviation of grain size distribution (SD), respectively. Specifically, AVG represents the overall average grain size across the entire calculation domain (including both recrystallized and unrecrystallized grains), while SD characterizes the degree of dispersion and fluctuation of grain size within the entire volume. Due to the discrete nature of finite element simulation and the inhomogeneous deformation during the forming process, AVG of each element differs, and this property is independent of the number of elements. Based on the discretization characteristics of finite element simulation, the objective functions of AVG and SD can be expressed as follows.

$$AVG = \frac{\sum_{i=1}^m \int d_i dV_i}{\sum_{i=1}^m \int dV_i} \quad (1)$$

$$SD = \left[\frac{\sum_{i=1}^m \int (d_i - D)^2 dV_i}{\sum_{i=1}^m \int dV_i} \right]^{\frac{1}{2}} \quad (2)$$

where m is the total number of elements in the simulated turbine disk; d_i is the actual average grain size of each element in the simulation; D is the overall average grain size over the whole simulated domain.

In our previous studies, we established a multi-field and multi-scale dynamic coupling model for GH4706 alloy, which consists of the GA-BP-ANN model [23] and the empirical dynamic recrystallization (DRX) model [24]. This model was further implemented in the DEFORM-2D software [21,23]. We conducted a numerical simulation of the integral hot forming process for a scaled turbine disk forging of GH4706 alloy with a diameter of 660 mm. It should be noted that the applicability of the DRX coupling model established by our research team in previous work is constrained to the parameter interval covered by the existing database, specifically the temperature range of 950–1150 °C and the strain rate range of 0.001–1 s⁻¹. When the working parameters exceed the aforementioned interval, non-negligible prediction

errors may arise. Furthermore, the proposed coupling model has been verified to achieve satisfactory prediction accuracy for the performance of GH4169 alloy [23]. Given that all nickel-based superalloys typically undergo the discontinuous dynamic recrystallization (DDRX) metallurgical mechanism during hot deformation [25 – 27], the coupling model constructed in this study can be effectively extended to predict the hot deformation behavior of other DDRX metals. Subsequent research will further expand the material databases embedded in DEFORM® and DIGIMU® software to improve the generalization ability of the proposed model.

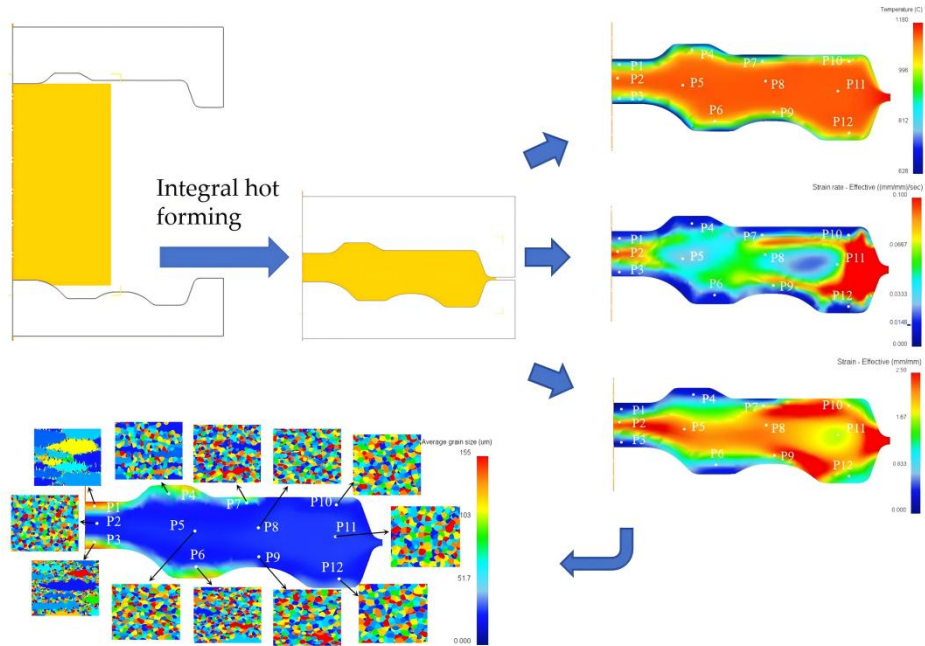


Fig. 1 One step integral forging process of GH4706 alloy turbine disk [21]

The process conditions employed in the finite element simulation are specified as follows [21]: Given the high-temperature and large-deformation characteristics of the process, elastic deformation is neglected. The billet is defined as a plastic body, while the dies are set as rigid bodies. The interfacial friction between the billet and dies is defined as shear friction with a friction coefficient of 0.3. Based on the soft canning process parameters, the heat transfer coefficient is set to $1 \text{ N} \cdot \text{s}^{-1} \cdot \text{mm}^{-1} \cdot ^\circ\text{C}^{-1}$. The ambient temperature is controlled at $20 \text{ }^\circ\text{C}$, and the die temperature is set to $350 \text{ }^\circ\text{C}$. Referring to previous research findings and equipment capacity constraints, the deformation temperature is set to $1120 \text{ }^\circ\text{C}$ and the strain rate is set to 0.05 s^{-1} ($\ln Z = 32.794$). The initial cross-section of the billet is discretized into approximately 5000 elements via automatic meshing technology. The optimized GA-BP-ANN model and the integrated DRX model for hot forming of GH4706 alloy are embedded in the simulation framework [23,28]. The simulation satisfies the equilibrium equation, geometric equation, volume incompressibility condition, and von Mises isotropic yield criterion. Microstructure evolution during hot forming is incorporated into the simulation.

As illustrated in Figure 1 [21], the macroscopic distributions of the strain field, temperature field, and strain rate field are firstly simulated separately. Twelve sampling points (P1–P12) are arranged on the cross-section of the turbine disk to form a grid that covers the entire cross-sectional area. The field values of the process parameters at these twelve points are imported as initial condition settings for the

corresponding positions in DIGIMU software, and the microstructure evolution simulation is subsequently performed [28]. The grain morphology and the distribution of AVG are obtained from the simulation. On this basis, the AVG and SD are calculated. Figure 1 also presents the simulation results obtained by the established multi-scale DRX model. The grain morphologies at P1–P12 are extracted through a fixed observation window. The simulation results show that the microstructure at the hub (Point P1) presents obvious coarse grain and mixed microstructures. Similarly, coarse and mixed microstructures also occur near the hub end face (Points P3, P4, P6, and P7). To address these issues, the AVG and SD are adopted as representative indicators for uniformity regulation and process optimization. Furthermore, the SNR of multiple experiments is employed for performance evaluation. Two evaluation objects are defined: Point P1 near the hub end face with severe coarse and mixed grains ($AVG_1 + SD_1$) and the entire turbine disk ($AVG_2 + SD_2$). Figure 1 also indicates that the distribution of mixed grain regions is basically consistent with that of uneven strain distribution, which verifies that inhomogeneous strain distribution is the main cause of mixed microstructures. Therefore, it is necessary to introduce a pre-forging process to increase the local strain of the turbine disk and optimize the uniformity of the overall strain distribution. This improvement can eliminate local coarse grains and mixed microstructures, and ultimately improve the homogeneity of the overall microstructure.

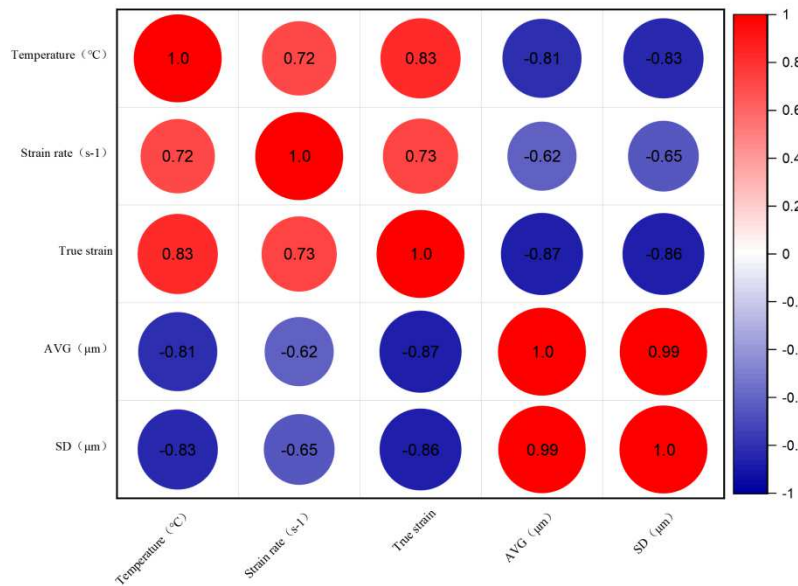


Fig. 2 Heatmap of Pearson correlation coefficients among the hot-deformation process parameters and the microstructural responses at the 12 monitoring points

The correlations between various process parameters, AVG and SD are presented in Figure 2. Figure 2 is a heatmap of Pearson correlation coefficients ranging from -1 to $+1$, which clearly reveals strong negative and positive correlations. In the current dataset, process parameters exhibit prominent negative correlations with the resultant AVG and SD. This indicates that an increase in the three process parameters leads to a gradual decline in the resultant AVG and SD. Strain shows the strongest negative correlation with a coefficient of -0.87 , followed by temperature and strain rate. Additionally, a strong positive correlation exists between the resultant AVG and SD,

suggesting that they share a consistent variation trend when reflecting the distribution characteristics of microstructure, where lower values indicate better performance.

3 Simulation and Multi-Objective Optimization

3.1 Process optimization design of pre-forging + final-forging

For the integrated pre-forging + final-forging forming process of super-large GH4706 alloy turbine disks, multi-objective optimization is applied to the geometric design of pre-forging dies to significantly increase the strain near the hub end face. This improves the uniformity of strain distribution across the entire turbine disk and enables effective control of microstructure uniformity during the integrated hot forming process. To increase the strain in the hub region and avoid excessively low local strain caused by upsetting, the pre-forged billet at the hub is designed with a concave shape, as shown in Figure 3. According to the authors' previous research [16], microstructure homogenization efficiency reaches its maximum at the optimal strain. Based on this finding, orthogonal parameter optimization is conducted on the geometric dimensions of the pre-forging die that affect the strain at the hub. This adjustment enables the strains at both the hub and the rim to approach or exceed the optimal strain, thus ensuring the uniformity of the overall microstructure of the turbine disk. The finite element simulation settings remain consistent with those used in the single-step forming trial.

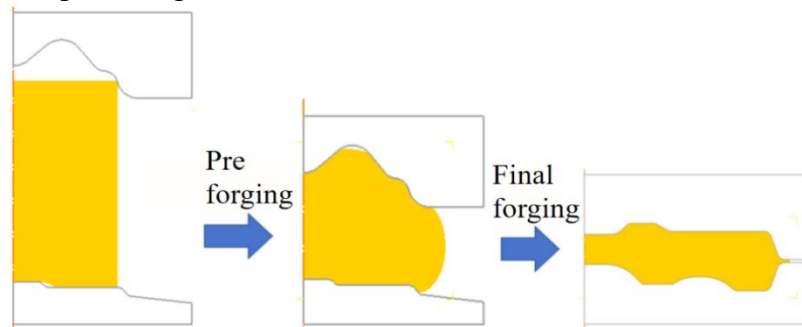


Fig. 3 Shape parameterization of super large turbine disk before hot forging

Based on the optimal parameter range (temperature: 1100–1150 °C, strain rate: 0.01–0.1 s⁻¹) established in the authors' previous study [16,24] and the quantitative relationship between the Zener–Hollomon (Z) parameter and microstructure [25,29,30], grains tend to grow rapidly when the value of lnZ is lower than 32 [24], while excessively high lnZ leads to incomplete DRX. Analysis of the evolution of the power dissipation coefficient η [31,32] indicates that the homogenization efficiency of the microstructure decreases significantly when the strain rate approaches 1 s⁻¹. Accordingly, strain rates of 0.02, 0.04, 0.06 and 0.08 s⁻¹ were selected as the optimized candidates. Combined with the approximate height of the pre-forging (250 mm), the above strain rates were converted to the corresponding ram speeds for the 800 MN press, namely 5 mm/s, 10 mm/s, 15 mm/s and 20 mm/s. Since the microstructure of specimens tested at 1100 °C failed to achieve a fully equiaxed state, temperatures of 1110 °C, 1120 °C, 1130 °C and 1140 °C were chosen for optimization. The optimized parameters for the orthogonal test of strain rate $\dot{\epsilon}$ and deformation temperature T are presented in Figure 4.

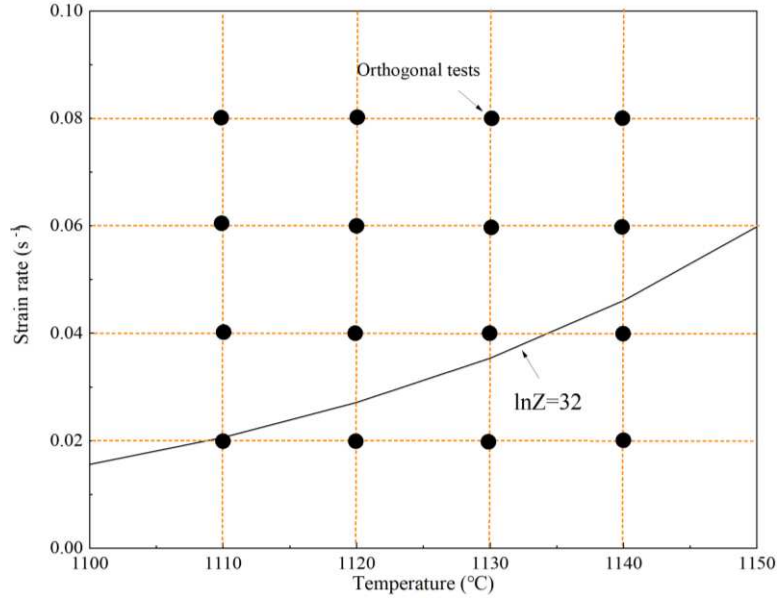


Fig. 4 Orthogonal experimental trial design of temperature and strain rate

A pre-forging plus final forging forming process was adopted for super-large GH4706 alloy turbine disks. Multi-objective optimization of the pre-forging die profile substantially increased the strain near the hub end face, which homogenized the overall strain distribution of the turbine disk and enabled effective regulation of microstructure uniformity throughout the entire hot forming process. To increase strain in the hub region and avoid excessively low local strain caused by upsetting, the pre-forged blank at the hub was designed with a concave shape, as shown in Figure 5. According to the authors' previous studies, microstructure homogenization efficiency reaches its peak at the optimal strain. Simulation results indicate that variations in the pre-forging die angle (A), concave radius (B) and underfill dimension (H), which are strongly correlated with strain distribution, directly affect the strain near the hub end face of the turbine disk. On this basis, orthogonal parametric optimization was performed for the geometric dimensions of the pre-forging die that govern hub strain, as illustrated in Figure 5. This ensures that strain values at both the hub and rim are close to or higher than the optimal strain, thereby guaranteeing uniform microstructure across the entire turbine disk. Meanwhile, these three parameters also govern the distribution of the initial AVG after pre-forging and before finish forging. A five-factor, four-level orthogonal experimental trial was established based on deformation temperature, strain rate and the strain-related parameters (A, B and H), as presented in Table 2. The finite element simulation settings were consistent with those used in the one-step forming trial.

The orthogonal experimental data for the multi-objective initial AVG obtained via simulation (after pre-forging and prior to finish forging) are summarized in Table 3. The microstructure index ($AVG_1 + SD_1$) at Point P1 in the near-hub end face region featuring severe coarse grains and mixed grains was selected as one output indicator. Additionally, the overall microstructure index of the turbine disk ($AVG_2 + SD_2$) was adopted to characterize the global microstructure evolution. It can be observed from Table 3 that obvious fluctuations and discrepancies exist among various objective values. Therefore, the optimal solution requires comprehensive evaluation of all objectives. SNR analysis and analysis of variance were conducted on all simulation

results, and the optimal compromised solution balancing all objectives was determined through quantitative comparison.

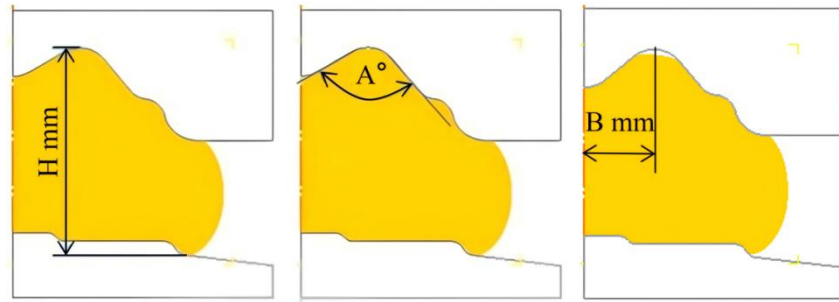


Fig. 5 Parameterization trial design of pre-forging dimension

Table 2 Five factors and four levels table

Level	T (°C)	$\dot{\epsilon}$ (s ⁻¹)	A (°)	H (mm)	B (mm)
1	1110	0.02	70	220	60
2	1120	0.04	80	230	70
3	1130	0.06	90	240	80
4	1140	0.08	100	250	90

Table 3 Orthogonal experimental design and simulated results

Trial	T (°C)	$\dot{\epsilon}$ (s ⁻¹)	A (°)	H (mm)	B (mm)	AVG ₁ (μm)	SD ₁ (μm)	AVG ₂ (μm)	SD ₂ (μm)
1	1	1	1	1	1	35.5	1.94	30.1	5.06
2	1	2	2	2	2	40.7	2.14	29.9	6.14
3	1	3	3	3	3	64.3	2.43	29.5	6.94
4	1	4	4	4	4	42.4	2.53	24.7	4.51
5	2	1	2	3	4	42.8	2.04	31.1	5.46
6	2	2	1	4	3	59.2	2.30	31.2	6.30
7	2	3	4	1	2	35.6	1.95	28.2	5.30
8	2	4	3	2	1	52.3	1.99	28.4	5.14
9	3	1	3	4	2	32.3	1.87	27.7	4.53
10	3	2	4	3	1	66.7	2.46	33.9	7.29
11	3	3	1	2	4	31.6	1.97	28.5	3.87
12	3	4	2	1	3	51.2	2.52	28.1	6.46
13	4	1	4	2	3	38.1	2.05	26.7	4.59
14	4	2	3	1	4	44.3	2.26	27.1	5.06
15	4	3	2	4	1	48.2	2.76	31.9	5.94
16	4	4	1	3	2	33.5	2.01	26.5	5.14

3.2 SNR analysis of multi-objective optimization results

The Taguchi method converts finite element analysis results into evaluation characteristic values for optimal parameter analysis using the SNR instead of the

mean value. The SNR can be used to evaluate the main effects of each parameter and its levels on the optimization objectives. According to the requirement that AVG and SD should be as small as possible [10], the SNR can be defined as follows [10]:

$$\frac{S}{N} = -10 \log k_i^2 \quad (3)$$

where k_i denotes the characteristic value of the i -th experiment. Based on finite element simulation and SNR analysis, the SNR values corresponding to the multi-objective functions of the sixteen experimental trials were calculated, as listed in Table 4. For each level, the mean value of the characteristic values is computed by:

$$\bar{k}_i = \frac{1}{n} \sum_{i=1}^n k_i \quad (4)$$

where n is the number of experiments at a given level. In the orthogonal array $L_{16}(4^5)$, n is a constant equal to 4. As shown in Table 4, the larger the total SNR output after summation, the smaller the variance between the characteristic values and the expected values, and the better the multi-objective optimization effect [16]. It can be observed from the curves in Figure 6 that trial 11 (33124) represents the optimal parameter combination, while trial 10 (32431) corresponds to the worst one. The optimized input parameters are listed as follows: temperature $T=1130$ °C, strain rate $\dot{\epsilon} = 0.06$ s⁻¹ (press speed: 15 mm/s), pre-forging angle $A=70^\circ$, underfilling height $H=230$ mm and concave radius $B=90$ mm. At this condition, $\ln Z=32.722$, which is consistent with the optimal $\ln Z \approx 32$ derived from the author's previous research [16].

Table 4 Multi-objective SNR

Trial	SNR for AVG1	SNR for SD1	SNR for AVG2	SNR for SD2	Sum of SNR
1	-31.005	-5.756	-29.571	-14.083	-80.415
2	-32.192	-6.608	-29.513	-15.763	-84.077
3	-36.164	-7.712	-29.396	-16.827	-90.100
4	-32.547	-8.062	-27.854	-13.084	-81.547
5	-32.629	-6.193	-29.855	-14.744	-83.421
6	-35.446	-7.235	-29.883	-15.987	-88.551
7	-31.029	-5.801	-29.005	-14.486	-80.320
8	-34.370	-5.977	-29.066	-14.219	-83.633
9	-30.184	-5.437	-28.850	-13.122	-77.592
10	-36.483	-7.819	-30.604	-17.255	-92.160
11	-29.994	-5.889	-29.097	-11.754	-76.734
12	-34.185	-8.028	-28.974	-16.205	-87.392
13	-31.618	-6.235	-28.530	-13.236	-79.620
14	-32.928	-7.082	-28.659	-14.083	-82.753
15	-33.661	-6.689	-30.076	-15.476	-85.902
16	-30.501	-6.064	-28.465	-15.284	-80.313

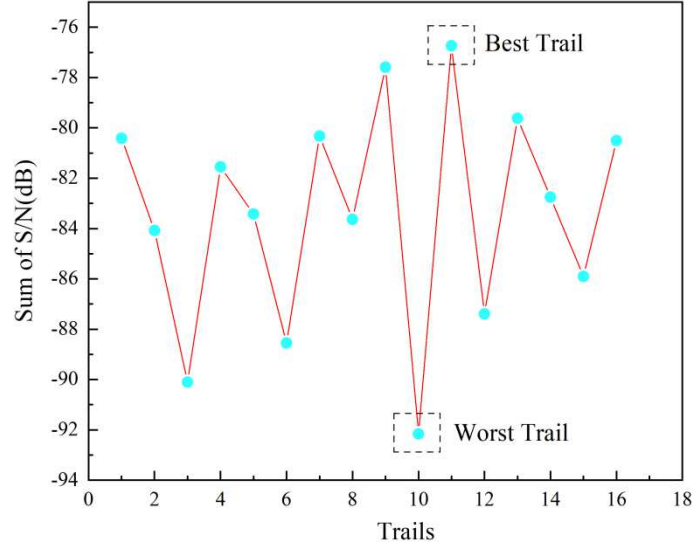


Fig. 6 Sum of SNR of sixteen trials

3.3 Contribution ratio of process parameters based on ANOVA

Analysis of variance (ANOVA) was adopted to quantitatively investigate and compare the effects of process parameters on the objective optimization. In the Taguchi method, the sum of squares (SS), which represents the total sum of squared deviations between multi-objective SNR and the overall average SNR, is utilized to evaluate the significance of process parameters on the optimization objectives. Let p and q denote the number of influencing factors, factor levels and experimental schemes in the orthogonal simulation tests, respectively. The overall average SNR is calculated as follows:

$$\left(\frac{S}{N}\right)_{avg} = \frac{1}{q} \sum_{i=1}^q \left(\frac{S}{N}\right)_i \quad (5)$$

Accordingly, the total SS and the sum of squares for the i -th influencing factor (SS_i) are computed as [5,22]:

$$SS = \sum_{i=1}^q \left(\left(\frac{S}{N}\right)_i - \left(\frac{S}{N}\right)_{avg} \right)^2 \quad (6)$$

$$SS_i = \sum_{j=1}^p p \times \left(\left(\frac{S}{N}\right)_{avg}^{ij} - \left(\frac{S}{N}\right)_{avg} \right)^2 \quad (7)$$

$$C_i = \frac{SS_i}{SS} \times 100\% \quad (8)$$

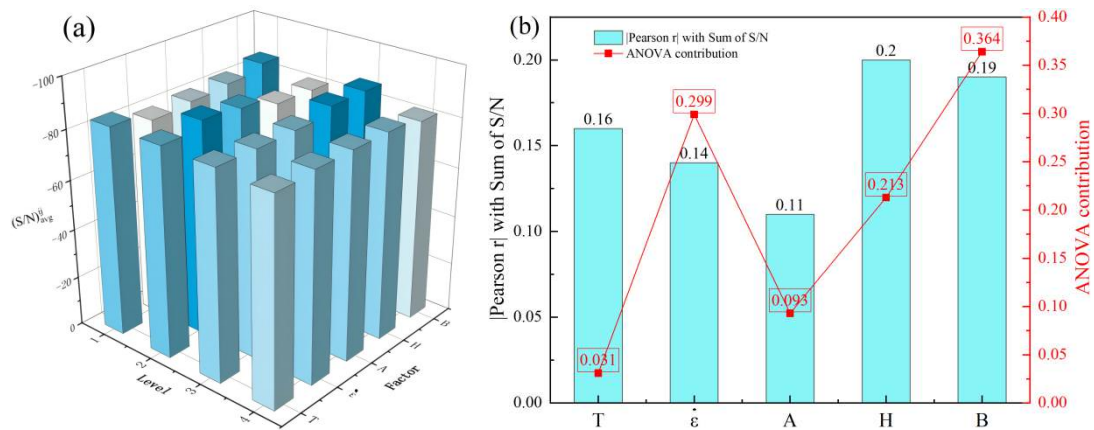
Where $\left(\frac{S}{N}\right)_{avg}^{ij}$ refers to the average SNR of the characteristic values for the i -th factor at its j -th level. The corresponding results are listed in Table 5. The contribution percentage of the i -th factor is determined by the formula below, with the results presented in Table 6 and visualized in Figure 7.

Table 5 Average SNR of the i -th factor on the j -th level

T (°C)	$(\frac{S}{N})_{avg}^{ij}$	$\dot{\epsilon}$ (s ⁻¹)	$(\frac{S}{N})_{avg}^{ij}$	A (°)	$(\frac{S}{N})_{avg}^{ij}$	H (mm)	$(\frac{S}{N})_{avg}^{ij}$	B (mm)	$(\frac{S}{N})_{avg}^{ij}$
1110	-84.035	0.02	-80.262	70	-81.503	220	-82.720	60	-85.528
1120	-83.981	0.04	-86.885	80	-85.198	230	-81.016	70	-80.576
1130	-83.470	0.06	-83.264	90	-83.520	240	-86.499	80	-86.416
1140	-82.147	0.08	-83.221	100	-83.412	250	-83.398	90	-81.114

Table 6 The contribution ratios of the i -th factor

Variables	$SSi - T$	$SSi - \dot{\epsilon}$	$SSi - A$	$SSi - H$	$SSi - B$
Values	2.315	22.044	6.845	15.746	26.825
Contributions	3.1%	29.9%	9.3%	21.3%	36.4%

**Fig. 7** (a) Average SNR distribution of the i -th factor at the j -th level; (b) Comparison of $|r|$ and ANOVA contribution ratio

As illustrated in Figure 7a, the average SNR of the characteristic values corresponding to the i -th factor under the j -th level presents moderate fluctuations, and the overall response exhibits an approximately random distribution pattern. This result indicates that there exist complex coupling interactions among the five investigated factors. Accordingly, further quantitative analysis on the contribution degree of each factor to the optimization objective is required. Based on the data recorded in Table 4, this study further calculated the Pearson relative analysis ($|r|$) and the parameter contribution rates, the results of which are summarized in Table 6 and visualized in Figure 7b. Figure 7b illustrates the Pearson correlation relationships among five process parameters and the overall SNR. The pairwise correlation among the five process parameters is generally weak, while each parameter exhibits a correlation of varying degrees with the overall SNR. These correlation coefficients can quantitatively reflect the contribution degree and sensitivity of each parameter to the overall SNR. The statistical results show that all five parameters present only weak linear correlations with the overall SNR ($|r| \leq 0.20$, $p > 0.4$); the nominally largest magnitudes occur for the underfilling height H ($r = -0.20$) and the concave radius B ($r = +0.19$), but these are not statistically distinguishable from the remaining three factors. This indicates that the influence of the process parameters on the

multi-objective performance is predominantly non-monotonic and non-linear, which is consistent with the moderate fluctuations of the level means shown in Figure 7 and the complex coupling interactions among the five factors. The influence of each parameter on the optimization objective follows the order: strain-related pre-forging geometry (67.0% = concave radius B 36.4% + underfilling height H 21.3% + pre-forging angle A 9.3%) > strain rate $\dot{\epsilon}$ (29.9%) > deformation temperature T (3.1%). The results reveal that strain exhibits a dominant effect on the multi-objective optimization performance, while variations in other parameters impose relatively minor influences on the fluctuation of the resultant microstructure. This result indicates that adjusting the global strain distribution of turbine disk via the introduction of a pre-forging procedure is the most critical approach to regulate the microstructure homogeneity of integrally hot-formed turbine disk forgings. The considerable contribution of strain rate originates from its non-uniform distribution inside the forging [21], which directly induces significantly distinct local microstructure evolution processes. The low contribution of deformation temperature (3.1%) can be ascribed to three primary causes. First, the candidate temperature levels (1110–1140 °C) were pre-screened to a narrow range centered at the optimal condition of $\ln Z \approx 32$ [16], meaning the temperature parameter was substantially optimized prior to the implementation of orthogonal experimental design. Second, both temperature and strain rate dominate DRX behavior primarily via the Z parameter; within the experimental parameter ranges investigated in this work, the span of $\ln Z$ corresponding to the temperature range is merely $\Delta \ln Z \approx 0.81$, which is far smaller than the value of 1.39 corresponding to the strain rate range, intrinsically leading to a weaker influence of temperature on the optimization objective. Third, the furnace-set temperature acts almost uniformly over the entire disk [21], shifting the grain-size field as a whole and thus altering AVG far more than SD, the dispersion-oriented optimization objective.

3.4 Global sensitivity analysis of the optimization framework

To extend the parameter influence quantified by Pearson correlation analysis (Figure 7b) and analysis of ANOVA (Table 4) to a global sensitivity framework, first-order Sobol indices were calculated via Monte Carlo simulation ($N = 2^{15}$) based on the main-effect response model constructed for the $L_{16}(4^5)$ orthogonal array [35,36]. Since the orthogonal array satisfies the balance property and its corresponding main-effect model conforms to additivity, the Sobol indices derived from the discrete experimental design are consistent with the contribution ratios obtained from ANOVA. Furthermore, when the model is extended to a continuous form over the entire tested parameter ranges via piecewise-linear interpolation between level mean values, the variation of the calculated Sobol indices does not exceed 0.07 (Figure 8a). The parameter sensitivity ranking obtained from both evaluation schemes is completely consistent: the pre-forging die geometric parameters collectively contribute approximately 67% – 70% of the total variance of the SNR, in which the contribution of parameter B is 0.29 – 0.36, the contribution of parameter H is 0.21 – 0.33, and the contribution of parameter A is 0.08 – 0.09. Strain rate ranks the next, with a contribution of 0.26 – 0.30. By contrast, deformation temperature exerts an almost negligible effect, with a contribution of only 0.03 – 0.04. It should be noted that the

$L_{16}(4^5)$ orthogonal array is a saturated design: all 15 degrees of freedom are fully occupied by the five four-level factors, thus total-order interaction effects cannot be identified solely based on the current experimental design, and an additional small set of verification simulations at parameter combinations outside the orthogonal array is required for further analysis.

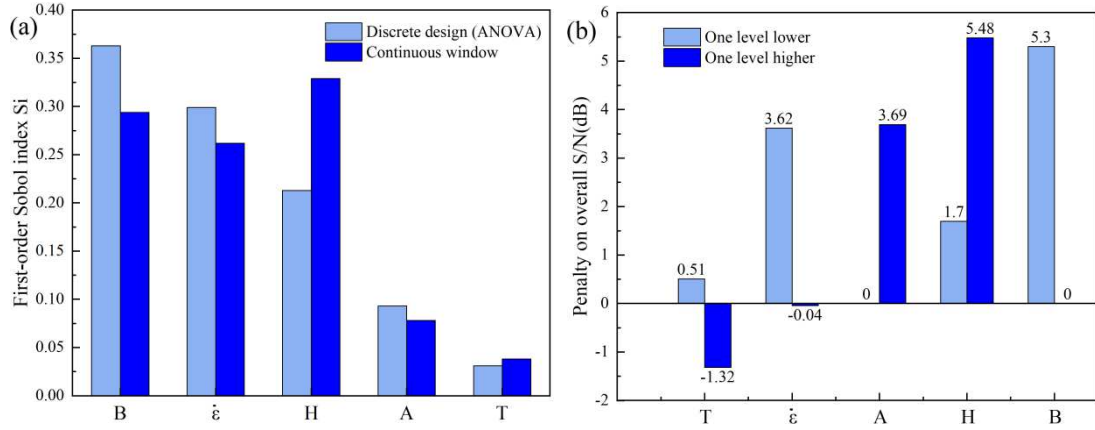


Fig. 8 Global sensitivity and robustness analysis: (a) first-order Sobol indices; (b) penalty on the overall SNR response when each parameter deviates by one level

The robustness of the selected parameter combination (trial 11) was further assessed by evaluating the penalty incurred on the overall SNR when each parameter deviates by one level from its selected setting (Figure 8b). The geometry parameters exhibit the steepest penalties: reducing the concave radius B from 90 to 80 mm costs 5.30 dB, increasing the underfilling height H from 230 to 240 mm costs 5.48 dB, and enlarging the pre-forging angle A from 70° to 80° costs 3.69 dB. In contrast, the deformation temperature is essentially free—deviating by ± 10 °C changes the overall SNR by at most 0.51 dB—and the strain rate penalizes only toward slower speeds (3.62 dB at 0.04 s⁻¹). This tolerance hierarchy provides direct guidance for process control: the pre-forging die geometry must be tightly manufactured and maintained, whereas the temperature window can be relaxed without compromising the optimization objective. The near-zero temperature sensitivity of the overall SNR further indicates that the deformation temperature is constrained primarily by the lnZ-based microstructure window rather than by the SNR response itself.

3.5. Physical mechanism underlying strain-induced microstructure homogenization

Existing studies indicate that the correlation between microstructure homogenization efficiency and strain does not follow a monotonic trend [33]. In prior work conducted by this research group, it was identified that the thermal deformation of superalloys corresponds to an optimal strain value, at which the efficiency of microstructure homogenization reaches its maximum [16,34]. This process involves dynamic interactions between grain refinement and grain coarsening, as well as between microstructure optimization and microstructure deterioration. With the increase of strain, the aforementioned two pairs of processes maintain a dynamic competitive relationship, and this complex interaction mechanism is reflected as a nonlinear correlation between strain and microstructure reconstruction efficiency [28]. With the further increase of strain, the plastic deformation mechanisms including basal slip, non-basal slip and twinning occur in a coupled manner. DRV and DRX are recognized as beneficial microstructure evolution mechanisms, while void formation,

cracking, adiabatic shear band development and other processes are deemed as microstructure-deteriorating mechanisms [24,26]. In the present study, through the optimization of process parameters, the local microstructure evolution of the turbine disk is controlled within the high-efficiency DRX regime, which realizes the refinement of local microstructure and improves the overall microstructure homogeneity of the turbine disk.

4 Optimized microstructure distribution and production verification

4.1 Comparative analysis of results before and after optimization

Figure 9 presents the simulation results obtained by the proposed overall microstructure uniformity control method for hot-formed turbine disk forgings after optimization (Trial 11), including the global AVG distribution of the entire turbine disk and the corresponding grain morphology observations at 12 pre-defined monitoring points. It can be seen that after the application of the optimization scheme, uniformly developed DRX microstructures are formed in the near-hub end face region, and the original coarse grain and mixed grain defects are basically eliminated. The grain morphology characteristics at other monitoring points are generally consistent with the pre-optimization results. The above results show that, via signal-through SNR analysis and variance analysis performed on the multi-objective simulation results of orthogonal tests, especially through the introduction of pre-forging dies with optimized geometric design, the coarse and mixed grain defects at the near-hub end face can be effectively improved.

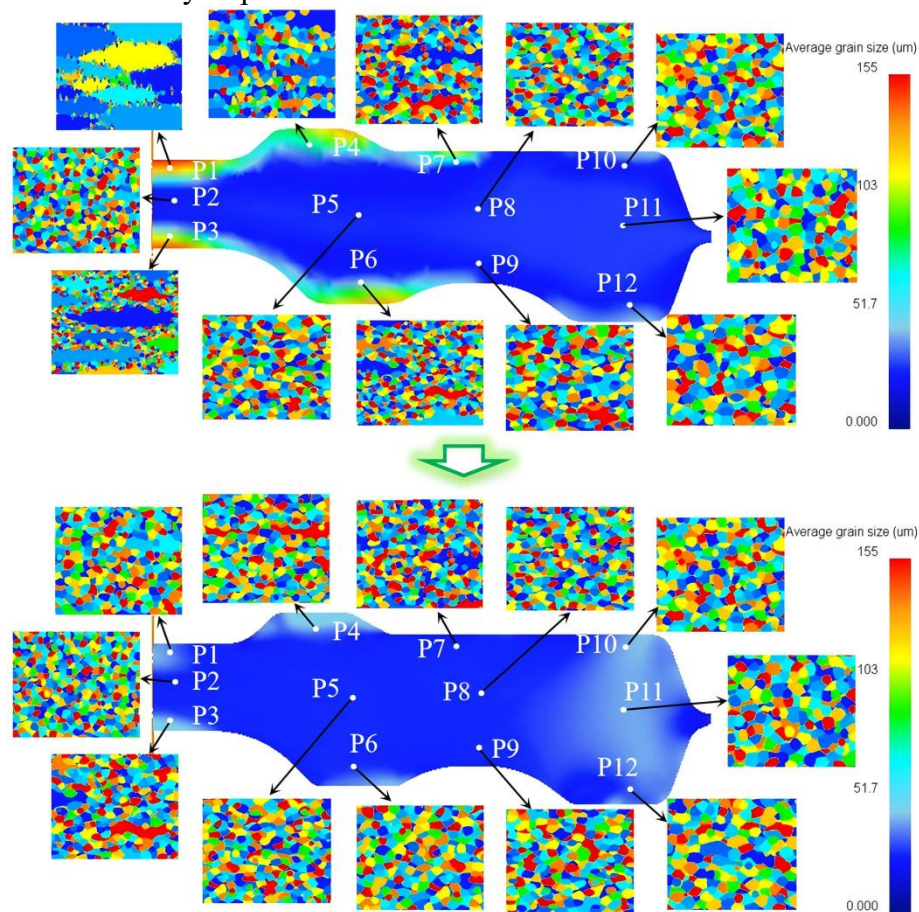


Fig. 9 Microstructure morphology of research points before and after optimization

The corresponding statistical histograms of AVG and SD at the 12 monitoring points before and after optimization are presented in Figure 10. Figures 10a and 10b respectively show that at the 12 monitoring points uniformly distributed along the full cross-section of the turbine disk, all AVG values and all SD values decreased to below 40 μm and 4 μm respectively after optimization. This indicates that coarse grains and mixed microstructures larger than 40 μm are mostly eliminated. Specifically, AVG and SD at the near-hub end face show the largest decrease, and the original coarse and mixed-grain microstructures are substantially eliminated. Simultaneously, both the overall average AVG and the overall average SD are reduced, which confirms that the multi-objective optimization of microstructure homogeneity has been achieved. The aforementioned experimental and simulation results collectively verify the effectiveness of the proposed method for controlling the overall microstructure uniformity of hot-formed turbine disk forgings.

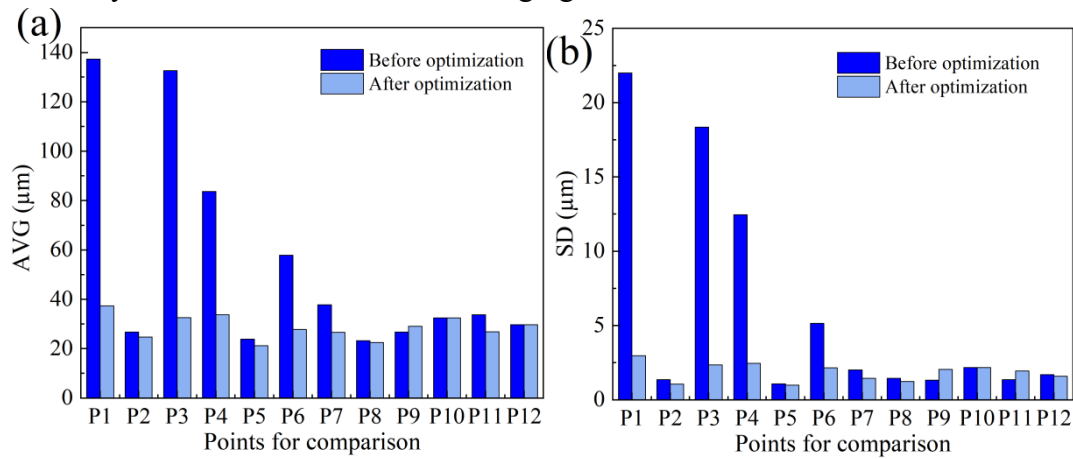


Fig. 10 Comparison of simulation results before and after optimization: (a) AVG; (b) SD

4.2 Production verification

To verify the effectiveness of the proposed microstructure uniformity control method for integrally hot-formed turbine disk forgings, as well as the prediction accuracy of the established multi-field and multi-scale coupling model, scaled-down forging trials were carried out in this work. The raw material employed in the trial production is semi-forged GH4706 alloy after primary cogging, which is consistent with the material used in the aforementioned hot compression tests. The main chemical composition of the raw material is listed in Table 1. All forging operations were implemented on an 800 MN hydraulic press, which is the largest-tonnage hydraulic press currently available globally. The heating process was completed in a high-temperature box-type forging furnace with a maximum heating capacity of 1300 $^{\circ}\text{C}$.

The overall trial production process of integral hot forming for turbine disks, which comprises two procedures: pre-forging and finish forging, is arranged as follows: hole machining $\rightarrow$ lubricant coating $\rightarrow$ cladding $\rightarrow$ pre-forging $\rightarrow$ hole re-machining $\rightarrow$ lubricant recoating $\rightarrow$ cladding $\rightarrow$ heating and heat preservation $\rightarrow$ finish forging $\rightarrow$ rough machining $\rightarrow$ ultrasonic flaw detection $\rightarrow$ specimen sampling. The optimized process parameters obtained from Trial 11 were adopted for the

pre-forging with pre-forging die, and finish forging procedures. The heating temperature of the forging furnace was set to 1130 ± 5 °C. The ram speed of the hydraulic press was acquired by converting the optimal strain rate of the hub end face, which is a region prone to severe mixed microstructure, based on the initial height of the turbine disk blank at the hub before pre-forging. Pre-forging and finish forging trials were conducted on scaled turbine disk forgings with a diameter of 660 mm, which is approximately one-third of the diameter of a full-size 2-m-class turbine disk, and the complete trial production process is illustrated in Figure 11. No forming defects including scratches, cracks and incomplete filling were detected on the surface of the forged components. Preliminary inspection results show that both the profile and dimensional accuracy of the obtained forgings meet the pre-specified technical requirements.

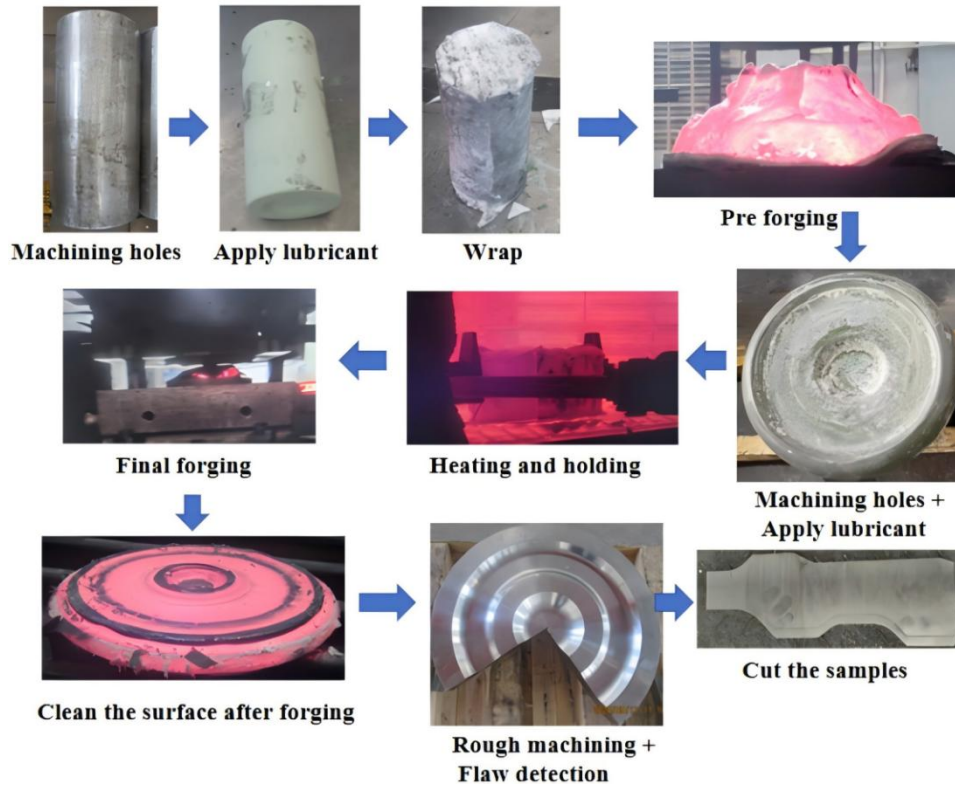


Fig. 11 Trial production process

The cross-section of the workpiece manufactured through the aforementioned pilot production process is exhibited in Figure 12. To validate whether the innovative process proposed in the present study can effectively regulate the microstructure homogeneity of turbine disks, wire electrical discharge machining (WEDM) was employed to extract samples at six typical locations [21] along the inward propagation path of cracks formed during the previous integral hot forming of the turbine disk. The sampling locations are the hub end face (S1, S2), web end face (S3, S4), and rim end face (S5, S6). These positions (S1–S6) correspond sequentially to P1, P3, P4, P6, P10, and P12 in the simulation results presented in Figure 9. Figure 12 also displays the EBSD microstructures of the specimens obtained from positions S1 to S6 on the workpiece cross-section. For the detailed procedures of EBSD data acquisition, readers are referred to Section 2.1.

It can be observed that following the implementation of optimization for microstructure homogeneity regulation, uniformly distributed dynamically

recrystallized microstructures are formed at all six sampling locations. Based on the grain distribution diagrams presented in the upper-right corner of each subfigure, the grain size at all positions presents an approximately random distribution within a narrow range. Compared to reference [21], the microstructure homogeneity in the vicinity of the turbine disk hub end face is significantly enhanced.

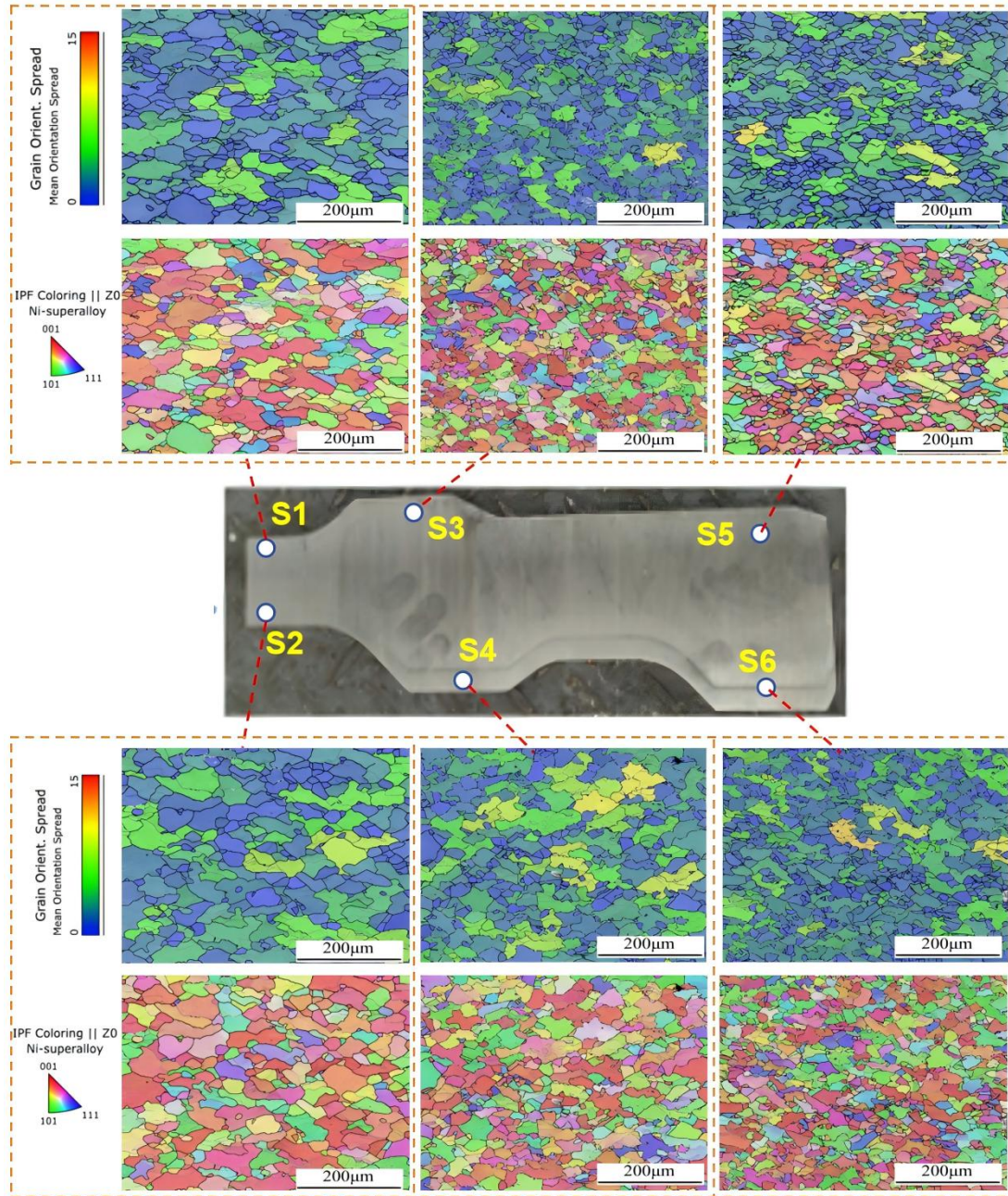


Fig. 12 Microstructure of research points for production verification

Figure 13 presents the corresponding statistical histograms of AVG, SD, and DRX fraction at six monitoring points before and after optimization, where the pre-optimization data are taken from Ref. [21]. As shown in Figures 13a and 13b, the six monitoring points are distributed along the entire cross-section of the turbine disk, which is the region most susceptible to microstructure deterioration. After optimization, all AVG values dropped to below 40 μm , and all SD values dropped to below 4 μm . Specifically, the most significant reductions in AVG and SD occurred at the hub end face. The original coarse and mixed-grain microstructures at this location were substantially eliminated, which in turn reduced both the overall average AVG

and the overall average SD of the entire forging. The simulation-based optimization results are fully corroborated by the production validation results presented above. To comprehensively evaluate the optimization performance, the DRX fraction was introduced for characterization and quantified via the grain orientation spread (GOS) method, with the visualization results shown in Figure 12. For superalloy, grains with $\text{GOS} < 2^\circ$ are classified as equiaxed grains, grains with $2^\circ \leq \text{GOS} \leq 10^\circ$ are classified as subgrains, and grains with $\text{GOS} > 10^\circ$ are classified as deformed grains [19 – 21]. The results in Figure 13c further confirm the conclusions drawn from Figures 13a and 13b: after optimization, the DRX fractions at the two monitoring points on the hub end face both increased to above 70%, and the DRX fractions at the two monitoring points on the web end face were close to full recrystallization. This improvement greatly enhances the homogeneity of the local microstructure of the forging, and effectively mitigates local microstructure deterioration in the turbine disk.

Compared with actual production verification of a 2-m turbine disk, the scaled trial mainly differs in the thermal–mechanical history and temperature-gradient field, the die-filling and loading characteristics governed by equipment capacity, and the absolute scale of the strain and strain-rate distributions; these size effects cannot be fully eliminated at reduced scale. Future work will therefore extend the verification to full-size 2-m-class turbine disks, addressing equipment constraints such as press capacity, furnace size and heating uniformity, and further quantifying the size-effect transferability of the optimized parameters and the homogeneity control strategy to industrial production.

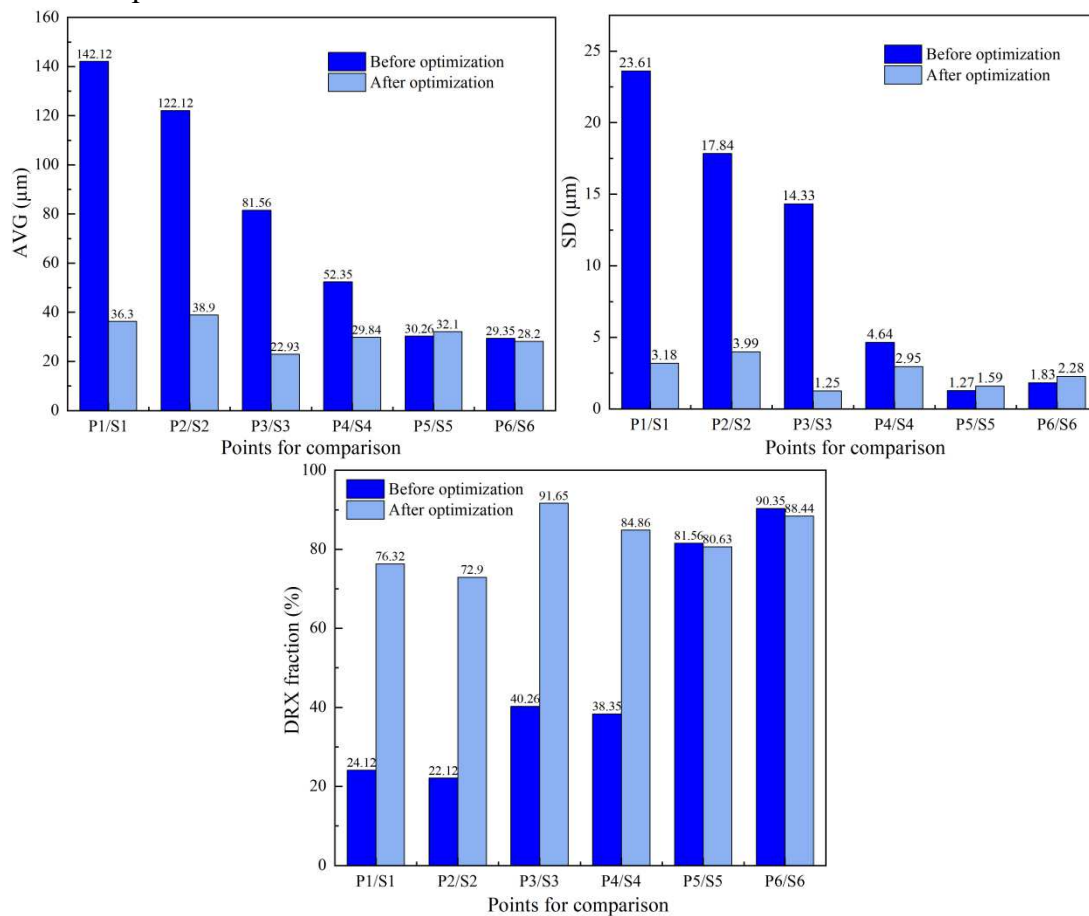


Fig. 13 Comparison of experimental results before and after optimization: (a) AVG; (b) SD; (c) DRX fraction

5 Conclusions

(1) This study conducted a multi-objective optimization on the microstructure homogeneity of the pre-forging and finish-forging process for ultra-large GH4706 alloy turbine disks by combining finite element simulation with the Taguchi method. The optimal process parameters are determined as follows: temperature $T=1130\text{ }^{\circ}\text{C}$, strain rate $\dot{\epsilon}=0.06\text{ s}^{-1}$ (press speed: 15 mm/s), pre-forging angle $A=70^{\circ}$, underfilling height $H=230\text{ mm}$ and concave radius $B=90\text{ mm}$. The influence degree of each parameter on the optimization objectives follows the order: pre-forging die geometry (67.0% = concave radius B 36.4% + underfilling height H 21.3% + pre-forging die angle A 9.3%) > strain rate $\dot{\epsilon}$ (29.9%) > deformation temperature T (3.1%). The results reveal that introducing the pre-forging process and rationally designing the pre-forging die geometry to adjust the overall strain distribution is the dominant factor for regulating the microstructure homogeneity of turbine disks during integral hot forging. The tolerance hierarchy further provides direct guidance for process control: pre-forging die geometry must be tightly manufactured and maintained, whereas the temperature window can be relaxed without compromising the optimization objective.

(2) Simulation results of twelve verification points uniformly distributed over the full cross-section of the turbine disk show that both AVG and SD remain at low values after multi-objective optimization. Particularly, these two indicators decrease substantially in regions near the hub end face. After optimization, at the 12 monitoring points uniformly distributed across the full cross-section of the turbine disk, all AVG values decreased to below $40\text{ }\mu\text{m}$, and all SD values decreased to below $4\text{ }\mu\text{m}$, respectively. This result indicates that coarse grains and mixed microstructures larger than $40\text{ }\mu\text{m}$ have been mostly eliminated, demonstrating that the overall microstructure homogeneity of the turbine disk has been significantly improved. The simulation-based optimization results are well corroborated by the scaled production validation results presented above.

(3) From an engineering-application perspective, this work delivers three outcomes: (i) a systematic framework that couples multi-field and multi-scale FE simulation with orthogonal-array experimentation, SNR analysis and Monte Carlo global sensitivity analysis for the homogeneity-oriented design of integral hot-forging processes; (ii) a quantified ranking of the process and preform-geometry parameters that govern microstructure homogeneity, which identifies pre-forging die geometry rather than deformation temperature as the dominant control lever; and (iii) a validated optimal parameter combination, verified on a 660-mm-diameter scaled GH4706 turbine-disk forging, providing a validated design basis for full-scale production.

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Declarations

Competing Interests The author declare no competing interests.

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