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EFFECT OF FOREIGN OBJECT DAMAGE ON THE HIGH CYCLE FATIGUE STRENGTH OF TI-6AL-4V

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ABSTRACT

The role of residual stresses on the fatigue behavior of Ti-6Al-4V samples that had undergone foreign object damage was investigated. Real and simulated impacts were conducted using spherical projectiles launched at 300 m/s and quasi-static chisel indentation, respectively. A unique test specimen configuration that replicates the leading edge of a typical fan blade was ballistically shot at 30° with 1 mm diameter spheres, while rectangular plates were indented quasi-statically using a 2 mm diameter steel indentor at 0°. Fatigue strengths were developed for both geometries at 350 Hz. A number of specimens from both configurations were stress relief annealed, after impacting and before HCF testing, to remove residual stresses. Attempts were made to correlate the measured damage (macro-/microscopic) to the debit in fatigue strength. Results indicate that stress relief generally improves the fatigue limit stress, indicating that tensile stresses are present after both quasi-static and dynamic indentation. For the dynamic impacts, the damage induced is not as severe on the fatigue strengths as that predicted from conventional notch fatigue analysis.

KEYWORDS

high cycle fatigue, foreign object damage, residual stress, fatigue limit stress

INTRODUCTION

The fatigue behavior of airfoils in gas turbine engines that have been subjected to foreign object damage (FOD) is a complex issue due to many contributing factors. These factors include, but probably are not limited to, notch geometry causing a stress concentration, residual stress arising from plastic deformation, microstructural damage to the material from the impact event, and the formation of cracks during the impact event [1]. In addition, changes in the geometry of the airfoil edge and residual stresses due to plastic deformation may produce local stress ratios at the notch tip which are, in general, different than the far-field applied stress ratio and may drive the initiation location from surface to sub-surface [2]. This paper deals with the fatigue behavior of axial fatigue test specimens that have been subjected to FOD, with a portion of the specimens having undergone a post-FOD event stress relief annealing in order to examine the effect of residual stresses.

EXPERIMENTAL PROCEDURES

Axial fatigue specimens were machined from a single Ti-6Al-4V forged plate that had been heat-treated to the STOA condition [3]. Two basic specimen configurations were used for this effort: a diamond cross-section tension (henceforth known as the LE, *i.e.* leading edge) specimen and a simple rectangular (flat) cross-section sample. The LE specimen was designed such that the edges of the gage section are tapered to radii representative of the leading edge on a fan blade. To span a range of leading edge configurations, two edge radii were examined: 0.38 mm and 0.127 mm. Details of the specimen geometries can be found in Ref [3]. Stress calculations for all samples were based on the gross area, excluding the slight loss in area due to the various FOD sizes.

The LE samples were ballistically impacted using a single-stage compressed gas gun. All of the samples were shot with a 1 mm glass sphere at a velocity of approximately 305 m/s. The glass sphere was chosen as being representative, in both size and properties, of sand or runway debris that is of concern in U.S. Air Force operational engines. It also produces damage which is geometrically similar to what is often observed in the field. Details of the ballistic impact procedures are likewise presented in Ref [3]. Quasi-static impact damage was performed on the flat samples. A hardened steel indentor with a 2 mm diameter round tip was used to induce damage to a specific depth on the thin side of the rectangular sample at a 0° angle [4].

To establish the fatigue strength, samples were fatigue tested using the step-loading procedures described by Maxwell and Nicholas [5]. Steps of 10^7 cycles were used in this investigation, while $\Delta\sigma$ was taken typically at 10 percent of the initial load block. This large increment (compared to 5 percent or less in other tests) was used to minimize the number of load blocks because of the wide scatter in fatigue strengths observed under FOD conditions. Testing was conducted at stress ratios (R) of 0.1 and 0.5 at a frequency of 350 Hz using an electro-dynamic, shaker-based test machine. All testing was performed under ambient laboratory air conditions.

The choice of tension-tension testing was made for several reasons. While a real blade may be subjected to combinations of bending and tension, it was felt that understanding one of the basic properties, tension fatigue, was important in characterizing FOD. Second, baseline data are available for the material tested to compare smooth [6] and notch [7,8] fatigue behavior. Finally, test apparatus is available to conduct high frequency axial fatigue testing whereas fully instrumented bend tests are more difficult to perform at high frequencies.

Prior to fatigue testing, the FOD sites of each LE sample were examined with a scanning electron microscope (SEM) to document the initial FOD defect. After test, the FOD site from which the fatigue cracking failure initiated, along with the fracture surface of each sample, were again examined to correlate the microstructural features with the ensuing fatigue strength. The flat samples were examined, prior to testing, under a standard optical microscope to determine the dimensions of the damage sites. Observations of whether there appeared to be material loss (chipping out) were noted. It should be noted here that during the testing process, the fracture faces tended to be crushed when the specimen failed. This action smeared the features on the fracture faces to the point that initiation sites were compromised.

Because of the expense of conducting ballistic tests, only a limited number of tests were carried out. In many cases, duplicate tests were not used. Because of this, as well as the scatter involved in this type of testing, only general trends are expected from the results.

A portion of the impacted samples, both from the ballistically impacted LE samples, and the quasi-statically impacted flat samples were stress relief annealed before fatigue testing. This process was performed to allow a comparison of fatigue limit stress of specimens impacted under identical conditions with and without residual stresses.

DISCUSSION OF RESULTS

Damage Characterization

The photos in Figures 1a and 1b show examples of ballistic impact damage on the LE samples. Although the conditions were the same for the ballistic impacting for these samples, the results were greatly different. Some of the impact sites exhibited a simple “dented” appearance with little or no loss of material evident (Fig. 1a), whereas other impact sites exhibited more damage with a much larger loss of material (Fig. 1b). The photos in Figures 2a and 2b show flat sample indents where there was no evidence of material loss (Fig. 2a) and where material loss occurred (Fig. 2b). The arrow in Figure 2b indicates an area where a crack occurred during the indenting process. A piece of material eventually chipped out during the handling of the sample. This behavior was typical in the samples with the large damage depths. LE samples were rotated in the SEM to provide the appropriate angle to measure the maximum depth of damage. These measurements (depth and width of impact notch) were used later to compute approximate values of the stress concentration factor, K_t, as well as a notch depth ratio, d/a. While the flat samples had a radius of the indent that was close to that of the quasi-static indentor, the LE specimens had notch root radii which had a larger amount of scatter. The scatter in these dimensions can be attributed to the scatter in the exact location of the impact on the thin LE samples and very small size of the projectile causing the impact.

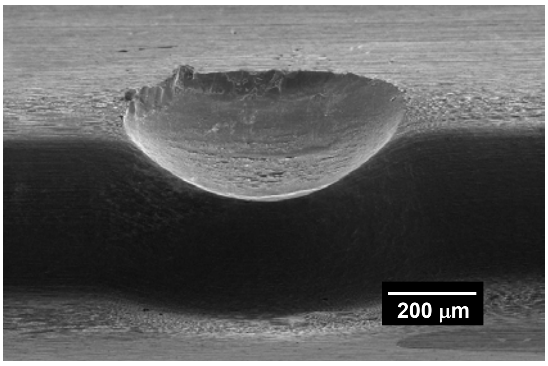

Figure 1a: Head-on view of a 30° ballistic impact FOD site for a 0.38 mm leading edge radius sample exhibiting little or no loss of material.

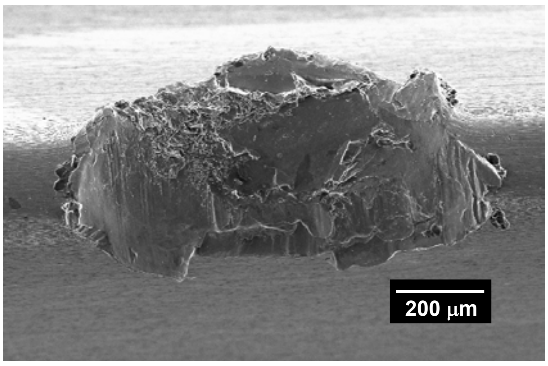

Figure 1b: Head-on view of a 30° ballistic impact FOD site for a 0.38 mm leading edge radius sample exhibiting a larger loss of material.

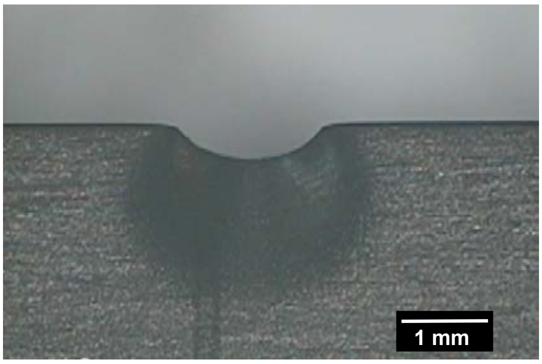

Figure 2a: Side view of a 0° quasi-static impact FOD site for a flat sample exhibiting no loss of material.

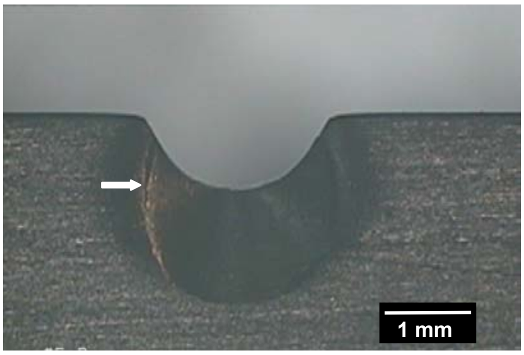

Figure 2b: Side view of a 0° quasi-static impact FOD site for a flat sample exhibiting a large crack (eventual loss of material).

Leading Edge (LE) Samples

The results for strength of ballistically impacted LE specimens are presented in Figure 3 where fatigue limit stress is normalized with respect to the smooth bar fatigue strength at the appropriate stress ratio. For this material, the maximum stresses for smooth bars are σ=568 MPa for R=0.1 and σ=660 MPa for R=0.5 [3,5]. It should be noted that in the figure, AR refers to specimens that were tested in the as-received (as-impacted) condition and SR refers to specimens that were tested in the stress-relieved condition. Symbols with upward arrows indicate notch geometries where failure occurred away from the notch at the indicated stress. From the data, it can be seen that the SR samples tend to have higher fatigue strengths than the samples tested in the as-impacted condition. Also shown in the figure are points that utilize a fatigue notch factor, K_f, which was calculated from the measured dimensions for radius and notch depth [4]. It can be seen that the SR samples lie above the predictions of large notch fatigue analysis, and many of the AR samples also lie above those points. It can only be concluded that the small size of the notches being dealt with here are not as severe as geometrically similar notches, a finding supported by the observations of Haritos, et al. [8] in notch fatigue studies on the same material. They observed that the detrimental effect of a notch decreased as the root radius became smaller for the same value of K_t, and attributed that finding to a size effect as formulated by other notch fatigue theories (*eg.* [9]).

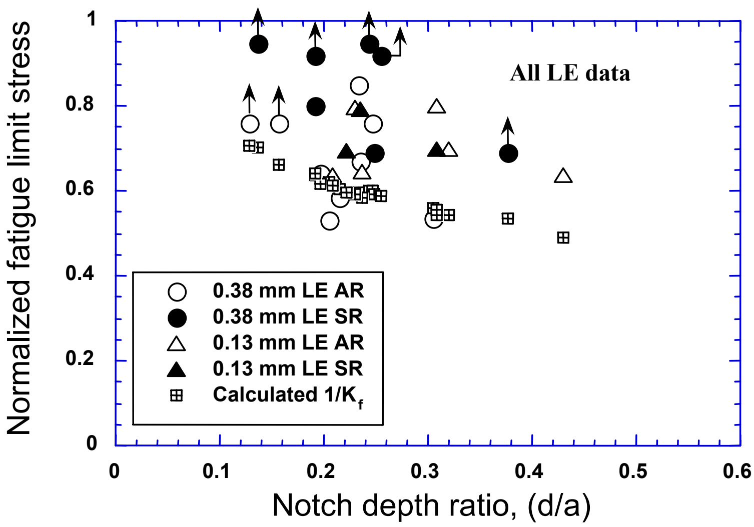

Figure 3: Effect of the notch depth ratio on the normalized fatigue limit stress for ballistically impacted 0.38 mm leading edge radius samples.

Flat Samples
Fatigue limit stress as a function of notch depth for the flat specimens subjected to a static indent with a 2 mm diameter chisel at a stress ratio (R) of 0.1 is shown in Figure 4. Data from this investigation, denoted MLS, are shown alongside those from a prior investigation using the same material and indentor, denoted AFIT [2]. While there are not many data points, it can be seen that the AR specimens (hollow symbols) clearly show a larger debit in fatigue strength. The greatest fatigue debit occurs in those specimens that exhibit a loss of mass through chipping, a finding consistent with prior observations by Kaufman and Meyer [10] and Martinez [11]. In the plot, the expected failure stress from a fatigue notch factor, K_f, is shown, based on the assumption that the radius of the indent is that of the indentor.

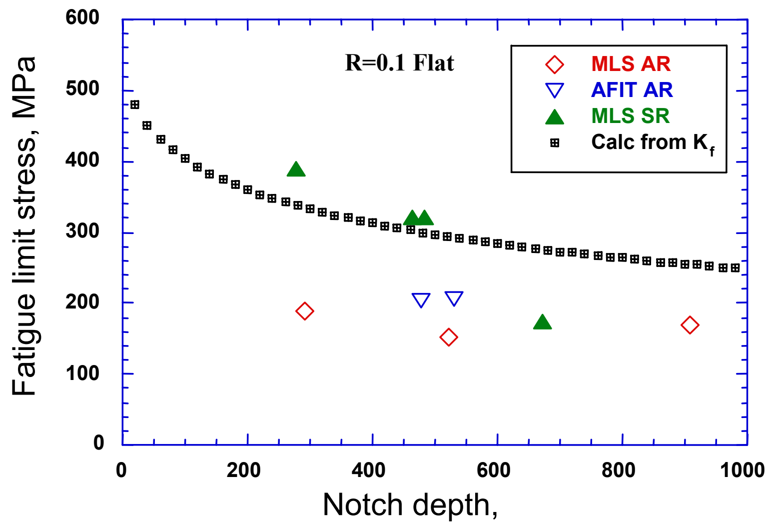

Figure 4: Effect of notch depth on the fatigue limit stress for R=0.1 on quasi-static impacted flat samples.

Role of Residual Stresses
Similar to what happens when compressive residual stresses are applied under surface treatments such as in laser shock peening [12], the beneficial effects of residual stresses seem to be more prominent at low stress ratios than at high ones. It is important to note that a residual stress superimposed on the stresses generated from fatigue loading does not change the stress range (or stress intensity factor range, ΔK, in the case of a cracked body) but, rather, changes the values of the maximum and minimum stresses by the same amount. Thus, compressive residual stresses superimposed on tensile fatigue stresses at a particular value of R will reduce the effective value of R for crack initiation. For low values of applied R, the effective R may be negative. Recent unpublished data from our laboratory indicate that the range of compressive stresses is much less effective than the same range in tension in high cycle fatigue. For the crack propagation phase after initiation, the compression region does not contribute to crack growth. For the situation where the residual stresses are in tension, the effective value of R increases although the stress range remains unchanged. In this case, tests at increasingly positive values of R can be detrimental because the magnitude of the fatigue limit stress decreases with increasing values of R, as evident in a Goodman diagram [5]. Further, any beneficial effects of compression for originally negative R can be removed.

SUMMARY AND CONCLUSIONS

Observations in this investigation and previous work [3,4] indicate that scatter in fatigue strength data involving FOD from ballistic impact, and even quasi-static indentations, have a tendency to obscure trends in causes of observed behavior. Nonetheless, the data obtained for fatigue limit strength on LE specimens indicate that the damage inflicted, excluding cases where material was removed, was less severe than that predicted by notch strength analysis. A similar trend was also observed in the flat samples that were quasi-statically indented. While the generally observed lower strength of the as-impacted samples can possibly be attributed to tensile residual stresses below the notch surface, the stress relieved samples exhibit fatigue strengths above which one would expect for the geometry of the observed notches. It appears that the notches produced from the ballistically impacted FOD have effective notch fatigue strengths higher than predicted by their geometries using conventional notch fatigue analysis; however, most work on notch fatigue deals with notches that are considerable larger than those being dealt with in this FOD investigation. It is concluded, therefore, that FOD that produces notch geometries involving the dimensions discussed herein is not as detrimental as FOD with larger dimensions of geometrically similar notches. This conclusion is based on the detrimental effects of the notch geometry and the calculated large notch fatigue factor, and does not consider the effects of residual stresses nor of irregularly shaped indents that may involve loss of material, tears, or other geometric discontinuities. The most detrimental effects of FOD appear to occur when irregularly shaped notches are produced from conditions such as tearing or material removal. Finally, the role of residual stresses in tension can be blamed for the low fatigue limit stress in many cases based on observations in nearly identical impact events where stress relief annealing improves the fatigue strength. It can only be concluded, in these cases, that tensile residual stresses led to the degradation of the fatigue behavior.

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