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An experimental study and fatigue damage model for fretting fatigue

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ABSTRACT

Fretting is associated with the small amplitude relative oscillatory motion between two solid surfaces in contact. Fretting fatigue is a damage mechanism observed in a machine components subjected to fretting in tandem with fluctuating bulk stresses. This paper presents the results of an experimental investigation of the fretting fatigue behavior of AISI 4140 vs. Ti-6–4 in a cylinder-on-flat contact configuration, and a computational fatigue damage model of the same configuration. In the experimental investigation, a fretting test fixture was designed and developed which was coupled with an MTS machine to impose the fretting fatigue damage. Fretting fatigue experiments were conducted under completely ($R=-1$) reversed axial stress amplitudes, a constant maximum Hertzian Pressure (P_h) of 3 GPa and at a frequency of 5 Hz. The test rig was also used in a fretting wear configuration under gross slip conditions to determine coefficient of friction for the same contacting pair of materials. In the computational modeling, damage mechanics constitutive relations were incorporated in a finite element model to analytically investigate the fretting fatigue. Voronoi tessellation was used to account for the randomness of the material microstructure and its effects on the fatigue behavior. Material properties needed for the damage model were determined using the analytical solution for maximum fretting stress ($\sigma_{fretting}$) at the trailing edge of the contact which is assumed to drive the fretting fatigue failure. The critical damage value for AISI 4140 was extracted using the method of variation of elasticity modulus. Fretting fatigue lives predicted from the analytical model show good agreement with the measured experimental results.

1. Introduction

Fatigue is the process of progressive damage accumulation which occurs when machine components are subjected to cyclic loading. Fatigue causes localized damage which is manifested by the formation of micro-cracks, debonding, voids, etc. in the areas of stress concentration within the material. These stress concentrations are typically associated with defects and inclusions at the microstructural level, grain boundaries which act as physical discontinuities in the polycrystalline material, or slip planes. The localized nature of fatigue damage coupled with random distribution of material microstructure results in a significant amount of variability in the fatigue life of machine components, making the fatigue life prediction a paramount aspect of the mechanical design. The fatigue failure process consists of three stages, crack nucleation, propagation and catastrophic failure.

Low amplitude tangential relative oscillatory motion between contacting bodies causes different forms of fretting damage such as pits, scarring, and material transfer on the surface. Fretting damage may be classified into two different regimes depending on the magnitude of displacement between the contacting surfaces. In the partial slip regime, a portion of contact sticks while the remainder slips. In the gross slip regime, all the points in contact experience relative slip. Crack formation mainly occurs under partial slip conditions while gross slip conditions cause wear or galling. If the material is concurrently subjected to partial slip fretting and fluctuating bulk loading, the geometrically significant stick zone in the fretted area causes a stress concentration at the contact region resulting in premature nucleation and acceleration of crack growth when compared to fatigue situations without fretting [1]. This type of fatigue damage is known as fretting fatigue. A number of mechanical, physical and environmental factors affect the fretting fatigue degradation process. These primarily include macroscopic factors such as bulk stress

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amplitude, contact geometry, normal contact load, coefficient of friction, slip amplitude, frequency, material properties, and temperature [2]. Fretting Fatigue damage is prevalent in mechanical components. The combination of vibratory surface load and centripetal force in the dovetail blade/disk type attachments in gas turbine engines makes them vulnerable to fretting damage. Aircraft wings subjected to alternating stress and splines also experience fretting. Due to the complex nature of the problem and its significance in the engineering applications, extensive research work has been undertaken over the past decades to characterize the fretting fatigue phenomenon both experimentally and analytically.

The large number of interacting variables which affect fretting fatigue makes experimental testing difficult. Therefore, efforts to establish fretting fatigue test standards have been going on since the late eighties. Attia and Waterhouse [3] summarized some of the previous works which examined the possibility of standardizing the fretting fatigue test methods and equipment. ASTM Task Group E0.05.05 has been developing a standard guide for fretting fatigue since 2007, with latest version ASTM E2789-10 [4] published in 2011. Neu [5] reviewed the current standards pertaining to fretting fatigue testing and discussed the new developments in the standardization. Depending on the objective of the tests, fretting fatigue tests can be performed in various contact and loading configurations: single clamp loading configuration (Szolwinski and Farris [6], Cortez et al. [7], Jin and Mall [8]), grip type loading configuration (Hutson et al. [9]), and the bridge type loading configuration (Rayaprolu and Cook [10], Pape and Neu [11]). In the current work, experimental results for the line contact between an AISI 4140 flat specimen and Ti-6–4 cylindrical contact pads are presented for the single clamp loading configuration. Fig. 1 illustrates a schematic of the single clamp fretting fatigue tests for cylinder on flat contact configuration as given in [4].

Many different approaches have been developed to analytically model both crack initiation and propagation aspects of the fretting fatigue phenomenon. Many investigators have studied the crack initiation process with strain or critical plane based parameters such as Smith–Watson–Topper (SWT), and Fatemi–Socie (FS) which predict fretting fatigue initiation life from uniaxial fatigue tests. Ruiz parameters have also been used to investigate crack initiation in fretting fatigue. Lykins et al. [12] have compared several commonly used fatigue parameters and found that strain or critical plane based parameters are more effective in predicting cycles to crack initiation and its location. Quraishi et al. [13], Aghdam et al. [14], Zhang et al. [15], and Hojjati-Talemi and Wahab [16] have employed continuum damage mechanics approach for predicting crack formation in fretting. On the other hand, most investigators (Golden and Grandt [17], Fadag et al. [18], Proudhon and Basseville [19]) use fracture mechanics to analyze the fretting fatigue crack propagation stage. Recently, Giner et al. [20] and Baietto et al. [21] have used XFEM to predict fretting fatigue crack propagation. Scatter in fretting fatigue has been analyzed by Golden et al. [22] using probabilistic analysis to predict total life and Slack et al. [23] using the randomness of material microstructure topology to predict initiation.

The focus of the analytical part of this paper is to develop a new approach to estimate fretting fatigue life using damage mechanics. A finite element model was developed using the commercial FEM software ABAQUS to evaluate the stress at the microstructure level. In order to incorporate the material randomness and disorder, the internal topology of the material microstructure is modeled using Voronoi tessellation with Voronoi cells representing grains of the material microstructure. Gradual material degradation induced by fretting fatigue is modeled using damage mechanics. Randomly generated Voronoi domains were subjected to fretting fatigue loading conditions and the fatigue damage model was applied to estimate the fretting fatigue lives and conduct life variability studies. Life estimates from analytical model compare well with the experimental results conducted as a part of this investigation.

2. Design of fretting fatigue test rig

2.1. Experimental setup

A fretting fatigue test rig was designed and developed to investigate the fretting fatigue behavior of an AISI 4140 specimen in contact with two Ti-6–4 pads. The contact pads are modularly designed so that the rig is capable of performing experiments with different contact configurations i.e. point contact (sphere on flat), line contact (cylinder on flat) and area contact (flat on flat). Also, by changing the geometry of contact pads, it is possible to perform tests in both bridge type and single clamp type loading configurations. In this study, experiments were conducted under the single clamp configuration with line contact.

A schematic of the fretting test rig is shown in Fig. 2. The test rig uses a 100 kN (22 kip) capacity Material Testing System (MTS) 810 machine. This system has hydraulic actuators capable of applying a precise axial load to the specimen gripped between the hydraulic clamps. The actuator is attached to the bottom grip while the top grip is attached to the crosshead which is held stationary. The position of the crosshead can be adjusted in order to incorporate various specimen sizes. The MTS machine is controlled by a computer and MTS Flex-Test SE which also acts as a data acquisition system. The amplitude and mean of the sinusoidal axial load applied to the specimen can be controlled via computer. In this study, the frequency was kept constant at 5 Hz to ensure that the rig was operated with minimal vibrations and the tests were completed in a reasonable amount of time. The MTS contains a load cell between the bottom grips and the actuator to

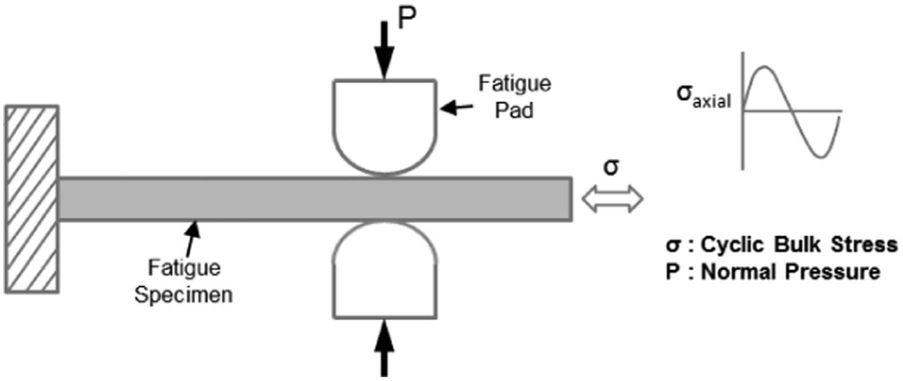

Fig. 1. Fretting fatigue test configuration as given in ASTM standard [4].