Experimental and simulation requirements for residual stress of TC4 titanium alloy based on ultrasonic rolling

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Abstract. The residual compressive stress can improve the fatigue performance and strengthen the material surface. In this paper, TC4 titanium alloy is chosen as the material to measure surface residual stress under different static pressures by automatic gradient stress detection and analysis system. ABAQUS software is used to simulate the variation of residual stress in ultrasonic rolling process. The results reveal that the experimental values and the simulation values are consistent basically. The residual compressive stress reaches its maximum when the static pressure is 1000N. When the static pressure is 1100N ~ 1200N, the depth of the residual compressive stress layer reaches its maximum.

1. Introduction

The titanium alloy is used extensively in the field of aeroengine[1,2]. Fatigue failure becomes the main failure mode of titanium alloy components in this complex service environment of high temperature and high pressure. At present, the surface damage and surface layer residual tensile stress caused by forming and manufacturing process have become the most prominent problems which destroy the fatigue performance of aviation key components. However, the residual compressive stress can restrain the generation and development of the surface cracks, thus improving the fatigue performance[3]. Therefore, the formation of surface layer residual stress has been a hot topic in recent years. With the development of research and application of ultrasonic vibration technology, the ultrasonic rolling shows many advantages as a new surface strengthening process[4]. Ultrasonic rolling device is simple and it can be directly installed on a lathe or milling machine as an independent machining device. Its processing path is controllable. The flowing micro-plastic deformation on the surface layer can be produced by ultrasonic rolling. At the same time, the residual compressive stress on the surface layer increases obviously[5].

In recent years, the influence of ultrasonic rolling parameters on surface layer residual stress has been extensively studied. Zheng Jianxin et al.[6] simulated the ultrasonic rolling of 7075 aluminum alloy using ANSYS software. The reasults indicated that the depth of residual compressive stress layer was 1.05mm. The maximum residual compressive stress reached 285MPa when it was 0.31mm away from the surface. Li Fengqin et al.[7] carried out ultrasonic rolling tests on TC4 titanium alloy under different static pressures with CA6140 lathe and tested the residual stress through experiments. The results showed that the maximum residual stress was about 260MPa when the static pressure was 600N. Liu Zhihua et al.[8] measured the surface residual stress of 18CrNiMo7-6 gear steel. It was found that the maximum residual compressive stress of surface layer increased by 667MPa under the effect of ultrasonic rolling. And the depth of residual compressive stress layer increased by 660 μm.
By analyzing the researches above, it can be seen that ultrasonic rolling contributes to form a certain depth of residual compressive stress layer. In addition, the residual stress can be measured by finite element simulation or measurement experiment. In this paper, the surface layer residual stress of the sample is measured by automatic gradient stress detection and analysis system. Then the residual stress is simulated by finite element method using ABAQUS software, which improves the reliability of the results.

2. Experimental procedures

2.1. Material and sample preparation
In the ultrasonic rolling experiment, TC4 titanium alloy plate is used as the material and cut into $25\text{mm} \times 50\text{mm} \times 25\text{mm}$ sample. Its chemical composition is listed in table 1. The surface quality of specimens after ultrasonic rolling is affected by parameters such as amplitude, static pressure, feed rate and rolling times. Therefore, the single-factor test method is usually used for experimental researches. H+VM1260 type ultrasonic rolling device was used for surface machining of specimens. The specific process parameters are listed in table 2.

| Elements | Al  | V  | Fe  | O  | C  | N  | H  | Ti |
|----------|-----|----|-----|----|----|----|----|----|
| Proportions | 5.5-6.8 | 3.5-4.5 | ≤0.3 | ≤0.2 | ≤0.1 | ≤0.05 | ≤0.015 | The rest |

Table 1. Main chemical composition of TC4 titanium alloy (wt%)

| Parameters | Static pressure (N) | Amplitude (μm) | Feed rate (m/min) | Frequency (KHz) | Rolling times |
|------------|---------------------|----------------|-------------------|----------------|---------------|
| Numerical values | 900/1000/1100/1200 | 7 | 2 | 27 | 1 |

Table 2. Process parameters in ultrasonic rolling process

2.2. Residual stress measurement
Blind hole method was first proposed by Mathar J in 1934. Nowadays it has been developed more mature and is widely used in residual stress detection. The automatic gradient stress detection and analysis system (as shown in figure 1) is used to measure the residual stress of the sample combined with the principle of blind hole method. Paste the strain gauge at the test point, and drill a certain depth of the test point. The drilling position and the paste method of the strain gauge are displayed in figure 2. It will cause the change of resistance of the strain gauge when the stress of the borehole is released. Then the corresponding residual stress can be obtained by the residual stress analysis system.

Figure 1. Automatic gradient stress detection and analysis system.  
Figure 2. Paste method of the strain gauge.
2.3. Finite element model

In the finite element simulation, the rolling head was defined as rigid body without deformation and strain. TC4 titanium alloy was set as the sample material, and cemented carbide was selected as the ultrasonic rolling head material. The specific material parameters are listed in table 3.

| Table 3. Basic material parameters |
|-------------------------------|----------------|----------------|
| Parameters                   | TC4            | Rolling head   |
| Density/kg.mm⁻³              | 4.50E-6        | 1.46E-7        |
| Elastic modulus/Gpa          | 110            | 510            |
| Poisson's ratio              | 0.34           | 0.3            |
| Yield strength/Gpa           | 1.098          | -              |
| Tensile strength/Gpa         | 1.092          | -              |

In the process of ultrasonic rolling, the surface of TC4 material will deform strongly. Therefore, Johnson-Cook model is introduced to describe the mechanical properties. The equation is given in the formula (1)

\[
\delta = (A + B\varepsilon^n)(1 + C \ln \dot{\varepsilon}^*)(1 - T^m)
\]

(1)

Where, \(\delta\) is the yield limit; \(A\) is the yield stress; \(B\) is the strain power index coefficient; \(\varepsilon\) is the equivalent plastic strain; \(n\) is the strain hardening index; \(C\) is the strain rate sensitive coefficient; \(\dot{\varepsilon}^*\) is the strain influence factor; \(\dot{\varepsilon}_0\) is the reference strain rate; \(T^r\) is the temperature influence factor; \(m\) is the temperature sensitivity coefficient. Input the above parameters, melting point and reference temperature of the material into ABAQUS software. The specific parameter values are listed in table 4.

| Table 4. Constitutive model parameters of TC4 material |
|----------------------------|--------------|----------------|
| A/MPa                      | B/MPa        | n              |
| 1098                        | 1092         | 0.93           |
| 1092                        | 0.93         | 1.1            |

In the process of ultrasonic rolling, the contact condition changes with the change of machining position. The explicit module of ABAQUS is usually used to solve such nonlinear problems. The assembly model and mesh generation are displayed in figure 3. The rolling area is densely gridded with mesh transition on both sides, which weighs the operation speed and calculation accuracy.
3. Results and discussion

The surface residual stress nephogram obtained by finite element simulation is presented in figure 4. It can be seen from the figure 4 that a uniform residual stress layer with a certain depth is formed in the stable rolling zone. The residual stress values are extracted from the stable rolling zone along the depth direction in the figure. The comparison results of experimental values and simulation values are shown in figure 5.

Figure 3. Assembly model and mesh generation.

Figure 4. Surface residual stress nephogram.

(a) 900N  
(b) 1000N
Figure 5. Comparison results between experimental values and simulation values.

It can be seen from figure 5 that the residual stress results obtained by experiment and finite element simulation are basically the same. When the static pressure is 900N ~ 1000N, the position of the maximum residual compressive stress is about 0.3mm away from the surface. When the static pressure is 1100N ~ 1200N, it is about 0.4mm away from the surface. When the static pressure is 900N, the residual compressive stress changes to the residual tensile stress at about 0.8mm from the surface. When the static pressure is 1000N, it changes to the residual tensile stress at about 1mm. When the static pressure is 1100N ~ 1200N, it changes to the residual tensile stress at about 1.1mm.

When the static pressure is 900N, 1000N, 1100N and 1200N, the maximum residual compressive stress values obtained by experiment are 656MPa, 699MPa, 820MPa and 759MPa respectively. The maximum residual compressive stresses obtained by finite element simulation are 686MPa, 732MPa, 870MPa and 780MPa respectively. The errors are 4.7%, 4.6%, 6.1% and 2.8%, respectively, which improves the reliability of the results.

4. Summary
In this paper, the residual stress is measured by automatic gradient stress detection and analysis system. And then the ultrasonic rolling process of TC4 titanium alloy is simulated by ABAQUS software. The simulation and experimental curves of surface layer residual stress under static pressure of 900N, 1000N, 1100N and 1200N are obtained. The experimental curve is roughly consistent with simulation curve. When the static pressure is 900N ~ 1000N, the position of the maximum residual stress is about 0.3mm from the surface. When the static pressure is 1100N ~ 1200N, it is located at the position about 0.4mm away from the surface. When the static pressure is 1100N, the residual compressive stress reaches the maximum. The experimental value is 820MPa and the simulation value is 870MPa. The error between experimental value and simulation value is 6.1%. And the errors are 4.7%, 4.6% and 2.8%, respectively when the static pressure is 900N, 1000N and 1200N, which improves the reliability of the results.

5. References
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