TITLE: An Assessment of Laboratory Techniques for Simulating Foreign Object Damage on a Leading Edge Geometry

AN ASSESSMENT OF LABORATORY TECHNIQUES FOR SIMULATING FOREIGN OBJECT DAMAGE ON A LEADING EDGE GEOMETRY

Steven R. Thompson
Air Force Research Laboratory, Materials and Manufacturing Directorate (AFRL/MLSC)
2179 12th Street, Wright-Patterson Air Force Base, OH 45433-7718, USA
steven.thompson@wpafb.af.mil

John J. Ruschau
University of Dayton Research Institute
300 College Park, Dayton OH 45469-0136
john.ruschau@wpafb.af.mil

Theodore Nicholas
Air Force Institute of Technology
AFIT/ENY
Wright-Patterson Air Force Base, OH 45433-7765
theodore.nicholas@afit.edu

ABSTRACT

Foreign object damage (FOD) from particles ingested into jet engines can have a detrimental effect on the fatigue strength of fan and compressor airfoils. The damage caused by these particles often is in the form of a geometric discontinuity like a notch. However the presence of residual stresses and substructural damage in regions adjacent to the notch prohibit the use of simple notch analyses. In this investigation, three different (quasi-static, pendulum, and ballistic) techniques of imparting damage are studied with respect to the damage they create and the resultant high cycle fatigue (HCF) strength of a titanium simulated airfoil geometry. The ballistic technique is used as a baseline as it most closely simulates an object being ingested into an aircraft engine. In this case, steel spheres having diameters ranging from 0.5 to 2.0 mm are used as the impacting objects at velocities over a range from 40 to 520 m/s. For the quasi-static and pendulum cases, hardened steel indentors with radii similar to those used for the ballistic impacting were used. Step loading tests in tension at a frequency of 350 Hz are used to establish the fatigue limit stress corresponding to 10^7 cycles. The role of residual stresses is identified through the use of samples subjected to stress relief annealing after impact. Simple notch analysis is used to estimate the effect of the geometry of the notch. Comparisons between as-impacted and stress relieved specimens were used to help identify the affect of residual stresses.

INTRODUCTION

In-service damage incurred by events such as foreign object damage (FOD), fretting, and low-cycle fatigue, in combination with high-frequency vibratory stresses, has been determined to be the source of many high-cycle fatigue (HCF) failures in turbine engines. FOD is caused by foreign particles such as sand or runway debris being ingested into the engine and the subsequent impact of these particles against both static and rotating components, typically in the fan and compressor regions. FOD, even in barely perceptible sizes, can have a very harmful effect on rotating components in aircraft turbine engines [1].

FOD will generally cause a crater or tear in the impacted component and reduce the fatigue capability of the material at the location of the impact. The degradation of the fatigue strength can be attributed to three primary factors: a stress concentration due to a notch-like geometry, the generation of residual stresses during the formation of the crater, and microstructural damage [2,3]. Of the factors affecting the fatigue strength, the stress concentration is easiest to handle by using theoretical or empirical notch fatigue factors applied to measured notch profiles. In many engineering and design applications, the geometry of the notch is simulated in the laboratory using quasi-static indenting methods as opposed to the more costly ballistic impact. There are certainly questions related to this procedure if the damage produced differs from the real event even though the notch geometry produced is identical [4].

The question of the role of residual stresses in altering the fatigue strength of material subjected to FOD has been handled through the use of stress relief annealing in titanium specimens [5,6]. By careful annealing, residual stresses are effectively eliminated while preserving the microstructural and mechanical characteristics of the material. The greatest challenge, however, is in characterizing the role of the actual damage on the fatigue strength. A secondary challenge is to relate the extent of the microstructural damage and the geometry of the impact damage to the characteristics of the impacting object including velocity and impact energy. In this investigation, damage induced by FOD in a leading edge geometry representative of a fan blade is quantified through a series of experiments involving variations of impact energy, size of impactors, and methods of inducing damage, ranging from quasi-static to ballistic impact.

EXPERIMENTAL PROCEDURES

The test material was Ti-6Al-4V forged plate approximately 20 mm thick that had been heat-treated to the STOA condition. The result was an alpha-beta titanium alloy microstructure with acicular Widmanstätten structures [1].

The simulated airfoil specimen configuration is a diamond cross-section tension specimen. The specimen was designed such that the edges of the gage section are tapered at an angle and to a radius representative of the leading edge on a fan blade. The samples were ballistically impacted using a single-stage compressed gas gun. Details of the specimen and the ballistic impact procedures can be found in Ref [7]. The samples were shot with steel spheres of nominal diameters of 0.5, 1.33, and 2.0 mm at velocities ranging from approximately 60 to 520 m/s at an angle of 30°, relative to a head-on impact to the tapered edge. Several combinations of impact conditions were selected to obtain similar kinetic energy impacts from different size projectiles.

Quasi-static indents were imparted using a servo-electric testing machine under displacement control to produce notches that were geometrically similar to those obtained via ballistic impact. This was accomplished using a steel indentor geometry with the same radius as the ballistically impacting spheres. These same indentors were also fitted onto a pendulum as a third method of imparting damage. Pendulum mass and velocity conditions were chosen to produce similar values of depth of penetration to those of the sphere impacts.

To establish the fatigue strength, samples were fatigue tested using the step-loading procedures described by Maxwell and Nicholas [8], which allows for the development of a fatigue limit stress using a single specimen with no load history effects. Steps of 10^7 cycles were used in this investigation with $\Delta\sigma$ set at 10% of the initial load block. Testing was conducted at a stress ratio (R) of 0.1 and a frequency of 350 Hz using an electro-dynamic, shaker-based test machine. All testing was performed under ambient laboratory air conditions. Further details of the experimental procedures can be found in [1,3,5,6,7].

DISCUSSION OF RESULTS

The reduction of fatigue strength due to a notch is commonly characterized by a fatigue notch factor, K_f, which is defined as the ratio of the smooth bar fatigue strength to that of the notched bar based on net cross sectional area. The value of K_f can be predicted from the elastic stress concentration factor, K_t, through an empirical formula that fits experimental data. For the purposes of this investigation, the notch is assumed to have a radius equal to the impacting sphere or the static indentor, an assumption that was verified in prior investigations on the same material [3,5,6]. Finite element analyses of ideal 30° notches were used to determine K_t for several different combinations of radii and depths. The values of K_f for this investigation are those given by Peterson [9], using a_p = 300 μm as a material constant obtained from fitting notch fatigue data on the same material [10].

Most of the data in this investigation were obtained for impacts with a ball diameter of 1.33 mm and quasi-static indents with the same diameter chisel indentor. The results for the fatigue limit stress, normalized with respect to the smooth bar fatigue strength at R=0.1, 10^7 cycles (568 MPa), are presented in Fig. 1 as a function of the notch depth. Shown also is a reference line corresponding to the fatigue notch factor as calculated for a notch radius of 0.67 mm from the formula for K_f. In the nomenclature used, hollow symbols refer to stress-relieved (SR) specimens, whereas solid symbols are for specimens tested as-is after impacting or indenting (AR). Data obtained at three different ballistic velocities having significantly different kinetic energies are presented, as well as results for the quasi-static and pendulum indents of similar impact depths.

The data trend of both the ballistically impacted and the quasi-statically indented specimens follows essentially the same curve, which is slightly lower than the prediction based solely on notch geometry using K_f. Since the fatigue strength is normalized, the prediction appears as a line calculated as $1/K_f$. Such a line does not take into consideration any microstructural damage imparted by the impacts or any residual stresses produced during the impacts. By comparison, the fatigue strength of specimens with machined notches of depths of approximately 0.2 and 0.4 mm was essentially that as predicted by the K_f formula. The hollow triangles in Fig. 1 show the effect of removing residual stress effects from the quasi-static and pendulum indents, which indicates that the fatigue strength increases due to stress relief. This would imply that the indenting procedure imparted tensile residual stresses. The apparent strengthening effect over that predicted by K_f analysis can be generally explained by observing the geometry of the non-ballistic notch after indentation. The indent produced by quasi-static methods produces substantial bulging, plastic deformation, and distortion of the notch. The net effect invalidates the K_t approximation because of the distorted geometry. Nonetheless, removing the residual stresses causes an increase in the fatigue strength over the as-impacted results using the quasi-static methods.

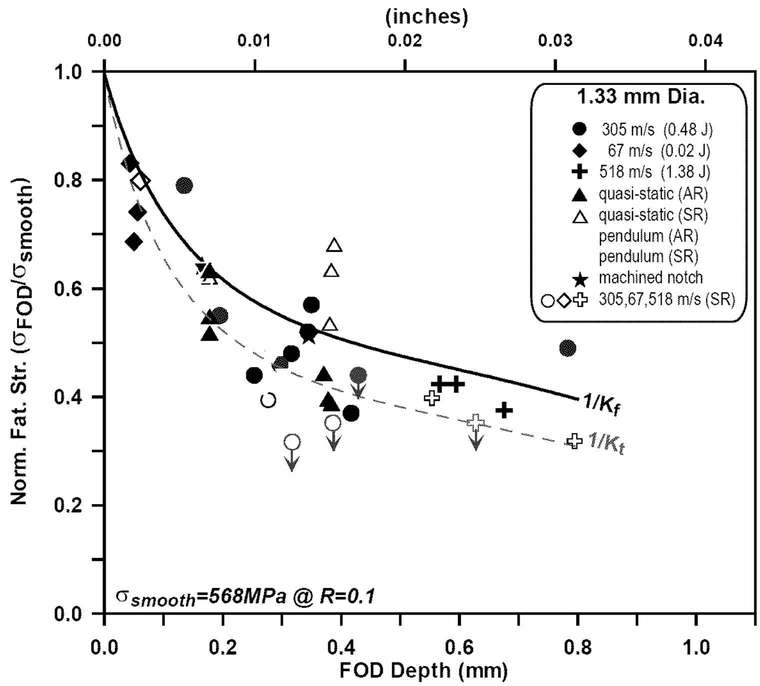
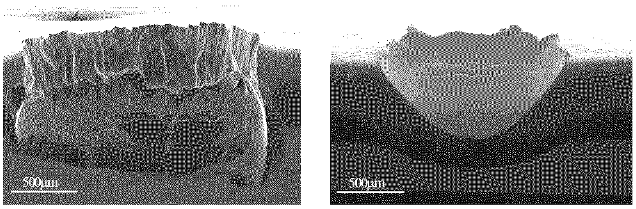


Figure 1. Normalized fatigue strength as a function of FOD depth for 1.33 mm dia. indents.

Stress relief of the specimens that were ballistically impacted, on the other hand, produced a slight reduction in fatigue strength as shown by the hollow circles and crosses in Fig. 1. Here it would appear that the ballistic impacting produces little or no tensile stresses and perhaps beneficial compressive stresses dominate. (A downward arrow in a data point indicates that the fatigue life of 10^7 cycles was not reached on the first loading block of the step test procedure.) This observation of apparent compressive residual stresses is consistent with observations from numerical simulations of spherical ball impacts on this leading edge geometry, which show tendencies for compressive stresses to develop near the exit side of the crater for an ideal impact [11].

The results for the specimens that were impacted/indented with the 0.5 and 2.0 mm diameter sizes, as well as an analysis into the energy levels used to impart the damage for all of the specimens are described in Ref [7]. A brief summary of these results is that for the damage imparted with the 2.0 mm diameter spheres, the K_f analysis tends to over-predict the fatigue limit stresses and the stress-relief procedure seems to have no effect on the fatigue strength. On the other hand, the impacts from the 0.5 mm diameter spheres produce fatigue limits that are higher in the stress-relieved case than for those tested without this procedure.

For the impacts with the larger damage sites, most of the leading edge specimens were chipped or fractured and exhibited what has been termed loss of material (LOM) [3,5], as seen in the SEM photo, Fig. 10(a). Some of the specimen impacts had only permanent deformation (dents) as seen in the SEM photo in Fig 10(b). The depth of penetration of all of the impacts can be correlated well with impact energy, as would be expected, except for cases where fracture occurred locally. In that case, the depth of penetration is generally higher and represents the worst-case scenario regarding fatigue strength debit as noted also in previous research [3,5]. Of particular interest here also is that for the quasi-static and pendulum indents, there were no instances where LOM occurred, even for the largest imparted energy cases examined.



(a) LOM (b) Dented

Fig. 10. SEM photos of indents showing (a) loss of material and (b) indentation

A general observation of all the data can be made that residual stresses that are produced by ballistic impact depend on the size and velocity of the impacting sphere and can be different in magnitude and type (tension vs. compression) depending on their appearance when going from ballistic impacts to quasi-static indentation. Further, it has been observed in numerical simulations that the residual stresses are extremely sensitive to the exact location of the impact on a leading edge geometry [11]. Perhaps the most significant observation is that the fatigue limit stress of a ballistically impacted leading edge specimen, can be reduced by as much as 70-80 percent in the specimens that had the largest amount of damage. While these were the most severe impact conditions in these experiments, this is still a rather small impacting object compared to stones, tools, and even some sand particles that have caused FOD in gas turbine engines in both military and civilian aircraft.

SUMMARY AND CONCLUSIONS

The fatigue limit strength of a ballistically impacted leading edge specimen is influenced by not only the geometry of the notch produced by the impact, but by the residual stress field and mechanisms producing the notch. For notches with lesser amounts of damage, the impact site was predominately plastic deformation that resulted in a notch fatigue strength that is reasonably predicted by conventional notch analysis using K_f. Residual stresses, which tend to alter these strengths somewhat, are very sensitive to the nature of the impact and can be either tensile or compressive and very hard to predict. For larger damage levels, the crater formed was caused by chipping, local failure, and loss of material. In these cases, the fatigue strength was degraded compared to that predicted by K_f analysis and the energy absorbed was lower than for a similar geometry notch caused by plastic deformation. The fatigue strength is degraded the most when loss of material occurs. Quasi-static and pendulum indenting used to produce craters of the same depth as the ballistic impacts resulted in plastic deformation in all the cases investigated. These types of FOD simulations can slightly over-predict the fatigue strength for the same depth of penetration when compared to the ballistic case where loss of material occurs. Further quasi-static tests will be performed such that the imparted damage consists of more than just plastic deformation. While a large LOM is not expected in these cases, it is anticipated that a condition can be found that will provide local fracture of material or small cracking, which should be enough to simulate the ballistic impact cases where LOM occurred.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of Donald Woleslagle of the University of Dayton Research Institute (UDRI) for his substantial contribution to this research, and to Nick Jacobs of UDRI and David Iddings of the Wright State University for their efforts in the quasi-static and pendulum indentation of test specimens.

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