Research on ultra-high cycle fatigue performance and reliability life analysis of TC4 by laser shock peening

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Abstract. The ultra-high cycle fatigue performance of TC4 titanium alloy specimens under different laser power densities was carried out by an ultrasonic fatigue testing machine. The fatigue fracture mechanism was analyzed by scanning electron microscope (SEM), and the reliability of ultra-high cycle fatigue life was analyzed. The results show that the specimen fatigue performance is obviously improved after laser shock peening, and the fatigue fracture surface shows a transgranular quasi-cleavage cracking mode with facets on the surface or subsurface, corresponding to high cycle fatigue and ultra-high cycle fatigue, respectively. At the same time, the position of the crack origin zone shifts sideways. The ultra-high cycle fatigue life obeys both lognormal distribution and three-parameter Weibull distribution, and the influence of reliability and confidence on reliability life depends on the sensitivity of unilateral tolerance confidence factor to both. According to the $p-\gamma-S-N$ fitting curves, it was concluded that the fatigue life is higher and the scatter is smaller under the power density of 3.42 GW/cm², so it is the best impact parameter.

1. Introduction

TC4 titanium alloy has the advantages of high specific strength, low density, high corrosion resistance, and good heat resistance, so it is widely used in the manufacture of aero-engine compressor blades and discs[1]. The study shows that most materials do not have a fatigue limit in the ultra-high cycle regime, and mechanical design according to the traditional fatigue limit design theory can not ensure safety[2]. With the continuous improvement of aero-engine life requirements, the number of stress cycles of rotating parts can even reach $10^{10}-10^{11}$ cycles[3], so it is necessary to study the ultra-high cycle fatigue performance of aero-engine blade materials. Liu et al[4] studied the ultra-high cycle fatigue properties of Ti-6Al-4V titanium alloy. It was found that the S-N curve shape is different under different stress ratios. With the decrease of stress level, the surface slip mechanism in high cycle fatigue regime changes to the internal cleavage mechanism in ultra-high cycle fatigue regime, and the facets formed by cleavage of primary $\alpha$ grains play an important role in the fracture process. Li et al[5] and Yang et al[6] had come to similar conclusions.

Laser shock peening is a new surface strengthening technology, its basic principle is to use the mechanical effect of the laser shock wave to introduce compressive stress in deeper thickness and change the material surface microstructure. As a result, the properties of metal materials such as fatigue resistance, wear resistance, and stress corrosion resistance are significantly improved. Zhang et al[7] used different laser shock times to treat Ti-6Al-4V alloy. The results show that the fatigue strength increased from 22.2% to 41.7% after the impact times are increased from 1 to 2 times. Spanrad et al[8] studied the effect of laser shock peening on the fatigue properties of simulated Ti-
6Al-4V titanium alloy blades damaged by foreign objects. The results show that the fatigue life of blades under different stress levels is increased by 5, 10, and 25 times, respectively. Zabeen et al[9] believed that laser shock peening can effectively improve the stress concentration in the damaged area and significantly increase the fatigue life. The results of laser impact on LY12CZ aluminum alloy holes and 7075-T6 aluminum alloy plates by Zhang et al[10,11] also show that the fatigue life of the strengthened components is increased by more than 3 times, the crack initiation on the specimen subsurface is increased, the fatigue fringe spacing is reduced, and the dimples in the fatigue fracture zone become smaller, indicating that the crack initiation and propagation are effectively suppressed under the action of the laser wave.

In fatigue research, the test data are often very scattered, which leads to a decrease in data reliability. The statistical method is used to process the fatigue data to determine the material fatigue life under a given probability, that is, the reliability life is of great significance to the structural safety design. In this paper, the ultra-high cycle fatigue properties of TC4 specimens treated by different laser power densities were studied, and the fatigue fracture mechanism was analyzed according to the fracture morphology. Through the fitting and comparison of the lognormal distribution and Weibull distribution of fatigue data, the distribution law of ultra-high cycle fatigue life was determined, the $p$-$γ$-$S$-$N$ curves with different reliability and confidence were obtained, and the influence of power density on fatigue performance was analyzed.

2. Materials and methods

The test raw material is the TC4 titanium alloy bar, and the plate die forging was carried out at 950 °C with deformation of 39.3%. The single-piece blanking size is 150 mm. The bar was heated to a specified temperature to keep 15~20 min and then forged and flattened along the radial direction. The heat treatment process is $720±10 °C \times 1 h + AC$, which aims to improve the plasticity and microstructure stability. The forged TC4 chemical composition is shown in table 1. The microstructure was observed by Zeiss Axio Scope A1 metallographic microscope. As shown in figure 1, the equiaxed primary $\alpha$ phase adheres to each other and there is a stacking morphology, and various forms of secondary $\alpha$ phase are uniformly distributed in the $\beta$ transformation matrix. The content of the primary $\alpha$ phase is 45.24%, and the average grain size is 42.54 $\mu$m, which is an equiaxed microstructure.

The mechanical properties of TC4 were obtained by the WDW-300 universal testing machine and DT-20 elastic modulus tester, and the test results were averaged three times, as shown in table 2.

| Table 1. Chemical composition of TC4 titanium alloy. (mass fraction, %) |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Al             | V              | Fe             | O              | C              | H              | N              |
| 6.27           | 4.08           | 0.048          | 0.021          | 0.020          | 0.004          | 0.031          | Bal.           |

Figure 1. Microstructure of TC4 titanium alloy

Table 2. Mechanical properties of TC4 titanium alloy.

| Tensile strength | Yield strength | Elongation | Shrinkage | Elastic modulus | Poisson's ratio |
|-----------------|----------------|------------|-----------|-----------------|-----------------|
| 967 MPa         | 898 MPa        | 16.2%      | 46.8%     | 115.85 MPa      | 0.317           |

The finite element modal analysis was used to carry out the specimen design. According to the degree to which the three-point bending modal frequency deviates from the 20 kHz, the specimen
length $L$ is adjusted to optimize the size, so that the frequency design error is less than 0.5%, and the specimen shape and size is obtained as shown in figure 2. The specimens were processed with YD60-R200B equipment with power densities of 3.42, 4.74, 6.05 GW/cm$^2$, corresponding to 2.6, 3.6, and 4.6 J laser energy respectively, the impact times was 1, and the spot overlap rate was 50%. The middle part of the specimen bottom bears the maximum tensile stress and the maximum longitudinal displacement, which is the expected fracture position, and the impact path and light spot arrangement are shown in figure 3. The three-point bending fatigue test was carried out on the HC-DF2020GD-K2 multi-function ultrasonic fatigue testing machine, and the details are referred to the reference [12]. The group method was used to carry out the test. Four stress amplitudes were selected at the interval of 15 MPa, and each stress level was tested 5 times. The specimen bottom was subjected to both static stress $\sigma_m$ and vibration stress $\sigma_a$, and the stress ratio $R=(\sigma_m-\sigma_a)/(\sigma_m+\sigma_a)=0.5$. The fatigue fracture morphology was observed by FEI Apreo S field emission scanning electron microscope (SEM).

3. Test results and fracture analysis

The fatigue life is shown in figure 4, in which the black solid line represents the S-N data fitting line before LSP, and most data points after LSP are on the right side, indicating that the fatigue performance has been significantly improved. By comparison, it is found that the fatigue performance of 6.05 GW/cm$^2$ is relatively poor, while 3.42 and 4.74 GW/cm$^2$ are relatively better after LSP, and the fatigue performance does not improve gradually with the increase of laser power density. The fatigue life shows a greater scatter between $10^7$ and $10^8$ cycles, which is related to the change of fracture mechanism during the transition from high cycle to ultra-high cycle fatigue.

Figure 4. Fatigue life of specimens under different power densities

Figure 5(a) shows the low magnification SEM morphology of the high cycle fatigue crack origin zone, and the crack propagation pattern is river-like and converges on the lower specimen surface, and no obvious inclusion trace is observed. Figure 5(b) shows the corresponding high magnification morphology. It is found that the origin zone shows a mixture of facets, cleavage steps, and microplastic tearing features (MPT), and there are two dark facets connected to the surface. Combined with the crack propagation path, it is inferred that the crack first initiates from the surface facet, then initially propagates with cleavage steps and MPT characteristics, and forms a rough initiation zone. Figure 5(c) shows the low magnification SEM morphology of the ultra high cycle fatigue crack origin zone, and the crack still propagates in the shape of a river but converges on the subsurface about 48
μm from the surface. Figure 5(d) shows the corresponding high magnification morphology. It is found that the facets are significantly increased compared with figure 5(b), and the facets are connected by cleavage steps and MPT features. Combined with the crack propagation path, it is inferred that the crack first initiates from the subsurface facet, and then the adjacent facet crack merges as the main crack, which finally leads to fatigue fracture. To sum up, the remarkable characteristic of fatigue fracture is the facet morphology connected by cleavage steps, MPT characteristics, and river-like expansion pattern, which shows a transgranular quasi-cleavage cracking mode with facets on the surface or subsurface, corresponding to high cycle and ultra-high cycle fatigue, respectively.

![Figure 5. SEM morphology of crack origin zones](image)

After laser shock peening, the SEM morphology of the crack origin zone is roughly the same as that of figure 5, except that the crack origin zone moves to the impact zone edge and no longer randomly appears on the specimen bottom. The location of fatigue crack initiation is transferred from the weakest middle area to the relatively weak area near the side, which reflects the fatigue strengthening effect of laser shock peening on the selected area, and the specimen fatigue life is obviously improved. At the same time, it also shows that laser shock peening can change the specimen fatigue failure mechanism, but it still shows a transgranular quasi-cleavage cracking mode with facets on the surface or subsurface as a whole.

4. Fatigue life distribution law

Under the condition of given stress, the low cycle fatigue life generally satisfies the lognormal distribution, and the high cycle fatigue life generally satisfies the Weibull distribution\[13\]. On this basis, the ultra-high cycle fatigue life distribution law was studied. If the logarithmic fatigue life $x=\log N$ obeys normal distribution, then the probability density function of $x$ is:

$$f(x) = \frac{1}{\rho \sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\rho^2}}$$  \hspace{1cm} (1)$$

Among them, $\mu$ and $\rho$ are the overall average and standard deviation of logarithmic life, respectively. Let $u=(x-\mu)/\rho$, and compare with the regression equation $Y=A+BX$, take $Y=X$, $X=u=\phi^{-1}(F(x))$, then the regression coefficient $A=u$, $B=\rho$. And $F(x)$ is obtained by the method of average rank estimation. The probability density function of $x$ can be expressed as follows:
5. Fatigue life reliability analysis

Because the specimen number is limited under a single stress level, there is a certain deviation in the fatigue life estimation when replacing the population parameter ($\mu, \sigma$) with the sample parameter ($x, s$). The probability $\gamma$ in which the estimated life value is less than the true value is called confidence, then the logarithmic life with the reliability $p$ and confidence $\gamma$ can be expressed as:

$$x_{p, \gamma} = x + ks$$  \hspace{1cm} (4)

Where $x$ and $s$ are the sample average and standard deviation of logarithmic life respectively, $k$ is called unilateral tolerance confidence coefficient, and its calculation formula is as follows[14]:

$$k = \left\{ \mu_x - u_x \sqrt{\frac{1}{n} \left[ 1 - \frac{u_p^2}{2(n-1)} \right] + \frac{u_r^2}{2(n-1)}} \right\} \left[ 1 - \frac{u_r^2}{2(n-1)} \right]^{-1/2}$$  \hspace{1cm} (5)

Among them, $u_p$ and $u_r$ correspond to the normal distribution bias of reliability $p$ and confidence $\gamma$ respectively. It is known from equation (5) that when the number of samples $n$ is large enough, the $k$ value is mainly determined by the reliability $p$. When the number of samples is constant, the $k$ value is affected by both $u_p$ and $u_r$, and the smaller $n$ is, the greater the influence of $u_r$ is. In order to clearly
express the relationship between the three, draw the curve of the $k$ value change with $u_p$ and $u_\gamma$ when $n=5$, as shown in figure 6.

![Figure 6. Variation curves of unilateral tolerance factor $k$](image)

As can be seen from figure 6, the $k$ value decreases with the increase of reliability and confidence level. Under the same reliability, the $k$ value difference of different confidence is relatively small, while under the same confidence, the $k$ value difference of different reliability is relatively large. The $k$ value decreases at 95% reliability or 95% confidence is accelerated, and the value is the smallest. This shows that the unilateral tolerance factor is more sensitive to reliability at a lower level and equally sensitive to reliability and confidence at a higher level.

The logarithmic fatigue lives under different survival rates and confidence levels are calculated according to formula (4), and the results are shown in table 4.

According to the logarithmic form of the Basquin equation[15], there is a logarithmic linear relationship between stress and fatigue life. The reliability life $N_{p,\gamma}$ considering the influence of reliability and confidence can be expressed as:

$$\lg \sigma_a = a + b \lg N_{p,\gamma}$$  \hspace{1cm} (6)

Where $\sigma_a$ is the stress amplitude, $N_{p,\gamma}=10^{\gamma_x_{p,\gamma}}$ is the reliability life, $a$ and $b$ are the constants related to the material. From formula (6), the $p-\gamma$-$S-N$ curves with different reliability and confidence levels can be fitted, as shown in figure 7 and 8. Under 95% reliability, almost all fatigue data is at the upper right of the fitting line, which reflects the leading role of reliability affecting reliability life. With the

| Power density /GW/cm² | $\sigma_a$ /MPa | Reliability degree $p=95\%$ | Confidence degree $\gamma=95\%$ |
|-----------------------|-----------------|-----------------------------|-------------------------------|
| 3.42                  | 285 6.439 | 270 7.161 | 255 7.658 | 240 7.907 | 285 6.417 | 270 6.445 | 255 7.287 | 240 7.987 | 285 6.417 | 270 6.445 | 255 7.287 | 240 7.987 | 285 6.417 | 270 6.445 | 255 7.287 | 240 7.987 | 285 6.417 | 270 6.445 | 255 7.287 | 240 7.987 |
| 4.74                  | 270 7.161 | 255 7.658 | 240 7.907 | 285 6.417 | 270 6.445 | 255 7.287 | 240 7.987 | 285 6.417 | 270 6.445 | 255 7.287 | 240 7.987 | 285 6.417 | 270 6.445 | 255 7.287 | 240 7.987 | 285 6.417 | 270 6.445 | 255 7.287 | 240 7.987 |
| 6.05                  | 240 7.987 | 285 6.417 | 270 6.445 | 255 7.287 | 240 7.987 | 285 6.417 | 270 6.445 | 255 7.287 | 240 7.987 | 285 6.417 | 270 6.445 | 255 7.287 | 240 7.987 | 285 6.417 | 270 6.445 | 255 7.287 | 240 7.987 | 285 6.417 | 270 6.445 | 255 7.287 | 240 7.987 |

As can be seen from figure 6, the $k$ value decreases with the increase of reliability and confidence level. Under the same reliability, the $k$ value difference of different confidence is relatively small, while under the same confidence, the $k$ value difference of different reliability is relatively large. The $k$ value decreases at 95% reliability or 95% confidence is accelerated, and the value is the smallest. This shows that the unilateral tolerance factor is more sensitive to reliability at a lower level and equally sensitive to reliability and confidence at a higher level. The logarithmic fatigue lives under different survival rates and confidence levels are calculated according to formula (4), and the results are shown in table 4.
improvement of confidence level, the $p$-$\gamma$-$S$-$N$ curves gradually move to the lower left, and the fatigue life has a larger safety margin. Under 95% confidence, the change rules of $p$-$\gamma$-$S$-$N$ curves with different reliability are similar, but at the same level, the position of the fitting line shifts to the upper right, and with the improvement of reliability level, the offset gradually decreases and even disappears. This shows that the influence of confidence on reliability life is weaker than that of reliability, which is attributed to the different sensitivity of unilateral tolerance confidence factor to the two.

Figure 7. Reliability life curves under different confidence degrees ($p=95\%$)
Figure 8. Reliability life curves under different reliability degrees ($\gamma=95\%$)

The coefficient of variation is introduced to measure the specimen fatigue life scatter under different power densities, and the calculation formula is as follows:

$$C_v = \frac{s}{\bar{x}} \tag{7}$$

The coefficient of variation of fatigue life under different power densities is wavy, as shown in figure 9. The coefficient of variation in stage I is larger than that in stage II, indicating that there is a stress platform area between $10^7$ and $10^8$ cycles, corresponding to the fatigue limit in the traditional sense. On the whole, the coefficient of variation corresponding to 3.42, 6.05, and 4.74 GW/cm$^2$ increases gradually. Combined with the reliability life curve, it can be seen that not only the fatigue strengthening effect is the best, but also the fatigue life scatter is lower under the 3.42 GW/cm$^2$ power density, which is the best impact parameter for the TC4 equiaxed microstructure in this paper.

Figure 9. Coefficient of variation of fatigue life under different power densities

6. Conclusion

In this paper, the ultra-high cycle fatigue performance and reliability life of TC4 titanium alloy irradiated by laser at different power densities are studied. The main conclusions are as follows:

The fatigue performance is improved by laser shock peening, and the fatigue performance of 3.42 and 4.74 GW/cm$^2$ is better than that of 6.05 GW/cm$^2$. The fracture mechanism changes during the transition from high cycle fatigue to ultra-high cycle fatigue, which leads to greater scatter of fatigue life in this stage.

The remarkable feature of fatigue fracture is the facet morphology connected by cleavage steps and MPT features and the river-like expansion pattern, which shows a transgranular quasi-cleavage cracking mode with facets on the surface or subsurface. Laser shock peening can change the fatigue failure mechanism and cause the crack origin zone to move sideways.
The fatigue life obeys the lognormal distribution and three-parameter Weibull distribution at the same time. Reliability is the dominant factor affecting reliability life, followed by confidence. The impact effect is related to the dynamic elastic limit of the material. 3.42 GW/cm² is the best impact parameter because of its higher fatigue life and smaller scatter.

Acknowledgments
Authors highly appreciate the financial assistance provided by Natural Science Basic Research Plan in Shaanxi Province of China, program No. 2020Q-477.

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