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Prediction of non-propagating fretting fatigue cracks in Ti6Al4V sheet tested under pin-in-dovetail configuration: Experimentation and numerical simulation

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ABSTRACT

This paper presents the results of fretting fatigue tests carried out on Ti6Al4V sheet specimens in contact with carbide rod in a cylinder-on-flat contact configuration. A new methodology of carrying out fretting fatigue experiments is proposed and successfully implemented using a pin-in-dovetail and pin-in-hole configuration. The advantage of this configuration is the simplicity and ease of application. The tests are carried out on MTS 810 at different loads, constant frequency (30 Hz) and ambient conditions. These tests reveal that the crack initiation and propagation are dependent on the applied load and the configuration of the contact. At low loads, non-propagating cracks are observed in the pin-in-dovetail configuration using metallurgical microscope. At high loads these cracks become longer but are still non-propagating. Numerical simulation using elastic–plastic material model is carried out to determine stress intensity factor and the mode of crack propagation. Maximum principal stress damage criteria approach is used to predict the crack initiation sites under different loads and a strong correlation with experimental results is observed. The crack propagation is simulated using XFEM, which successfully simulates the non-propagating crack length.

1. Introduction

Fretting fatigue is responsible for the damage which occurs when two components in contact with each other start relative movement against each other due to vibration or some other force and may lead to premature component failure. Fretting fatigue is one of the principal problems affecting the life of turbine blades, gears, splines and other bearing surfaces subjected to vibration loads [1]. Fretting fatigue failure usually occurs at the contacting surface or at the edge of the contacting surfaces [2]. The prediction of fretting fatigue cracks initiation may be done analytically using SWT parameter and propagation can be predicted by using fracture mechanics approach [1,3–6] or through numerical simulations [1,3,7–12].

Many studies have been carried out on the evaluation of fretting fatigue phenomenon in Ti6Al4V alloy [13–15]. The researchers typically used the fretting pads on a tensile specimen configuration for these tests [4,7,13,14,16]. The configuration may be sphere pad on flat specimen [5,17], cylindrical pad on flat specimen [18], flat pad on flat specimen [19] and end rounded end flat pad on flat specimen [19]. These configurations require a transverse loading mechanism with load cells and an actuator. To circumvent the extra installation some researchers have used a dovetail specimen on cylindrical contact pads [20,21]. A biaxial testing machine has been used as well with a dovetail joint configuration with flat contact [10]. High temperature fretting has also been investigated in a dovetail configuration [22]. Some special configurations are also developed by researchers specific to the applications [23–27].

The dovetail configurations created in this manner usually have very heavy construction to reduce the amount of deflection caused by the wedge effect of the dovetail joint. The specimen developed in this research does not require such heavy construction or extra installations to run the experiment as shown in Fig. 1. The simple ASTM E399 [28] fracture toughness testing fixtures for Compact Tension (CT) specimens can be used. The contact type is similar to a cylinder on flat plate. However the force on the cylinder (fretting pad) is controlled by the testing load of the machine.

In most of the fretting fatigue tests, the initiation and propagation phases overlap. Some researchers have proposed a combination of initiation and propagation phases for total life estimation of the components

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Nomenclature

Acronyms

MTS	Material Testing System
XFEM	Extended Finite Element Method
SWT	Smith Watson Topper
CT	Compact Tension
ANN	Artificial Neural Network
SIF	Stress intensity factor
HCF	High Cycle Fatigue
LCF	Low Cycle Fatigue

List of symbols

F_u	Force in upper portion of the specimen
F_b	Force on the lower portion of the specimen
R	Stress ratio
$\sigma_{fretting}$	Fretting stress
σ_0	Axial bulk stress
P_h	Hertzian pressure
F_T	Tangential load between specimen and contact rod
F_N	Average contact force
μ	Co-efficient of friction
P	Axial load
a	Contact half width
E_1 & E_2	Modulus of elasticity of carbide and titanium respectively
ϑ_1 & ϑ_2	Poisson's ratio of carbide and titanium respectively
R_1 & R_2	Radii of carbide rod and titanium flat plate specimen
L	Contact length
K_{II}	Stress intensity factor (mode II)
J	J-integral

[18]. Others have tried to find initiation and crack propagation based on microstructure scale [29,30].

In the testing procedure designed here, the specimen can be dimensioned such that the crack initiation phase can be easily identified. The crack stops propagating after exiting the process zone of the fretting contact.

The fretting crack initiation and propagation prediction is of great interest in the fretting fatigue problem. The initiation phase has been characterized through strain-life parameter, Smith–Watson–Topper (SWT) and the critical plane based parameter [13,31]. Some researchers have characterized the initiation through continuum damage mechanics approach [32,33]. Most however, find it more convenient to determine the fretting fatigue life as a combination of initiation and propagation and use fracture mechanics approach for characterization [12,20,34–36].

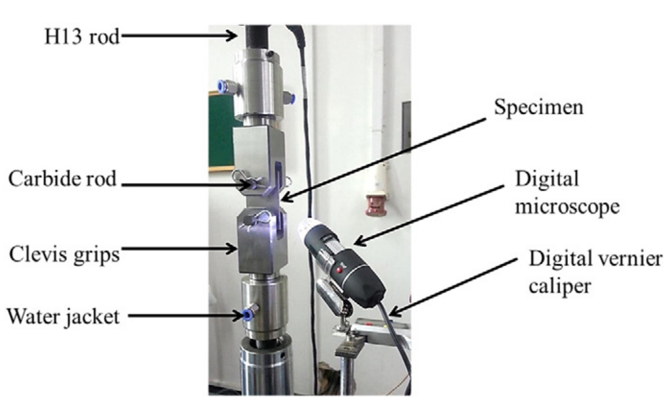

Fig. 1. Experimental setup for fretting fatigue test.

Recently, Extended Finite Element Method (XFEM) has been employed by different researchers to predict the position, shape and stress intensity factor (K_I) value of the fully developed crack. The use of XFEM is considered to be advantageous from the point of view of simplicity in modeling and prediction of crack propagation [37]. Using this method the user is not required to create a mesh specific to the geometry [38,39]. The effect of loading conditions on crack initiation shape and propagation is studied [40–42]. The effect of using a bridge type pad and comparison with a flat pad was also successfully analyzed using XFEM [43]. Artificial Neural Network (ANN) technique was found to be a good analytical tool with a potential to successfully predict the fretting wear behavior of surface mechanical attrition treated and untreated Ti6Al4V specimens fretted against alumina and steel counter bodies [44].

In this research, maximum principal stress criterion is used to predict the crack initiation sites and XFEM is used to predict the propagation of the crack in the dovetail joint. The evolution of the stress intensity factor is determined with respect to the depth of the crack. It is shown that as the crack progresses in this specific configuration the value of the SIF reduces, causing crack arrest. The configuration of the test specimen requires that the crack face contact be modeled as a large part of the propagation is in mode II. Most of the numerical simulations in the literature use a monotonic loading for the calculations of the stress intensity factor (SIF). Elastic–plastic material model has been employed to study the effect of crack length on SIF. The testing is performed at different loads where it is shown that in the High Cycle Fatigue (HCF) regime, the probability of initiation of a crack on each side of the contact surface is higher, while in high load near Low Cycle Fatigue (LCF) regime only one crack initiates around the contact scar. This effect is also explained using the FEM simulations.

2. Design of fretting fatigue test rig

2.1. Experimental setup

A special fretting fatigue test rig is designed and developed to investigate the fretting fatigue behavior of Ti6Al4V specimen with a unique internal dovetail and circular hole in contact with the carbide rod. The contact configuration used is cylinder-on-flat (line contact). The fixture is made up of H13 tool steel and it consists of U-blocks, washers, rods with external threads, water jackets for cooling purpose and digital microscope having 500× zoom attached to a digital vernier caliper for crack observation during testing. The arrangement of the test rig is shown in the Fig. 1. Testing is performed on a 100 kN capacity servo hydraulic universal testing machine MTS 810 using force control. The tests are conducted at loads of 5 kN, 7.5 kN, 9.5 kN and 11 kN at constant frequency of 30 Hz under ambient conditions. Since the cross head is held stationary and axial load is applied at lower end, a tangential force is induced at the contact between the carbide rod and specimen. Due to this tangential force, different axial loads (F_u & F_b) are experienced by the specimen in the upper and lower portions of the contact as shown in Fig. 2.

2.2. Specimen and contacting rod

Material selected for the specimen is ASTM Grade 5 titanium alloy, Ti6Al4V. It is a flat specimen with thickness of 2 mm having one dovetail and one circular slot. Carbide rods of 12 mm diameter are inserted in these slots and the clevis of the CT type specimens. To avoid edge effects, the specimens are edge relieved. The friction between the specimen and contacting rod restricts the carbide rod from any rolling. The drawing of the specimen and contact rod is shown in the Fig. 3 and stress strain curve for Ti6Al4V obtained by the standard tensile test is provided in Fig. 4, which was conducted using ASTM E8 [45].