

Evolution of residual stresses in a stress-free titanium alloy subjected to fretting fatigue[☆]

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Abstract

This study investigated the complete history of residual stress evolution in a stress-free titanium alloy, Ti–6Al–4 V under fretting fatigue loading condition. Compressive residual stress developed in the contact region due to the local plastic deformation between contacting bodies. The compressive residual stress then increased initially with increasing number of fretting fatigue cycles reaching to a maximum value, and then it decreased (or relaxed) with further cycling. This relaxation of compressive residual stress was due to the delamination and detachment of flake-like (wear sheet) material in the fretted region.

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1. Introduction

Fretting fatigue occurs when a component subjected to fatigue load is in contact with a mating component in a presence of contact load. This causes oscillatory micro-sliding at the contact surface which fosters an earlier crack initiation and thereby leads to a premature catastrophic failure of material. Fretting fatigue is commonly observed in several practical situations, such as riveted and bolted joints, disk and blade attachment (dovetail joints) in gas turbine engine, etc. [1]. During fretting fatigue, contact surface between mating components experiences stress concentration and local plastic deformation, which change surface condition. One effect of fretting fatigue on surface condition is the development of residual stress in the contact region [2]. Residual

stress in the surface region is often induced intentionally during manufacturing processes such as quenching, cold working and shot-peening. It has a significant effect on fatigue behavior since compressive residual stress normally inhibits crack initiation and propagation under tensile fatigue loading [1]. Therefore, shot-peening process, which induces compressive residual stress in the surface region, is widely used in many practical applications to enhance both plain and fretting fatigue performance of components.

The behavior of residual stress during fretting fatigue has been investigated in shot-peened (i.e. pre-stressed) material [3,4]. In the pre-stressed material, fretting fatigue resulted in relaxation of compressive residual stress as the locally concentrated stress in the contact region reached to the yield strength of material [3,4]. On the other hand, fretting fatigue induced compressive residual stress in the contact region of stress-free material [2]. However, there is a lack of understanding about the complete history of evolution of residual stress in a material when it is subjected to fretting fatigue. There are several questions which need investigation, i.e. residual stress will only develop, relax or both, and if so why.

[☆] The views expressed in this article are those of the authors and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government.

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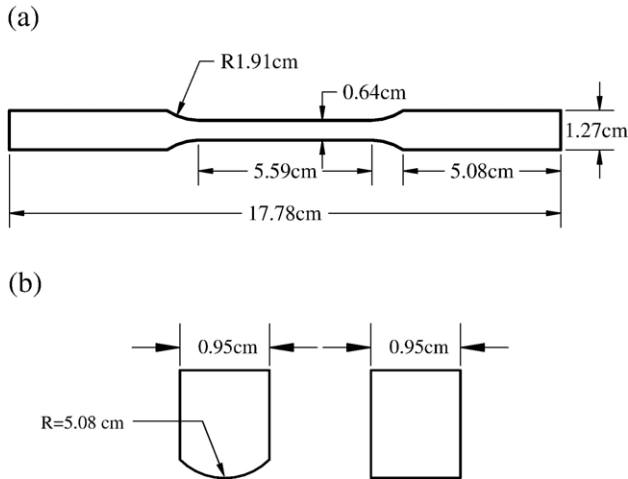


Fig. 1. Schematic drawing of (a) specimen and (b) pad.

The present study is a step in this direction. In addition, it is a continuation of a previous work [2] where the development of residual stress on a stress-free titanium alloy, Ti–6Al–4 V was observed. In a previous work [2], compressive residual stress first developed even from the application of contact load only, and then it increased with increasing number of fretting fatigue cycles reaching to a stabilized value at 50,000~100,000 cycles depending upon the magnitude of applied contact load. The higher contact load induced faster increase in residual stress as well as earlier stabilization. However, the stabilized residual stress was the same with both the lower and higher applied contact loads. Further, specimens fractured at about 130,000 cycles, which was close to the number of cycles where residual stress stabilized. Therefore, the complete picture of the evolution of residual stress could not be established in a previous study [2]. In the present study, behavior of residual stress under fretting fatigue in high cycle regime was investigated using a relatively lower applied cyclic load which ensured much longer fretting fatigue life as compared to a previous study [2]. In addition, scanning electron microscopy was utilized to observe damage mechanisms on contact surface during fretting fatigue test in order to relate it with the evolution of residual stress.

2. Experiments

Specimens of the present study were also machined from Ti–6Al–4 V plate which was preheated and solution treated at 935 °C for 105 min, cooled in air, vacuum annealed at 705 °C for 2 h, and then cooled in argon. Microstructure showed a nucleation of the α phase (HCP) in the β phase (BCC) matrix. The material had an elastic modulus of 119 GPa and a yield strength of 930 MPa. Specimens were machined to 17.8 cm long dog-bone shape with both width and thickness of reduced gage area of 6.4 mm. After machining, specimens were ground, and then polished by 600 grit silicone carbide. Residual stress on the surface of specimen was removed by heat treatment at 704 °C for 1 h in a vacuum. The complete relaxation of residual stress was confirmed by X-ray measurements after the heat treatment. Pads with cylindrical end radius of 50.8 mm were also made of Ti–

6Al–4 V. Fig. 1 shows schematic drawings of both specimen and pad.

Constant amplitude fretting fatigue tests were conducted on a servo-hydraulic uniaxial test frame equipped with a rigid fretting fixture at a frequency of 10 Hz. The details of fretting fatigue test set-up and procedure can be found in previous studies [3,4]. Two cylindrical pads were pressed against the width surface of specimen with a constant contact load of 1335 N via lateral springs which resulted in the Hertzian peak pressure of 292 MPa in the contact region. The maximum and minimum applied cyclic stresses were 260 and 26 MPa, respectively. Several tests were conducted up to prescribed numbers of fretting fatigue cycles, and then residual stress at the contact surface was measured. A commercial X-ray diffraction residual stress analyzer with two X-ray detectors covering both ψ_+ and ψ_- angles was used to measure the residual stress. X-rays from a copper K- α source, collimated to 2 mm diameter circular spot were used to examine the specimens. Diffraction peak from (302) crystallographic planes of the α phase of the Ti–6Al–4 V alloy was utilized for all measurements. The changes in the d spacing were measured at seven ψ tilt angles and a plot of d vs. $\sin^2 \psi$ was obtained. The slope of the curve determined from the least square fit to a line and the X-ray elastic constant of Ti–6Al–4 V were used to compute the residual stress. Residual stress measurements were performed in two orientations, i.e. parallel and perpendicular to the fatigue load direction, to investigate the directional dependency. The details of X-ray measurement can be found elsewhere [5].

3. Results and discussion

Fig. 2 shows the evolution of compressive residual stress on the contact surface of an initially stress-free material during fretting fatigue. These were measured after applying fretting fatigue cycles ranging from 1 million to 5 million cycles. However, specimens did not fail up to 7 million cycles, i.e. they had considerably longer fatigue life as compared to that of previous study, i.e. about 130,000 cycles [2]. The 7 million cycles was chosen as the run-out limit of fretting fatigue tests in the present study. Fig. 2 clearly shows that the compressive

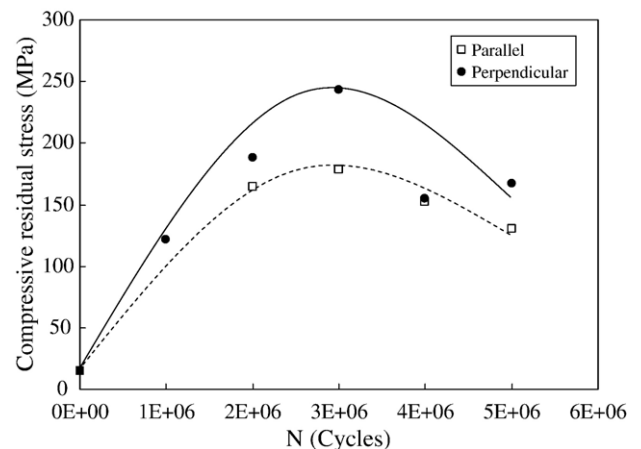


Fig. 2. Evolution of stress along the parallel and perpendicular directions to the loading direction during fretting fatigue.

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