STUDY ON FATIGUE PROPERTIES OF TITANIUM ALLOY BASE MATERIAL AND WELDED STRUCTURE IN THERMAL COMBINED ENVIRONMENT

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Abstract

In this paper, the high temperature fatigue test of TC4 titanium alloy base material and laser Welded structure specimen was carried out, the fatigue life was obtained at room temperature, 200 ℃ and 400 ℃, and an exponential Walker life model was established. The results show that the fatigue life of TC4 base material and laser Welded structure specimen decreases with the increase of temperature, and the dispersion of TC4 base material and Welded structure is higher at room temperature and high temperature, the dispersion coefficient of base material decreases with the increase of temperature, but the Welded structure has no similar rule. The fatigue life rule of TC4 titanium alloy base material and laser Welded structure specimen can be well described by the exponential Walker life model.

Keywords: Fatigue Life, Thermal Environment, Laser Welded, Walker life model.

1. Preface

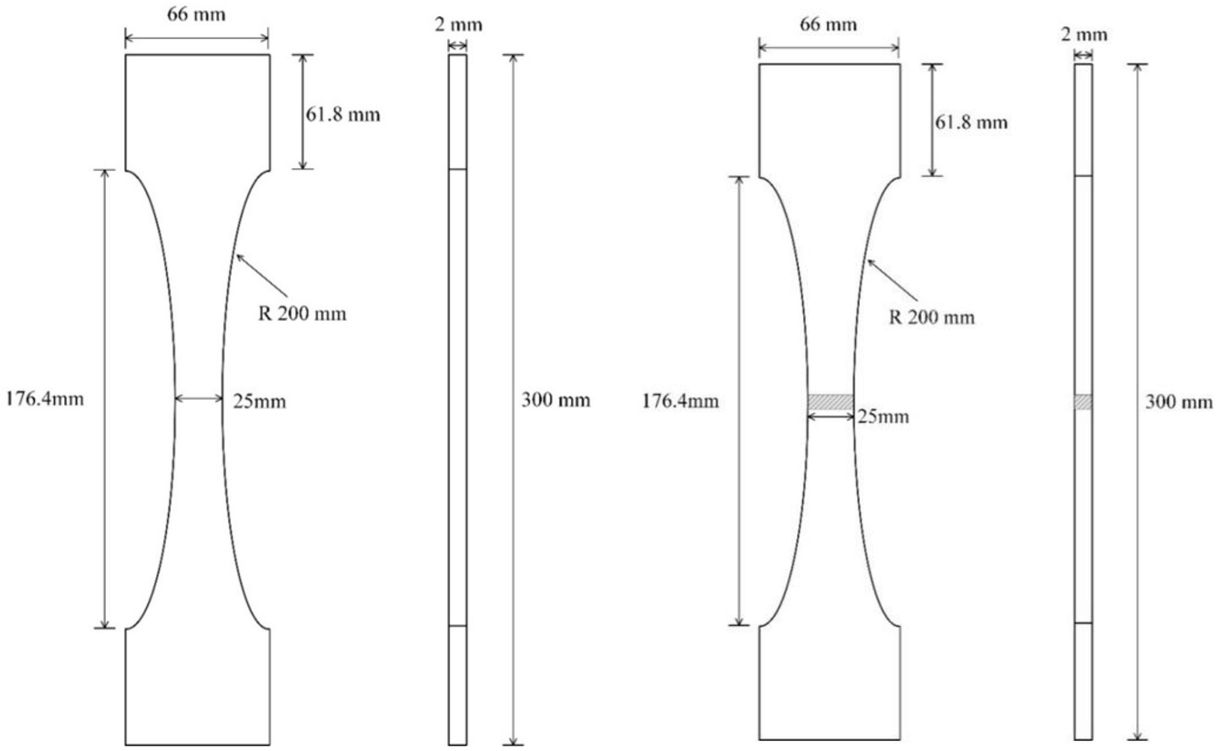
TC4 (Ti-6A1-4V) titanium alloy is a kind of (α + β) two-phase titanium alloy, which has excellent specific strength, plasticity, toughness, high temperature resistance and weld ability, so it is widely used in aerospace, vehicles, ships and other industrial fields[1].

Titanium alloy materials used in aircraft structures tend to bear alternating loads and exhibit fatigue failure modes[2-3], the fatigue and crack propagation properties have become the focus of titanium alloy research[4-7]. With the increasing requirement of aircraft performance, the environment of aircraft structure is becoming worse and worse. The environment of aircraft structure in the area affected by engine wake is worse than that of traditional aircraft structure. In the wake high temperature environment, the mechanical properties of structural materials will change greatly, so that the fatigue life of the structure will be greatly reduced under the harsh environment. Therefore, the fatigue and crack propagation properties of titanium alloy structure under high temperature is a hot research topic[8-11]. In this paper, the fatigue life of TC4 titanium alloy base material and Welded at different temperature is evaluated based on Walker strain life prediction model, and the high temperature fatigue property of TC4 titanium alloy base material and Welded structure is revealed, which provides some reference for the application of TC4 titanium alloy in high temperature area of aircraft structure.

2. Fatigue Test of TC4 Titanium Alloy Base Material and Welded Structure

2.1 Specimen

The TC4 titanium alloy base material and laser Welded structure specimen were selected to carry out the fatigue test at room temperature and high temperature. The base material specimen is 300mm long, the clamping end is 66mm wide, the center part is 25mm wide and the thickness is 2mm. The structure size of the Welded structure specimen is consistent with the base material. Laser Welded is used in the center of the specimen for Welded. The structure and size are shown in Figure 1.



(a) Base material specimen (b) Welded structure specimen

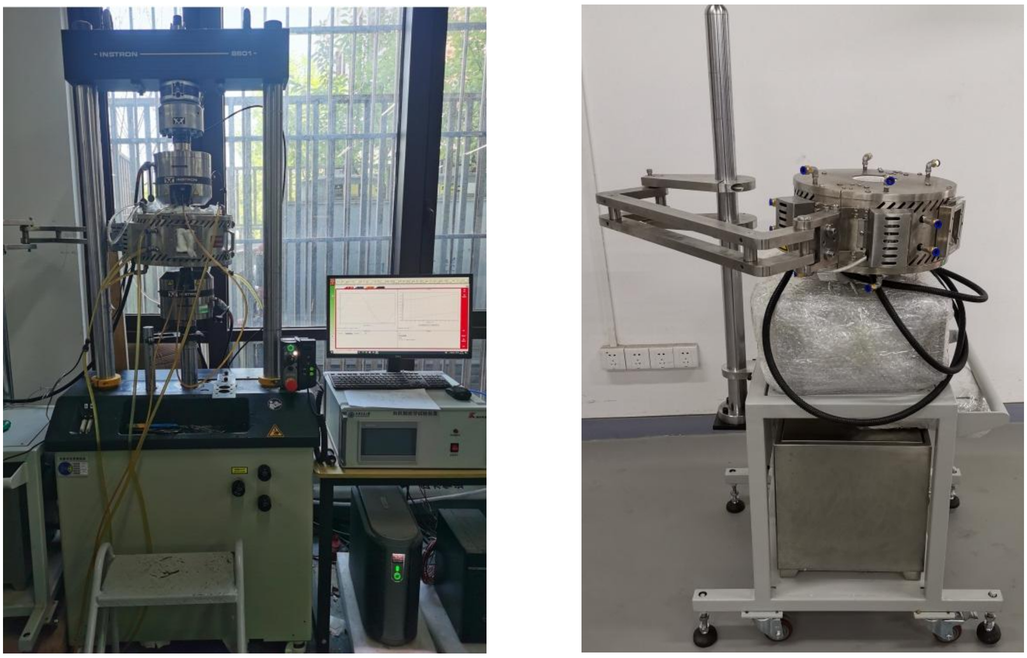
Figure 1-TC4 titanium alloy specimen

2.2 Fatigue test

The fatigue test is loaded with the same amplitude sine wave load spectrum, the test frequency is 5 Hz, the middle part of the specimen is used as the stress reference part, the peak stress of the reference part of the base material and the Welded structure specimen is 600 MPa, the stress ratio R = 0.06. Instron 8801 hydraulic fatigue testing machine and custom high temperature furnace are selected for the test equipment, as shown in Figure 2. At room temperature,200 ℃ and 400 ℃, TC4 titanium alloy base material and Welded structure fatigue tests were carried out respectively. Ten fatigue tests were carried out under each working condition. Chauvenet criterion was adopted to ensure that the number of effective parts was not less than 7, and the specific test arrangement was shown in Table 1. During the test, the high temperature furnace is heated to the target temperature. The fatigue test is then carried out at the target temperature until the specimen is destroyed and then the temperature of the specimen is reduced to room temperature.

Table 1 Fatigue test of TC4 titanium alloy base material and Welded structure

Specimen	Temperature (℃)	Peak stress at reference position (MPa)	Number of specimens
Base material specimen	RT	600	10
	200	600	10
	400	600	10
Welded structure specimen	RT	600	10
	200	600	10
	400	600	10



(a) Test loading system (b) High temperature furnace

Figure 2-High temperature fatigue test

The test spectrum mainly includes temperature spectrum and fatigue load spectrum.

The temperature load is heated by a custom-sized resistance wire heating furnace. The target temperature is room temperature,200 ℃ and 400 ℃. For high temperature test design, the temperature load spectrum is shown in Figure 3, where T1 is room temperature and T2 is the test target temperature. The temperature load spectrum is as follows: the heating process is 30 min, the holding time is 30 min, the fatigue test is carried out under the constant temperature environment until the specimen is destroyed, and then the temperature is reduced 30 min.

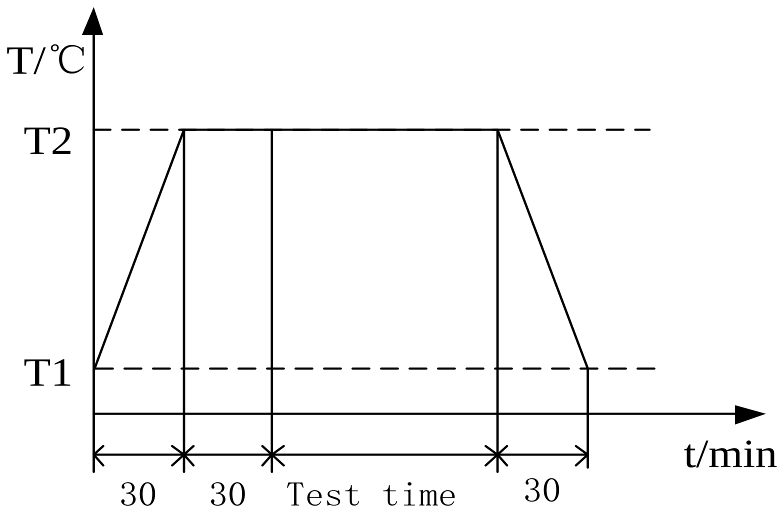


Figure 3- Fatigue Analysis Test Temperature Spectrum

The fatigue test load spectrum is shown in Figure 4. All the tests were carried out with equal amplitude load spectrum and sine wave. The load frequency was 5 ~ 15 Hz, R = 0.06, and the two ends of the test pieces were constrained.

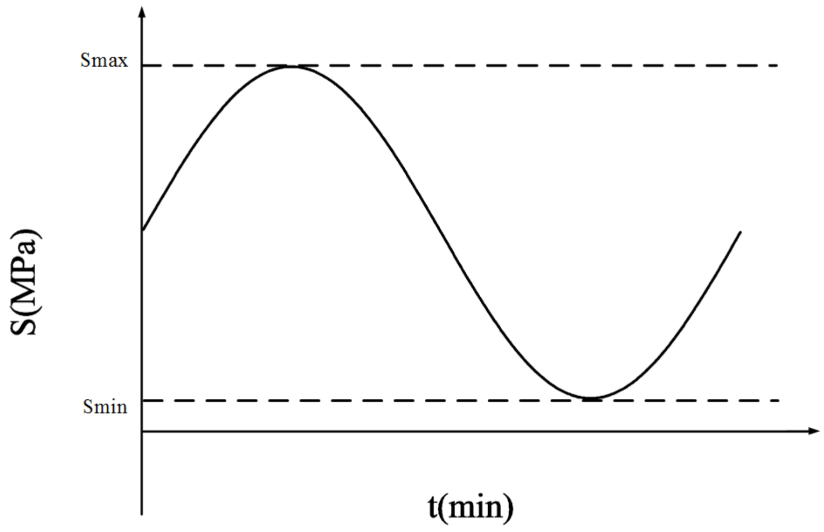
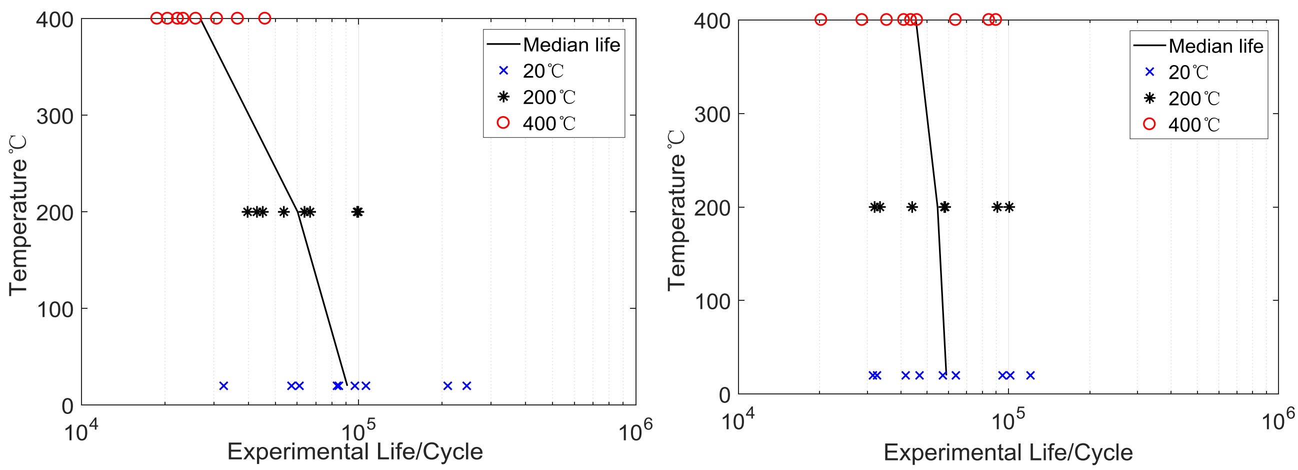


Figure 4- Fatigue test load spectrum

2.3 Fatigue test results

The fatigue test results of TC4 titanium alloy base material and Welded structure and the median fatigue life curves at different temperatures are shown in Figure5. When the peak stress of reference position is 600 MPa, the fatigue life of base material specimen is between 18000 and 250000 at room temperature, 200 ℃ and 400 ℃. When the peak stress of reference position is 600 MPa, the fatigue life of Welded structure specimen is between 20000 and 120000 at room temperature, 200 ℃ and 400 ℃. The mean fatigue life of the base material specimen and Welded structure specimen decreases with the increase of temperature. The results of fatigue life at room temperature and high temperature of TC4 titanium alloy base material and Welded structure show high dispersion. The fatigue life of Welded structure decreases relatively slowly with the increase of temperature. At the temperature below 200 ℃, the median fatigue life of the base material is better than that of laser Welded structure. At the temperature above 400 ℃, the laser Welded structure is better than that of the base material.



(a) Base material specimen (b) Welded structure specimen

Figure 5-Fatigue test life results

3. Stress analysis of specimen

A finite element model is established in Figure 6 according to the parameters of the base material specimen in Figure1. The Welded structure specimen is similar to the base material specimen. According to the loading characteristics of the specimen, one end of the specimen is fixed, the other end is applied 227.27 MPa uniform pressure load (stress state of the specimen corresponding to the peak stress of fatigue), the elements are 6-hedron 8-node reduced integral element (C3D8R). The material parameters of TC4 is shown in Table 2.

Table 2 Material parameters of TC4 titanium alloy at different temperatures

Temperature (℃)	RT	200	400
E (GPa)	112	104	92
v	0.34	0.34	0.37

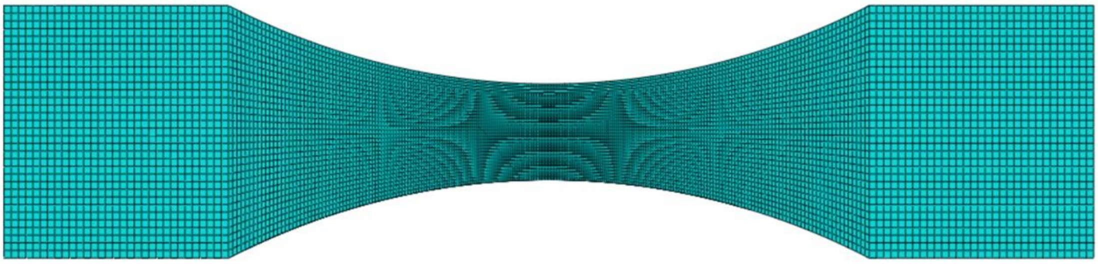


Figure 6-Finite element model of TC4 specimen

By finite element calculation, the cloud diagram of the maximum principal stress distribution of the specimen at room temperature is shown in Figure 7. The results show that the maximum principal stress of the specimen is located at the edge of the center of the specimen, the maximum principal stress is 622 MPa, the stress distribution of the specimens of base material and Welded structure at 200 ℃ and 400 ℃ is similar to that of Figure 7. During the fatigue test, the crack is caused by the maximum principal stress, and the crack propagates until the specimen is destroyed.

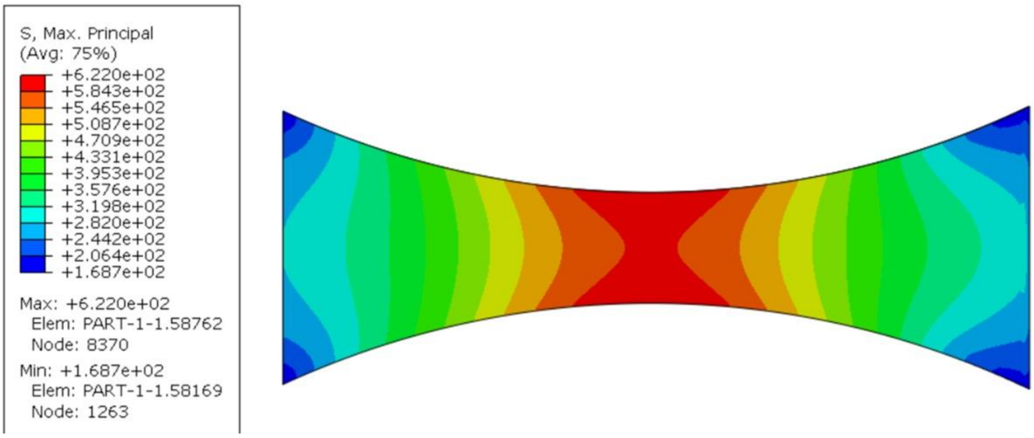


Figure 7- Cloud diagram of maximum principal stress distribution

4. Walker strain life prediction model

Walker's strain life prediction model is based on the local strain of the stress concentration part or the dangerous part to estimate the fatigue life[12]. This method deals with the complicated geometry and irregular cyclic load history, and considers the stress-strain state of the local position, so the more accurate fatigue life estimation can be obtained. Walker equivalent strain is defined as follows.

$$\varepsilon_{w} = \left(\frac{\sigma_{max}}{E}\right)\left(\frac{E\Delta\varepsilon}{\sigma_{max}}\right)^{m} \quad (1)$$

Among them, ε_w is Walker strain parameter, m is equivalent strain parameter, σ_{max} is maximum stress, E is elastic modulus, $\Delta\varepsilon$ is strain range, m is material constant, m can be valued as 0.55.

In order to improve the prediction accuracy, many scholars have revised the above-mentioned

Walker model. The Walker strain life model of anti-hyperbolic tangent function is proposed by Jaske[13].

$$\lg N_f = A_0 + A_1 \operatorname{arctan} h \left\{ \frac{\lg\left[\varepsilon_e \varepsilon_u / (\varepsilon_w)^2\right]}{\lg(\varepsilon_u / \varepsilon_w)} \right\} \quad (2)$$

Among them, A_0,A_1 is parameter for regression; ε_u is the strain corresponding to the quarter cycle, ε_e is strain corresponding to fatigue limit.

There are 4 material constants in Walker life model, and the fitting experiment data is complicated, which limits its application in engineering. However, since Walker lifetime model does not involve average stress correction, it has been widely concerned by scholars. Zhang Guoqian et al. pointed out that in the range of 10^3 ~ 10^5 cycles, it can be simplified by using the following exponential Walker life model[14,15].

$$\varepsilon_w = a \cdot b^{\lg N_f} + c \quad (3)$$

Among them, a, b and c is fitting parameters.

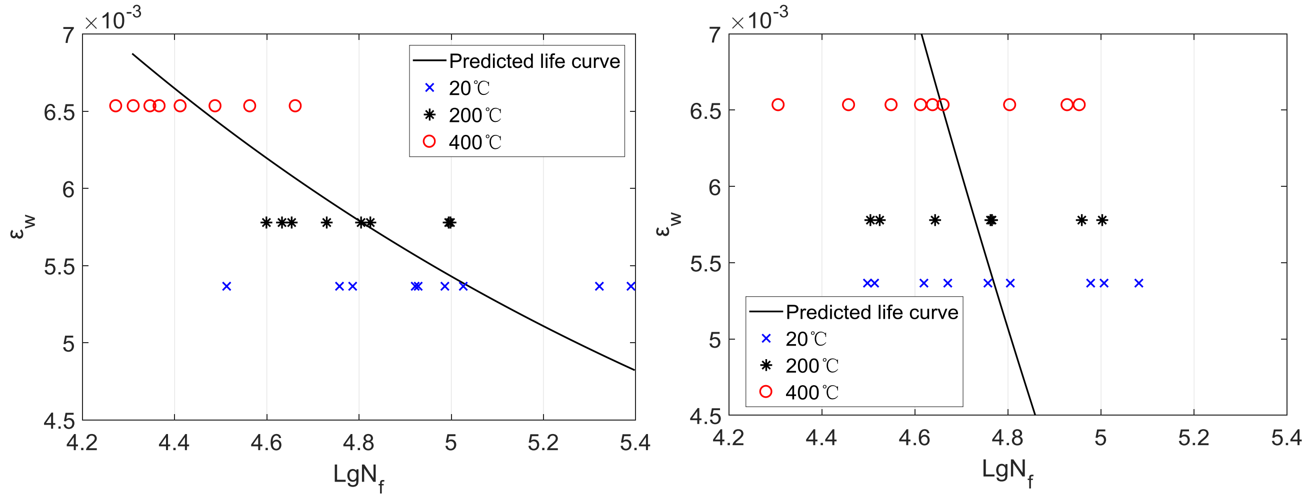
5. Results and discussion

According to the fatigue test results of TC4 titanium alloy base material and Welded structure specimen in Figure5, the parameters of Walker life model in exponential form are obtained, as shown in Table 3.

Table 3 Parameters of Walker life model in exponential form

Specimen	*a*	*b*	*c*	Life model
Base material	0.05057	0.56953	0.0024	$\varepsilon_w = 0.05057 \cdot 0.56953^{\lg N_f} + 0.0024$
Welded structure	0.26348	0.56769	-0.01233	$\varepsilon_w = 0.26348 \cdot 0.56769^{\lg N_f} - 0.01233$

Based on the Walker life model in exponential form, the Walker life model curves and test results in exponential form of TC4 titanium alloy base material and Welded structure specimens can be drawn, as shown in Figure 8. It can be found that at the same stress level, the higher the temperature, The larger the Walker strain parameter ε_w is, and the smaller the life-span result is.

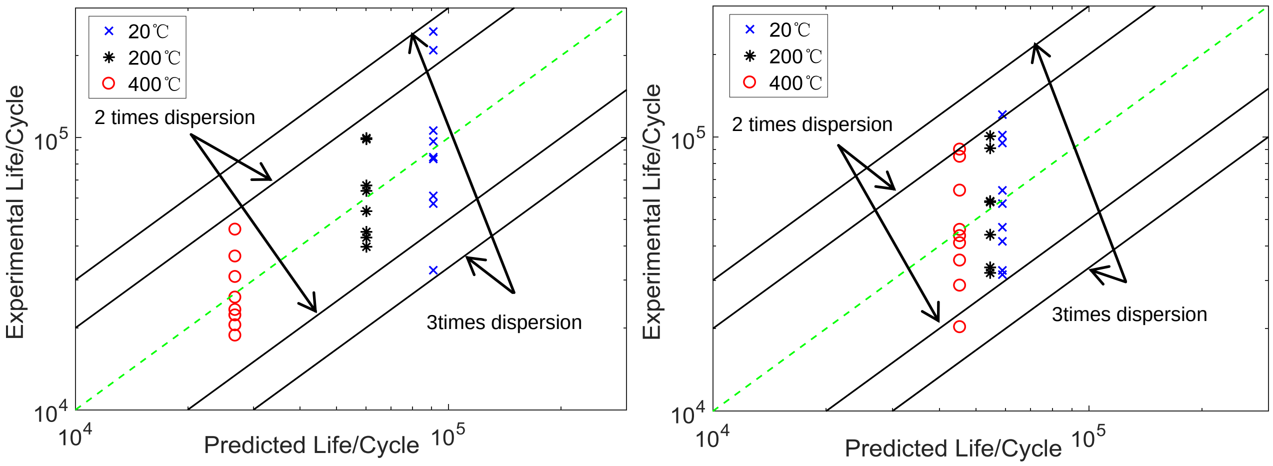


(a) Base material specimen (b) Welded structure specimen

Figure 8-The Walker life model curve in exponential form of TC4 titanium alloy specimen

Figure 9 is a comparison between the life prediction results based on the Walker strain life prediction model and the experimental results. It can be found that the fatigue life rule of TC4 titanium alloy base material and Welded structure specimen can be well described by the exponential Walker life model. Most of the test results of TC4 titanium alloy base material and Welded structure specimen are within 2-fold dispersion zone, some of the test results are beyond

2-fold dispersion zone. The main reason is that TC4 titanium alloy base material and Welded structure have high dispersion at room temperature and high temperature, which leads to some test results exceeding 2 times dispersion zone. In addition, it is found that at 200 and 400 ℃, the fatigue test results of TC4 titanium alloy base material have little dispersion, and all the test results are within 2 times dispersion zone.



(a) Base material specimen (b) Welded structure specimen

Figure 9- Comparison of life prediction results with experimental results based on Walker strain life prediction model

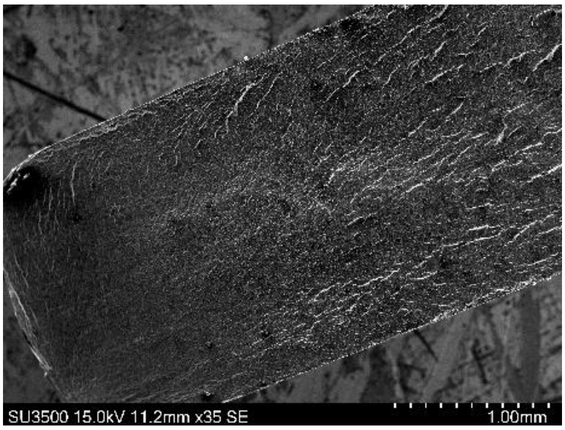
6. Fracture analysis

Figure10 is the fatigue failure mode of macro-fracture of Welded structure specimen at room temperature. The failure mode is fatigue fracture. The fracture position of base material and Welded structure specimen is basically at the minimum cross section.

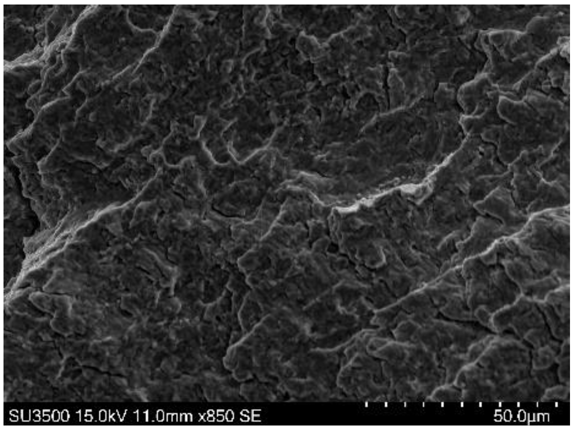
Figure 10-Typical macroscopic fracture of specimen

In order to further analyze the fracture characteristics of the specimen, the fracture of the typical failure specimen was analyzed by scanning electron microscope (FEI Quanta FEG250).

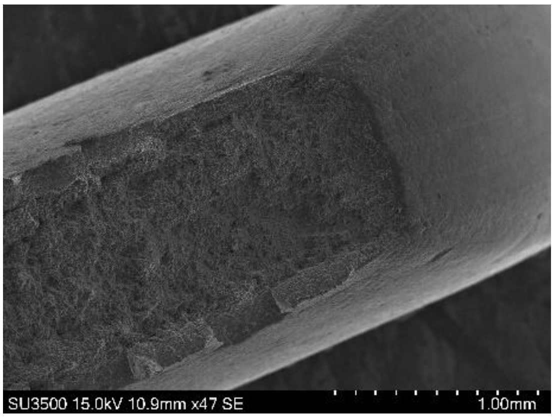
Figure11 (a) is a micrograph of the crack initiation at the base material fracture. It can be seen from the graph that the crack initiation end is flat, the crack source converges at one point, there are obvious tear edges around the crack, and there is a radial strip around the crack. Figure11 (b) is a local magnification of Figure11 (a). A small number of secondary cracks and many small blocks of varying size and height can be observed. The edge of the block is a raised tear edge. Figure11 (c) is the micro-morphology of the instantaneous fracture, from which it can be seen that there is necking phenomenon before fracture, and the fracture surface is low in flatness, which belongs to ductile fracture. Figure11 (d) is a local magnification of Figure11 (c), from which it can be seen that the dimples are relatively uniform in size, small and deep, with a few flat sticky surfaces.



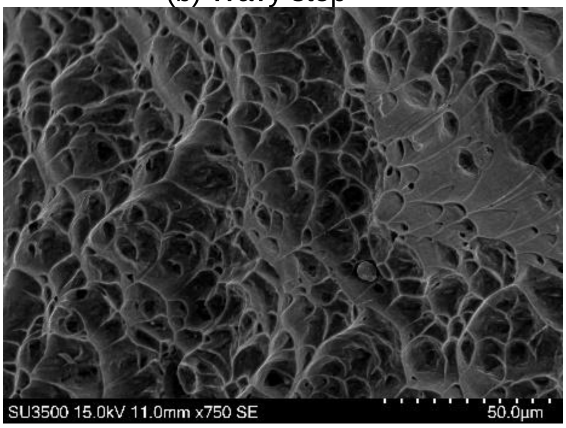
(a) Crack initiation end of the specimen



(b) Wavy step



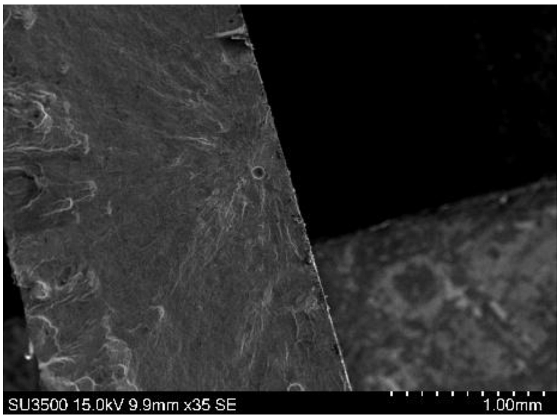
(c) Fatigue transient region



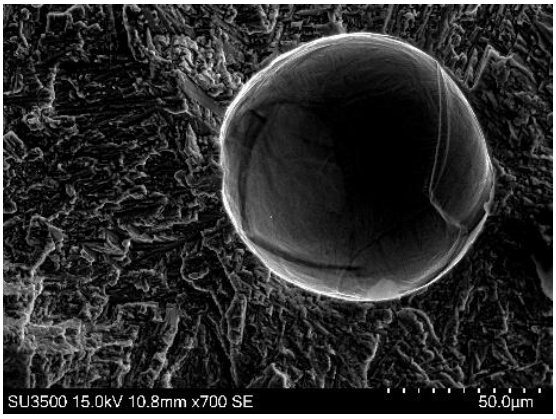
(d) Morphology of dimple

Figure11-Typical fracture morphology of base material specimen

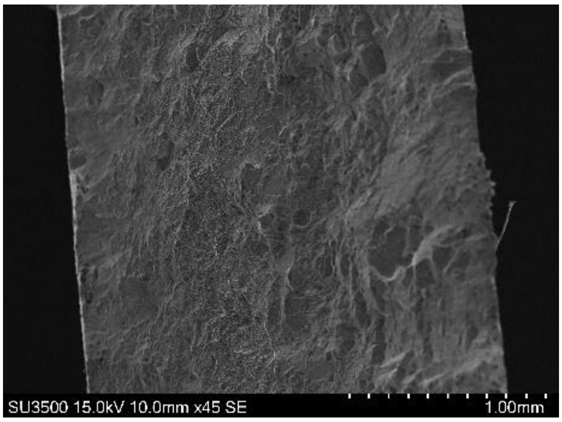
Figure 12 (a) and 12 (b), respectively, show the fracture morphology and local magnification at the crack initiation of the laser Welded structure specimen, from which a number of obvious pores can be observed, which are the fatigue source. It is also found that there are many radiation fringes on the fracture surface and the height of the step is different, but the fracture surface is relatively flat. It is observed that the fatigue source area of Welded structure specimen shows brittle characteristics through a large number of fatigue fracture surfaces, and it is also found that most of the fatigue cracks originate from the pores on the weld surface. Figures 12 (c) and 12 (d) are the local magnification of the fatigue transient and the local region, from which scattered tear edges and larger dimples of different sizes can be observed. Lateral observation of the fracture, from Figure12 (e) and Figure12 (f), shows a dense and oriented wave-like step with small and dense steps , it can also be observed that the dimple is deep.



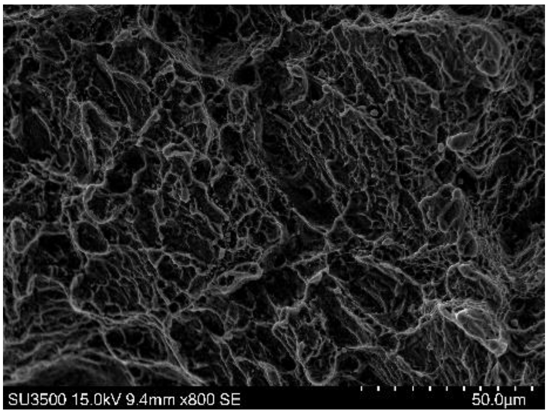
(a) Pores



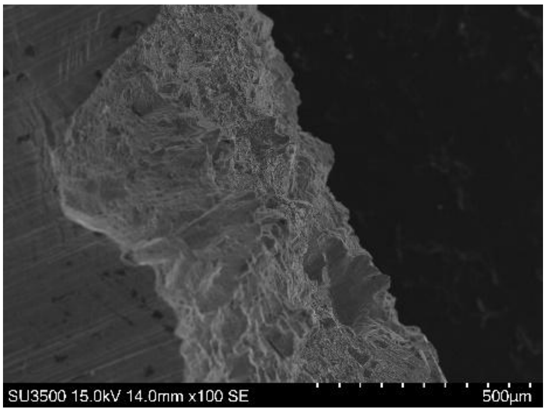
(b) Local magnification diagram of pores



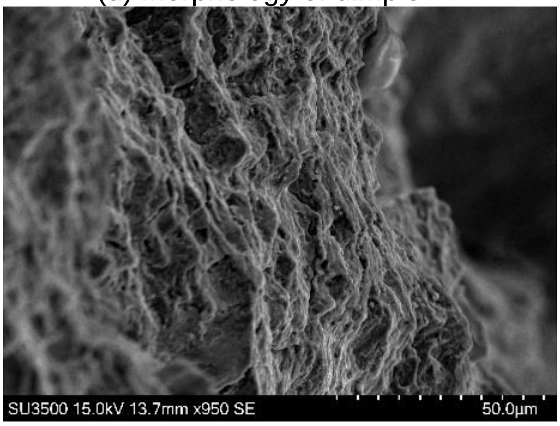
(c) Fatigue transient region



(d) Morphology of dimple



(e) Fracture lateral topography



(f) Lateral dimple morphology

Figure12 -Typical fracture morphology of Welded structure specimen

7. Conclusion

In this paper, the thermal fatigue tests of TC4 titanium alloy base material and laser Welded process were carried out. The fatigue life of TC4 base material and Welded structure specimen was obtained at room temperature, 200 ℃ and 400 ℃. The fatigue life of TC4 base material and Welded structure specimen were predicted and analyzed based on the established exponential Walker life model. The conclusions are as follows:

(1) In the range of 400 ℃, with the increase of temperature, the median fatigue life of TC4 base material and Welded structure specimen decreases gradually, the fatigue life of base material decreases obviously with the increase of temperature compared with the Welded structure specimen. The median fatigue life of base material is better than that of Welded structure specimen when the temperature is below 200 ℃, and the Welded structure specimen is better than that of base material when the temperature is higher than 200 ℃.

(2) The results of fatigue life at room temperature and high temperature of TC4 titanium alloy base material and Welded structure show high dispersion. The dispersion coefficient of base material decreases with the increase of temperature, but there is no similar rule in Welded structure specimen.

(3) The fatigue life rule of TC4 titanium alloy base material and Welded structure specimen can be well described by the exponential Walker life model, and the test results are basically within 2 times dispersion zone of the result predicted by the Walker life model, only a few are outside the 2-fold dispersion zone.

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9. Copyright Statement

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