Numerical and experimental study on microstructure evolution of Ti-6Al-4 V alloy shaft preform in cross-wedge rolling process

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Abstract
To seek a fundamental understanding for further improving the Ti-6Al-4 V alloy utilization of cross-wedge rolling (CWR) and the comprehensive mechanical properties of shaft parts, the effect of the CWR processing parameters on the microstructure evolution of Ti-6Al-4 V alloy shaft preform is studied in this paper. An Arrhenius-type microstructure evolution model was employed and implemented into the finite element software DEFORM-3D. The average grain size and dynamic re-crystallization (DRX) volume fraction distribution in the α + β two-phase region and the β single phase region under different rolling temperature, roller rotating speed, and area reduction were analyzed, respectively. It is found that the microstructure evolution of Ti-6Al-4 V alloy is affected by CWR processing parameters. Meanwhile, the corresponding CWR metallographic experiments were conducted to verify the reliability of the FE-simulation results. The difference in average grain size in the β phase region between simulation and experimental is ranged from 5.77 to 18.56%. However, the agreement of the process parameter effect on dynamic recrystallization in the α + β two-phase region is reasonably well. The evenly distributed microstructure can be found as the area reduction rate of 50%, rolling temperature of 950°C and the speed of 5 ร⋅min⁻¹ were employed. In addition, the higher tensile strength of Ti-6Al-4 V alloy shaft preform increased by 18.57% and the plasticity enhanced significantly due to smaller grain size and α + β two-phase microstructure can be obtained by CWR under optimized processing conditions.

Keywords Ti-6Al-4 V · Shaft preform · Cross-wedge rolling (CWR) · Average grain size · Dynamic re-crystallization (DRX) volume fraction · Microstructure evolution

1 Introduction
Titanium alloy has superior material properties, which has been widely used in aircraft and automobiles to reduce weight and save energy. The safety of the equipment can be improved as well [1, 2]. Ti-6Al-4 V (TC4) is the most typical representative of two-phase titanium alloy considered the most widely used titanium alloy at present. There is still a huge potential market for TC4 applications in automobiles. To achieve better mechanical properties of the shaft such as drive shafts, piston bolts, drive rods, and support center rods, TC4 is more and more widely used in shaft-type components [3–5].

It is well known that titanium alloy has a limited forming window due to the lower thermal conductivity. To obtain the desirable microstructure with excellent mechanical behavior, hot forging is a conventional and preferred process to manufacture shaft. However, the drawbacks of the conventional process are multiple operations, high production cost, and limited tool life [6, 7]. Thus, cross-wedge rolling (CWR), an innovative near-net plastic forming process, has been put forward to be a substitute process for manufacturing preform of shaft [8]. In addition, CWR is one of the most effective plastic deformation methods that is utilized for the production of shaft parts with refined grains and improved mechanical properties, such as high-speed railway axles and hollow valves [9]. Many investigations have been carried out...
on the CWR process [10–12]. Pater et al. [13–15] researched the modelling method and the experimental rolling of CWR using theoretical and experimental studies. Li and Lovell [16–19] systematically investigated failure conditions and criterion for CWR as well as the reason for slipping, necking, and internal defects in the workpiece during the CWR process. Li and Lovell [20] optimized the CWR process based on the response surface methodology to prevent internal hole defects from forming. The above scholars have made great contributions in promoting the field of CWR. However, the traditional forming method has many shortcomings in the production of light-weight shaft parts. To solve this problem, the technique of CWR forming for shaft parts of the ideal light-weight material TC4 alloy was employed in this paper.

In recent years, many scholars have done a lot of researches on forming titanium alloy shafts using cross-wedge rolling (CWR). In general, the investigations of TC4 alloy generally fall into two categories. The first category mainly focused on the TC4 alloy shaft preform forming quality and properties. Li et al. [21, 22] investigated the effects of forming angle, stretching angle, and area reduction on the formability of TC4 alloy CWR parts. Pater and Tomczak. [23, 24] researched on the formability of TC4 alloy CWR driving shafts on helicopters using numerical simulations with the considerations of deformation resistance of aluminum alloy, titanium alloy, and magnesium alloy during the rolling process. Pater et al. [25] compared the forming quality of TC4 alloy stepped shafts formed by CWR and forging, and found that the precision of CWR was much higher than that of forging. Researches on the macroscopic structure of titanium alloy CWR shafts have also been attempted. Arkadiusz [26] investigated the effects of process parameters on the mechanical properties of CWR TC6 alloy in terms of temperature and strain rate sensitivities.

Different from the macroscopic viewpoint investigated, the second research category falls into the field of microstructure structure which plays a major role in influencing the mechanical properties of alloys, such as strength, ductility, creep resistance, fracture toughness, and crack propagation resistance. Li et al. [27] found that the control and optimization of microstructure are key issues in the quality control of TC4 alloy shaft forming during CWR. Ding and Guo [28] investigated the microstructure evolution and mechanical properties of a TC6 alloy blade preform produced by CWR. As a dual-phase (α + β) titanium occurred, the two phases’ effects of process parameters on dynamic recrystallization for TC4 were studied [29]. With more slip systems, the body center cubic (BCC) structure is easier to be formed than the hexagonal close-packed (HCP) structure [30]. Accommodation deformation mainly occurred in β-phase grain growth is extraordinarily easy to be generated in β-phase during CWR [31]. A better understanding of the influence of TC4 dynamic recrystallization and average grain size on mechanical properties during CWR is extremely significant for obtaining higher quality shaft part [32–34]. Compared with the macroscopic analysis of titanium alloy shafts by CWR, few researches on the evolution of microstructure for CWR shafts were made, which would result in the limited application of CWR technology in TC4 titanium alloy shaft preform forming.

In this paper, the influence rules of the dynamic recrystallization and average grain size of TC4 alloy during CWR were studied, which would provide guidance for the application of TC4 alloy to improve the mechanical properties of the shaft parts. The microstructure model of TC4 alloy was employed and implemented into the finite element software DEFORM to study the microstructure evolution under different conditions of CWR. To verify numerical predictions, a comparison of microstructures in average grain size and dynamic recrystallization between simulated and experimental was conducted for TC4 alloy. Furthermore, TC4 alloy shaft preform was successfully fabricated by CWR based on optimized parameters, which was confirmed experimentally to have the strengthened mechanical properties of the shaft preform produced by CWR.

2 FE simulation of cross-wedge rolling

Due to the limitation of the experimental study on the evolution of TC4 microstructure in the process of CWR process, the finite element simulation was employed to predict the microstructure change in the CWR process of TC4 shaft parts. Thus, the main methodological approach applied was based on a combination of FE-simulation system with experimental analysis. Firstly, the effect of rolling parameters during CWR on microstructure evolution can be analyzed by FE simulation. Secondly, the metallographic experiments on the microstructure of the TC4 alloy shaft before and after CWR can be conducted. And then the comparisons of FE simulation and experimental study of rolling moment are carried out. The rolling parameters of mold and processing conditions can be optimized by trial and error method in final. Briefly, the flowchart of combination between FE simulation and experimental in this paper is shown in Fig. 1

2.1 Constitutive equation and re-crystallization model of material Ti–6Al–4 V alloy

The material used in this work was Ti–6Al–4 V (TC4) alloy, as an ideal lightweight material for shaft parts, whose chemical compositions are listed in Table 1. The initial microstructure of TC4 alloy is mainly composed of equiaxed α-phase, lamellar α-phase, and intergranular β-phase.

Under the CWR experimental conditions, the deformation temperature and strain rate have great influence on the
rheological stress of Ti–6Al–4 V (TC4) alloy. The constitutive model equation of materials is a basic mathematical expression to describe the stress and strain relationship of materials, and the evolution of microstructure [33] of materials as well. The Arrhenius strain equation has been widely used to describe the relationship among flow stress, strain rate, and temperature [35−37]. In this paper, constitutive equations of α + β two-phase region and β single-phase were employed according to literatures [33, 34]. For α + β two region, the material constant A is $e^{17.61}$, the stress index N is 5.18, and the thermal deformation activation energy Q is 418400 J·mol$^{-1}$. In β single-phase region, the material constant A is $e^{4.43}$, the stress index N is 6.3, and the activation energy Q of thermal deformation is 316500 J·mol$^{-1}$. The constitutive equation and microstructural evolution model of Ti–6Al–4 V (TC4) alloy in different phase regions are shown in Table 2.

Specially, compared with β single-phase alloy with obvious grain boundaries in microstructure, α + β two-phase has no obvious grain boundaries in microstructure. Therefore, the α + β two-phase dynamic recrystallization grain size equation was not explored in this paper.

### 2.2 The establishment of finite element model

The CWR model was established with Cro-E software and then was imported into DEFORM-3D software in STL format. The main calculation parameters of the CWR simulation are presented in Table 3.

To achieve simulation, a DEFORM-3D elastic–plastic FE model was applied under the following assumptions: (1) the tools and guide plates are assumed to be rigid body due to their negligible deformation. The billet was considered a plastic body due to the negligible elastic deformation. (2) Half of the shaft was taken to build the symmetrical shaft; the symmetry constraint is applied to save the computation time. (3) The friction coefficient between the top and bottom dies and the billet was assumed to be a constant value of 0.9 [34]. The billet was divided into tetrahedral elements of

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**Table 1 Chemical element content of Ti–6Al–4 V alloy (mass fraction %)**

| Element | Ti  | Al  | V   | O   | N   | C   | H   |
|---------|-----|-----|-----|-----|-----|-----|-----|
| Percentage | 89.221 | 6.4 | 4.2 | 0.15 | 0.01 | 0.01 | 0.01 |
50,000. Figure 2 shows finite element model of cross-wedge rolling that includes CWR rolls, guide plates, and billets.

To study the influence of the microstructure evolution of Ti-6Al-4 V (TC4) alloy shaft during CWR, the derived material parameters and microstructure model tabulated in Table 2 were imported into DEFORM-3D. Numerical experiments under different process parameters tabulated in Table 4 were carried out. Please be noted that the forming angle and stretching angle, which are not substantial in the phase transformation and temperature distribution, were not considered a variable in the present work.

### 2.3 Simulation results and analysis

#### 2.3.1 Microstructure evolution at each stage of CWR

The dynamic recrystallization volume fractions in different phase regions at the wedging, stretching, and sizing sections during CWR process are shown in Figs. 3 and 4.

When rolling temperature is 950 °C, Ti-6Al-4 V (TC4) alloy is in the α + β two-phase region. During the wedging section of the rolling process, dynamic recrystallization only occurs in the contact area between the rolled workpiece and the cross-wedge rolling die, and the volume fraction of dynamic recrystallization gradually decreases from the surface to the inside, while no dynamic recrystallization occurs in the uncontacted area, as shown in Fig. 3a. After entering the stretching section, the area of dynamic recrystallization continues to expand and has penetrated to the core of the rolled piece. At this time, the volume fraction of dynamic recrystallization in the deformation area of the whole billet has reached 100%, but there is still no dynamic recrystallization at the undeformed big end of the billet, as shown in Fig. 3b. In the sizing section, the process of dynamic recrystallization in the forming area is almost completed, and the volume fraction of dynamic recrystallization in the deformation area has basically reached 100%, and the dynamic recrystallization volume fraction at the big end of rolled piece still shows a decreasing trend from the surface to the center, as shown in Fig. 3c. It can be observed that completion of the dynamic recrystallization is easier as the contact and deformation occurred, as shown in Fig. 3a–c. This is because the contact areas have the largest dislocation density and the maximum distortion energy stored in the deformed alloy. Therefore, there will be more activation energy provided to the recrystallization in the contact and deformed area.

As shown in Fig. 4, when rolling temperature is 1050 °C, the Ti-6Al-4 V (TC4) alloy arrives at the status of the β phase transformation and temperature distribution, were not considered a variable in the present work.

### Table 2 The constitutive equation and microstructural evolution model of Ti-6Al-4 V alloy [34]

| Parameter | α + β phase expression | β-phase expression |
|-----------|------------------------|-------------------|
| $\varepsilon_c$ | $\varepsilon_c \geq 0.015\varepsilon_p$, $\varepsilon_c = 0.0156\varepsilon_p$ | $\varepsilon_c \leq 0.015\varepsilon_p$, $\varepsilon_c = 0.048\varepsilon_p$ |
| $\varepsilon_p$ | $\varepsilon_p = 0.00045\varepsilon^{0.016}\exp(54264/RT)$ | $\varepsilon_p = 0.000319\varepsilon^{0.62}\exp(6588/RT)$ |
| $\dot{\varepsilon}_{\alpha/0.5}$ | $\dot{\varepsilon}_{\alpha/0.5} = 0.0017\varepsilon^{0.0937}\exp(35824/RT)$ | $\dot{\varepsilon}_{\alpha/0.5} = 0.000407\varepsilon^{0.1002}\exp(4574/RT)$ |
| Fraction of DRX, $X_{\text{drex}}$ | $X_{\text{drex}} = 1 - \exp\left[-1.362\left(\varepsilon_{\alpha/0.5}\varepsilon_{\text{exp}}\right)^{1.416}\right]$ | $X_{\text{drex}} = 1 - \exp\left[-1.323\left(\varepsilon_{\alpha/0.5}\varepsilon_{\text{exp}}\right)^{1.7}\right]$ |
| Grain size of DRX, $d_{\text{drex}}/\mu m$ | $d_{\text{drex}} = \left(0.55 + 2.90 \times 10^{22}\exp\left(-\frac{64273.96}{T}\right)\right)^{1/3}$ | |

$\varepsilon_c$ is the critical strain of dynamic re-crystallized, $\varepsilon_p$ is the peak strain of dynamic re-crystallized, $\varepsilon_{\alpha/0.5}$ is the strain at 50% of the dynamic re-crystallized volume fraction, $T$ is the deformation temperature. $X_{\text{drex}}$ is the influence coefficient of dynamic re-crystallized, $d_{\text{drex}}$ is the grain size of dynamic re-crystallized.

### Table 3 Main simulation parameters of the CWR

| Parameter | Value |
|-----------|-------|
| Forming angle of tools (°) | 24 |
| Stretching angle of tools (°) | 4 |
| Tools temperature (°C) | 20 |
| Ambient temperature (°C) | 20 |
| Friction coefficient | 0.9 |
| Heat transfer coefficient/(N/s/mm/°C) | 11 |
| Convection coefficient/(N/s/mm/°C) | 0.02 |

Fig. 2 Finite element model of cross-wedge rolling
single-phase region. Dynamic recrystallization occurs in the contact area and its adjacent area during the wedging section, as shown in Fig. 4a. In the stretching zone, it is observed that the dynamic recrystallization area expands continuously with the increase of the deformation area but the dynamic recrystallization does not occur at the undeformed regional core, as shown in Fig. 4b. After entering the sizing zone, dynamic recrystallization occurred almost throughout the rolled parts, as shown in Fig. 4c. Comparing Figs. 3 and 4, it can be seen that completion of the dynamic recrystallization is more abundant in $\beta$ single-phase than that in the $\alpha + \beta$ two-phase rolling process. The primary cause is that there will be more activation energy provided to the recrystallization when rolling temperature is 1050 °C.

### 2.3.2 Effect of rolling temperature

To more efficiently and completely study the effect of process parameters on the microstructure of Ti-6Al-4 V (TC4) alloy during cross-wedge rolling, the temperature-dependent microstructure evolution model was employed to study the effect of process parameters on dynamic recrystallization in $\alpha + \beta$ two-phase region. However, the influence of process parameters on the average grain size of dynamic recrystallization will be explored in $\beta$ single-phase region due to the almost completion of recrystallization in $\beta$ single-phase region.

Figure 5 shows the dynamic recrystallization volume fraction effect of Ti-6Al-4 V (TC4) alloy shaft under different rolling temperatures for an area reduction of 50% and roller rotating speed of 5 r·min$^{-1}$. It is observed that the rolling temperature had a remarkable effect on dynamic recrystallization. When the initial temperature was 850°C, there was no dynamic recrystallization in the large dark blue area at the end of the rolled workpiece, and the dynamic recrystallization volume fraction was still 0, as shown in Fig. 5a. When the initial temperature is 900°C and 950°C, the center area at the end of the rolled piece without dynamic recrystallization continues to shrink, as shown in Fig. 5b, c. Comparing Fig. 5a, b and 6c, it is found that dynamic recrystallization is becoming more complete as the rolling temperature is increased from 850°C to 950°C.

Figure 6 shows the distribution of the average grain size of Ti-6Al-4 V (TC4) alloy shaft at different rolling temperatures as an area reduction of 50% and a rolling speed of 5r/min are employed. It can be seen that the average grain size distribution of the rolling workpiece was approximately 156–206 μm at 1000°C, 165–227 μm at 1050°C, and 226–286 μm at 1100°C, as shown in Fig. 6a, b, and c, respectively. It is clearly shown that grain refinement occurs in the rolling parts after cross-wedge rolling at all temperatures. By comparing the grain size at different rolling temperatures, it can be seen that the values of average grain size gradually grow as the rolling temperature increased. This is mainly because high temperatures provide enough driving force and lead to a substantial amount of nucleation and fast growth.

### 2.3.3 Effect of the roller rotating speeds

Figure 7 presents the dynamic recrystallization volume fraction of Ti-6Al-4 V (TC4) alloy shaft under different roller rotating speeds of 2 r·min$^{-1}$, 5 r·min$^{-1}$, and 8 r·min$^{-1}$ when an area reduction rate of 50% and the rolling temperature of 950°C are employed. As the roller speed is changed from 2 r·min$^{-1}$ to 5 r·min$^{-1}$, the region of dynamic recrystallization

| Serial no | Rolling temperature(°C) | Roller rotating speed(r/min) | Area reduction (%) |
|-----------|-------------------------|----------------------------|-------------------|
| 1         | 850,900,950             | 5                          | 50                |
| 2         | 950                     | 2.5,8                      | 50                |
| 3         | 950                     | 5                          | 50,55,70          |
| 4         | 1000,1050,1100          | 5                          | 50,55,70          |
| 5         | 1050                    | 2.5,8                      | 50                |
| 6         | 1050                    | 5                          | 50,55,70          |

Table 4 Main process parameters of FE simulation
is larger due to competing effect of temperature, as shown in Fig. 7a, b. However, it is observed that the region of the dynamic recrystallization becomes smaller with large roller rotating speeds of 8 r·min⁻¹ due to rolling time shortened significantly, as shown in Fig. 7c.

The average grain size results of Ti-6Al-4 V (TC4) alloy shaft under different roller rotating speeds are shown in Fig. 8. It is observed that the rolling speed has a great influence on the grain size. At the rolling speed of 2 r·min⁻¹, the grain size of the rolled piece was ranged from 225 to 275 μm. The grain size of the rolled piece was ranged from 165 to 227 μm as the rolling speed is 5 r·min⁻¹. The grain size of the rolled piece decreased to 187 μm as the rolling speed of 8 r·min⁻¹ was employed. It is found that the faster the rolling speed is, the smaller the grain size is. This is mainly because the rolling time will be shortened as the rolling speed increased and thus the dynamic recrystallization grain nucleation does not have enough time to grow up, as expected.

2.3.4 Effect of the area reduction rate

Figure 9 shows the dynamic recrystallization volume fraction of Ti-6Al-4 V (TC4) alloy shaft under different area reduction rates of 30%, 50%, and 70% as the roller rotating speed of 5 r·min⁻¹ and the rolling temperature of 950℃ were employed. When the area reduction is 30%, the dynamic recrystallization volume fraction is nearly 0% at the center of unrolled workpiece end, as shown in Fig. 9a. When the area reduction rate is 50%, it is found that the region without dynamic recrystallization is significantly reduced, as shown in Fig. 9b. When the area reduction is 70%, dynamic recrystallization continues to spread in all areas of the rolled workpiece and the volume fraction of the rolled workpiece increases gradually from the inner area to the surface, as shown in Fig. 9c. It is obvious that the averaged dynamic recrystallization volume fraction in the center of unrolled workpiece end gradually increases as the area reduction rate increased. This is mainly due to that the activated energy
provided for dynamic recrystallization will increase as the area reduction rate increases.

Figure 10 shows the average grain size distributions of rolled workpiece in β single-phase region under different area reduction rates of 30%, 50%, and 70%. From the results of numerical simulation, it can be seen clearly that the area reduction rate has a significant effect on the grain size. The averaged grain size of rolled piece was ranged from 246 to 288 μm, 165 to 227 μm, and 99.8 to 182 μm when the area reduction was 30%, 50%, and 70% respectively, as shown in Fig. 10. By comparing their grain size, it is found that the average grain size decreases with the increase of area reduction rates. This is mainly because the increase of the area reduction will result in the increase of material deformation and making it easier for grains to be broken. Therefore, the dynamic recrystallization energy also increases, which will promote the increase of the numbers of dynamic recrystallization nucleation, and finally lead to more refined grains.

3 Experimental verification

3.1 Experiment preparations

To verify FE simulation results of the CWR process, the corresponding CWR experiments were carried out on the H630 CWR machine at the Zhejiang Provincial Key Lab of Part Rolling Technology, China. The CWR machine (Brand H630, made in Beijing, China) in the laboratory is shown in the left side of Fig. 11. Before rolling, the billet should be heated to the temperature range of 850 ~ 1050 °C, and the high temperature furnace was used for heating. After the billet was heated to the set temperature, the heated billet was transferred to the rollers. Then, the rolling experiment was carried out. The Ti–6Al–4 V alloy shafts before (red) and after cooling (dark) are enlarged and shown in the right side of Fig. 11 in different colors. The comparison of simulated and experimental rolled shape of Ti–6Al–4 V alloy shaft is
shown in Fig. 12. It is observed that the similar shape results of simulated and experimental rolled part can be obtained.

The primary aim of metallographic experiment was to study the microstructure of the Ti–6Al–4 V alloy shaft before and after CWR. Firstly, the specimen was sampled at the specific position of the rolled shaft and then the sample was fabricated by a mosaic machine (type: XQ-1, made in Shanghai, China). Secondly, the sample was grinded by metallographic sanding paper with different grain sizes on metallographic grinding (type: YM-2C, made in China). Thirdly, the grinded sample was polished at the top surface using metallographic polishing machine (type: PG-2A, made in China). For the best observation of the polished surface, the specimen surface was eroded effectively by the etching solution which was mixed by hydrofluoric acid (HF), nitric acid (HNO₃) and water (H₂O) at 1:2:7. Finally, the specimen surface after corrosion was observed using optical metallographic microscope (type: HiROXKH-8700, made in Shanghai, China) and the average size of grain was measured by Nano-measurer software. The flowchart for measuring metallographic microstructure of the Ti–6Al–4 V alloy shaft is outlined in Fig. 13. To check microstructures at different positions, the samples are chosen at three different locations of the part for measuring, as shown in Fig. 14.

3.2 Results and discussion

3.2.1 Effect of rolling temperature

To verify simulation results of the microstructure evolution with the rolling temperature, the metallographic experiment under different rolling temperature for an area

![Fig. 8 The average grain size of Ti-6Al-4 V at different roller rotating speeds during β single-phase region: (a) 2 r·min⁻¹, (b) 5 r·min⁻¹, (c) 8r·min⁻¹](image)

![Fig. 9 The dynamic recrystallization volume fraction of Ti-6Al-4 V under different area reduction rates in α+β two-phase region: (a) 30%, (b) 50%, (c) 70%](image)
reduction rate of 50% and roller rotating speed of 5r/min were conducted and the metallographic images obtained, as shown in Fig. 15. It can be clearly seen that there are a bulk of connected primary α in Fig. 15a as the rolling temperature is 850 °C. As the rolling temperature increases to 900 °C, the primary α is significantly reduced both in shape and contents and equiaxial primary α are occurred, as shown in Fig. 15b. It is mainly because the primary α phase is transformed from the original bulk continuous grain to the independent equiaxed α grain. As the rolling temperature continues to rise at 950 °C, most of the primary α-phases are still equiaxial, but its content is sequentially reduced. Meanwhile, the lamellar α-phases appear, as shown in Fig. 15c. These bimodal microstructures of α phase have the advantages of equiaxed and lamellar microstructure, which has the comprehensive properties of high strength, good plasticity, good toughness, and heat stability. This can be a remarkable indicator to measure the quality of a shaft [3]. With the rolling temperature increase to 1000 °C, it can be seen that the content of primary-α phase is minimized and the average grain size of β phase gradually increases, as shown in Fig. 15d. This is because the transition from α phase to β phase is further enhanced under the rolling temperature of 1000 °C.

Fig. 10  The average grain size of Ti-6Al-4 V under different area reduction rates in β single-phase region: (a) 30%, (b) 50%, (c) 70%

Fig. 11  The H630 CWR mill and rolling process
As shown in Fig. 15e, the comparison of experimental and simulated average grain size under different rolling temperatures in β-phase region is illustrated. It can be observed that at the higher temperatures of 1050°C and 1100°C, the average grain size increases with the increase of rolling temperature. This is mainly because the higher temperatures provide enough driving force and lead to a substantial amount of nucleation, fast grain growth. The agreement of average grain size between experimental and simulated results is reasonably good.

3.2.2 Effect of the roller rotating speeds

Figure 16 shows the metallographic images with different roller rotating speeds under the process conditions of the area reduction of 50% and rolling temperature of 950°C. When the process conditions are kept unchanged, the microstructure with primary α and equiaxed α-phase can be observed as the roller rotating speed of 2 r·min⁻¹ is employed, as shown in Fig. 16a. As the roller rotating speed increased from 2 to 5 r·min⁻¹, the content and form of primary α have a little change. However, the grain content and grain size of platelet α phase increased obviously, as shown in Fig. 16b. When the roll speed increased from 5 r·min⁻¹ to 8 r·min⁻¹, the long-strip α primary phase and many smaller α primary phases appeared but the grain content of platelet α and equiaxed α phase decreased drastically, as shown in Fig. 16c. This is mainly because when the roller rotating speeds are slow, there is enough time for the grain to grow. On the contrary, when the roller rotating speeds are too fast, the time for grain growing is insufficient and will result in incomplete recrystallization of grains. In addition, with the increase of roller rotating speeds, the temperature rise (plastic heat effect) in Ti–6Al–4 V alloy shaft is remarkable and will result in a decrease in the content of primary α phase.

In a word, the evolution in microstructure of Ti–6Al–4 V alloy shaft versus roller rotating speed during CWR is complicated. After having several trials by error, the bimodal microstructure with 20% primary α phase can be achieved as the roller rotating speed of 5 r·min⁻¹ is employed, which have a positive impact on the microstructure and thus higher the performance of final products.

3.2.3 Effect of the area reduction

Figure 17 shows the metallographic images with different area reduction rate under processing conditions of roller rotating speeds of 5 r·min⁻¹ and rolling temperature of 950°C. As the area reduction rate is 30%, both primary α and equiaxed α-phase can be observed in Fig. 17a, which is similar to Fig. 16a. As the area reduction rate increased from 30 to 50%, the grain morphology and content of the primary α-phase did not change significantly but the grain size of the primary α phase gradually decreased and the distribution of platelet α became more uniform, as shown in Fig. 17b. When the area reduction rate continues to increase from 50 to 70%, the microstructure is mainly composed of long-strip α and equiaxed α, and the average grain size further decreases, as shown in Fig. 17c.

This is because the higher dislocation density and the stored energy due to the larger area reduction rate would
be added so as to provide more driving force to promote the occurrence and completion of dynamic recrystallization, which can reduce the grain size. However, it also should be noted that excessive cross-sectional area reduction rate will make the primary α become abnormally slender and deteriorate the microstructure. The optimized area reduction rate of 50% around was chosen in this study with consideration of microstructure of Ti–6Al–4 V alloy.

4 Application

To fabricate shaft preforms made of a TC4 alloy that has excellent mechanical properties is an innovative but challenging task. In the paper, TC4 alloy shaft was manufactured successfully by CWR. Combined with the simulation results of DEFORM-3D, the optimal rolling parameters of the rolling temperature of 950°C, the roller rotating speed of 5 r·min⁻¹, and the area reduction rate of 50% around were selected to conduct the rolling experiment on H630 mill, and the results of DEFORM-3D simulation were verified in accordingly.

In torque measurement, the wireless torque sensor was used, and the strain gauge, node, and gateway were fixed on the transmission shaft through the connection method as shown in Fig. 18. The rolling moment results of rolling experimental and simulation are shown in Fig. 19. It is observed that the moment in rolling experimental is slightly larger than that in the simulation. This is because the actual influencing factors in the experimental measurement are more complicated than that in the simulation. However, the agreement between simulated the experimental rolling moment is reasonably well, which the relative error is less than 12%. The changing trend of the moment in both experimental and simulation is consistent, which implies that the reliability of the simulation results can be accepted.

Furthermore, the physical experiments for tensile test are designed to check its tensile strength of rolled part according to national standard and the samples are prepared by wire cutting in accordingly. The thickness of the sample is 1 mm, the experimental equipment used in the tensile test is the universal material testing machine (type: Instron5966, made in China), and its sample diagram and tensile test process are shown in Fig. 20. In the experiment, the fracture of all tensile specimens occurred in the central part. The experimental results of tensile strength for the original material and the rolled formed shaft are listed in Table 5. The average tensile strength of the original material is 902.55 MPa, and the average tensile strength of the rolled shaft parts after cross-wedge rolling is 1070.23 MPa. It is found that the increase rate of tensile strength reached 18.57% for rolled shaft part, as expected.

To facilitate observation and understanding of the fracture form of the tensile specimen, so as to further understand the mechanical properties of the rolled shaft, scanning electron microscope (type:SU500, made in Japan) was used to observe the surface morphology of the tensile fracture specimen. The fracture surface morphology of the tensile specimen of original billet and rolled shaft is shown in Fig. 21. It is observed that the ductile fracture is dominant, which is mainly composed of dimples with different sizes and inclusions, as shown in Fig. 21. In addition, it can be found that the more and deeper dimples of rolled shaft shown in Fig. 21d–f than that in Fig. 21a–c. In general, for a plastic material with the more dimples, the deeper and larger dimples will provide the better plastic performance. It implies that the plastic properties of rolled pieces are significantly improved, as expected.
Fig. 15  Effect of rolling temperature on microstructure for an area reduction rate of 50% and roller rotating speeds of 5r·min⁻¹: (a) 850 °C, (b) 900°C, (c) 950, (d) 1000°C, (e) average grain size in β single-phase region under different rolling temperature
Fig. 16  Effect of roller rotating speeds on microstructure of the rolled Ti-6Al-4 V alloy shaft for an area reduction of 50% and the rolling temperature of 950 °C: (a) 2, (b) 5, (c) 8 r·min⁻¹

Fig. 17  Effect of area reduction rates on microstructure of the rolled Ti-6Al-4 V alloy shaft for the rolling temperature of 950 °C and roller rotating speeds of 5r·min⁻¹: (a) 30, (b) 50, (c) 70%
Fig. 18 Wireless torque measurement system

Fig. 19 Comparison of simulation and experimental results

Fig. 20 The flowchart of tensile test

Table 5 Comparison of tensile strength

| Serial no | Tensile strength (MPa) | Average (MPa) |
|-----------|------------------------|---------------|
| Billet ($\sigma_{bl}$) | | |
| 1         | 898.96                 | 902.55        |
| 2         | 903.13                 |               |
| 3         | 905.56                 |               |
| Rolled shaft ($\sigma_{br}$) | | |
| 4         | 1058.24                | 1070.23       |
| 5         | 1071.89                |               |
| 6         | 1080.56                |               |

The increase rate of tensile strength = $\frac{|\sigma_{br} - \sigma_{bl}|}{\sigma_{bl}} \times 100\%$
5 Conclusions

In this paper, a study is carried out both numerically and experimentally on the microstructure evolution of Ti–6Al–4 V (TC4) alloy in cross-wedge rolling (CWR) process. The conclusions can be made as follows:

1. The microstructure evolution of Ti-6Al-4 V (TC4) alloy during CWR can be predicted and measured both numerically and experimentally. The difference of the average grain size between the simulation and experiment is ranged from 5.77 to 18.56%, which is reasonably good.

Fig. 21 Surface morphology of tensile fracture a) Serial no. 1; b) Serial no. 2; c) Serial no. 3; d) Serial no. 4; e) Serial no. 5 and f) Serial no. 6
2. The influence rules of different CWR conditions on the microstructure evolution in the $\alpha + \beta$ two-phase region were obtained both numerically and experimentally. The dynamic recrystallization volume fraction increases with the increase of rolling temperature and area reduction rates, but decreases with the increase of roller rotating speeds. The temperature change has the greatest effect on the content of primary $\alpha$, and the content of primary $\alpha$ decreases with the increase of rolling temperature. The grain size of primary $\alpha$ decreases with the increase of rolling temperature, roller rotating speeds, and area reduction rates.

3. With the increase of rolling temperature, the average grain size increases. With the increase of roller rotating speeds and area reduction rates, the average grain size decreases. Both numerical simulation and experimental results show that the products formed by the CWR process possess a fine grain and bi-model microstructure. Through CWR, the tensile strength of Ti-6Al-4 V (TC4) alloy shaft preform increased compared with the billets and the plasticity enhanced significantly. The results will provide a fundamental understanding for further improving the Ti-6Al-4 V (TC4) alloy material utilization of CWR and the comprehensive mechanical properties of shaft preform.

4. When the rolling temperature was selected to be 950°C, the roller rotating speed of 5 r·min$^{-1}$ was employed, and the area reduction rate of 50% around was selected, the tensile strength of Ti-6Al-4 V (TC4) alloy shaft parts during the CWR process could be significantly enhanced by 18.57%.

**Author contribution** The corresponding authors Baoshou Sun and Xing Chen were responsible for determining the suitable structure and contents of this paper. Chen Xing was also responsible for reviewing and editing this paper. Jiayao Yuan was responsible for writing this paper and analyzing all the obtained experimental data. Zhilong Zhao was responsible for all the simulation results. Xuedao Shu was responsible for conceptualization, funding acquisition, and project administration.

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**Data availability** The manuscript has no associated data or the data will not be deposited.

**Declarations**

**Ethics approval** There is no conflict of interest existing in the submission of this manuscript, and the manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was an original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed. The results are clear and honest. We have ensured objectivity and transparency in research and ensured that accepted principles of ethical and professional conduct have been followed.

**Consent to participate** All the authors listed have approved the enclosed manuscript, and we consent to participate.

**Consent to publish** I declare on behalf of my co-authors that we agree with the Copyright Transfer Statement, and we consent to publish.

**Competing interests** The authors declare no competing interests.

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