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An Ultra-High Frequency Vibration-Based Fatigue Test and Its Comparative Study of a Titanium Alloy in the VHCF Regime

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Abstract: This paper proposes an ultra-high frequency (UHF) fatigue test of a titanium alloy TA11 based on electrodynamic shaker in order to develop a feasible testing method in the VHCF regime. Firstly, a type of UHF fatigue specimen is designed to make its actual testing frequency reach as high as 1756 Hz. Then the influences of the loading frequency and loading types on the testing results are considered separately, and a series of comparative fatigue tests are hence conducted. The results show the testing data from the present UHF fatigue specimen agree well with those from the conventional vibration fatigue specimen with the loading frequency of 240 Hz. Furthermore, the present UHF testing data show good consistency with those from the axial-loading fatigue and rotating bending fatigue tests. But the obtained fatigue life from ultrasonic fatigue test with the loading frequency of 20 kHz is significantly higher than all other fatigue test results. Thus the proposed ultra-high frequency vibration-based fatigue test shows a balance of high efficiency and similarity with the conventional testing results.

Keywords: vibration-based fatigue; ultra-high frequency; very high cycle fatigue; fatigue test; titanium alloy

1. Introduction

Aviation equipments, such as aeroplanes and aeroengines always undergo cyclic stress during service time, thus fatigue damage has been a major concern in the researches of aeronautical materials and structures. In recent decades, the academic and engineering communities have gradually realized that fatigue fracture of materials can occur after 10^7 cycles or even 10^8 cycles. Especially for aviation equipment, the failure forms of many structural components belong to very high cycle fatigue (VHCF) regime. As a result, VHCF has gradually been paid an increasing number of attentions in the design of the aviation equipments [1], with the higher requirements of service life and reliability.

Fatigue testing is an essential aspect in fatigue researches. Due to the ultra-high failure cycles, improving the loading efficiency is very crucial in the VHCF testing. Several testing equipments have been used for the testing of VHCF, such as rotating-bending fatigue tester, servo-hydraulic fatigue tester, electromagnetic resonance tester and ultrasonic fatigue tester. The first three types of the testing approaches are usually regarded as conventional fatigue testers, which have the general

loading frequency range within 10 to 100 Hz. Thus it would be extremely time-consuming using the conventional fatigue testers in the VHCF regime [2]. In contrast, the development of the ultrasonic fatigue tester has greatly improved the loading efficiency of the VHCF testing since the actual loading frequency reaches up to 20 kHz [3]. Benefit from the huge progress in fatigue testing efficiency, the researches in VHCF of titanium alloys and other metals have been widely conducted and some interesting fatigue testing data and failure mechanism have been obtained [4–6].

However, the significant increase in loading frequency would remarkably influence the fatigue strength and life of some materials in the VHCF regime, which have been reported by many researchers [2,4,7]. Also it is controversial whether the fatigue failure mechanism under the conditions of ultrasonic fatigue testing is similar to those of conventional high-frequency fatigue testing [8,9]. Meanwhile, some investigations have supported that the results from the ultrasonic fatigue tester were close to those from the conventional fatigue testers [2]. Anyway, it can be stated that the application of the ultrasonic fatigue testing in the VHCF regime is still in controversy. Furthermore, a widely-accepted testing standard of the ultrasonic fatigue has not been proposed, while the currently existing testing standards (e.g., ISO and ASTM standards) are only applicable for the conventional fatigue tests.

For aviation engineering, VHCF issues are generally introduced by the vibration of the moving components such as blades and vanes. When subjected to fatigue loadings during the working condition, these components would always experience bending or twist loads at high frequencies [10,11]. For one thing, the actual working frequency of these aviation components cannot reach as high as the loading frequency (i.e., 20 kHz) of the ultrasonic fatigue testing. For another thing, axial-loading fatigue data does not provide a sufficient representation of HCF or VHCF behaviors of the vibrating components [12]. These situations are not adequately simulated by axial-loading fatigue tests. In short, both of the conventional axial loading fatigue testing and the ultrasonic fatigue testing data are insufficient for the design of the vibrating components in the VHCF regime.

Accordingly, vibration-based fatigue tests have been developed and carried out to obtain more meaningful data for the vibrating components. Also it is a proper testing approach to study the bending fatigue properties within the reduced experimental period since the testing frequency is much larger than the conventional axial-loading fatigue tests [13]. In other words, the vibration-based fatigue test is a sort of speeding-up fatigue test. Vibration-based bending fatigue tests have been usually carried out by electrodynamic shakers. It is widely known that the response amplitude of a specimen reaches its maximum value when the specimen vibrates under resonance condition for same excitation amplitude [14]. Thus the specimens are usually excited in a high frequency resonant mode for the purpose of reducing the power-consuming of the testing system [15,16]. This can be supported by several vibration fatigue studies of different materials [17,18], most of which have been carried out in the regime of conventional fatigue cycle though. And few work of vibration fatigue has been reported in the VHCF regime of materials.

This research proposes an experimental method for ultra-high frequency fatigue of materials using an electrodynamic shaker. For a type of titanium alloy commonly used in aero engines, an ultra-high frequency (UHF) fatigue specimen is independently designed and the fatigue experiments in the HCF and VHCF regimes are conducted. Furthermore, the influences of the loading frequency and loading types on the testing results of the fatigue life are considered separately, and a series of comparative fatigue tests are hence conducted, with the testing results compared with the present UHF results finally.

2. UHF Fatigue Specimen Design

The fatigue testing method used in the present study is actually based on resonance. Thus the loading frequency of the present fatigue testing system is very close to the resonance frequency of the specimen. It is widely known that the number of the vibration mode of a continuous system is infinite, and each vibration mode has the corresponding natural frequency. For the moving components in power engineering, such as blades, the first-order bending mode is the most common form in actual service. In other aspect, the first-order vibration mode is easy to be conducted in fatigue tests compared

to the higher-order vibration modes. Thus only the first-order longitudinal vibration mode has been merely considered in both the conventional electromagnetic loading and ultrasonic loading. Similarly, the first-order bending vibration mode is considered in the present UHF specimen. And the natural angular frequency ω in the first-order mode is the key parameter to be concerned during the design.

$$\omega = f(l, \rho, E, \mu) \quad (1)$$

where ρ , E and μ denote density, Young's modulus and Poisson's ratio, respectively. By dimensional analysis, a derived equation with a dimensionless form can be obtained by transferring Equation (1), as shown in Equation (2):

$$\frac{\omega l}{\sqrt{\frac{E}{\rho}}} = f(\mu) \quad (2)$$

For two specimens with the same shape, material and boundary condition, the only difference is the characteristic length or size l , thus the proportional relation expressed by Equation (3) can be obtained.

$$\frac{\omega_1}{\omega_2} = \frac{l_2}{l_1} \quad (3)$$

Accordingly, any higher natural frequency of a fatigue specimen could be achieved by reducing the size proportionally in theory. However, the clamping reliability and the fatigue dangerous zone (i.e., working section of specimen in which the fatigue failure is most likely to occur) should be simultaneously considered, thus a novel UHF fatigue specimen cannot be determined by simply reducing the size proportionally of the existing vibration-based fatigue specimen. In the present study, an iterative method was adopted to obtain the geometry of UHF fatigue specimen, with the flow chart shown in Figure 1. Here, two basic goals should be mentioned: One of them is that the first-order bending natural frequency or resonance frequency f of UHF fatigue specimen should fall within the range $1600 \text{ Hz} < f < 2000 \text{ Hz}$, which ensure the testing period of 10^9 cycles is less than one week. Of course, the resonance frequency beyond 2000 Hz is also not welcome in order to avoid possible frequency effect. Furthermore, the present frequency range is close to that of the aeroengine blade with the present titanium alloy in order to make the present fatigue testing results more valuable for the blade. The other basic goal is that the maximum stress $\sigma_{\max}$ in the fatigue dangerous zone should be significantly larger than the mean value σ_m in the same zone. And a relation $\sigma_{\max} \geq 1.5\sigma_m$ is adopted in the present study.

Accordingly, finite element method (FEM) was employed to determine the geometry of UHF fatigue specimen. A series of FEM models with different geometries was established by a commercially available FEM code ABAQUS (v6.14, Dassault Systemes, Providence, RI, USA). Generally, the maximum stress levels for HCF and VHCF tests are far less than the yield strength of specimens. Thus the present specimen is modeled as a linear-elastic solid, with the fundamental material properties listed in Table 1. Only the first bending vibration mode was considered in the study and the natural frequencies can be obtained by the Lanczos eigensolver integrated in ABAQUS. And the stress distribution on the surface of the specimen during the vibration can be also obtained.

Table 1. Material parameters of TA11titanium alloy [19].

Material Parameters	Value
Young's modulus E (GPa)	107
Poisson's ratio μ	0.334
Yield strength σ_y (MPa)	930
Density (g/cm^3)	4.37

Figure 1. Iterative method to design ultra-high frequency specimen.

After the FEM calculation, a design of UHF specimen was finally determined, with the geometry shown in Figure 2. The two holes in the right side are used to install bolts to mount the specimen on testing system, while the three small holes in the left side are used to adjust the natural frequency and stress distribution of the specimen. The first-order mode bending natural frequency by the FEM calculation is 1775 Hz, which just meets the aforementioned frequency requirement. And the surface normalized axial stress contour S_{11} is shown in Figure 3a. Noting the area with the two mounting holes would be totally clamped by the fixture, thus clamping area can be replaced by the boundary condition of fixed support, and the two holes are not necessarily included in the FEM model.

Figure 2. Geometry of the present ultra-high frequency (UHF) fatigue specimen (unit: mm).

In order to validate the FEM result, a stress measurement based on strain gauge was used to obtain the stress values along the central line of the area with arc segment. Benefit from the FEM calculation, a continuous stress distribution curve along the same central path can be obtained and shown in Figure 3b, with O and E representing the origin and end points on the central path, respectively. The comparison of the stress distributions from the FEM and strain gauge can be found in Figure 3b, which shows very good consistency. It should be noted that the maximum stress point is located not exactly at the midpoint, but slight near to the clamping end (normalized location = 0.41353), which is

resulted from the bending deformation of the specimen. Furthermore, the mean stress σ_m along the central path can be obtained by the Equation (4):

$$\sigma_m = \frac{1}{l} \int_{\text{path}} \sigma_{11} dl \quad (4)$$

where l denotes the length of the path. The normalized value of σ_m can be hence obtained, with the value of 0.56. Noting the normalized maximum stress $\sigma_{\max}$ is equal to 1, thus the aforementioned relation $\sigma_{\max} \geq 1.5\sigma_m$ can be satisfied.

Figure 3. FEM calculation and validation of the present UHF specimen: (a) Surface normalized axial stress contour; (b) comparison of the stress distributions from FEM and strain gauge (O and E represent the origin and end points on the central path of the specimen).

Furthermore, it should be pointed out the optimal geometry of the present UHF fatigue specimen is dependent on the material and geometrical parameters. And the geometry of the present UHF specimen is proposed based on the present titanium alloy. Although this geometry is not exactly applicable to other materials, it is still important reference geometry for the similar fatigue tests of other materials.

3. Material and Experimental Details

3.1. Experimental Material

A near-alpha titanium alloy TA11 alloy equivalent to Ti-8Al-1Mo-1V was used in the present fatigue study. It has been usually used in advanced turbine engines as low pressure compressor blades and due to its excellent damping capacity, low density, high Young's modulus, and fine welding and anti-oxidation performance [20]. The chemical composition of TA11 used in the present study is list in Table 2.

Table 2. Chemical composition of TA11 titanium alloy (mass fraction/%).

Al	V	Mo	Fe	C	N	H	O	Ti
7.79	1.00	0.98	0.04	0.01	<0.01	0.006	0.06	Balance

3.2. UHF Fatigue Testing Setup

A vibration-based bending fatigue test was subsequently conducted using the present UHF specimens shown in Figure 2. All the specimens were cut from the same batch of raw material in order to make the results reliable. The test was conducted on a vibration-based fatigue testing system, of which the major body is an electrodynamic shaker (ES-10D-240 Electrodynamic Shaker System) located in a soundproof room. The maximum loading capacity of the shaker is 10 kN and the frequency range is 5 to 3000 Hz, which meets the mode-I bending vibration testing requirement of the present specimens. Similar to conventional fully-reversed bending fatigue tests, the ratio between the maximum and minimum stress in the present test is equal to -1 .

In order to clamp the specimen firmly, a specified fixture was designed and manufactured. As same as illustrated in Figure 4, one end was clamped firmly and the other end was free, which is shown in Figure 4a. An accelerometer was used to monitor the shaker input load and a laser vibrometer was located above the free end to monitor the amplitude. The excitation direction was vertical to the specimen, with the excitation force having a sine waveform. Simultaneously, a small-size strain gauge was mounted longitudinally on the surface of the specimen, exactly locating at the maximum stress location, as shown in Figure 4a. It should be mentioned that a small-size strain gauge (sensitive pattern area: $1 \times 1 \text{ mm}^2$) was adopted since both of the specimen and the fatigue dangerous zone are small.

Figure 4. Vibration-based fatigue experiment for the UHF specimen: (a) Testing equipment (b) Sketch of the experimental system.

In this test, the amplitude of the free edge was a main object feedback, by which the excitation frequency could be automatically adjusted. The specimens were expected to be tested in the resonance condition and the excitation frequency could be adjusted automatically to keep the vibration amplitude stable [16]. Consequently, the amplitude could be steadily controlled. Benefiting from the automatic self-adjusting, the experimental system could run by the means of so-called closed-loop control, which is sketched in Figure 4b.

3.3. Resonance Frequency and Stress Calibration

It is widely known that the response amplitude of a specimen can reach its maximum value when the specimen vibrates under resonance condition for the same excitation load. Therefore, the vibration-based fatigue tests are always expected to be carried out under the resonance condition for the purpose of reducing the power-consuming of the experimental system. Accordingly, the resonance frequency should be identified before the vibration-based fatigue test. In order to obtain the vibration characteristics, the excitations with a series of increasing frequency was imposed upon the specimen, and the excitation frequency-response curves can be hence obtained and the resonant frequency of the specimen can be further determined, with the value of around 1756 Hz, which is obtained by the frequency sweeping testing shown in Figure 5. Noting that specimen is clamped by the designed fixture in the test, the resonant frequency obtained from the test is actually that of the combination of the specimen and the fixture, and it would be less than the natural frequency (i.e., 1775 Hz) of the single specimen, which is obtained by the computation presented in Section 2.

Figure 5. Determination of the resonance frequency of the UHF specimen by frequency sweeping.

During the vibration-based fatigue test process, the resonant frequency was monitored to determine the failure moment of the specimen. In this study, the excitation frequency was preset using the same value of the obtained resonant frequency, which is a stable value (i.e., around 1756 Hz) during the fatigue testing process. As the crack propagates in the fatigue dangerous zone, the resonant frequency decreases gradually to a critical value. When the resonant frequency drop rate reaches to a critical value with the value of 1%, the fatigue test will be terminated and the specimen is considered to be failure.

Since the strain gauge would fail soon after several cycles in the fatigue test, the stress-control of vibration-based fatigue tests has been always achieved by controlling the amplitude. Thus a calibration relation between the measured strain and the amplitude should be determined prior to the fatigue testing. The clamped specimen is similar to a normal slender cantilever beam and the transverse stress can be ignored. Accordingly, three typical values of the amplitude were selected and the peak-valley values of the strain along the 1-direction were measured during the vibration testing. A linear calibration relation between the measured strain (peak-valley value ε_{p-v}) and double-amplitude $2a$ of the present UHF specimen can be obtained, shown in Figure 6. For a specific amplitude a , the value of σ_1 can be gained by the strain gauge measure together with the stress-strain relation $\sigma_1 = 0.5 \cdot E\varepsilon_{p-v}$.

Thus the present stress-control vibration-based fatigue test is actually realized by control the amplitude, and various stress levels can be realized by varying amplitude a .

Figure 6. Calibration relation between the measured strain and displacement amplitude of the UHF specimen.

3.4. Fatigue Tests for Comparison

In order to verify and compare the present UHF fatigue testing results, some comparative tests have been conducted from two aspects:

On one hand, the effect of the loading frequency on the testing results should be verified. Some previous studies for VHCF tests have also considered this issue [7,9], But the comparative studies have been always performed among different types of fatigue tests, such as the comparison between the rotating bending fatigue test and ultrasonic fatigue test. Although the loading frequencies of the tests are definitely different, the loading condition also influences the testing results. Accordingly, the effect of the loading frequency can best be considered separately. In the present study, a conventional vibration fatigue (CVF) specimen shown in Figure 7 was used to explore the influence of the loading frequency. The two holes in the right side are used for mounting bolts to fix the specimen on the testing system. The minimum width of the fatigue dangerous zone is 10 mm. The geometry of the conventional vibration fatigue specimen is taken from a Chinese testing standard HB 5277, which is widely used in the field of vibration-based fatigue testing for the aeroengine blade materials in China. After a similar frequency-response test mentioned by Section 3.3, the actual loading frequency close to the resonance frequency is obtained, with the value of approximately 240 Hz.

Figure 7. Geometry of the conventional vibration fatigue (CVF) specimen (unit: mm).

On the other hand, the effect of the fatigue loading types should be considered. Some other types of fatigue tests were also conducted, which includes conventional axial loading (CA) fatigue test, rotating bending (RB) fatigue test and ultrasonic axial loading (UA) fatigue test. All these tests have been widely carried out in fatigue community, thus the comparison with them is helpful to verify the applicability of the present testing method in VHCF testing. Here, the CA loading fatigue

test and RB fatigue test were carried out in an electromagnetic resonant fatigue testing system and a rotating bending fatigue tester, respectively. And the UA fatigue test was carried out in a commercial ultrasonic fatigue test machine (USF-2000, Shimadzu, Japan). All the fatigue tests were conducted in room temperature, with the stress ratio R equal to -1 . The loading frequencies for the CA, RB and UA fatigue tests were 120 Hz, 83.3 Hz and 20 kHz, respectively. Considering the ultra-high loading frequency (i.e., 20 kHz) in the UA fatigue testing, a compressive dry air cooling system was used to cool the UA specimen during the testing in order to ensure the specimen temperature is maintained at room temperature. Furthermore, an infrared thermometer was used to monitor the surface temperature of the specimen during the UA fatigue test.

The geometry of the specimens for comparison is shown in Figure 8. All the specimens have hourglass-type shape. It should be pointed out all the specimens for comparison were machined from the same batch of raw materials with the present UHF specimen, in order to make the testing results more comparable.

Figure 8. Geometry of the specimens used in fatigue tests for comparison (unit: mm): (a) Conventional axial loading (CA) specimen; (b) rotating bending (RB) specimen and (c) ultrasonic axial loading (UA) specimen.

4. Results and Discussion

4.1. Vibration-Based Fatigue Testing Results

Figure 9 shows the obtained $S-N$ data and the relevant fitting curves for the present vibration-based fatigue tests, which involves the UHF and CVF specimens, with the actual loading frequencies of about 1756 Hz and 240 Hz, respectively. Several stress levels have been selected in the present UHF fatigue testing, covering the stress range from 400 MPa to 540 MPa. And the maximum failure cycle can reach up close to 10^9 . In order to compare the results between the two types of vibration-based fatigue tests, the same stress levels have been also considered in the test for CVF specimens. Noting the actual loading frequency of CVF specimens is about 240 Hz, the fatigue testing in the VHCF regime (i.e., $>10^7$ cycles) has not been considered due to its high time-consuming. Finally, there are 20 and 17

valid data obtained in the UHF and CVF tests, respectively, which are given in Table 3. Considering the significant scatter of the obtained fatigue lives by the tests, several specimens were tested at the same stress level in order to make the results statistically reliable.

Figure 9. *S-N* data and the fitting curves for the present vibration-based fatigue tests involving the UHF and CVF specimens.

Table 3. *S-N* testing data from the UHF specimens and CVF specimens.

Specimen No.	Stress Level (MPa)	Failure Cycle	Specimen No.	Stress Level (MPa)	Failure Cycle
UHF1	540	4.66×10^5	CVF1	540	1.66×10^5
UHF2	540	2.20×10^5	CVF2	540	2.56×10^5
UHF3	540	2.99×10^5	CVF3	540	1.50×10^5
UHF4	540	2.82×10^5	CVF4	540	2.30×10^5
UHF5	540	2.25×10^5	CVF5	540	2.36×10^5
UHF6	540	1.93×10^5	CVF6	480	1.27×10^6
UHF7	540	2.65×10^5	CVF7	480	2.62×10^5
UHF8	480	4.26×10^5	CVF8	480	2.96×10^5
UHF9	480	4.05×10^5	CVF9	480	3.18×10^6
UHF10	480	5.07×10^5	CVF10	480	2.19×10^5
UHF11	480	4.18×10^5	CVF11	480	2.79×10^5
UHF12	480	1.73×10^6	CVF12	440	5.27×10^6
UHF13	440	6.43×10^6	CVF13	440	1.00×10^7
UHF14	440	1.70×10^6	CVF14	440	3.40×10^6
UHF15	440	7.84×10^6	CVF15	440	1.00×10^7
UHF16	440	3.09×10^6	CVF16	440	4.53×10^5
UHF17	440	4.14×10^6	CVF17	440	2.27×10^5
UHF18	440	6.49×10^5	—	—	—
UHF19	420	1.19×10^8	—	—	—
UHF20	400	8.20×10^8	—	—	—

The *S-N* curves can be obtained by a regression calculation with a three-parameter *S-N* model, which is named as Stromeier model [21], expressed by:

$$\lg N_f = a - b \lg(\sigma_{\max} - S_0) \quad (5)$$

where N_f and $\sigma_{\max}$ denote the failure cycle and stress level (or maximum cyclic stress). And a , b and S_0 are the fitting parameters. Noting $\sigma_{\max}$ would approach to S_0 when N_f approaches to infinite, thus S_0 can be regarded as a fatigue limit from a mathematical point of view. Consequently, the *S-N* curves from Stromeier model would exhibit obvious curvature characteristics and the fitting model has been

widely used in the fatigue community. The values of a , b and S_0 for UHF specimens are 10.7, 2.50 and 395, respectively, while those for CVF specimens are 8.05, 1.32 and 421, respectively.

In addition, typical surface crack morphology when UHF specimen fails are shown in Figure 10. It can be found an obvious continuous crack locating approximately at normalized location of 0.38 initiated at O point shown in Figure 3b, which is close to the maximum stress point determined in Section 2, not at the narrowest width of the specimen. And the crack propagation direction is basically perpendicular to the axial stress direction (i.e., 1-direction). Thus it is reasonable to determine the strain measurement location as mentioned in Section 3.2.

Figure 10. Typical crack morphology when UHF specimen fails.

4.2. Effect of the Loading Frequency

As shown in Figure 9, the S - N curves between the UHF and CVF specimens are close to each other in the same life cycle regime. Both of the UHF and CVF specimens are sheet specimens used in the vibration-based testing with the same type of fatigue loads. The major difference between them is merely the loading frequency, which does not influence the S - N curves clearly as shown in Figure 9. Considering the two cases share the same fatigue stress levels and several testing data have been obtained at those fatigue stress levels, further comparison and analysis can be conducted in order to explore the effect of loading frequency further.

In the present vibration-based fatigue testing, three fatigue stress levels were considered with the values 440 MPa, 480 MPa and 540 MPa. Figure 11 shows the comparison of fatigue lives from the UHF and CVF specimens at these fatigue stress levels. It can be found the fatigue lives for the two types of specimens are close to each other at these stress levels. Strictly speaking, the fatigue lives for the CVF specimen are slightly shorter than those for the UHF specimen, which is clear at the stress level of 440 MPa. One reason leading to the tiny discrepancy is probably the influence of the specimen size. It can be found there is a significant difference in the size of the two types of specimens, despite their shapes are similar. It has been previously pointed out a smaller size fatigue specimen would have a longer fatigue life due to the smaller risky volume and less likelihood of containing defects [22]. Thus the present tiny discrepancy in fatigue lives between the two specimens can be mainly attributed to specimen size instead of the loading frequency.

In addition, the error bars shown in Figure 11 to reflect the dispersion of result data are worth mentioning. The length of the error is generally increased as the fatigue stress level is decreased. It suggests the dispersion of the fatigue lives is more significant for the lower stress level, which has been widely verified by the previous HCF and VHCF researches [23,24]. It should be noted the length of error bars for UHF specimen is significantly shorter than those for CVF at the low fatigue stress levels (i.e., 440 and 480 MPa), which suggests the results for UHF specimens are probably less dispersive than the CVF specimens. Although there is no solid reason to explain it, it is at least concluded the data stability by the present UHF specimens is not inferior to the conventional specimens with the lower frequency.

Figure 11. Comparison of fatigue life results from the UHF and CVF specimens for the same fatigue stress levels.

4.3. Effect of the Testing Types

Figure 12 shows the comparison of the results of the present UHF specimens and other types of fatigue specimens in consideration. The S - N curves can be also obtained by Equation (5), with the values of the fitting parameters given in Table 4.

Figure 12. Comparison of the results of ultra high frequency (UHF) specimen and other types of fatigue specimens.

Table 4. Fitting parameters of Equation (5) for the comparative tests.

Testing Type	a	b	S_0 /MPa
UA	10.8	1.94	523
RB	13.5	3.97	418
CA	15.8	4.78	407

In general, the S - N data based on the present UHF specimens get close to those based on the conventional HCF methods, including the CA and RB specimens. In contrast, the S - N curve from the UA specimens has significant discrepancy compared with those from all other testing methods. It can be found that the fatigue life data obtained by the UA test are much longer than other types of tests at the same stress level.

Generally, the factors influencing the fatigue testing results includes the temperature rise of specimen, material uniformity and testing method. Noting the cooling system was simultaneously used during the UA testing process, the surface temperature was kept at the range of 12~15°C obtained by the infrared thermometer. Thus the temperature rise of the UA specimens can be neglected. In addition, all the fatigue specimens in this study were obtained based on same batch of Ti-alloy, thus it can be inferred the discrepancy of the results shown in Figure 12 is caused by the testing method.

For fatigue testing method, an important factor is the specimen size, which can be usually considered to explain the discrepancy of the testing data. It has been usually widely thought that the fatigue specimen with smaller size would have longer fatigue life [22,25]. The specimen in the UA testing usually has a small risky volume which means the specimen volume subjected to a stress amplitude larger than the 90% of its maximum value [26]. Some previous studies have attributed the size effect of fatigue specimens to the influence of the risky volume [25,26]. However, another important factor should be noted is the loading frequency. Since both the loading frequency and the risky volume could influence the fatigue life of specimens, the explanation from the risky volume is feasible when the loading-frequencies of the fatigue tests are close to each other. For example, for the present two conventional comparative fatigue tests involving the CA and RB specimens, their loading frequencies are both close to 100 Hz. Accordingly, the discrepancy between their corresponding *S-N* curves could be explained by the risky volume theory, which means the risky volume of RB specimen is smaller than that of CA, resulting in the fatigue life of RB specimen is longer. It should be pointed out the risky volume of the UA specimen is actually small, but still larger than that of the present UHF and RB specimens. Note the fatigue life obtained by the UA test is much longer than other types of tests, the discrepancy between their results cannot be explained by the risky volume theory.

Instead, another important factor in the testing method is the loading frequency, which could be the major factor to cause the discrepancy of the testing results. It has been found that the fatigue lives of some materials have been proved to be almost unaffected by the loading frequency, while the situation of some other materials are opposite [9]. In general, the materials with an obvious strain rate-related effect are more susceptible to loading frequency [7], thus it can be inferred the present titanium alloy is a material with obvious strain rate-related effect and the UA testing method is probably not suitable for its VHCF testing. In contrast, although the frequency of the present UHF fatigue method is also high (1756 Hz) compared with the conventional testing methods, the obtained fatigue lives by the present UHF method are not clearly influenced by the high frequency.

4.4. Discussion

Although the testing results from the present UHF specimens is generally close to those from CA and RB specimens, especially in the long life regime, the discrepancy between them deserves further explanation from the perspective of the failure criterion. It should be paid attention that the present vibration-based UHF test has a different failure criterion compared with that of the aforementioned conventional fatigue tests. Actually, the failure criterion of the most conventional fatigue tests is the separation of specimen. However, the present UHF test adopts the failure criterion that the resonance frequency of specimens drops by 1% of the initial value. The critical value of resonance frequency used as the failure criterion was determined based on the previous vibration-based fatigue tests [27]. It has been widely known that the life of the crack initiation and the growth of the micro-structurally small crack accounts for a large proportion of the total life in long life regime [28]. For the low stress cases in present UHF test, once the crack initiation occurs, the specimen would fail very soon since the loading frequency is very high. Thus the critical frequency for the failure criterion can be feasible. However, for the high stress cases in the present UHF test, the proportion of crack initiation life in the total life decreases while the proportion of the crack propagation life increases. Consequently, the specimen would not fail very soon after the crack initiation and the growth of the micro-structurally small crack.

Here, it should be clarified the reason why the specimen separation is not applicable for the failure criterion of the present UHF test. Firstly, the present vibration-based fatigue specimen has been

usually clamped at only one side, with the other side free. If the testing continues until the specimen is separated, the free side is likely to impact and damage the surrounding devices and personnel when the separation occurs, because the loading frequency is very high. Secondly, the stress control of the testing is achieved by controlling the vibration amplitude of the specimen. As the fatigue test continues, the damage evolution would continue so that the resonance frequency would drop simultaneously. But the vibration amplitude should be maintained during the whole testing period to satisfy the testing stress condition, which needs a close-loop control method. However, in the period before the specimen's final separation, the resonance frequency drops dramatically as the damage evolution develops sharply. Thus it is so difficult to maintain the vibration amplitude at a constant in the final period. Considering the final period approaching to the separation of specimen is usually short, thus a critical frequency drop has been usually adopted as the failure criterion, instead of the specimen separation.

However, the failure criterion that the resonance frequency of specimens drops by 1% is just an empirical one, which has been proved feasible in some conventional vibration-based fatigue tests. Thus it has been adopted as a recommended failure criterion in the Chinese vibration-based fatigue testing standard HB 5277, which is also followed in the present study. However, the failure criterion of the frequency drop by 1% may be not the optimal one for the present non-standard UHF specimen especially in the higher fatigue stress cases. Thus it is necessary to figure out the optimal failure criterion for the present UHF specimen in the future, which helps to further improve the accuracy of the present testing results.

5. Conclusions

In summary, this paper proposes an ultra-high frequency (UHF) fatigue test of a titanium alloy TA11 based on electrodynamic shaker in order to develop a feasible testing method in the VHCF regime. Firstly, a type of UHF fatigue specimen is designed to make its actual testing frequency reach as high as 1756 Hz. Then the influences of the loading frequency and loading types on the testing results of the fatigue life are considered separately, and a series of comparative fatigue tests are hence conducted. The results show the testing data from the present UHF fatigue specimen agree well with those from the conventional vibration fatigue specimen with the loading frequency of 240 Hz. Furthermore, the present UHF testing data show good consistency with those from the axial-loading fatigue and rotating bending fatigue tests. But the fatigue life obtained from the ultrasonic fatigue test is significantly higher than all other fatigue testing results. Thus the proposed ultra-high frequency vibration-based fatigue test will have a good application prospect in the VHCF testing due to its balance of high efficiency and similarity with the conventional testing results.

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