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Characterization of foreign object damage (FOD) and early fatigue crack growth in laser shock peened Ti-6AL-4V aerofoil specimens

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Abstract

Foreign object damage (FOD) has been identified as one of the primary life limiting factors for fan and compressor blades, with the leading edge of aerofoils particularly susceptible to such damage. In this study, a typical aerofoil specimen of Ti-6Al-4V alloy was used. The leading edge of the specimen is representative of a generic aerofoil geometry. The specimens were treated by laser shock peening (LSP) to generate protective residual stresses in the leading edge region prior to impact. FOD was simulated by firing a cubical projectile at 250m/s head-on at the leading edge using a laboratory gas gun. The specimens were then subjected to fatigue testing under high cycle (HCF), low cycle (LCF) and combined LCF and HCF loading conditions.

Scanning electron microscopy (SEM) was used to characterise the damage features due to FOD. Crack initiation and early crack growth due to FOD and subsequent fatigue loading were examined in detail. An analysis with a backscatter electron (BSE) detector was also carried out to investigate the microstructural deformation due to FOD, LSP, as well as the early fatigue crack growth mechanism in a complex residual stress field.

Keywords: Ballistic impact; Damage characterisation; Titanium; Foreign object damage, SEM

1. Introduction

Foreign object damage (FOD) to rotating components in modern aircraft engines is of great concern in gas turbine engines, where small hard particles such as stones or metallic debris can impact turbine blades during takeoff and landing at high speeds up to 500m/s [1]. The result of the impact is localised damage in the form of a notch or dent, often close to the leading edge, together with possible material loss, extensive plastic deformation at both macro and micro levels. Many fatigue failures in jet engines have been attributed to a combination of high frequency vibration loading and prior damage in-service events such as FOD, with significant implication on the reduction of component service life [1,2].

The evaluation of FOD resistance of materials and structural components has been carried out in a typical blade material, Ti-6Al-4V, in laboratory test conditions. Nicholas et al [3] were probably the first to study the effects of
FOD on titanium leading edge. They found that the morphology of the damage consisted of tears and loss of mass in addition to dents, and dents with tears were more damaging in reducing fatigue life in the low-cycle fatigue (LCF) regime. More recent work at Berkeley [4,5] was on the influence of FOD on high cycle fatigue (HCF) threshold. They found a marked reduction in fatigue life post FOD, compared with that of undamaged specimens. Impacts using hard cubes were carried out on plates [7], generic aerofoil specimens [8] and a more realistic aerofoil shape similar to real compressor blades [9,10]. The cubical projectile was considered more representative of “worst case” damage seen in the engine. Whilst work at Oxford [9,10] was more concerned with the reduction in fatigue strength due to FOD, work at Portsmouth [7,8] was focused on early fatigue crack growth due to FOD under more realistic loading conditions, including LCF, HCF and combined LCF and HCF.

The aim of this study is to characterize cubical head-on FOD impacts using SEM and evaluate the role of the damage features in crack initiation and early crack growth in laser shock peened Ti-6Al-4V simulated aerofoil blades. A comparison is also made between well studied spherical FOD damage impacts [11,12] and the present cubical FOD impacts.

2. Experimental procedures

2.1. Materials and specimen design

The material used is titanium alloy Ti-6Al-4V with a typical microstructure of a bimodal distribution of primary α phase and lamellar colonies of α+β. The specimens were machined from blanks for the production of fan blades. The material was first forged in the α phase and continued into the α+β phases, then rolled and creep flattened in the α+β phase, as illustrated in Fig. 1. The materials properties at room temperature are: Young’s modulus, 103 GPa, yield stress, 860 MPa and tensile strength, 980 MPa [7].

FOD damage on blades in aero-engines is known to occur mostly on the leading edge of an aerofoil section, thus a symmetrical, elliptical-shaped cross section was used to simulate the generic form of aerofoil components, see Fig. 2a-b. A four-point bend geometry was chosen to perform the fatigue tests.

Fig. 1. The bimodal microstructure of Ti-6Al-4V (as received).
2.2. LSP process

A description of the physical and mechanical mechanisms of the LSP process can be found in [13]. The specimens were laser shock peened over the leading edge by Metal Improvement Company (USA), using a power density of 10 GW/cm², a pulse duration of 27 ns, a spot size of 3×3 mm², 50% overlap and 200% coverage. The total LSPed area consists of 27 strikes and measure approximately 65 mm x 6 mm wide. To ensure adequate depth of the ensuing residual stress layer, two layers of identical spot location and conditions were performed. A sketch of a typical laser spot pattern can be found in [13].

2.3. Simulation of foreign object damage

Foreign object damage was simulated by firing a 3 mm hardened steel cube onto the leading edge of the specimen at a velocity of ~ 200m/s. A light gas gun (Oxford University, UK) was used to fire the projectiles. The gun consisted of a 2-litre gas cylinder connected via a pneumatic valve to a 2.5 m long sleeved barrel, as described in [9]. The target was held in a cross-vice which can be rotated and translated with micrometer precision. The barrel was keyed symmetrically to ensure no rotation of the projectile. Velocity was measured using photodiodes. The cube impacted edge first onto the leading edge of each specimen in the centre of the gauge length and its trajectory was at 0° to the impacted face, as shown in Fig. 2b. Figure 3 shows a typical FOD crater in a shape of a V notch, representative of the “worst case” damage observed in service conditions.

2.4. Fatigue testing methods

Fatigue testing of the simulated and FODed airfoil specimens were carried out under a four-point bend, constant amplitude (CA) loading in a servo-hydraulic twin actuator 100kN testing machine. The support span used in all tests was 107 mm and the loading span was 57 mm, with all rollers free to rotate and move apart slightly as the specimen is loaded. The conjoint action of LCF and HCF cycles, referred to as combined LCF+HCF loading, representing a simplified flight spectrum as described in [7-8] was used. The test frequency for all CA tests was 80 Hz. When a predefined step test block of cycles was reached, the test was stopped, the stress range was increased by the designated percentage (either 3-5%), and the test was resumed for another block or failure, whichever occurred first. Crack initiation and growth was monitored using a direct current potential drop technique. Visual measurement of crack length was also performed on both sides of the FOD notch, using the acetone replica method.
2.5 Notch characterization

Prior fatigue testing, the FOD notches were photographed in different orientations for profiling and measurement of the notch depth by an optical microscope.

To characterize FOD notches a scanning electron micrograph (SEM) study was carried out using a JEOL JSM-6100 SEM. A set of 5 specimens were characterized. The notches were examined using a variety of orientations, and different stages in the fatigue failure progress to characterize damage features, crack initiation and early crack growth. These steps were a) prior fatigue testing, b) after fatigue crack initiation and early growth, and c) after fatigue fracture. The micrographs of the two latter steps provide insight into the location and nature of the crack initiation and early crack growth, as well as the interaction with the FOD damage features.

3. Results and discussion

3.1. FOD characterization

The FOD features were characterized using the SEM and the results are shown in Fig. 3, including the notch depth, loss of materials (LOM), material shear and material folding over the LE, heat formation resulting in fused areas and microcracks.

3.1.1. Notch Depth

The notch depths were measured by positioning the SEM stage to achieve a profile view of each notch depth in x-direction. The average notch depth of 9 FOD shot specimens with an average speed of 197 m/s was 1.43mm. The preferred crack initiation sites were reported to be the deeper notch[2, 5]. This seems to be confirmed by the fretting debris due to fatigue near the root of the FOD notch, shown in Figs 4.

3.1.2. Loss of material (LOM) and material shear

LOM and material shear from the surface of the notch are evident in all FODed specimens (Figs 3, 4a, 5, 6b). Fig. 4a shows an overview of the impact site, including all observed impact features. LOM and material shear are evident on the notch surface in the form of shear dimples and shear lips. Typical tears (LOM) are clearly visible in Fig. 3b. LOM is mostly found on the edges of the notch, as shown in Fig. 4. LOM may be associated with crack initiation and early growth (Fig. 5e), although LOM alone does not appear to have a direct effect on the fatigue strength [6].

3.1.3. Material folding and heat formation

Material folding over the leading edge also occurred on all FODed specimens and can be seen in Figs. 3a, b, 4a, 5, 6. Material folding is a result of material pile-up, due to the cubical impact. When the cube strikes the LE, material is shuffled ahead of the impacting cubical edge. The shuffled material is partly sheared off at the beginning of the impact notch (LOM), or piled up preferably at the notch periphery (Figs. 3a, b, 4a, 5, 6) as well as in the root of the notch (Figs. 3a, 5). The folded and piled-up material at the periphery of the notch creates a sharp notch, as shown in Figs. 3a, b, 5.

The surface of the folded material next to the root of the notch at the periphery shows a different smoothness. The folded material is much smoother which indicates a heat formation resulting in fused layers of material, see Fig. 3b. Another evidence of heat formation during the impact can be seen in Fig. 3e, where the material was folded in the root of the notch and “droplet” structures can be seen adjacent to the areas of incipient melting around the 'cleavage' surfaces [14]. Thirdly, microcracks and micro notches can be seen in the area of re-fused materials (Fig. 3b, d) at the root of the notch. The origination of these microcracks will be explained as followed.
3.1.4. Shear bands and micro cracks

Material pile-up and folding at the crater rim results in sharp notches (Figs. 3a, b, 5, 6) and microcracks (Figs. 3c, 5a, c, e, ee). A typical microcrack length (Fig. 5ee) is about 40 μm. Multiple microcracks were also found on the root surface of the notch (Fig. 5b), as well as shear bands [5]. These shear bands were induced due to high shear stress during impact. As shown earlier, the impact produces a high temperature on the surface locally, which may result in strain-mismatch, leading to microcracks.

Micronoches, as identified in [5], on the surface of the FOD notch may be a result of plastic flow and LOM, which can be seen in Fig. 3a, b, 4a, 5.
3.2. Characterization of early crack growth

For the characterization of early crack growth, the specimens were fatigue tested and examined using the SEM before failure (Figs. 4, 6a, c, e). Subsequently, they were fatigued until failure and the two halves of the specimen were examined under the SEM (Figs 6b, d, f). The pictures obtained pre-fatigue testing were compared with those done post fatigue testing of the same areas (Fig. 6).

3.2.1. Multiple crack growth and fretting fatigue

After a fatigue crack length of about 7 mm, the FOD notch was examined using the SEM. An overview of a notch is shown in Fig. 4a. Bright particles can be seen primarily in the notch root, as well as on the surface of the notch. Fig. 4b shows these particles at a higher magnification and Fig. 4c at a 45degree angle with respect to the notch plane. These particles appear to be loose, possibly due to fretting fatigue and/or increased level of crack closure as a result of the residual stresses due to LSP and FOD impact. The loose particles vary in size, between ~16 and 68 μm in length. Figs. 4c, b show these particles at the rim of the notch, where the crack paths are “marked out” by these particles, indicating multiple fatigue cracks, especially near the rim of the FOD notch.

3.2.2. Fracture surface analysis and crack initiation

Figs. 5a and c show the notch rims of both ends of the notch root after the FOD impact. Figs. 5b and d correspond to the same area of the FOD notch after the fatigue fracture. The comparison shows that the sharp notches at the notch rims may have served as the crack initiation sites.
Fig. 5: Fracture surfaces pre- (a, c, e) and post- (b, d, f) fatigue testing. a) Material pile-up and folding over the leading edge created a sharp notch from which microcracks were formed and subsequent crack growth was detected in (b); b) The sharp notch due to FOD served as a crack initiation site (post testing); c) Material folds and pile-ups occurred near the rim of FOD notch; d) Two crack initiation sites due to material pile-ups and material folds (Post testing); e) Microcrack formed at the crater rim after FOD impact, inset shows the crack at higher magnification; f) Micro fatigue crack-growth at material pile-ups from the microcrack in (e) (post testing).

On the fracture surface (Fig 5a) a 'flake-like' material is evident which may be a result of crack growths at different planes. The striations from the bottom side of the fracture surface are continued onto the flake surface. This indicates that one crack initiation was developed from the left rim side. To create crack coalescence more crack fronts are needed; one from the top and one from the right rim side, originated from the middle of the FOD notch with respect to the rims. This flake on the fracture surface may well be a result of multiple crack growths originated on different planes. A reconstruction of the possible successive crack growth patterns from the crack initiation sites is shown in Fig. 5b.
3.3. Damage features: Comparison of cubical and spherical impacts

For spherical projectiles, FOD damage, as characterized by size and shape of the indents and location of microcracking, was found to depend on the impact velocity. At velocities above 250 m/s, a pronounced pile-up of material was evident at the crater rim; additionally circumferentially orientated shear bands were also seen, emanating on the surface of the impact crater; whilst such effects were not apparent for 200 m/s. For impact velocities of 300 m/s, plastic flow of material at the crater rim resulted in multiple micro notches and microcracking. Therefore velocities below ~250 m/s do not necessarily induce all the damage processes associated with a realistic simulation for FOD.

The FOD damage created by a cubical projectile at an impact velocity of 200 m/s seems to be more detrimental compared to spherical FOD impacts at the same speed. Damage characteristics such as shear bands and microcracking were found only at higher impact velocities (>250 m/s) for spherical impacts, whilst using a cubical projectile these features are observed at a low velocity (200 m/s). This seems to suggest that the relationship between impact velocity and damage characteristics observed in [5] for spherical projectiles may be subjective of the projectile shapes. For a V-notch created by cubical projectiles the stress concentrations in the base of the notch and at the rims are greater compared to those under spherical impacts. The sharp notches created due to circumferentially piled-up material were favourably orientated with respect to the applied stress axis on subsequent fatigue cycling. The microcracks and shear bands at root of the notch are predominately orientated in the favourable crack plane, prompting crack initiation along the base of the notch. The multiple shear bands in the base of the notch might be responsible for plastic deformation at microstructural level hence residual stresses, which could then be responsible for multiple crack initiation and growth in the early stage.

4. Conclusions

Experimental studies on FOD of a generic aerofoil specimen and fatigue crack growth post FOD seem to suggest:

1. Damage from high speed cube impact on leading edge of aerofoil specimens may be characterised as a mixture of notch indent, loss of materials, material shear, material folding, heat formation, shear bands and microcracks.
2. Damage features preferably occurred at certain areas of the FOD notch, as shown in Table 1.
3. Crack initiations seem to occur a) at the FOD-induced microcracks and micronotches near the crater rims, where the stress concentration was highest as a result of material pile up and LOM; and b) in the notch root where surface irregularities such as shear-bands and microcracks were formed.
4. Multiple crack growth and crack growth on different planes may be a result of non-uniform residual stress distribution created by LSP and FOD and the irregularities at the notch root.
5. The FOD damage created by a cubical projectile seems to be more detrimental compared to spherical FOD impacts at a given speed.
6. The relationship between impact velocity and damage characteristics observed in [5] for spherical projectiles may be subjective of the projectile shapes.

Table 1. Typical material damage features observed for head-on FOD impact and the locations of their appearance.

<table>
<thead>
<tr>
<th>Impact feature of head-on impacts</th>
<th>Area of</th>
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<tr>
<td>LOM</td>
<td>Predominantly at the notch rims</td>
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<td>Folding over the LE</td>
<td>Notch rims</td>
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<tr>
<td>Material pile-up</td>
<td>Notch rims and notch root</td>
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<tr>
<td>Shear-bands</td>
<td>Notch root, created by the cube edge</td>
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