Materials Science & Engineering A 600 (2014) 153–158

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

A very high cycle fatigue thermal dissipation investigation for titanium alloy TC4

Zhi Yong Huang [a,*], Qing Yuan Wang [a], Danièle Wagner [b], Claude Bathias [b]

[a] Sichuan University, School of Aeronautics and Astronautics, No. 29 Jiuyanqiao Wangjiang Road, Chengdu 610064, China
[b] Université ParisOuest Nanterre La Défense, France

ARTICLE INFO

Article history:
Received 22 October 2013
Received in revised form
3 February 2014
Accepted 4 February 2014
Available online 12 February 2014

Keywords:
Titanium alloy
VHCF
Inelastic deformation
Thermal dissipation
Fatigue dispersion

ABSTRACT

Titanium alloy TC4 is widely used in aeronautics applications where it is subjected to high frequency fatigue loads. Tests are performed to investigate the alloy fatigue behavior sustaining ultrasonic fatigue load in Very High Cycle Fatigue (VHCF) regime. Thermal dissipation for the alloy in 20 kHz frequency is studied and a model is proposed to describe the temperature increment in the framework of thermodynamics by estimation of the anelastic and inelastic thermal dissipation at microscopic active sites in the reference element volume. The failure probability prediction method is used to evaluate the VHCF dispersion based on the two scale model and fatigue thermal dissipation analysis.

1. Introduction

With fatigue test method development, especially the application of piezoelectric fatigue test system, Very High Cycle Fatigue (VHCF) life can be obtained in a reasonable time. In High Cycle Fatigue (HCF) or VHCF, the specimen is normally loaded in the macroscopic elastic domain. Fatigue strength below the conventional fatigue limit was found and the fatigue failure still happened when the fatigue life was beyond 10^7 cycles in terms of the report [1]. The crack initiation often lies in the subsurface of the specimen ("fish eye") in the VHCF regime. Through the thermal dissipation investigations [2,3], it is confirmed that the temperature rising under the load of ultrasonic frequency is induced by the anelastic and inelastic deformation at some local sites in microscopic scale.

Some authors [4] have worked on the mean fatigue limit estimation based on the temperature measurements for high cycle fatigue which consists of applying a series of stress amplitudes to obtain the average temperature increments. After a certain number of cycles loading, the evolution of temperature increase tends to be relatively stable. It is also observed that the temperature starts to increase more rapidly when the load exceeds a certain stress level. In the HCF self-heating test, the mean fatigue limit can be rapidly determined by the curve [5].

Calloch [6] has proposed a two-scale probabilistic approach to predict the fatigue life scatter in HCF based on the estimation of fatigue thermal dissipation caused by local plastic deformation. The sites like inclusions, pores, grains, grain boundaries [6,7] can be excited and have inelastic deformation under low cyclic load. With the increasing of the load and number of cycles, the quantity and volume of the sites are growing. Owing to the material heterogeneity, the local anelastic and inelastic deformation around the defects or the grains of the material are the thermal dissipation sources in the VHCF test [8].

Titanium alloy is an important metallic material with excellent mechanical response and has been widely used in aeronautical applications. Some aero-engine components like compressor blades and disks fabricated in this alloy would reduce the weight by up to 30% when compared to other alloys that have been employed for such applications. Titanium alloy is also widely used in aircraft components such as beams, joints and bulkheads, in order to undertake the loads. The high frequency of the load could lead to fatigue failure in their service period with very high cycles.

In the article, the fatigue thermal dissipation of the titanium alloy (TC4) in 20 kHz frequency for VHCF is investigated by considering the local anelastic and inelastic deformation to estimate the temperature increment with load amplitude. Based on the investigation, the fatigue life dispersion approach is extended to VHCF regime to predict the scatter of VHCF with the help of the VHCF thermographic observation and failure probability analysis.

2. Material

The investigated material is a titanium alloy, TC4 (Chinese standard). The chemical composition and mechanical properties

* Corresponding author. Tel./fax: +86 28 85406919.
E-mail address: huangzy@scu.edu.cn (Z.Y. Huang).

http://dx.doi.org/10.1016/j.msea.2014.02.012
0921-5093

are shown in Tables 1 and 2, respectively. It contains 6% Al and 4% V for α phase and β phase stabilization, respectively. The bar with 12 mm diameter was annealed at 700–800 °C and cooled in air for 1–2 h; followed by solution in 910–940 °C and aging treatment in 520 °C–550 °C. From the observation of the polished section in the optical microscope, two kinds of phases α, β (Fig. 1) are displayed clearly.

The ultrasonic fatigue test machine is chosen to perform the VHCF test which requires the specimen working at the resonance vibration state in 20 kHz. Hourglass shape is chosen for the specimen as shown in Fig. 2. The analytical solution for the vibration equations [1] gives out the dimensions of the specimen. The fatigue tests are performed in the machine in VHCF regime and the results are plotted in Fig. 3. It is easy to find that the fatigue strength keeps reducing with the number of cycles increasing and the fatigue life scatter is important for the titanium alloy in VHCF.

In order to obtain the temperature evolution on the specimen surface, an infrared camera is employed, whose spectral range is near the infrared domain (the wavelength is between 3.7 μm and 4.8 μm). The camera is calibrated by a black body in the temperature range of 20–400 °C. Same kind of specimen for the VHCF test is used to carry out the thermal dissipation experiments. They have been coated with a strongly emissive black and high-temperature resistance painting layer for limiting the errors (in this case, the emissivity coefficient is regarded as 1).

In the same test condition, the temperature increment depends on the load level. The temperature reaches a relative stabilization corresponding to the heat balance between the mechanical deformation dissipated energy and the thermo energy lost by the convection and radiation at the specimen surface and conduction through the connection parts. The average temperature increment values (Fig. 4) recorded by the infrared camera for different stress amplitudes are plotted in Fig. 5. It comprises two relative linear curves with an "intersection point": the first one is below 450 MPa with a slow temperature increasing slope; the second curve has a higher one. In the article, the 2 stages seem to be contributed by 2 kinds of deformation dissipations: anelastic and inelastic in VHCF which will be discussed in the next part of the article.

Fig. 6 shows the SEM observation of the broken surface of the specimen (tested with stress amplitude of 520 MPa and failed at 9×10^8 cycles). The crack initiates from one of the active sites in the subsurface and forms a "fish eye" crack as shown in Fig. 6(a). In the center of the crack, a white zone (Fig. 6(b)) is observed which looks rougher than the rest of the parts where Sakai called it Fine Granular Area (FGA) [9] and it is considered as the VHCF initiation

Table 1
TC4 chemical composition.

	Al	V	Fe	C	N	H	O
wt%	6	4	0.3	0.1	0.05	0.015	0.2

Table 2
Mechanical properties of TC4.

σ_b (MPa)	$\sigma_{p0.2}$ (MPa)	E (GPa)	ν	C_p (J/(kg °C))	ρ (kg/m^3)
≥900	≥830	110	0.34	0.52	4420

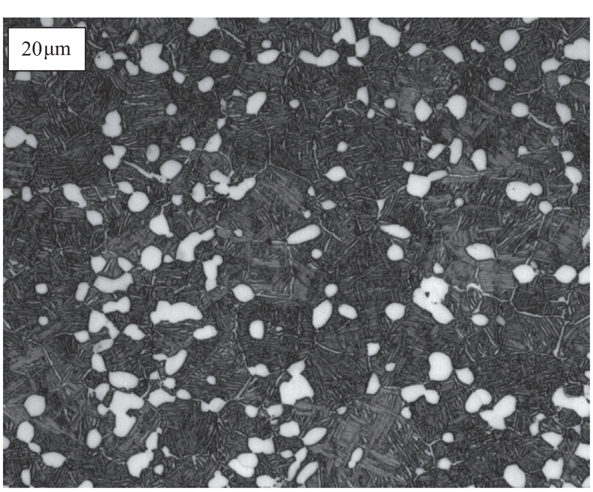

Fig. 1. TC4 microstructure.

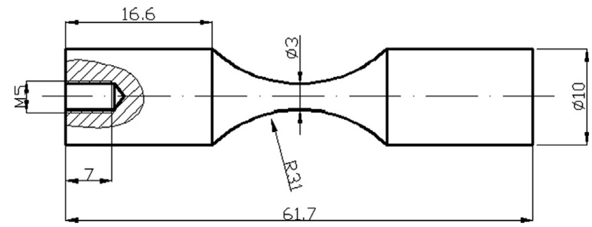

Fig. 2. VHCF specimen.

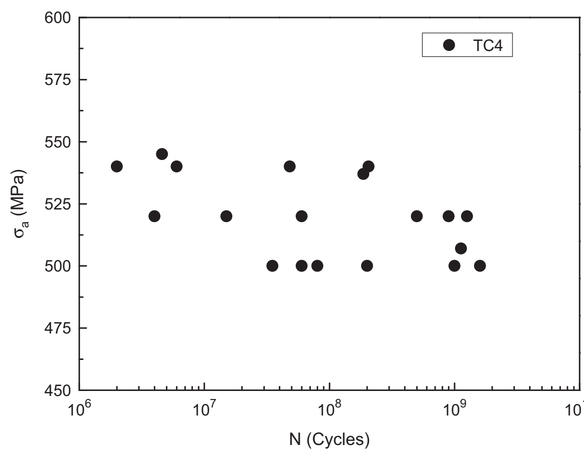

Fig. 3. VHCF test results (TC4, room temperature, $R = -1$).

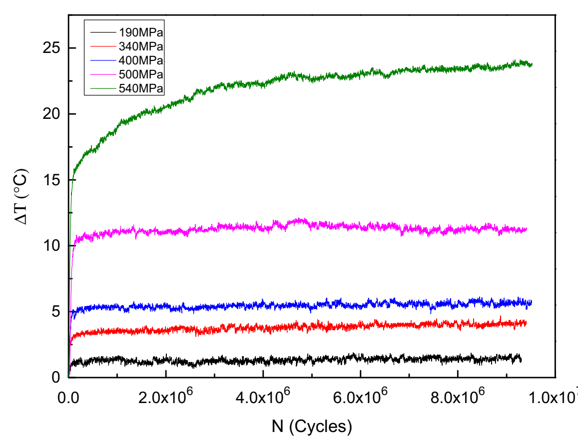

Fig. 4. Temperature evolutions at different load levels in VHCF tests.