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Effects of fatigue and fretting on residual stresses introduced by laser shock peening

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Abstract

The effects of fatigue and fretting fatigue on the distribution of residual stresses in shot and laser shock peened Ti–6Al–4V samples have been investigated. Residual elastic strains have been determined using high-energy synchrotron X-ray diffraction. Laser shock peening introduces a considerable compressive residual stress, the compressive zone extending 1.5 mm below the surface. The effects of fatigue loading have been investigated using a notched three-point bend geometry. The residual stress field was found to be largely insensitive to fatigue cycling, at least for the applied stress range studied. For fretting fatigue, while the residual stresses at depth were little affected, within 0.5 mm of the surface significant stress relaxation was observed; the extent of relaxation being greatest in the direction parallel to the fretting direction. The states of residual stress have been quantified using the concept of eigenstrain, which quantifies the retained plastic misfit resulting from peening. Finite element modeling has been used to determine the eigenstrain profiles causing the measured elastic strain profiles, and the changes to these eigenstrain profiles due to fretting. Our results suggest laser shock peening confers much greater fretting fatigue resistance than traditional shot peening alone due to the much deeper compressive zone.

Keywords: Fretting; Fatigue; Shakedown; Laser shock peening; Synchrotron XRD; Eigenstrain

1. Introduction

The fan forms the first compression stage of a turbofan aero-engine. In contemporary high bypass ratio engine designs, the fan may provide as much as 80% of the total thrust [1]. This requires that the fan has a large diameter (2.8 m in the Rolls-Royce Trent-800 engine), and hence that the blades are of large size. Blades are attached to the fan disc by a mechanical dovetail style joint. These joints are subjected to large centripetal loads from the rotating blades while the engine is running, which vary with engine speed during a flight cycle [2]. In addition, high-frequency vibrations in the blade aerofoil are also transmitted to the root [3,4]. Therefore, the root of the blade experiences a combination of high and low cycle fatigue (HCF, LCF) loading. The contact surfaces of the dovetail joint also experience fretting, due to relative movements between the blade root and the fan disc [5].

Fretting is the term used to describe damage which occurs due to small relative sliding movements of contacting surfaces [6]. Fretting fatigue occurs when the relative movement of contacting bodies is combined with cyclic applied loading. Fretting typically results in a significantly reduced fatigue strength compared to plain fatigue loading. Fretting is associated with severe short-range shear stress gradients, and may result in surface damage and fatigue crack initiation [5]. Initiated cracks may then propagate through other fatigue mechanisms [3,4]. A range of surface treatments have been applied industrially to fan blade roots in order to improve their resistance to fretting damage. These include surface coatings such as MoS_2, which reduce frictional forces and localised stress concentrations, and mechanical surface treatments, which produce near surface compressive residual stresses and work hardening. Peening treatments plastically deform the near surface region, generating a shape misfit between the deformed region and the bulk material. The plastic misfit thus introduced is termed the eigenstrain, the strain that would be observed in the absence of any constraint [7]. The compressive residual stresses generated in the vicinity of the treated surface are

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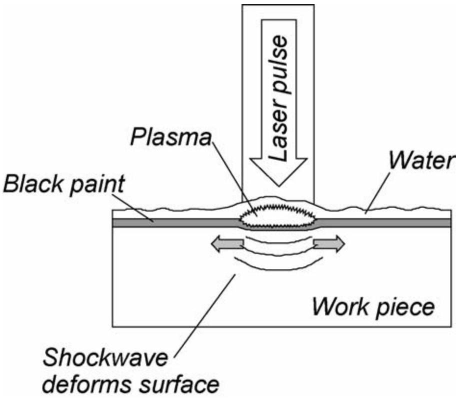

Fig. 1. Schematic of the laser peening process.

balanced by tensile stresses located either sub-surface or laterally.

Compressive residual stresses improve fatigue performance by hindering the propagation of fatigue cracks. Conventional shot peening (SP) is a well-established technique, in which the surface of a component is plastically deformed by multiple overlapping impacts of metal or ceramic shot [8,9]. This method has been remarkably successful in extending the life of many engineering components, however, the depth of the compressive residual stress is typically only around 250 μm, which provides poor resistance to fretting fatigue. As a consequence there is considerable interest in the aerospace industry in the application of new mechanical surface treatments such as laser shock peening (LSP) and low plasticity burnishing (LPB) and deep fields deeper into blade roots [10–12]. The LSP process is illustrated schematically in Fig. 1. The region to be treated is covered by a laser light-absorbing layer, over which a curtain of water is run. A high-energy laser pulse is directed on to the surface, which passes through the water and is absorbed by the layer or coating. The surface of this layer is vaporized, and continues to absorb energy, forming a plasma. The expansion of the plasma is constrained by the water, resulting in a very rapid increase in pressure, which drives a shockwave into the material, plastically deforming the near surface region. Compared to conventional SP, LSP is capable of producing compressive stresses to greater depths (∼1.5 mm) with lower levels of work hardening [10,13,14]. One would expect greater depths of compressive stress to provide better resistance to fretting fatigue. Furthermore, improved thermal stability of peening residual stresses has been identified and is believed to be due to the lower levels of near surface work hardening compared to SP [13]. If the residual stresses relax during service fatigue life improvements might be less significant than measurements of the as-peened stress state might suggest [14]. To assess the benefits resulting from LSP it is important to characterise both the initial stress distribution produced (including the magnitude and location of balancing tensile stresses) and the extent of any relaxation of these stresses that may occur during fatigue and fretting fatigue. That is the aim of the current investigation.

2. Experiments

2.1. Samples

This investigation is based on two generic sample geometries. The Dovetail Biaxial Rig (DBR) sample geometry (Fig. 2a) represents the complex loading conditions typical of a mechanical joint. LCF conditions were applied using mechanical actuators, with the multi-axial characteristics of contact loading introduced using mechanical shakers to supply additional HCF loads. Under such conditions the contact surfaces of the root profile experience a complex fretting fatigue history for which the local stress state is ill-defined. The fretting regime during the test is mixed. Initially, gross slip occurs under the action of the low cycle loading, until an equilibrium position is reached when the joint becomes “locked-up”. Beyond this point, partial slip occurs at the ends of the contact due to the high cycle loading.

Being a simpler loading geometry, it is easier to determine the loads experienced for blunt notched three-point bend (3PB) samples (Fig. 2b). These experience uniaxial fatigue only, without fretting. The rounded notch in the sample is designed to introduce a localised geometric stress concentration. These samples were loaded under combined HCF and LCF. The loading cycle corresponded to a mean stress of 1040 MPa at the root of the notch, superimposed on which are 7200 minor cycles with a stress amplitude of 110 MPa. Such conditions typically result in a fatigue life of the order of 1500 loading cycles.

All samples were manufactured from the same grade of Ti–6Al–4V alloy, which is commonly used in aero-engine fan blades. LSP was performed by Metal Improvement Company using a power density of 9 GW/cm^2. Samples were peened to 200% coverage. For the Dovetail Biaxial Rig samples no lubricating surface coating was applied to the contact surfaces of the sample in order to increase the loads caused by fretting, simulating the situation where any solid lubricant has been worn away from the contact surface of a root. Fretting damage to the contact surfaces was apparent, as shown in Fig. 2c.

The coordinate systems used to describe these samples are also shown in Fig. 2. In essence, the z-axis is normal to the peened surface. The x-axis lies in the peened surface parallel to the major applied load. The y-axis lies in the surface, perpendicular to the applied load.

2.2. Energy dispersive synchrotron X-ray diffraction

Residual elastic strains have been measured using high-energy synchrotron X-ray diffraction (XRD), using beamlines ID15a, ESRF, Grenoble, and 16.3, SRS, Daresbury. The high photon energies and flux available from a synchrotron source allows measurements to be made in transmission geometry through a significant thickness of material [15]. The extent of residual elastic strain is determined from reversible changes in the lattice spacing (d_{hkl}) of atoms in the crystal. These changes are determined from small shifts in the diffraction peak positions using Bragg’s law ($\lambda = 2d_{hkl}\sin\theta$, where λ is the wavelength of diffracted radiation, d_{hkl} the crystal plane spacing, and 2θ is the scattering angle). Measurements were