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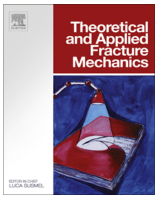

An investigation into the effect of elevated temperatures on fretting fatigue response under cyclic normal contact loading

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ABSTRACT

In this investigation, the effect of elevated temperature on fretting fatigue life of Al7075-T6 under cyclic normal contact loading was investigated by experiment using a new testing apparatus. A Finite Element model using FRANC2D® was developed to study the influence of elevated temperature on crack propagation lifetime. The crack initiation life was calculated by a combination of numerical and experimental results. It was found that, elevated temperature has reducing effect on fretting fatigue life, particularly for Low Cycle Fatigue (LCF) regime. The reduction was about 29–44% and 30–46% depending on stress level for temperatures of 100 and 200 °C, respectively. The results of FE simulation showed that elevated temperature significantly diminishes both the crack propagation and initiation lives. At lower bulk stresses where the life is dominated by the crack initiation phase, the detrimental effect of elevated temperature was more profound for crack propagation lifetime. In contrast, at higher bulk stresses where the life is dominated by the crack propagation phase, the effect of elevated temperature was more profound for crack initiation lifetime. Finally, the FE simulation was validated by a comparison between the numerical crack growth rate and the experimental measurements using replica.

1. Introduction

Fretting fatigue occurs when a small amplitude oscillatory motion between two contacting bodies is caused by a cyclic bulk load. Fretting reduces the fatigue lifetime of components drastically. A general feature of fretting fatigue problems is that crack nucleation and early crack propagation are significantly accelerated by fretting action [1]. This phenomenon may occur in many applications such as bolted lap-joints, press fit connections, splined couplings, helicopter power transitions, bio-implant devices, bearings shafts, leaf spring, bolted and riveted connections and dovetail roots of turbine blades [2]. The disk slot and blade attachment in the gas turbine engines have been found to be highly susceptible to fretting fatigue [3]. Due to flow induced vibration and aerodynamic forces, this components are operated under both cyclic bulk and contact loads simultaneously. In addition, the operating temperature of this components can be as high as 260 °C [4]. These harmful condition associated with demands to improve the performance of gas turbines has caused a drastic changes in the design criteria of gas turbine engines during the past two decades. Many factors such as friction, contact pressure, contact geometry, frequency, slip amplitude and temperature can considerably affect fretting fatigue life behavior of materials. The effects of these factors have broadly been investigated under constant contact load over the past decades [5–16]. However, less attention has been paid to effect of the factors under cyclic contact loading [17–22]. Further, none of these studies has investigated the effect of elevated temperature under cyclic contact loading which is the main concern in this study.

Most investigations have shown that the fretting fatigue life of the components bulk at high temperatures is much shorter than that at room temperature. Hamdy and Waterhouse [23] showed that fretting fatigue strength of Ti-6Al-4V decreases with the increase of temperature. They argued that the reduction of fretting fatigue life was due to degradation of the material rather than the fretting damage itself. Mall et al. [24] concluded that fretting fatigue performance of a nickel-based super-alloy IN100, improved at 600° in comparison to that at room temperature. This behavior was different for titanium alloys, where elevated temperatures caused a shorter crack initiation time due to greater stress relaxation thus accelerating crack development.

Both increase and decrease in friction coefficient under elevated temperature have been reported in the literature. Jina et al. [25] found that the static coefficient of friction at 260 °C increased slightly during the early stage of fretting cycling and then

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remained constant throughout the rest of the life. Mutoh [26] showed that the values of the friction coefficient at 500 °C was almost equal to that at room temperature, and the reduction of fatigue life and strength in the fretting test were significant at both temperatures. Waterhous [27] found that raising the temperature increased the oxidation rate of most alloys. The thicker oxide film prevents metal-to-metal contact and reduces the coefficient of friction. Waterhous [28] showed that if the oxides are harder than the base material, friction and fretting damage can increase. On the other hand, if the oxides are soft relative to the base material, it lowers friction and fretting damage reduces significantly. Majzoobi et al. [29] found that fretting fatigue life of Al7075-T6 at sub-zero temperatures rises significantly up to around 220%, depending on the temperature, for low bulk stresses and reduces to about 50% for higher bulk stresses. Majzoobi and Soori [30] showed that fretting fatigue life of Al7075-T651 increases with temperature by 180% for low stresses and decreases by 40% for high stresses. This fashion of variation of fretting fatigue life versus temperature was believed to be due to degradation of material properties which occurs by over-aging and wear resistance increase due to oxidation of aluminum alloy. Kawagoishi et al. [31] studied the effect of temperature on fretting fatigue behavior of the Ni-based super-alloy IN718. Shahinian and Sadananda [32] related the increase of temperature dependent crack growth rate in IN718 to the change in the elastic modulus. Makhlouf and Jones [33] showed that fatigue crack growth rate of ferritic stainless steel increased with increasing temperature. Sarhan et al. [34] showed that hard anodized coating on Al 7075-T6 can significantly improve fretting fatigue life of specimens at low stresses and reduce it at high stresses. The reason for the decrease is believed to be the brittleness of the coating material. Zhang and Liu [35] indicated that Ti811 titanium alloy was susceptible to fretting fatigue damage at both 350 °C and 500 °C, and the sensitivity to fretting fatigue enhanced as the temperature increased.

There are various approaches for life assessment of materials under fretting fatigue condition. Some of the approaches consider only the initiation phase as the total fretting fatigue life, while the other methods, assuming a short initiation phase, take only the propagation phase into consideration. Many researchers have developed crack growth models using LEFM or modified LEFM approaches. Most of these ignore the multi-axial nature of the stress field, assuming that the mode I stress intensity dominates. However, some authors have developed methods for predicting the shear contributions [36]. Vallellano et al. [37] used some realistic stress intensity factor approximations to predict fatigue limits and non-propagating crack lengths for fretting fatigue under a spherical indenter. A different, and very interesting approach has been taken by Ciavarella and Berto [38] who have modeled the fretting fatigue situation as a crack or notch. They suggested that the stress field created near the contact pad is similar to that created ahead of a sharp crack. If the Crack Like Notch Analogue (CLNA) can be made, then it might be possible to predict the behavior in the contact problem by finding an equivalent crack. For more information on CLNA model refer to references [39–45].

As stated before, all previous studies have been performed under constant contact loading. However, some components such as turbine dovetails are exposed to cyclic contact loading which can remarkably change the fretting fatigue behavior of the component. In this work, the influence of elevated temperature on fretting fatigue of Al7075-T6 under cyclic contact loading is investigated using a new testing apparatus. Details of damage mechanisms of fretting fatigue is studied by optical microscopy. A Finite Element (FE) model based on LEFM is developed using the FRANC2D® [46] to study the influence of the elevated temperature on crack propagation/initiation lifetimes. Finally, the numerical results are validated by fretting fatigue experiments.

2. Experiments

2.1. Testing apparatus

In order to perform the fretting fatigue tests under cyclic contact loading, a new fretting fatigue testing device (called in this paper as CCLFFD) was developed by the authors in this work to produce cyclic contact load. A general view of the test device is presented in Fig. 1. The main chassis of testing apparatus has been developed to work in conjunction with the uniaxial variable crank system machine developed by Majzoobi et al. [47], which have the capacity of 20 kN for axial fatigue loading. The axial or the bulk fatigue loading is supplied by a variable crank shaft [47]. A schematic view of the cyclic contact loading system is illustrated in Fig. 2. The cyclic contact load is applied by a simple cam-follower mechanism. The cam has four lobes, and lifts a flat foot follower four times in each revolution. In order to supply the rotational movement of the cams, a servomotor, illustrated in Fig. 2, is connected to the cam-shaft on both side of the specimen. The contact load is measured using force-link piezoelectric load cells, attached to the pads as shown in Fig. 2 and monitored continuously during the experiment. One of the important features of the newly designed test-rig is its capability to perform fretting fatigue tests at elevated temperatures. For this purpose, two heaters can symmetrically be mounted on the device to heat up the specimen in situ, as shown in Fig. 1.

2.2. Material and specimens

Aluminum alloy 7075-T6 and stainless steel 410 were used in this investigation for specimens and fretting pads, respectively. Yield stress and ultimate strength of the material were obtained from a number of uniaxial tensile tests performed according to ASTM standard [48]. The material properties used in present study are given in Table 1.

The dog-bone specimens shown in Fig. 3(a) were prepared according to ASTM standard [48]. The bridge-type fretting pads were used in this study. This type of contact typically involves two bridge-shaped fretting pads which are pushed against the gage section of fatigue specimen as illustrated in Fig. 3(b). The fretting pads are constrained against vertical displacement as this may affect the sliding oscillations between specimen and fretting pads. Fig. 3(c) illustrates the fretting pad's geometry used in this study. Experiments conducted at room and elevated temperatures of 100 and 200 °C. The specimens are heated in situ by using two hea-

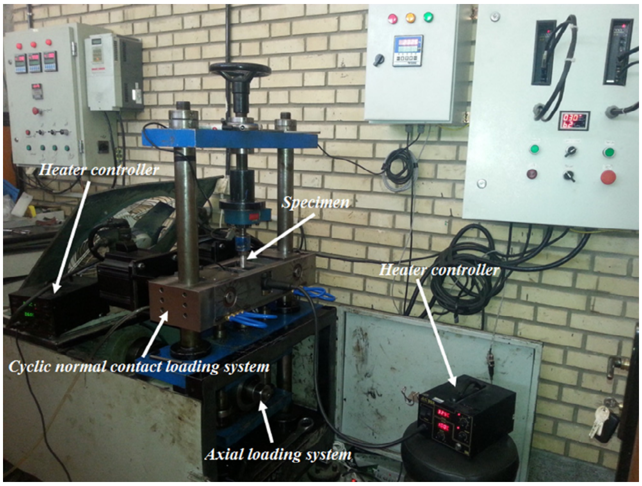

Fig. 1. A general view of test rig.

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