Formability Difference between TC4 Titanium Alloy Hollow Shaft and AISI 1045 Steel Hollow Shaft Formed by Cross Wedge Rolling with a Mandrel

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Abstract. Production of TC4 alloy hollow shaft formed by cross wedge rolling (CWR) can meet the needs of the lightweight structures in aviation field. Different from the steel, the formability of TC4 alloy is sensitive to deformation temperature. In this work, the formability difference of TC4 alloy hollow shaft and AISI 1045 steel hollow shaft formed by CWR with a mandrel was studied numerically and experimentally. The results show that the influence of temperature on TC4 alloy flow stress is larger than that of 1045 steel, and the peak stress of TC4 alloy at 900 ℃ is close to that of 1045 steel at 1050 ℃. For the hollow shafts of two materials, the ellipticity increases with increasing the inner hole diameter. For the same size of thin-walled billets, the forming quality of TC4 alloy at 900 ℃ is better than that of 1045 steel at 1050 ℃. The CWR temperature range of TC4 alloy is narrower than 1045 steel. The increase of the initial deformation temperature can significantly increase the ellipticity of TC4 alloy and the appropriate forming temperature range of CWR TC4 alloy hollow shaft should be lower than 950 ℃. Moreover, the rolling force and torque of TC4 alloy hollow shaft are smaller than that of 1045 steel when CWR hollow billet with the same dimensions.

Keywords. Cross wedge rolling, TC4 titanium alloy, AISI 1045 steel, hollow shafts, formability.

1. Introduction

Compared with steel, titanium has the advantages of low density and high specific strength, which can well meet the requirements of lightweight in aviation field. TC4 titanium alloy, as a kind of medium strength two-phase titanium alloy with excellent comprehensive properties, is the most widely used aerospace material [1]. On the premise of ensuring the performance, the application of hollow shaft parts can reduce the structural weight and save materials. Therefore, developing TC4 titanium hollow shafts in aerospace field can well cater for lightweight demand. At present, titanium alloy shafts are usually manufactured by forging or hot extrusion processes. Owing to the large deformation resistance and narrow forging temperature range of titanium alloy in traditional forging process, it is easy to cause forming defects such as cracking. In addition, the huge temperature rise caused by plastic deformation and the long-time contact between the workpiece and the tool during the process can greatly shorten the service life of the hot extrusion tool and increase the production cost [2, 3]. Based on these, the cross wedge rolling (CWR) process is proposed to form TC4 titanium alloy hollow shaft.

CWR is a near-net forming process for manufacturing various types of shafts with high efficiency.
Under the action of continuous rotating rollers, the billet is rolled with continuous local plastic deformation [4]. Nowadays, the steel hollow shaft parts manufactured by CWR have gradually been applied in automotive industry [5-7]. These applications show that it is feasible to form steel hollow shafts by CWR. However, titanium alloy is a typical temperature sensitive material with large deformation resistance and narrow forming temperature range [8], and CWR is a non-isothermal plastic forming process. The formability of titanium alloy is closely related to initial deformation temperature, which is quite different from that of steel. Çakırcalı et al. [9] experimentally and numerically analyzed the deformation and failure of the Ti6Al4V (ELI) alloy solid billets formed by CWR and found the temperature distribution in the rolled piece was non-uniform. Li et al. [10] investigated the forming defects of powder sintering TC4 alloy solid shafts and found that the relative density of rolled piece was increased after CWR. Li et al. [11] also manufactured a TC6 alloy blade preform that meet the current technical requirements by CWR. Feng et al. [12] studied the influence of CWR process parameters on formability of TC4 alloy hollow shafts and found that the TC4 alloy hollow shaft formed by CWR is feasible.

The study on titanium alloy shafts formed by CWR is quite different from that of steel shafts formed by CWR due to the different properties of materials. And the investigation of steel hollow shafts formed by CWR can be taken as reference and guidance for investigating the formability of titanium alloy in CWR process. However, there are few researches on the formability difference between titanium alloy hollow shaft and steel hollow shaft. In this work, the formability of TC4 alloy hollow shafts and AISI 1045 steel hollow shafts formed by CWR were investigated. In order to analyze the characteristics of the two materials, the flow behaviour of TC4 alloy and 1045 steel were studied. The CWR experiments of TC4 alloy and 1045 steel hollow shafts with different billet dimensions were carried out and the corresponding finite element (FE) models were established to analyze the formability difference between the two materials. Based on these, the appropriate initial forming temperature range of CWR TC4 alloy hollow shaft was determined.

2. Research Arrangements

2.1. Materials and Flow Behaviour

The experimental materials applied in this work are the hot-rolled bars of TC4 titanium alloy and AISI 1045 steel. The corresponding beta transus temperature of TC4 titanium alloy is about 990 °C.

In order to well understand and analyze the characteristics of the two materials, it is necessary to know the flow behaviour of the two materials. According to DEFORM-3D material library, the constitutive relations of the two materials are shown in figure 1. It can be seen that the peak stress of both materials increases with the decrease of temperature and the increase of strain rate. The peak stress of 1045 steel is higher than that of TC4 alloy at the same temperature. Figure 2 shows the peak stress of TC4 alloy and 1045 steel at different temperatures. The peak stress of TC4 alloy at 900 °C is close to that of 1045 steel at 1050 °C at different strain rates, showing similar flow stress characteristics in steady state. Moreover, compared with 1045 steel, the flow stress of TC4 alloy decreases more with the increase of temperature, indicating that the flow behaviour of TC4 alloy is more sensitive to temperature than that of 1045 steel.
Figure 1. Flow stress-strain curves of TC4 alloy and 1045 steel at different temperatures and strain rates.

Figure 2. Comparison of peak stress of TC4 alloy and 1045 steel at different temperatures and strain rates.

2.2. Experimental Arrangement

The experiments of CWR hollow shafts with mandrel were completed on H630 mill, and the forming wedge tools used in the experiments came from the previous work [13], as shown in figure 3. The forming angle (α) and the stretching angle (β) were selected 38° and 4°, respectively. The outer diameter of the hollow billet (D₀) was 35 mm. The gap between the two dies was adjusted to 29.2 mm, which represents the outer diameter of the rolled piece (D₁) after rolling. To well compare and analyze the difference of two materials in formability, hollow billets with different inner hole diameters (d) were designed in this work. The d varied from 15 mm to 20 mm with an interval of 2.5 mm. Combined with the previous studies [5, 12] and the flow behaviour characteristics of the two materials (figure 2), the initial deformation temperatures (T) of TC4 alloy hollow shaft and 1045 steel hollow shaft in actual CWR experiments were determined to be 900 °C and 1050 °C, respectively.
2.3. Finite Element Model

The FE model was established through DEFORM-3D software, as shown in figure 4. It can be seen that the billet was surrounded by the wedging dies and guide plates. The dies and guide plates were set as rigid bodies and the billet was set as a plastic body. Half model was simulated by setting symmetric constraint and the mesh of deformation area was refined locally to improve the efficiency of computer operation. The shear friction model was used in this work. The friction between the billet and the mandrel was ignored owing to the synchronous rotation of them. The specific simulation parameters are shown in table 1.

In order to better analyze the formability difference of the two materials in CWR, the simulations of TC4 alloy hollow shaft and 1045 steel hollow shaft formed by CWR at 950–1050 °C were added. The specific simulation process parameters of CWR are summarized in table 2.

![Figure 4](image)

**Figure 4.** The simulation model of CWR hollow shafts.

| Parameter                                      | Value |
|------------------------------------------------|-------|
| Speed of roll (rpm)                            | 10    |
| Friction factor between billet and dies        | 0.9   |
| Friction factor between billet and guide plate | 0.3   |
| Temperature of dies, guide plates, and mandrel (°C) | 20    |
| Temperature of environment (°C)                | 20    |
| Contact heat transfer coefficient (W·m⁻²·K⁻¹)   | 25×10³(TC4 alloy); 40×10³(1045 steel) |
| Convection coefficient (W·m⁻²·K⁻¹)             | 20    |

**Table 1.** Simulation parameters of FE model for CWR.
Table 2. Specific process parameters of CWR simulation.

| $\alpha$ (°) | $\beta$ (°) | $d$ (mm) | $T$ (℃) | Material               |
|-------------|-------------|----------|---------|------------------------|
| 38          | 4           | 15/17.5/20 | 900     | TC4 alloy              |
| 38          | 4           | 15/17.5/20 | 1050    | 1045 steel             |
| 38          | 4           | 20        | 900/950/1050 | TC4 alloy        |
| 38          | 4           | 20        | 900/950/1050 | 1045 steel        |

3. Results and Discussion

3.1. Verification of the Finite Element Model

In the process of CWR, the rolled piece metal is compressed radially and extended axially. Due to the restriction of the mandrel, the radial flow of the rolled piece metal is hindered, and the axial flow of the rolled piece metal in the wedging zone is smaller than that in the stretching zone and sizing zone owing to the characteristics of tool design (figure 3(b)). Thus the compressed metal is forced to flow in the circumferential direction, resulting in ellipticity ($e$). The larger the ellipticity of the workpiece is, the worse the forming quality of the workpiece is. In technical standards, the ellipticity is an important index to measure the forming quality of hollow rolled piece, which is defined as follows [12]:

$$e = \frac{2(D_{\text{max}} - D_{\text{min}})}{D_{\text{max}} + D_{\text{min}}} \times 100\%$$

Here, $D_{\text{max}}$ and $D_{\text{min}}$ are the maximum outer diameter and the minimum outer diameter of the rolled piece, respectively. In this section, the reliability of the FE model is verified by taking the forming condition that the inner hole diameter of the billet $d$ is 20 mm as an example. The experimental rolled pieces of 1045 steel and TC4 alloy are compared with the corresponding simulated rolled pieces, as shown in figure 5. The errors in the maximum and minimum outer diameters of 1045 steel hollow shaft and TC4 alloy hollow shaft are less than 0.92 mm and 0.42 mm, respectively. The results show that the FE model established is reliable.

3.2. Analysis on the Formability Difference

Figures 6(a) and 6(b) show the rolled pieces with different inner hole diameters of TC4 alloy hollow shafts and 1045 steel hollow shafts formed by CWR, and figure 6(c) shows the relationship between the ellipticity and inner hole diameter at the symmetrical cross section of the rolled piece. It can be seen that the formability of TC4 alloy hollow shaft is significantly different from 1045 steel hollow shaft, but the variation trend of the ellipticity with inner hole diameter is similar. The ellipticity increases with increasing the inner hole diameter. The increase of inner hole diameter means that the
decrease of wall thickness of the workpiece, resulting the decrease of the ability of the workpiece to resist flattening deformation and the increase of the ellipticity [5]. Moreover, when the inner hole diameter of the billet is the same, the ellipticity of 1045 steel hollow shaft formed at 1050℃ is obviously larger than that of TC4 alloy hollow shaft at 900 ℃, especially for thin-walled hollow billet. The results show that the forming quality of CWR thin-walled hollow shaft of TC4 alloy formed at 900 ℃ is better than that of 1045 steel formed at 1050 ℃.

To well understand the formability difference between the two materials in CWR, the TC4 alloy hollow shaft and the 1045 steel hollow shaft formed at 900–1050 ℃ were simulated (for d = 20 mm), as shown in the figure 7. The ellipticity increases with the increase of temperature owing to the decrease in the deformation resistance of the workpiece. When the initial forming temperature of TC4 alloy hollow shaft increases to 1050 ℃, the ellipticity increases sharply from 9.8% to 32.5%, with an increase of 22.7%. When the initial forming temperature of 1045 steel hollow shaft decreases to 900 ℃, the ellipticity decreases from 28.3% to 16.3%, with a decrease of 12.0%. The ellipticity of TC4 alloy increases more significantly than that of 1045 steel with the increase of temperature, indicating that the formability of TC4 alloy is more sensitive to temperature than that of 1045 steel. Combined with the flow behaviour of the two materials (figure 1), it can be seen that the influence of temperature on the flow stress of TC4 alloy is greater than that of 1045 steel. And the increase of temperature makes the flow stress of TC4 alloy much lower than that of 1045 steel. The results show that the CWR temperature range of TC4 alloy is narrower than 1045 steel. The appropriate forming temperature range of CWR TC4 alloy hollow shaft should be lower than 950 ℃. In addition, compared with the TC4 alloy, the initial deformation temperature is a non-significant influencing factor for the forming quality of 1045 steel hollow shaft, but the forming quality can be improved by adjusting the tool parameters, such as reducing the stretching angle [5].
In CWR process, rolling force and rolling torque are important basis for mill design and motor power selection to ensure sufficient plastic deformation of workpiece. Figure 8 shows the distribution of rolling force and torque for TC4 alloy at 900 °C and 1045 steel at 1050 °C during the CWR process. The results show that the radial force and torque of 1045 steel at 1050 °C are higher than TC4 alloy at 900 °C. Different from the TC4 alloy, the radial force of 1045 steel increases continuously at the stretching stage (about 0.5–2.5 s). It is consistent with the increasing trend of 1045 steel flow stress (figure 1(d)) after entering the plastic deformation stage. Moreover, the force fluctuation of 1045 steel is greater than that of TC4 steel owing to the influence of the ellipticity. When CWR hollow billet with the same dimensions, the rolling force and torque of TC4 alloy hollow shaft are smaller than that of 1045 steel on the premise of good forming quality.

4. Conclusions
(1) The flow stress of TC4 alloy is more sensitive to temperature than that of 1045 steel. The peak stress of TC4 alloy at 900 °C is close to that of 1045 steel at 1050 °C.
(2) When CWR TC4 alloy hollow shaft and 1045 steel hollow shaft, the ellipticity increases with increasing the inner hole diameter of the workpiece. When CWR the thin-walled hollow billet with the same dimensions, the forming quality of TC4 alloy formed at the 900 °C is better than that of 1045 steel at 1050 °C.
(3) Compared with TC4 alloy, the initial deformation temperature is a non-significant influencing factor for the forming quality of 1045 steel hollow shaft formed by CWR. The increase of the initial...
deformation temperature can significantly increase the ellipticity of TC4 alloy. The initial forming temperature of TC4 hollow shaft should be lower than 950 °C. 

(4) When CWR hollow billet with the same dimensions, the rolling force and torque of TC4 alloy hollow shaft are smaller than that of 1045 steel on the premise of good forming quality.

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