Very High Cycle Fatigue Properties of 2024 Aluminum Alloy Samples in Three Sizes

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ABSTRACT: An ultrasonic fatigue testing system was used to carry out very high cycle fatigue (VHCF) tests on 2024 aluminum alloy in three different sizes of specimens. The influence of specimen size and optimization on the experimental results was discussed and the VHCF properties of 2024 aluminum alloy were obtained at the same time. The results show that: The S-N curves of all specimens show a continuous decreasing tendency and the curve of the dog-bone-shaped specimen (the half-length of the testing volume L0 > 0) is lower than that of the hourglass-shaped specimen (L0 = 0) at low-cycle and high-cycle fatigue stages, which is opposite at the VHCF stage; The optimized specimen solves the problem of fracture position deviation and effectively improves the accuracy of experimental data; 2024 aluminum alloy will still fracture when the fatigue life exceed 10⁷, and there exist no fatigue limit; All cracks initiate at surface and the fracture morphologies show characteristics of the crack initiation and propagation.

1. Introduction

During the service of the aero-engine, the wide range of frequency of aero-dynamic excitation, the variable extreme operating condition can easily cause the high-frequency and low-amplitude load to engine blades and cause fatigue failure of the blades. Taking a certain turbofan engine for instance[1], After over 18,000 hours’ operating, the first/second-stage aluminum alloy stator blades of the compressor have fatigue failure. Why does this happen? Let’s try to answer by a calculation: assuming that (1) the stress at the crack initiation position of the blade is 20MPa, (2) the average vibration frequency is 2800Hz, (3) this load affects 60% of the blade life, then the load cycle sustainable to the blades with over 15000 hours of service life should be at least: 0.6×15000×2800×3600 cycles =9.072×10¹⁰ cycles. This obviously exceeds the 10⁷ cycles prescribed by traditional fatigue studies. Observing the fracture by Scanning Electron Microscope (SEM), it can be seen that when the service life of the blade exceeds 15000 hours, cracks are initiated on the subsurface rather than from the densely pitting surface. There are mainly four types of cracks initiated on the subsurface: initiating from grain boundaries, from inclusions of intermetallic compounds (IMC), from cross-slip zones, and from quasi-cleavage and river pattern. This is not an exceptional case. It can be seen from lots of research that, most
materials (or blades) experience more than $10^7$ cyclic loads during service, that is, the materials could likely undergo fatigue damage or even failure[2-8] at the very high cycle fatigue stage.

Nowadays, researches on VHCF mainly focus on two aspects: exploring the test method and studying on metal material properties. Ultrasonic fatigue testing system can significantly reduce the testing time and economic cost, which makes it the most widely used method for VHCF testing. A very important thing to the ultrasonic fatigue testing is the design of the specimen. According to the statistics of 200 papers in the field of VHCF in recent years, it is found that, there are several types of specimens commonly used in ultrasonic fatigue testing, including: hourglass-shaped specimen, dog-bone-shaped specimen, thin-plate specimen, and the Gauss-type specimen[9] that has just been proposed by scholars lately. The hourglass-shaped specimen is the most widely used type, amounting to about 73% while the dog-bone-shaped specimen comes the second, amounting to about 18%. And the thin-plate specimen and Gauss-type specimen respectively amount to 7% and 2%.

With the rapid improving of ultrasonic fatigue test methods and increasing of testing demands, dog-bone-shaped specimen has been developed and applied gradually[10-15]. Literature [13] adopted dog-bone-shaped specimen in ultrasonic fatigue testing and obtained results featured in good consistency with that of the hourglass-shaped specimen. Furuya designed four high-strength steels dog-bone-shaped specimens in different sizes, and the fatigue performance of the specimens were studied. Results showed that, because the intermediate constant cross-section was introduced in dog-bone-shaped specimens, the “testing volume” (defined by Murakami in literature[16], referring to the specific zone of the specimen where the maximum stress distributes evenly) of the specimen was enlarged effectively. As a matter of fact, the greater the testing volume, the lower the S-N curve, which was because that the specimen with testing volume more likely contained impurities or defects to cause cracks, so that it needed less stress. [17-19]. D. S. Paolino[20, 9] designed Gauss-type specimen which further expanded the testing volume of ultrasonic fatigue specimens and made stress distribute in the testing region evenly. Then, they made comparison with the dog-bone-shaped specimen which had the same size of the testing volume. The results showed that, the testing volume section of the Gauss-type specimen was featured in more evenly distributed stress. And under the same stress distribution evenness conditions, the Gauss-type specimen has greater testing volume. However, compared with the dog-bone-shaped specimen, Gauss-type specimen was more difficult for processing and controlling precision for its "drum shape" shape. Xue[21] analyzed the resonance length influences of specimens in different shapes and sizes on the displacement and stress distribution. They found that the length of the intermediate constant cross-section could significantly influence the magnitude and distribution of stress in the specimen, and the stress amplification coefficient could increase significantly as the diameter of the intermediate constant cross-section decreases. Which meant that the specimen performance in the ultrasonic fatigue testing was affected by its size significantly. Cheng[22] gave out the constraint conditions and optimization indexes of key parameters for specimen designing by building up the theoretical model of the specimen size for ultrasonic fatigue testing.

From the current research situation, most investigation on specimen size design and optimization focus on theoretical calculation and simulation, and few auxiliary verification tests are carried out. At the same time, as the most widely used aluminum alloy material in aviation industry, there are few studies on the very high cycle fatigue properties of 2024 aluminum alloy. In this paper, three kinds of ultrasonic fatigue tension compression specimens of 2024 aluminum alloy were designed based on reference[22]. aiming to check the effect of the size optimization method and provide references for the optimization and design of ultrasonic fatigue testing specimens, and obtain the very high cycle fatigue properties of 2024 aluminum alloy.

2. Experimental Techniques

2.1. Experimental Equipment
Due to the low loading frequency, traditional fatigue testing methods often require a large amount of testing cost. But the ultrasonic fatigue test system can solve this problem very well, because it usually
works in the 15~30Hz frequency[23]. As shown in Figure 1(a), the ultrasonic fatigue testing system is composed of a resonance subsystem, a cooling subsystem, a measurement subsystem and an environmental chamber. When the system works, the ultrasonic frequency generator converts the 50Hz AC signal into 20kHz high-frequency electrical signal, and then converts it into axial mechanical vibration signal of the same frequency through piezoelectric ceramics. After having its amplitude enlarged by horn, the high frequency vibration signal drives the specimen to achieve axial resonance.

Figure 1 Very high cycle fatigue testing system
In this test, the 20kHz ultrasonic fatigue testing system built in the laboratory was used to conduct the symmetrical cycle fatigue testing for 2024 aluminum alloy specimens in three sizes under the stress ratio of R=-1. And the number of cycles was set within the range of $10^5$~$10^{10}$ cycles. Figure 1(b) and (c) show the physical diagram of ultrasonic fatigue test system. Due to the high loading frequency of the ultrasonic fatigue testing, the specimen could easily suffer serious overheat or ablation caused by friction among materials. Compressed air and intermittent loading were taken in this study to cool the specimens and satisfy the test requirements. (Figure 1(d))

The resonance frequency of the ultrasonic fatigue testing system is around 20kHz but the amplitude that it outputs is small. The amplitude measurement should be in the range of 1μm to 199μm, and the resolution can reach 0.1μm, which is kind of impossible to most traditional measurement instruments. In this study, MTI-2100 optical fiber vibration sensor produced by American MTI Corp. was adopted. Owning resolution as high as 2.5nm and frequency as high as 500kHz, it is typically a non-contact optical fiber vibration and displacement measurement system featured in high resolution and high frequency. Meanwhile, the system was also equipped with the MTI-2032R optical fiber dual-range probe with 120kHz sampling rate. The two ranges are: (1) 102μm linear range, 0.01μm resolution, 0.016μm/mV sensitivity; (2) 305μm linear range, 0.1μm resolution, and 0.076μm/mV sensitivity.

2.2. Materials and Specimens
Three sizes of 2024 aluminum alloy specimens were designed in this experiment. Figure 2(a) shows a typical dog-bone-shaped specimen. When the half-length of the testing volume $L_0=0$ mm, it should be hourglass-shaped specimen. The initial sizes of the arc radius $R_0$, the radius of thick section $R_1$ and thin section $R_2$ of specimen were: 10mm, 1.5mm, and 4.5mm respectively. By selecting different size of $L_0$ and correcting by ABAQUS finite element software, the specific size parameters of the specimens were finally obtained, which was shown in Table 1. The size of $L_0$ for specimen c is obtained According to the parameter optimization in reference[22]. The parameter $C_S$ in Table 1 is the stress displacement coefficient, which can reflect the ratio of amplitude to stress. $L_3$ is the length of resonance (the resonance between the specimen and the test system can be achieved by adjusting it) and $L$ is the half length of the specimen section. Figure 2(b) shows the three types of the specimens which are (from top to bottom): Specimen a (hourglass-shaped), Specimen b (dog-bone-shaped), and Specimen c (dog-bone-shaped).

![Figure 2 Specimen for ultrasonic fatigue tension-compression testing](image)

Table 1 2024 aluminum alloy specimens for ultrasonic fatigue tension-compression testing

| Parameters | $R_0$/mm | $R_1$/mm | $R_2$/R_1 | $L_0$/mm | $L_1$/mm | $L_2$/mm | $2L$/mm | $C_S$/MPa/μm |
|------------|----------|----------|------------|----------|----------|----------|----------|--------------|
| Specimen a | 10       | 1.5      | 3          | 0        | 7.1414   | 27.7100  | 75.2828  | 13.2015      |
| Specimen b | 10       | 1.5      | 3          | 2        | 7.1414   | 16.2000  | 70.2828  | 11.0254      |
| Specimen c | 10       | 1.5      | 3          | 5        | 7.1414   | 18.0000  | 60.2828  | 7.9121       |

![Image of specimen sizes](image)
according to the requirements of GB/t228.1-2010 and GB/T2975-1998. The data is provided in Table 2.

| Mechanical properties | Tensile Strength $R_m$ (Pa) | Modulus of Elasticity $E$ (GPa) | Percentage Elongation after Fracture $A$ | Poisson’s Ratio $\mu$ |
|------------------------|----------------------------|---------------------------------|--------------------------------------|------------------|
|                        | 583.85                     | 75.25                           | 16.81                                | 0.33             |

Table 2 Mechanical properties and Chemical compositions of 2024 aluminum alloy

| Chemical compositions (mass percent %) | Si  | Fe  | Cu  | Mg  | Zn  | Mn  | Cr  | Ti  | Ni  | Zr  |
|----------------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|                                        | 0.19| 0.15| 4.3 | 2   | 1.56| 0.10| 0.59| 0   | 0.09| 0.01|

Targeting at the three sizes of 2024 aluminum alloy specimens, 6 levels of stress were selected, which increased by a 20Mpa intervals from the initial stress amplitude. At each level of stress, 3 specimens of each size were conducted with ultrasonic axial tension and compression testing. And the imposed stress amplitude was determined according to the mechanical properties of materials showed in Table 2, the stress amplification factors of the three sizes of specimens, and the power rate that the smart digital ultrasonic wave generator could reach (30-60%). The stress was controlled by adjusting the power of the smart digital ultrasonic wave generator. And the stress measurement was achieved by method of using optic fiber vibration meter to monitor the amplitude at the ends of specimen.

3. Results and Discussion

3.1. Experimental Results

Figure 3 (a) (b) (c) shows the S-N curves of the 2024 aluminum alloy specimens. The arrows in the figures indicate the specimens that have not fractured when the number of loading cycles reached $10^{10}$. The data of dog-bone-shaped specimens is more decentralized than that of hourglass-shaped specimens. This may be because the dog-bone-shaped specimen has a greater surface area of the testing volume, which is more susceptible to surface defects and leads to the decentralization of fatigue life.

By linear fitting of the experimental data, it can be seen that, the fatigue S-N curves of all specimens show continuous decline, and there exist no traditional fatigue limits. Figure 3(d) shows the S-N curves of all three sizes of specimens at the same time. It can be seen that in the low cycle and high cycle fatigue stages, the S-N curve of the dog-bone-shaped specimen is slightly lower than that of the hourglass-shaped specimen. Among them, the dog-bone specimen with the optimized size (specimen c) has the smallest fatigue strength and the most conservative result. This situation is just the opposite in the very high cycle fatigue stage. In the low cycle and high cycle fatigue stage, the stress level is high, so the cracks initiation and propagation are mainly due to surface defects. The testing volume of dog-bone-shaped specimen is larger than that of hourglass-shaped specimen, the larger the surface area, the more likely to produce cracks on the surface, which results in the fatigue strength lower. In the very high cycle fatigue stage, it is easier for the hourglass specimen to initiate cracks on the surface under cyclic sliding because the stress distribution of the hourglass-shaped specimen is uneven and the stress size is higher than that of the dog-bone-shaped specimen.
During the experiment, the phenomenon that fracture position deviated from the intermediate section appeared on hourglass-shaped specimen (Figure 4(a)), which proved that the stress is not evenly distributed in the middle of the hourglass-shaped specimen[22]. Figure 4(b) shows the fracture position of the dog-bone-shaped specimen (specimen c). It can be seen that when the dog-bone-shaped specimen (specimen c) is used for the ultrasonic fatigue tension-compression testing, the fracture positions are all in the testing section. In this sense, the actual stress can be very close to the applied stress of the ultrasonic fatigue tension-compression test. Therefore, the dog-bone-shaped specimen (specimen c) can not only meet the resonance requirements of the test system, but also ensure that the fracture positions are all within testing volume. This is of great guiding significance in practical work.

Figure 3 S-N Curves of three sizes of 2024 aluminum alloy specimens

(a) S-N Curves of specimen a  
(b) S-N Curves of specimen b  
(c) S-N Curves of specimen c  
(d) S-N Curves of all three specimens  

Fig. 4 Fracture positions of 2024 aluminum alloy specimens

(a)  
(b)
3.2. Micro Analysis

The scanning electron microscope (SEM) was applied to observe the fractography morphology of the very high cycle fatigue fractures in the same stress amplitude and the order of magnitude of fatigue life in order to reveal the influence of different specimen sizes on the fatigue fracture morphology.

(a) Specimen a ($\sigma_{\text{max}} = 175\text{MPa}$ $N_f=5.18 \times 10^7$ cyc)

(b) Specimen b ($\sigma_{\text{max}} = 175\text{MPa}$ $N_f=6.23 \times 10^7$ cyc)

(c) Specimen c ($\sigma_{\text{max}} = 175\text{MPa}$ $N_f=7.13 \times 10^7$ cyc)

Figure 5 Morphology of 2024 fracture

The fracture cross-section of the specimens is shown in Figure 5 and Figure 6. It can be seen that cracks of all three types of specimens initiate from the surface and there are many small holes and micro-cracks around the crack source region. Figure 6 shows the micro morphology of fracture. It can be seen that in specimen b, a number of micro holes gather in the crack initiation region, which could cause concentration of stress. When they gather together, cracks could be easily initiated therefrom. A lot of secondary cracks can be seen at the crack initiation region (Figure 12(c)), which is a kind of cracks propagating from the fracture surface to the inside.
Figure 6 Morphology of crack initiation regions of three types of 2024 specimens

Figure 7 shows the morphology of crack propagation regions which are different from that of other metal materials. It has an extremely rough surface and unique "claw pattern" morphology. In the stable propagation region of Specimen c, it can be seen that the distribution of secondary cracks is dispersed and discontinuous. Even the cracks on a same direction cannot be wholly seen.
The morphology of the final rupture regions of the three sizes of specimens are shown in Figure 8. When the crack reaches the critical size, it will propagate unstably and form a final rupture region. It can be seen from the figures that the tear ridge and dimple exist in all specimens. The dimple is a sign of ductile fracture. Since the aluminum alloy is featured in good toughness, its dimple in the final rupture region is characterized by small but dense opens, and deeper depth. It also can be observed that, the longer the fatigue life, the larger the dimple.

4. Conclusions
The ultrasonic fatigue testing system was applied in this study to explore the very high cycle fatigue properties of 2024 aluminum alloy specimens in three different sizes, thus to provide references for the design and optimization of very high cycle fatigue testing specimens. Results as below were obtained through the analysis and experiments:

(1) The experimental data of dog-bone-shaped specimens is more scattered because of the larger surface area of the test volume. In the low cycle and high cycle fatigue stage, the fatigue S-N curve of dog-bone-shaped specimens are lower than that of hourglass specimen, the data obtained are more conservative, and the fatigue strength of dog-bone-shaped specimen with size optimization is the smallest; the situation is opposite in very high cycle fatigue stage.

(2) The dog-bone-shaped specimen with Optimizing gets rid of the disadvantage of uneven stress distribution on hourglass-shaped specimen, guarantees that all fatigue fractures are within the testing
volume while satisfying the system requirements on resonance. This helps improve the credence of the experiment.

(3) The S-N curves of the 2024 aluminum alloy show a continuous decreasing trend as the stress level decreases, and there is no traditional fatigue limit. Fractography shows that the very high cycle fatigue cracks of all three sizes of 2024 aluminum alloy specimens appear on the surface. There are many small holes, micro-cracks, and secondary cracks in the crack initiation region. The unique "claw pattern" cracks show up in the crack propagation region. There are tear ridges and dimples in the final rupture regions of the three types of specimens, and the longer the fatigue life of the specimen, the larger the dimples.

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