Available online at www.sciencedirect.com

ScienceDirect

Acta Materialia 83 (2015) 216–226

Acta MATERIALIA

www.elsevier.com/locate/actamat

Evolution of a laser shock peened residual stress field locally with foreign object damage and subsequent fatigue crack growth

S. Zabeen,[a] M. Preuss[b] and P.J. Withers[b,*]

[a]*Materials Engineering, Walton Hall, The Open University, Milton Keynes MK7 6AA, UK*
[b]*School of Materials, University of Manchester, Grosvenor St., Manchester M13 9PL, UK*

Received 7 July 2014; revised 17 September 2014; accepted 17 September 2014
Available online 22 October 2014

Abstract—Foreign object damage (FOD) can seriously shorten the fatigue lives of components. On the other hand, laser shock peening improves fatigue life by introducing deep compressive residual stress into components. In this paper we examine how the non-uniform steep residual stress profile arising from FOD of laser peened aerofoil leading edges varies as a function of fatigue crack growth under high cycle fatigue and mixed high and low cycle fatigue conditions. The ballistic FOD impacts were introduced by impacting a cube edge head-on (at an angle of 0°) to the leading edge. The residual stress distributions have been mapped by synchrotron X-ray diffraction prior to cracking and subsequent to short (~1 mm) and long (up to 6 mm) crack growth. The results suggest that the local residual stress field is highly stable even to the growth of relatively long cracks.

Keywords: Residual stress; Foreign object damage (FOD); Fatigue crack growth; X-ray diffraction; Ti–6Al–4V

1. Introduction

Compressive residual stresses induced by laser shock peening (LSP) have been found to affect fatigue crack growth behaviour by delaying the crack initiation and by decelerating the crack propagation rate in both aluminium alloys [1–4] and Ti–6Al–4V [5–8]. For thick Ti–6Al–4V components, the residual stresses introduced by laser peening are typically ~600 MPa near the surface and reduce linearly to a depth of around 2 mm, whereupon balancing tensile stresses are encountered [9]. For thin aerofoil specimens (a few millimetres thick), the compressive stresses typically extend through the thickness, provided there is sufficient material to restrain the lateral expansion of the peened region [10,11]. LSP is used to enhance material lifetimes predominantly under fatigue related conditions, although benefits have also been seen under other damage modes, such as galling, stress corrosion cracking, corrosion, wear and fretting fatigue [9,12]. The stability of the residual stress field has been investigated by a number of researchers for shot peened steel [13–17], nickel base superalloys [18–20] and titanium alloys [21]. However, the relaxation of LSP'd residual stress has not been extensively studied to date, although resistance to fretting has been quantified [9]. The residual stress state and the stability of different materials are summarized in Refs. [22,23].

In the aerospace industry, foreign object damage (FOD) is one of the major life limiting factors that can markedly reduce the fatigue life of aeroengine components. A small (<3 mm in depth) FOD notch may reduce fatigue life by over 50% [6]. The effect is a complex one. Hall et al. [24] have found that fatigue cracks initiate much faster under low cycle fatigue (LCF), high cycle fatigue (HCF) and LCF + HCF from cube edge impact FOD notches that have been stress relieved relative to those that have not, suggesting that the compressive residual stresses at the notch tip [25] may be beneficial. Conversely, Thompson et al. [26], using spherical indents, found that stress relief improves the fatigue limit stress invoking tensile stresses at the edge of the crater rim (near where the cracks initiate) [27]. LSP has been found to improve the fatigue resistance of Ti–6Al–4V [6] in the presence of FOD, at low stress ratios ($R = 0.1$). However, no improvement has been observed at higher stress ratios ($R = 0.8$). Hammersley et al. [28] observed similar results.

From published fatigue test results, it is easily understood that the deep compressive residual stresses introduced by LSP treatment causes the observed improvement. In order to incorporate any associated fatigue life benefit arising from LSP into a damage tolerant design, it is important to be able to quantify these residual stresses and their evolution through life accurately. There have been a handful of research studies where residual stresses have been mapped post-FOD [25,27]. These tend to show a compressive stress immediately below the notch, with tensile stresses located at a greater depth below the notch and near the edge of the

* Corresponding author.; e-mail: Philip.withers@manchester.ac.uk

http://dx.doi.org/10.1016/j.actamat.2014.09.032
1359-6462/

crater. This broad pattern seems to occur irrespective of the impactor geometry, although the actual levels of stress vary. The effect of FOD impact on laser peened specimens has also been examined for both head-on (0°) and 45° simulated impacts [11,29]. Local to an edge-on cube impact, the residual stress is characterised by a peak compressive stress parallel to the leading edge immediately below the notch [25]. Comparison of the stress fields introduced by leading edge FOD with [11,29] and without [25] prior LSP under similar conditions indicate that the stresses introduced at the notch tip are surprisingly similar. The effects of the prior laser peening are seen some distance further from the notch tip: both the tensile region around the crater and, most importantly, the tensile region lying some distance below the notch tip have been removed. This may explain the increase in fatigue life for impact damaged specimens for which the crack propagates from the notch tip.

In view of the potentially beneficial effects of the residual stresses arising from the FOD impact immediately below the notch and those introduced by laser peening somewhat further below the notch tip, it is critical to quantify their stability and redistribution during fatigue crack growth. Rotating components of aeroengines, such as fans and blades, are generally subjected to high frequency vibratory loading (HCF), which is superimposed onto low frequency centrifugal loading (often at high stress). Consequently, in this paper the redistribution of the residual stresses have been quantified as a function of fatigue cycling and crack growth both for LCF and combined cycle (LCF + HCF) fatigue cycling prior, and subsequent, to short (<1 mm) and long (up to 6 mm) levels of crack growth.

2. Materials and methods

2.1. Material

Ti–6Al–4V is widely used for compressor blades and is thus studied here. The manufacturing process involves forging the material above and below the β transus to break up the coarse lamellar microstructure. Subsequently, the alloy was solution treated at about 927 °C (below the β-transus), followed by a stress relief heat treatment at 705 °C for 2 h. This thermomechanical processing route produced a bimodal microstructure comprising ~60% primary α and 40% (by volume) lamellar colonies (see Fig. 1). The room temperature mechanical properties of Ti–6Al–4V can be represented by a Young's modulus of $E = 103$ GPa, a Poisson's ratio of $\upsilon = 0.3$, a yield strength of $\sigma_Y = 860$ MPa and an ultimate tensile strength of $\sigma_{UTS} = 980$ MPa [30]. Specimens were machined from the forged blocks to form a generic leading edge profile, as shown in Fig. 2.

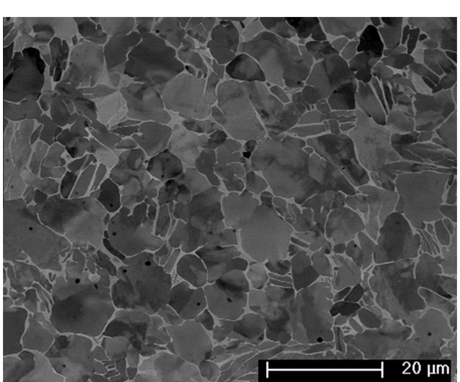

Fig. 1. Scanning electron micrograph of the as-received microstructure of Ti–6Al–4V.

2.2. LSP treatment

The specimens were laser shock peened over the leading edge using parameters that provided an optimum balance between induced residual stresses (FOD tolerance) and acceptable distortion of the leading edge profile. This was carried out by the Metal Improvement Company, USA at a power density of 10 G W cm^{-2}, using a square spot (size 3×3 mm^2), 50% overlap and 200% coverage, with a pulse duration of 27 ns. The LSP'd region extends 6 mm from the leading edge and over 65 mm along it (Fig. 2a).

2.3. Simulated FOD

To simulate the FOD damage that occurs as a result of ingested particles at high velocities and strain rates, the specimens were impacted ballistically using a 12 mm bore light compressed gas gun at the Department of Engineering Science, Oxford University, UK. The gas gun was equipped with a 2 l gas cylinder connected to a 2.5 m long sleeved barrel. Details of the damage simulation technique are described elsewhere [31]. To replicate the "worst case" damage, hardened steel cubes were chosen having a hardness value between Rockwell C 62 and 64. The steel cube was mounted in a nylon sabot to prevent rotation and to ensure that the steel cubes hit the leading edge in a controlled manner. Each sample was mounted in a cross-vice that could be rotated and translated using a motor-driven system with micrometre precision. A 3.2 mm hardened steel cube was directed at an angle of 0° to the leading edge (parallel to the transverse "x" direction) with an impact velocity of 200 ms^{-1}. In this case, the cube hit the specimen edge first (Fig. 2b). The notch depth for each specimen was measured by an optical microscope from a profile view of the notch.

2.4. Specimens studied

The specimens were fatigued by Spanrad and Tong at Portsmouth University as described in Ref. [32] under four-point bend, constant amplitude cyclic loading using a servohydraulic twin actuator 100 kN testing machine. The support span was 107 mm and the loading span was 57 mm. In order to represent conditions appropriate for aeroengines, LCF and combined (HCF + LCF) cycle fatigue were studied (Fig. 3). HCF was conducted at a frequency of 80 Hz and a load ratio of $R = 0.7$, whilst low cycle fatigue was conducted at 0.25 Hz and a load ratio of $R = 0.1$. Each combined cycle (CCF) block comprised 1000 HCF fatigue cycles and 1 LCF cycle. The direct current potential drop (DCPD) method was used to monitor crack initiation and growth to ~10 μm resolution. The corresponding fatigue loading conditions are summarized in Table 1.

2.5. High energy synchrotron X-ray diffraction

The residual stress field has been tracked for a set of specimens (see Table 1) as a function of the number of LCF or CCF cycles. In order to do this it was necessary