Numerical and experimental study on the hot cross wedge rolling of Ti-6Al-4V vehicle lower arm preform

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Abstract
Cross wedge rolling (CWR) has unique advantages in the production of shaft preforms with refined grains and improved mechanical properties. Considering the sensitivity of Ti-6Al-4V(TC4) alloy to heat treatment temperature, the effect of different initial deformation temperatures (IDTs) on the forming quality, mechanical properties, and microstructure evolution of the TC4 alloy lower arm preforms in CWR forming was studied in this work. The flow stress curves of TC4 alloy in the two-phase region were obtained by isothermal compression experiments. The Arrhenius constitutive model was established and applied to DEFORM-3D finite element (FE) software to simulate the CWR forming process of TC4 alloy lower arm preforms. The forming quality of TC4 alloy parts was compared and analyzed by 3D FE simulation and experiment. And their mechanical properties at room temperature were tested by tensile test. The results showed that the rolled part has well forming quality (no steps and necking defects) and higher geometric dimension accuracy at the IDT 885°C. Moreover, with the increase of IDT, the radial force and torque in the rolling process decrease. In addition, there were no internal defects in the parts rolled by different IDTs, because the die gap reduces the number of alternating cycles of tensile-compressive stress in the rolled workpieces. Compared with the initial state, the microstructure was refined. When the IDT is 885 °C, the ultimate tensile strength (UTS), yield strength (YS), and elongation (EI) of the parts were 987 MPa, 924 MPa, and 16.8%, respectively, which was able to ensure the mechanical performance requirements of the lower arm preform. The results provide theoretical guidance for the actual production of lower arm preform by CWR.

Keywords Cross wedge rolling · TC4 alloy · Microstructure evolution · Mechanical properties · Lower arm preform

1 Introduction
Wheeled armored vehicle plays an extremely important role in the modern battlefield, anti-terrorism, peacekeeping, and other fields. The number of its equipment is also increasing according to strategic needs. The lower arm is the key component of wheeled armored vehicle suspension. Ti-6Al-4V(TC4) has the advantages of light weight, high strength, strong corrosion resistance, making it an ideal material in the aviation industry and military industry [1–3]. As the preferred material for the lower arm of wheeled armored vehicle, TC4 alloy not only contributes to reducing the weight of the vehicle, but also ensures that it can meet the requirements of service life under harsh road conditions. Most of the forging of lower arm preforms are produced by free forging and precision forging. Due to the large forging force, the free forging process is easy to form eccentricity, bending, or crack when forging shaft parts. The precision forging process also has the disadvantage of expensive equipment and low production efficiency [4–6]. Cross wedge rolling (CWR) is a new near-net forming process, which can reduce the processing cost of shaft parts and improve their quality [7].

Steel products with good quality can be obtained by selecting suitable die parameters and process parameters during CWR [8, 9]. It is necessary for us to further explore and research how to control the surface quality and internal quality...
of TC4 alloy shaft parts in the rolling process. Li et al. [10] investigated the effects of forming angle, the stretching angle, and the area reduction on the spiral groove, internal defects, and necking of the rolled workpiece by large number of CWR experiments. Zhou et al. [11] established a two-stage CWR finite element model (FEM), and explained the necking law in detail. Pater et al. [12–14] used the method of combining experiment with 3D FE software Deform to systematically investigate various defects, temperature distribution, stress-strain distribution, and rolling force change of workpiece during CWR. Maraghechi et al. [15] studied the central damage during CWR, and revealed the formation mechanism and development process of central damage by analyzing the central stress-strain state of rolled workpiece. Lee et al. [16] used the response surface method to optimize the CWR process parameters and obtained the process parameters to prevent the center hole defects of rolled workpiece. In addition, studies have shown that the use of gaped die can significantly reduce the torsional deformation of the workpiece [17]. When the area reduction of rolled workpiece is in the range of 35–55%, the use of gaped die was conducive to reducing the rolling force in the CWR process [18]. Pater et al. [19] studied the temperature and damage distribution in the process of CWR forming TC4 alloy drive shaft. The results showed that the damage factor reaches the maximum at the center section of the rolled workpiece. Çakırcalı et al. [20] revealed the generation and development of cracks in TC4 alloy workpiece during CWR process by FE simulation and experiments. However, the study by Huang et al. [21] showed that when the hollow shaft parts with different wall thicknesses were rolled by the gaped die in the CWR process, step defects with different heights appeared on the outer surface of the rolled workpiece. With the increase of ellipticity of hollow parts, the step defects were more obvious. He pointed out that this was caused by the elliptical deformation of the rolled workpiece in the rolling process. Ji et al. [22] studied the temperature distribution, force energy parameters, and forming accuracy of the TC4 alloy blade preforms during the rolling process by CWR. Li et al. [23] studied the effects of die parameters and initial rolling temperature on the surface quality of TC4 alloy during CWR process.

The mechanical properties of titanium alloy are closely related to the microstructure characteristics, and the evolution of its microstructure will affect the flow behavior of the material [24]. TC4 alloy is sensitive to hot processing parameters. Different heat treatment conditions and deformation processing parameters can regulate the size, morphology, and volume fraction of the phase. The equiaxed microstructure with an average grain size of 1.9 μm was obtained by multidirectional isothermal forging (MDIF) of TC4 alloy by Zhang et al. [25], and the mechanism of grain refinement was studied. The tensile strength, yield strength, and elongation of the alloy after grain refinement were greatly improved at room temperature and 400 °C. Zhai et al. [26] studied the effects of α phase content and morphology on the microstructure and mechanical properties of TC4 alloy during multiple heat treatment processes by experimental method. Wang et al. [27] established the rate/temperature/microstructure constitutive model of TC4, and successfully predicted the evolution law of β-phase volume fraction and grain size during the process of hot ring rolling. Li et al. [28] studied the effects of IDT, area reduction, and rolling speed on the volume fraction of α phase in TC6 alloy during CWR by FEM and experimental method. CWR is a thermal-mechanical coupling process of non-isothermal continuous large plastic deformation. The regular radial and axial deformation of the billet during the rotation with the roller not only causes different changes in the quality of the surface and the core, but also changes in the morphology and composition of the phase, grain size, and mechanical properties [29–31]. However, in the existing research, there are few studies on the influence of CWR parameters on the forming quality, microstructure evolution, and mechanical properties of TC4 alloy. Based on these, the influence of different initial deformation temperatures on the forming quality, mechanical properties, and microstructure evolution of the TC4 alloy in CWR forming were studied in this work.

The hot deformation behavior of TC4 alloy with bimodal microstructure was first studied by isothermal hot compression method, and the constitutive equation of TC4 alloy was established for FE simulation. Secondly, the thermodynamic coupling numerical simulation of CWR process of TC4 alloy lower arm preform was carried out by using software Deform, and the accuracy of FEM was verified. Thirdly, the mechanism of forming steps and slight necking on the rolled workpiece surface under different IDTs were systematically analyzed. The internal quality of the rolled workpiece was tested and analyzed. Finally, the microstructure evolution and tensile mechanical properties at room temperature of parts were compared and analyzed.

2 TC4 alloy material characteristic

2.1 Materials and experimental procedure

Figure 1 shows the microstructure of initial TC4 alloy bar. The microstructure has globular primary α phase and lamellar secondary α phase. The chemical composition of the raw material used in this experiment is shown in Table 1.

The Gleeble-1500D thermo-simulation machine was used to obtain isothermal compression data. The deformation temperatures and strain rates were set at 850°C, 900°C, and 950°C, and 0.1, 1, and 10 s⁻¹, respectively. After the test, the temperature of the specimen was immediately brought down to room temperature by water cooling.
then the flow stress-strain curve tends to be stable. Flow softening and work hardening reach a balanced state, and the isothermal compression test data at different strain rates and temperatures. It is expressed as follows:

\[
\dot{\varepsilon} = A\sinh(\alpha \sigma)^n \exp\left(-\frac{Q}{RT}\right)
\]  

(1)

where \(Q \text{ (J mol}^{-1}\)) is the activation energy, \(R\) is the gas constant of 8.3145 (J mol\(^{-1}\) K\(^{-1}\)), \(\varepsilon\) is the strain rate, \(\sigma\) is the flow stress (MPa), \(T\) is the absolute temperature (K), while \(A, \alpha,\) and \(n\) are the constants. Each material constant was determined in accordance with the peak stress under different conditions of the compression tests via a series of calculations [33].

The \(\varepsilon\) parameters for TC4 alloy can be described by following:

\[
\dot{\varepsilon} = 1.3678 \times 10^{40} [\sinh(0.0061 \sigma)]^{0.1302} \exp\left(-\frac{914135}{RT}\right)
\]  

(2)

The constitutive equation will be applied for the FE simulation of the TC4 alloy shafts formed via CWR. The correlation coefficient (RR) and average absolute relative error (AARE) were used to evaluate the accuracy of the equation, as follows:

\[
RR = \frac{\sum_{i=1}^{N} (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{N} (X_i - \bar{X})^2 \sqrt{\sum_{i=1}^{N} (Y_i - \bar{Y})^2}}}
\]  

(3)

\[
AARE = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{Y_i - X_i}{Y_i} \right| \times 100\%
\]  

(4)

In the equations, \(X_i\) and \(Y_i\) are the predicted and experimental peak stress, \(\bar{X}\) and \(\bar{Y}\) are the average predicted and experimental peak stress, and \(N\) is the number of peak stresses. Figure 3 shows the comparison between the predicted and experimental peak stress. \(RR\) and \(AARE\) are 0.9737 and 8.4342\%, respectively, indicating that the constitutive equation of TC4 alloy established in this paper has high credibility.

### 3 Finite element simulation and experiment

#### 3.1 Finite element simulation

The FEM for the CWR study is shown in Fig. 4. As the geometrical model of the test specimens and the rolling dies were symmetrical, the boundary conditions of the FEM were set to be symmetrical relative to the center plane. The original diameter and length of the workpiece are 49mm and 135mm, respectively. The rolled part is a sample that is scaled down by five times according to the actual product, and its specific dimensions are also shown in Fig. 4. The following assumptions were made in the course of this study. (1) Because the deformation can be ignored, the roll dies and guide slats are considered rigid bodies. (2) The workpiece is regarded as a plastic body. (3) The friction factor between workpiece and tool contact surfaces was assumed to be constant. The shear friction model was used for the type of friction: \(f_s = m \times k\), where \(f_s\), \(k\), and \(m\) are the friction stress, shear yield stress, and the friction factor, respectively. (4) The heat transfer coefficient

Table 1 Chemical composition of TC4 alloy (in wt%)  

| Main chemical component | Impurity content |
|------------------------|------------------|
| Ti         | Al | V | Fe | C | N | H | O |
| Bal. | 6.14 | 4.15 | 0.18 | 0.011 | 0.008 | 0.002 | 0.16 |

Fig. 1 Optical micrograph of received TC4 alloy

**Fig. 2**

**Fig. 3**

**Fig. 4**

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*Image 52x560 to 289x737*
between the workpiece and the environment and the workpiece and the dies are listed in detail in Table 2.

The parameters of the plane layout of a CWR die are shown in Fig. 5. Only the wedging, stretching, and sizing zone in the middle of the die were used. From the cross-sectional diagram (C-C, D-D, E-E, F-F) of Fig. 5, it can be seen that the additional side steps on both sides of the die are not involved in the rolling work. The surface of the dies was machined with a gap of 1 mm in depth, which is shown in red in Fig. 5. The red area is the gap area, when the workpiece passes through this area in the rolling process, its surface does not contact the workpiece. This makes the workpiece no longer rolled by the die. TC4 alloy parts with an area reduction of 48%. The main technical parameters are shown in Table 2.

3.2 Cross-wedge rolling experiment

The H630 CWR mill of the Beijing University of Science and Technology was used for experiments. The experimental equipment is shown in Fig. 6a and the forming wedge dies are shown in Fig. 6b. Depending on the recrystallization temperature and β-phase transus temperature of TC4 alloy, four different IDTs were selected: 855 °C, 885 °C, 915 °C, and 945 °C. Before the experiment, the workpiece was heated in a
tubular furnace and hold for 50 min. Shorten the transfer time between tube furnace and mill to reduce temperature loss. Water cooling was adopted after rolling.

### 3.3 Microstructure observation and mechanical properties test

The parts were cut into symmetrical sections along the axial direction and in the mirror plane position respectively after rolling. The microstructure and internal quality of TC4 alloy parts were observed by cutting samples in the core of the complete forming zone.

The microstructure was observed by optical microscope (OM) at room temperature. Preparation of OM specimens includes mechanical grinding with sandpaper of different fineness, electrolytic polishing with 5% alcohol perchlorate solution, and chemical etching with Kroll’s solution. Image Pro-plus software was used to quantitatively measure the value of primary α phase. The tensile tests at room temperature were carried out according to GB/T228.1-2010.

### 4 Results and discussion

#### 4.1 Verification of the CWR FEM

Figure 7 shows the appearance of TC4 alloy parts. The part at the IDT of 855 °C shows necking in the middle, while the part at 885 °C has a smooth outer surface with no folding, no spiral mark, and no crack. However, the central of the parts at the IDT of 915 °C and 945 °C showed obvious steps and slight spiral marks.

Geomagic Qualify software was used to compare the geometric dimensions of FEM and high-precision 3D scanning parts. As shown in Fig. 8a to d, the different colors in the cloud chart represent the radial distance between the FE simulation results and the experimental results at that point. The positive values indicate that the radial dimensions of the FE simulation results are larger than the experimental results. The negative values indicate that the radial dimension of the simulated result is smaller than the experimental result. The greater the absolute value of the numerical value, the greater the radial distance between the FE simulation results and the experimental results. The radial differences of the maximum and minimum diameters of the parts corresponding to the four simulation results are distributed in the range of 1.002~1.115 mm and −1.002~−1.115 mm, respectively. The maximum radial dimensional error is only 3.1%. The geometrical dimensions’

### Table 2  Main parameters of CWR simulation

| Parameters                                      | Value  |
|------------------------------------------------|--------|
| Heat transfer coefficient (Wm⁻²K⁻¹)            | 1×10³  |
| Convection coefficient (Wm⁻²K⁻¹)               | 20     |
| Thermal conductivity (KWh⁻²K⁻¹)                | 17     |
| Coefficient of mechanical energy to heating    | 0.9    |
| Temperature of tools (°C)                      | 20     |
| Friction factor between workpiece and slats    | 0.1    |
| Friction factor between workpiece and die      | 0.9    |
| Environment temperature (°C)                   | 20     |
| Speed of roll (rpm)                            | 8      |
difference between the simulation results and the experimental samples is small. This shows that it is reliable to simulate the CWR forming process of TC4 alloy by FEM.

### 4.2 Non-roundness analysis

The CWR and step forming process of the TC4 alloy lower arm are shown in Fig. 9. When the workpieces with IDT of 915 °C and 945 °C entered the stretching zone for a short time, steps appeared on their surface. After rolling, the steps were still retained. The generation of steps not only reduces the forming accuracy of the parts, but also produces defects such as folding in the follow-up forging process, causing serious harm to the performance of the lower arm, which should be avoided.

The material flow has a great influence on the forming quality of rolled workpiece. Figure 10 shows the influence of different IDT on the material flow of the TC4 alloy. The influence of different IDTs on the axial flow of the material was analyzed by selecting 11 equidistant tracing points with 3 mm interval from symmetrical section (Fig. 10a). Such tracing points were distributed on five sections from A to E. Ten tracing points with a spacing of 1.5 mm were selected from the surface of the billet along the axial direction to study the influence of different IDTs on the radial flow of metal (Fig. 10a). The rolled workpiece at t = 2.4 s was selected for
that the higher the IDT, the smaller the displacement of the metal along the axial flow. The trend of metal flow along the axial direction is basically the same for sections A, B, and C at different IDTs, and the displacement of tracing points decreases first and then increases from the core to the surface. This is probably due to the small contact surface between the rolled workpiece and the die surface during the wedging stage, and the low frictional resistance. As a result, the hysteresis tendency of the metal flow near the surface is relatively small. At IDTs of 855°C, 885°C, and 915°C, the displacement along the axial direction of the tracing points in sections D and E shows a gradual decrease from the core to the surface. At an IDT of 945°C, the axial displacement of the surface tracking point of D and E section is less than that of the internal near the surface metal. This may be because the contact area between the die and the rolled workpiece is gradually increasing; the friction between them is also increasing. The surface metal of the rolled part appears to be difficult along the axial flow.

Figure 10f shows the radial displacement of the tracing points for the rolled workpieces with different IDTs. There is a significant difference in the radial displacement of the tracing point near the symmetrical section, and the radial displacement increases gradually in the order of 945 to 855°C. The axial displacement of the metal in the core of the rolled
workpieces with IDTs of 945 °C and 915 °C is smaller than that of 885 °C, and the radial displacement near the symmetrical section is smaller than that of 885 °C. The volume of the billet remains unchanged after being compressed by the die, and the material is more likely to flow in the radial direction into the cavity composed of the die and guide slat, and the ellipse phenomenon occurs. Their radial displacement has a height difference along the axis direction, so steps were formed on the surface of the two rolled workpieces. The axial displacement and radial displacement near the symmetrical section of the rolled workpiece with IDT of 855 °C are larger than that of 885 °C, so there is a slight necking on the surface of the rolled workpiece.

As can be seen from Figs. 11 and 12, before entering the gap area (before \( t = 1.84 \)s), the material was gradually compressed along the axial direction by the dies. The symmetrical section of the workpiece with IDT of 945 °C was still elliptical, while the symmetry section of the rolled workpiece at 885 °C was circular, and the diameter was consistent with the die surface spacing. After \( t = 1.84 \)s, the rolled workpiece entered the gap area. The maximum diameter of the symmetrical section of the rolled workpiece with IDT of 945 °C was larger

Fig. 9 Different stages of CWR and step forming

Fig. 10 The axial and radial displacement in the CWR process: a the location of the tracing points, b the axial displacement of tracing points at IDT = 945 °C, c the axial displacement of tracing points at IDT = 915 °C, d the axial displacement of tracing points at IDT = 885 °C, e the axial displacement of tracing points at IDT = 855 °C, f the radial displacement of tracing points
Fig. 10 (continued)

Fig. 11 Cross-section profile of the numerical simulation of the forming process at IDT of 945 °C: a initial status t=0s, b wedging stage t=0.8s, c stretching stage t=1.52s, d preparing to pass through the gap area t=1.84s, e passing through the gap area t=2.4s, f sizing stage t=3.2s, g completion status t=5.64s
than the distance between the surfaces of the top and bottom 
dies gap area. Therefore, the material was extruded into the 
cavity due to the oval deformation during rolling. The work-
piece with IDT of 885 °C had no material squeezed into the 
cavity of the gap area, and no step was formed on the surface 
of the rolled workpiece. The material deformation resistance is 
low at the high temperature, and the tangential material flow 
tends to increase, resulting in more serious oval deformation 
during rolling, which eventually leads to the formation of 
steps at high temperature.

In Fig. 13a–b, the periodic contacts between the workpiece 
and the surface of die gap area during rolling were recorded by 
smearing pink paint evenly on the surface of the die gap area. This 
is because the rolled workpiece before entering the gap area did 
not form a standard circular section but form an oval section with a 
larger size. The oval cross-section contacts with the surface of the 
roll cavity, and the contact scratches can be recorded after rolling.

To study the variation of different cross-sectional 
shapes in the forming area of parts, a non-circularity 
index should be defined [21]. The following formula 
(5) was used to calculate the non-circularity:

\[
e = \frac{2(D_{\text{max}}-D_{\text{min}})}{D_{\text{max}} + D_{\text{min}}} \tag{5}\]

\(D_{\text{max}}\) and \(D_{\text{min}}\) represent the maximum diameter and min-
imum diameter, respectively. And \(e\) represents the non-
circularity.

In Fig. 14, the rolled workpiece of FEM with IDT of 945 
°C matches well with the outer surface shape of the experiment. The projection contour curves of 15 equidistant cross-
sections along the axis direction of the experimental parts 
were selected to analyze the dimensions of the parts after 
forming.
Figure 15a shows the influence of IDT on the non-circularity of symmetrical sections. The non-circularity of the symmetrical section increases with the increase of the IDT. The lower the IDT is, the shorter the time for the non-circularity of the outer surface at the symmetrical section of the part to reach a stable value. This may be because the rolled workpiece with low IDT first reached the temperature range that is not easy to deform, which weakens the flow performance of the material. In Fig. 15b, the non-circularity value at the symmetric section position reaches the maximum, and decreases gradually along the axial direction on both sides. The reason is that at the beginning of the rolling stage, the volume of the material without deformation is relatively large. The material in the deformed zone is subjected to relatively large resistance to flow in the axial direction, which weakens the material flow. The material in deformation area only expands along the radial direction, which weakens the material axial flow. In the subsequent rolling process, the volume of material without deformation decreases gradually, and the resistance to the flow of material along the axial direction decreases, which is relatively easy to be driven. That can also be seen from Fig. 10 that the axial displacement of these tracking points gradually increases along the axis of the workpiece to both sides of the symmetrical section. Thus, the distribution law of the non-circularity value is obtained, which is the largest in the symmetric section and decreases gradually along the axial direction.

4.3 Stress and strain analysis

This paper further analyzes the formation mechanism of non-circularity by studying the evolution of stress and strain distribution of workpieces at different IDTs. Figure 16 shows the stress distribution of the symmetrical section of the workpiece at 1.84s. Under the IDT of 945 °C and 915 °C, the symmetrical sections of the workpieces are elliptical to varying degrees. Radial stress (Stress-R) and circumferential stress (Stress-Theta) have obvious orthogonal distribution. The radial stress is tensile stress along the long-axis direction of the elliptical section and compressive stress along the short-axis direction. The distribution of circumferential stress is exactly opposite to the radial stress. With the decrease of IDT, the tensile and compressive stress distribution of radial stress tends to be uniform. The circumferential compressive stress transfers to the center of the section, and its distribution also tends to be uniform. The axial stress (Stress-Z) at the center of the cross section at different IDTs is shown as tensile stress. In the process of IDT decreasing from 945 to 855 °C, the
axial tensile stress range gradually expands from the central region to the outer surface. Finally, the axial stress of the section is all tensile stress.

Figure 17 shows the strain distribution of the symmetrical section of the workpiece at 1.84s at different IDTs. The radial strain (strain-R) gradually decreases from the outer surface to the center. When the IDT is at 945 °C, due to the compressive stress, the distribution of compressive strain along the long-axis in the central region is wider than that along the short-axis, and the distribution of compressive strain near the outer surface is opposite to that in the central region. It can be observed in the circumferential strain (Strain-theta) distribution that the compressive strain is all along the long-axis direction, and a circular tensile strain band appears on both sides of the long-axis near the outer surface. The axial strain (Strain-Z) distribution has no significant change. The workpiece material flows to the intersection area of the long-axis and the outer surface under the combined action of the above strain, and the
ovality is more obvious than other IDT conditions. As the IDT decreases, the radial strain annulus area near the outer surface gradually becomes homogeneous, and the tendency of the material flowing from the outer surface to the center tends to be the same everywhere. When the IDT decreases to 885 °C, the circumferential tensile strain gradually disappears and the circumferential compressive strain dominates the distribution. A uniform compressive strain ring is formed on the surface layer, which enables the surface material to flow uniformly along the circumferential direction, and the ovality of the section decreases. With the further decrease of IDT, the axial tensile strain value increases, the radial compressive strain region and the compressive strain value also increase, and a necking trend appears in the middle of the workpiece.
4.4 Analysis of the force energy parameters

The force condition of the workpiece is particularly complex in the CWR process. Large plastic deformation often occurs along the axis and diameter direction of the workpiece. In order to achieve large plastic deformation, the mill needs to be able to provide sufficient rolling force and torsional moment. This is an important basis for the design of the mill and the selection of the appropriate motor power [34]. Therefore, it is essential to analyze the radial force and torque corresponding to the different moments in the forming process. The FE simulation and experimental results of the radial force and torque of TC4 alloy workpiece during CWR are shown in Fig. 18.

From Fig. 18 a and b, it can be observed that distribution of radial force predicted by FEM is similar to the experimental results. The experimental results of the radial force are slightly higher than those predicted by FEM, which may be due to the difference between the actual thermal and theoretical conditions. There is also a difference at the sizing stage. The decrease rate of radial load in the experiment is slower than that of FEM, because the cooling rate of workpiece surface is faster than that predicted by FEM. The steady radial force and torque gradually increase with the decrease of IDT. When the IDT is 945 °C, the radial force and torque are about 73 kN (74 KN in experiment) and 8 kN·m, respectively. When the IDT is 855 °C, the radial force and torque are about 106 kN (109 KN in experiment) and 11.5 kN·m, respectively. The steady radial force at the IDT of 855 °C increased by 45% compared with that at 945 °C, and the torque also increased by 44%. This rapid increase in radial force and torque is due to the relatively high resistance to flow of TC4 alloy at relatively low temperature during the rolling process. When the IDT is 885 °C, the non-circularity of the part keep a low level along the axial direction, and the radial force shows a smooth transition during CWR process. The difference is that under the

![Fig. 18](image-url) Effective of the IDTs on force and torque in CWR processes: a FE simulation results of radial force, b experimental results of radial force, c FE simulation results of torque

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IDT conditions of 945 °C and 915 °C, the radial force is not uniform in the rolling cycle, and a typical elliptical peak appears at the beginning of rolling, and the elliptical phenomenon occurs in both workpieces.

4.5 Internal quality analysis

In the process of plastic forming, the alternating tension-compression stress may lead to the generation of cracks, and the tensile stress along the axis direction may lead to the propagation of micro cracks, with cavities eventually arising as a result. The internal defects will reduce the strength of the formed parts. The distribution of the stress in the stretching zone is given according to Fig. 16. During the CWR process, the tensile-compression stress alternating region is formed in the symmetric center of the cross section. The stress state in this area changes four times per revolution of the workpiece. The more the number of alternating cycles in the center of the workpiece, the greater the trend of internal defects will occur. The stress in the CWR process increases with the decrease of IDT, which means that the stress state of material is more serious in the rolling process at relatively low temperature. When the IDT is high, the CWR process will make the grain boundary of the material easy to form micro holes [34].

Figure 19 is the internal quality of samples at different IDTs. The microstructure at the central position is shown in Fig. 19b to e. Compared with the specified standard GB/T5168-2008, it is difficult to find any internal cave in the center of the four parts processed at different IDTs under low and high magnifications. This is mainly because the die gap reduces the interaction time between the dies and the workpiece, reduces the number of alternating cycles of tension-compression stress, and prevents the occurrence of central defects.
4.6 Mechanical properties and microstructure

The mechanical properties of rolled parts were investigated by the room temperature tensile experiment. Two tensile samples were taken along the axial direction of rolled parts; their location is shown in Fig. 20, in which samples 1 and 2 are located in the middle and core of finished zone, respectively. The room temperature tensile strengths of the TC4 alloy in its initial state (received TC4 alloy) were 933 MPa, 856 MPa, and 19.6% for UTS, YS, and EI, respectively.

The room temperature mechanical properties at different IDTs are shown in Fig. 21. The UTS and YS values of rolled workpieces with different IDTs are higher than those of the initial state. It can be seen that the UTS and YS values for both core and middle samples show a tendency to increase and then decrease with increasing IDT, with the maximum value occurring at 885°C. The maximum UTS and YS values are 987 MPa and 924 MPa, respectively, which are 5.7% and 7.9% higher than those in the initial state. It has the smallest EI of 16.8%, which is 14.2% lower than the initial state.

At the same IDT, the UTS and YS in the middle are higher than those in the core; this may be due to the different degrees of deformation of the microstructure along the radial direction from the surface to the center of the part. Because the effective stress and strain gradually decrease from the contact surface along the radial direction to the core position (Fig. 16 and Fig. 17), the deformation of the microstructure according to Fig. 23a–h is also decreasing. The thickness of lamellar α phase at the middle is smaller than that at the core. The α phase of the microstructure in the middle and core was refined, which improves the UTS and YS properties of the parts with different IDTs.
From the volume fraction of the equiaxed \( \alpha \) phase \( (f_{\alpha_e}) \) in Fig. 21 a and b, the \( f_{\alpha_e} \) decreases with the increase of IDT because the volume fraction of the transition from primary \( \alpha \) phase to \( \beta \) phase increases with the increase of temperature [28]. The \( f_{\alpha_e} \) at the CSP corresponding to the different IDTs are lower than that at the MSP. According to Fig. 22 a and b, the plastic temperature rise level at the two points is nearly close. The MSP is close to the mold, and the temperature drop is faster than the CSP. The deformation of the MSP during rolling was larger than that of the CSP, and the lamellar \( \alpha \)

![Fig. 23 The microstructure of CSP and MSP of parts at different IDTs: a T=855°C, CSP; b T=855°C, MSP; c T=885°C, CSP; d T=885°C, MSP; e T=915°C, CSP; f T=915°C, MSP; g T=945°C, CSP; h T=945°C, MSP](image)
phase undergoes equiaxed transformation, which promotes the increase of the \( f_{\alpha-e} \).

It can be seen from Fig. 23a–b and Fig. 21 that when the IDT is reduced to 855 °C, the \( f_{\alpha-e} \) value in the microstructure is the largest. With the increase of the \( f_{\alpha-e} \), the stability of the residual \( \beta \) matrix is also higher [35], which reduces the driving force for the nucleation and growth of the secondary \( \alpha \) phase, and further increases the EI value of the material and decreases the UTS and YS values. There are many lamellar secondary \( \alpha \) phases with small length-width ratio in the microstructure of Fig. 23c and d. The lower length-width ratio of the secondary \( \alpha \) phase means that the smaller the clusters with the same orientation arranged between the secondary \( \alpha \) phase and \( \beta \) phase, the more the corresponding clusters. As a result, the crack is more likely to encounter obstacles in the process of propagation, resulting in increased tensile strength of the material [26]. The secondary \( \alpha \) phase cluster distribution in the microstructure is mostly parallel to each other. The same \( \alpha \) cluster has the same habit plane. At the beginning of sliding, the coarse slip band can be formed through the parallel \( \alpha \) cluster without hindrance. Dislocation plugs are easily generated at the grain boundary of \( \alpha \), resulting in uneven deformation in small regions. This promotes the formation and development of voids, and leads to premature fracture and poor plasticity. With the increase of IDT, a large number of primary \( \alpha \) phase and lamellar secondary \( \alpha \) phase transformed into \( \beta \) phase. The number of grain boundaries decrease, which reduce the strength of the material. Compared with the microstructure with IDT of 885 °C, many lamellar secondary \( \alpha \) phase with large interlayer spacing appear in the microstructure of Fig. 23e to h, and the thickness of lamellar secondary \( \alpha \) phase increases and the distribution is chaotic. This makes the UTS and YS of the material decreased, and the EI value increased slightly.

### 5 Conclusions

1. The surface steps of the parts are mainly caused by the elliptical deformation in the rolling process. With the increase of IDT, the elliptical deformation is serious, so there are obvious steps on the surface of the rolled parts after rolling at high temperatures. After several IDT experiments, the results showed that surface quality of the rolled workpiece is the best at 885 °C.
2. Compared with the CWR process at different IDTs, the lower the IDT is, the greater the radial force and torque are required. When the IDT is 945 °C, the radial force and torque are about 73 kN and 8 kN•m, respectively. When the IDT is 885 °C, the radial force and torque are about 106 kN and 11.5 kN•m, respectively, which are 1.4 times higher than those at 945 °C.
3. The die gap reduces the interaction time between the die and the workpiece and the number of alternating cycles of tensile-compression stress in the rolled workpiece, resulting in no internal defects in the TC4 alloy rolled workpiece in the high IDT range of 855–945 °C.
4. The mechanical properties of UTS, YS, and EI of TC4 alloy were jointly affected by primary \( \alpha \) phase content and microstructure morphology. The microstructure of the parts was refined after rolling, and the mechanical properties were improved compared with the initial state. At the IDT of 885 °C, the UTS, YS, and EI were 987MPa, 924MPa, and 16.8 %, respectively. It shows that the parts with high tensile strength and elongation can be obtained by hot CWR process, which can meet the requirements of the mechanical properties of the lower arm preform.

### Author contribution
Peiai Li: conceptualization, investigation, methodology, data curation, writing-original draft, reviewing, and editing.
Boyu Wang: supervision, conceptualization, methodology, funding acquisition, reviewing, and editing.
Pengni Feng: supervision, methodology, reviewing, and editing.
Jinxia Shen: supervision, methodology, reviewing, and editing.
Jiapeng Wang: supervision, methodology, reviewing, and editing.

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### Data availability
The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

### Declarations

#### Conflict of interest
The authors declare no competing interests.

#### Ethical approval
The article follows the guidelines of the Committee on Publication Ethics (COPE) and involves no studies on human or animal subjects.

#### Consent to participate
Applicable.

#### Consent to publish
Applicable.

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