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Fretting fatigue behavior of Ti–6Al–4V under seawater environment☆

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Abstract

Fretting fatigue behavior of titanium alloy, Ti–6Al–4V, was investigated in ambient laboratory and under a controlled environment consisting of synthetic seawater. Tests were performed over a wide range of the maximum axial stresses ranging from 380 to 760 MPa to examine both low and high cycle fatigue regimes. It was found that seawater had a deleterious effect on fretting fatigue life in the low cycle fatigue regime but improved the life in the high cycle fatigue regime. The normalized tangential force showed negligible difference between the two conditions. More debris was found on the fracture surface of specimens exposed to seawater, which also resulted in larger fretting scar volume as compared to specimens tested under the ambient laboratory condition. Analysis of tests showed that both effective stress and a critical plane-based multi-axial fatigue parameter could be used to predict seawater fretting fatigue life from the ambient laboratory fretting fatigue life data in the high cycle fatigue regime.

Keywords: Fretting fatigue; Titanium alloy; Corrosion; Fatigue parameters

1. Introduction

Fretting is the surface damage that occurs when contacting surfaces between mating bodies experience an oscillatory motion of small amplitude. When fretting occurs under cyclic loading conditions, the process is termed fretting fatigue. Fretting fatigue increases the tensile and shear stresses at the contact surface producing surface defects which can act as stress concentration sites. Cracks can nucleate at these sites leading to an overall reduction in the fatigue performance of the material. Failure of the blade/disc dovetail joint in gas turbine engines is one of the several examples where failure due to fretting fatigue is commonly seen [1].

Titanium alloys are common materials used in aerospace applications and are used in aircraft gas turbine engine blades and discs as well as in highly stressed components such as forged wing structures and landing gear components. Ti–6Al–4V is the most commonly used titanium alloy within the aerospace industry as it exhibits an excellent strength to weight ratio, high operational temperature, and corrosion resistant properties due to the protective nature of the surface oxide film [2]. Although many studies have focused on the fretting fatigue behavior of Ti–6Al–4V under ambient laboratory condition [3–5], few studies have been conducted on fretting fatigue behavior in a corrosive environment. It is well known that when subjected to fretting condition; the surface oxide film is damaged, thereby leading to a reduction in corrosion resistance [6–9]. The titanium alloy then becomes susceptible to the chemical and mechanical mechanisms of fretting fatigue-induced damage as well as the electrochemical reactions occurring in the corrosive environment. Waterhouse and Dutta [9] found that 1% NaCl solution was more detrimental than air on the fretting fatigue strength of titanium and its alloys. However, the detrimental effect was dominant at higher alternating stresses than lower stresses. In fact, the 1% NaCl solution improved the fretting fatigue life of Ti–6Al–4V at lower stresses. Wharton and Waterhouse [10] also showed that corrosive environments were more detrimental to the fretting fatigue life at higher stresses

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but extended the life at lower stresses. They suggested that the corrosive environment increased the crack propagation rate at higher stresses thus leading to a reduction in fretting fatigue life, while the corrosive debris provided a protective action at the lower stresses resulting in a decrease in the initiation of fretting fatigue cracks and improving the fretting fatigue life.

So far, investigations in fretting fatigue of Ti–6Al–4V in the corrosive environment have been conducted under either complete immersion or continuously dripping condition [8–10] which resulted in a large change in frictional behavior at the contact surface and thereby contact condition, i.e. partial slip to gross slip. Moreover, the detailed study of variables during fretting fatigue under the partial slip contact condition in the corrosive environment, e.g. coefficient of friction and crack growth rate, is still lacking. Thus, the objective of this study was to evaluate the fretting fatigue behavior of Ti–6Al–4V under laboratory air (ambient) and non-continuous seawater environments. Fatigue tests were performed over a wide range of axial stresses to examine both low and high cycle fretting fatigue regimes. Once the specimens failed, fracture surface debris, scar volume, and fatigue striations were investigated to determine the effects of seawater on fretting fatigue behavior. Finally, two fatigue parameters, the applied effective stress range and a critical plane-based multi-axial fatigue parameter using the stresses in contact region, i.e. including the effect of contact mechanics, were evaluated to determine if an equivalence could be established between seawater and ambient laboratory fretting fatigue life data.

2. Experimental procedure

Fretting fatigue tests were conducted under laboratory condition at room temperature on a servo-hydraulic fatigue test machine equipped with a rigid fretting fixture (Fig. 1). Laboratory humidity ranged from 20 to 65% throughout the course of this study. Two cylindrical fretting pads, each with a radius of 50.8 mm, were held against each side of the fretting specimen via the fretting fixture. Both the fretting pads and specimens were machined from Ti–6Al–4V forged plates using the wire electrical discharge machining method. The plates were received after being preheated and solution treated at 935 °C for 105 min, cooled under flowing air, vacuum annealed at 705 °C for 120 min, and cooled under flowing argon. The resulting microstructure consisted of 60% hexagonal closed pack α phase and 40% body center cubic α platelets in a β matrix phase. The grain size was approximately 10 μm. Fig. 2 shows micrographs of the microstructure of specimens used in this study. The length of machined specimens was 17.8 cm, and both width and thickness of the reduced gage area were 6.4 mm. Fig. 3 shows the schematics of specimen and pad. The contact configuration of this study was cylinder-on-flat.

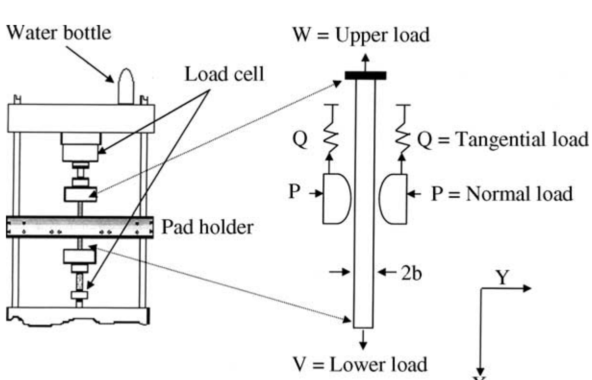

Fig. 1. Fretting fatigue test apparatus.

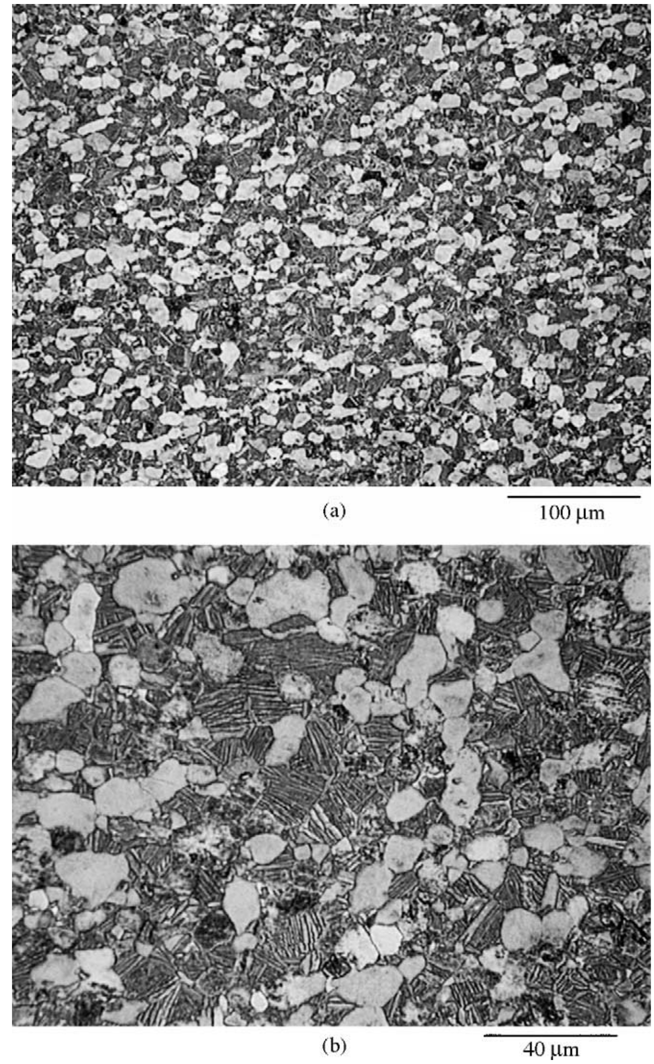

Fig. 2. Microstructure of Ti–6Al–4V after acid etch at 200× (a) and 500× (b) magnification.

The fretting fatigue tests for both ambient laboratory and seawater conditions were conducted at 5 Hz over a wide range of the applied axial stresses (*x* direction in Fig. 1) from σ_{max} = 380–760 MPa, with stress ratios, *R*, ranging from 0.03 to 0.54. Two load cells on either side of specimen measured