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Fretting fatigue of single crystal nickel at 600 °C

H. Murthy*, G. Gao, Thomas N. Farris

School of Aero. & Astro., Purdue University, 315 N. Grant St., West Lafayette, IN 47907, USA

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Abstract

An experimental setup has been developed to conduct fretting fatigue tests at 610 °C and fretting fatigue lives are characterized for the contacting pair of IN100 and single crystal nickel subjected to a range of loading conditions. A well characterized set of experiments have been conducted to obtain the friction coefficient in the slip zone. A robust quasi-analytical approach, based on solution to singular integral equations, has been used to analyze the contact stresses. Different multi-axial fatigue parameters have been investigated for their ability to predict the initiation life of the specimens. An estimation of crack propagation life was made using conventional fracture mechanics approaches, after making certain assumptions to simplify the problem. Total life was predicted using nucleation life from different parameters and propagation life from conventional fracture mechanics approach. These predicted lives were compared with experimentally observed failure lives. The quality of the comparison provides confidence in the notion that conventional life prediction tools can be used to assess fretting fatigue at elevated temperatures.

Keywords: Fretting fatigue; Single crystal; Life prediction

1. Introduction

Fretting fatigue is a structural damage mechanism arising from a combination of wear, corrosion, and fatigue of two clamped surfaces subjected to an oscillatory loading. The aggressive damage mechanisms associated with fretting pose a palpable threat to the structural integrity of aerospace systems. From the nucleation of widespread fatigue damage in riveted lap joint structure to the initiation and rapid propagation of edge-of-contact cracks at the blade/disk pair in jet engines, the sharp near-surface gradients of stress associated with the partial slip of contacting surfaces can severely degrade the fatigue performance of critical structural elements and mechanical systems [1].

To have an understanding of fretting fatigue of contacts in engine components, it is important to simulate engine temperature, load and contact conditions in the laboratory and develop tools to analyze the contact conditions. The contact stresses that drive crack nucleation are very sensitive to the shape of the contacting surfaces and the coefficient of friction. This paper details an effort designed to couple fundamental mechanics and tribological insight with material fatigue response to develop a predictive methodology for fretting failures at elevated temperatures representative of aircraft engine-turbine stages.

2. High temperature testing

2.1. Fretting chassis

Fretting experiments involve a large number of independent parameters such as normal and tangential contact loads, bulk loads and shape of the contacting pairs. The relationship between normal and tangential contact loads depends upon the friction coefficient which changes during the fatigue process. Fretting tests may be carried out in the full sliding regime or the partial slip regime. As highlighted by Hills and Nowell [2], it is very difficult to achieve a well controlled experiment using an external actuator due to the low displacement amplitudes involved. Therefore, it is beneficial to utilize compliance of the specimen to generate necessary tangential load, as a bulk load is applied to the specimen. A bridge-type setup utilizing the compliance of

*Corresponding author. Tel.: +1 765 496 1990; fax: +1 765 494 0307.
E-mail address: hsnmurthy@gmail.com (H. Murthy).

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the bridge or specimen or both to generate tangential force has been used for the fretting fatigue tests.

Fig. 1(a) shows a photograph of the rig designed for high temperature tests. Components of the rig closer to the zone of elevated temperature were designed using a titanium alloy (Ti-6Al-4V). 4140 steel was used to design the components that were far away from the region of high temperature.

Fig. 1(b) shows a schematic of the rig along with pads and specimens. *Stiff beam* provides the bulk of stiffness of the chassis. Load transfer in the high temperature rig is achieved through webs (or membranes) connected to the platforms that hold the fretting pads. Due to the directional stiffness of the webs, the majority of the normal load (>95%) is transferred to the pads while the greater web stiffness in the tangential direction gives rise to tangential (shear) load at the contact. Normal load is applied using two hydraulic actuators. Two rods on either side of the contact ensure that the pressure is applied symmetrically to the pads. Tangential force produced is monitored throughout the fretting fatigue experiments, by recording the difference of the upper and lower load cell readings. With this setup, which utilizes a single actuator at the bottom, the tangential loads are in phase with the bulk loads.

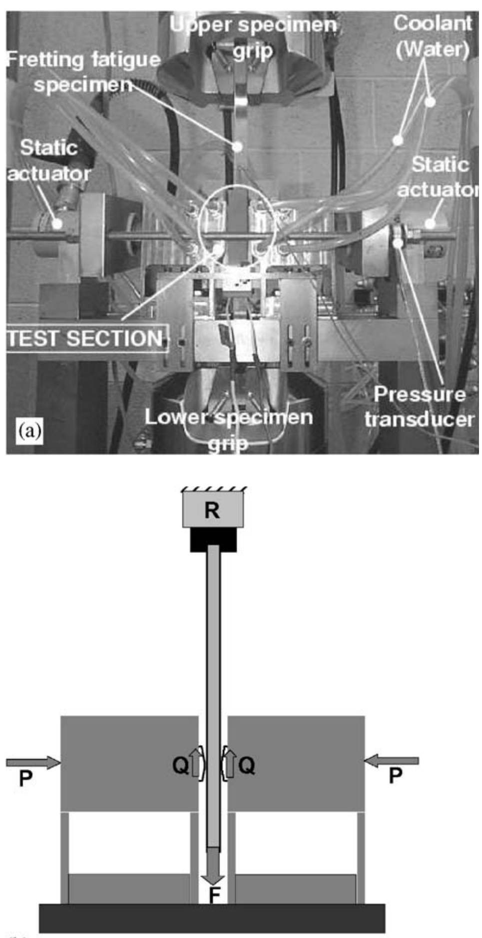

Fig. 1. (a) Photograph of the elevated temperature fretting fatigue setup. (b) Schematic of different loads. P is the normal load applied using actuators. Experiment is controlled by feedback from top load cell which measures R. Bulk load, F, bottom is measured by another load cell at the bottom. $Q = 0.5 \times (F - R)$ is calculated from loads F and R.

Temperature of the local area of contact was increased using a pair of igniters on either side of the specimen. Heat transfer from the igniter to the specimen and pads is achieved through radiation and convection with air as the medium. Influence of air currents is minimized by forming a shield (or oven) around the zone of elevated temperature, using ceramic blocks and sheets. Temperature of the specimen was measured using a *K-type* thermocouple spot welded on to the specimen, halfway between the two contacts. Voltage output of the thermocouple was used to control the temperature at the contact using an on/off type controller. However, there was a fluctuation of $\pm 5\,^{\circ}C$ observed when the target temperature was $610\,^{\circ}C$. Since fluctuation was less than 1% ($6\,^{\circ}C$) of the desired value, it was neglected. In spite of covering the surface of the webs with ceramic sheets, there was heat transfer to the rig via surrounding high temperature air and conduction from the pad to the pad holder. To absorb the heat generated in the rig, the pad holders are cooled by passing water through channels machined in the block (Fig. 1(a)). Heat is also conducted to the wedges that hold the specimens. Hence, water cooled wedges were used for clamping the specimens.

Assuming a linear spring behavior for the specimen and the diaphragms, a simple model of the rig was studied to assess the effects of various dimensions and parameters of the rig. Detailed description of design and characterization of the elevated temperature fretting fatigue setup has been presented by Murthy et al. [3].

2.2. Experimental procedure

Fretting tests were conducted with flat specimens in contact with nominally flat pads in plane strain configuration. Nominally flat pads had a flat length of 3.05 mm and edge radii of 3.05 mm. Specimen was prepared by inertia-welding two WASPALOY tabs of length 114 mm to single crystal nickel gage-section of length 178 mm. Specimen thickness (distance between two contacts on either side of the specimen) was chosen to be 15 mm in order to minimize the interaction between two contacts. Traverse widths of both the specimen and the pads were chosen to be the same (9.6 mm) in order to minimize three-dimensional effects [5]. To ensure compliance with ASTM standards on specimen alignment for fatigue, an alignment specimen with eight strain gages was used. The strain gages were connected to four Wheatstone half-bridge circuits. By loading the specimen to a prescribed bulk load and adjusting the alignment fixture, the bending strain was minimized. This results in the minimization of the undesirable effects of the bending strains on the results. In addition, it was important to ensure that the pads were in proper contact with the specimen. Before applying the normal load, the pads were lightly pressed against the specimen, with a pressure