APPLICATION OF LOW PLASTICITY BURNISHING TO IMPROVE DAMAGE TOLERANCE OF A Ti-6Al-4V FIRST STAGE FAN BLADE

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ABSTRACT

This paper describes the application of Low Plasticity Burnishing (LPB) to increase the damage tolerance and fatigue strength of a Ti-6Al-4V fan blade that is fatigue life limited by the occurrence of leading edge foreign object damage (FOD) as small as 0.1mm (0.005 in.). The size and location distributions of service generated FOD were documented; no FOD exceeded a depth of 0.5mm (0.020 in.). LPB processing of the fan blade leading edge was therefore designed to provide tolerance of 0.5 mm deep FOD. A zone of –100 ksi through-thickness compression was achieved extending back 6.3 mm chord-wise from the leading edge along the lower half of the blade from the platform to the mid-span damper. Residual stress distributions were measured as functions of depth and position along the leading edge using x-ray diffraction mapping. HCF testing was with the leading edge cantilever loaded under a sustained mean stress (R=0.1). FOD was simulated with 60-degree "V" notches machined into the leading edge at the point of maximum applied stress. The 620 MPa (90 ksi) endurance limit of as-received blades was reduced to less than half by 0.5mm. FOD. LPB produced an HCF strength of 861 MPa (125 ksi) without FOD, and strengths equal or greater than the as-received blades for FOD up to 1.3 mm (0.050 in.) deep - an order of magnitude improvement in damage tolerance. Fatigue life modeling confirmed the HCF strength achieved, and suggests FOD tolerance can be further increased by optimizing the size and shape of the compressive zone.

INTRODUCTION

High cycle fatigue (HCF) accounts for 56% of major aircraft engine failures[1], and ultimately limits the service life of most critical rotating components. Fan and early stage compressor blades are prone to HCF failure initiating from foreign object damage (FOD) on, or near, the leading edges. FOD creates crack initiation sites and can reduce the HCF strength by half or more, depending upon the depth and form. Because ingestion of fatigue-failed blades can cause catastrophic engine failure, extensive inspection and maintenance programs are required to detect and replace damaged parts. An estimated $400M[1] is expended annually for HCF related inspection and maintenance, greatly increasing the total ownership cost of military aircraft. As the fleet continues to age, the costs for engine inspection and maintenance, and the associated reduction in time on-wing, are projected to increase exponentially.

Low Plasticity Burnishing (LPB) produces a layer of compressive residual stress in Ti-6Al-4V approaching the alloy yield strength and extending to depths exceeding 1.3 mm (0.050 in)[2]. Deep compression from LPB has been shown to dramatically improve both the damage tolerance and fatigue strength of steels[3], titanium[2], nickel[4,5], and aluminum[6] alloys. LPB[7] performed in a machine shop environment using conventional CNC machine tools, is easily incorporated into existing manufacturing and overhaul operations. The objective of this investigation was to determine the potential improvement in HCF life and damage tolerance achievable using LPB to create a zone of through-thickness compressive residual stress on leading edge Ti-6Al-4V fan blades.

Blade Selection and Initial Characterization

Ti-6Al-4V fan blades removed from service during F404 engine overhaul, and containing service generated FOD, were obtained from the Cherry Point Naval Engine Airfoil Center (NEAC) and the Jacksonville Depot.

Proceedings 44th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics & Materials Conf.
Norfolk, VA, April 7-10, 2003

Ten randomly selected blades were examined in detail to determine the depth and spatial distributions of service generated FOD using low power optical microscopy. FOD was distributed along the concave side of the blades ranging from the platform toward the tip, with a higher concentration of FOD near the higher velocity tip. Typical FOD generated on the concave side is shown in Figure 1. A complex and irregular distribution of minor indentations covers the surface, including leading edge impacts. The distribution of FOD along the leading edge is plotted for 50 µm depth increments in Figure 2. More than 400 examples of 50 µm FOD were found, and none larger than 0.5 mm. The frequency of small FOD increased nearly linearly from the platform to the tip of the blade. The FOD depth distribution, regardless of location on the blade, is shown in Figure 3.

Glass bead peening of the blades imparts residual stress and cold work distributions that affect fatigue crack initiation. Existing span-wise (longitudinal) residual stresses were determined by mapping of the residual stress at several depths along the leading edge. The surface was in uniform high compression on the order of -550 to –620 MPa, with cold work ranging from nominally 30 to 50 percent. The subsurface span-wise residual stress distribution is shown in Figure 4 from the surface to 0.38 mm, nominally half of the blade thickness. The shallow compressive layer is typical of glass bead peening of Ti alloy blades.

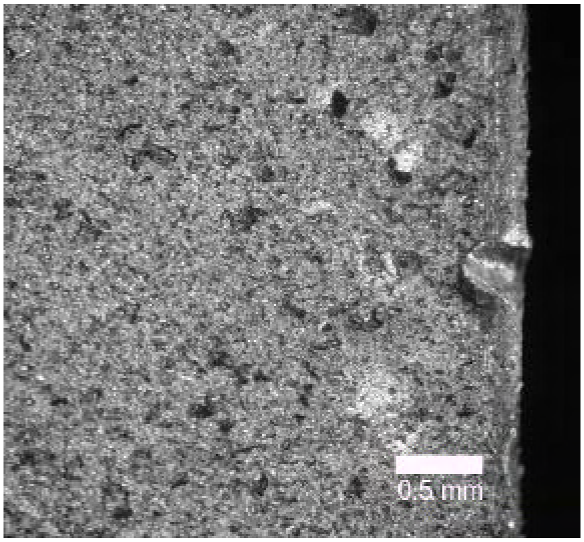

Figure 1 – Typical FOD, consisting of numerous small impact zones and including a single large impact on the leading edge, concave side, of the Ti-6Al-4V first stage fan blade.

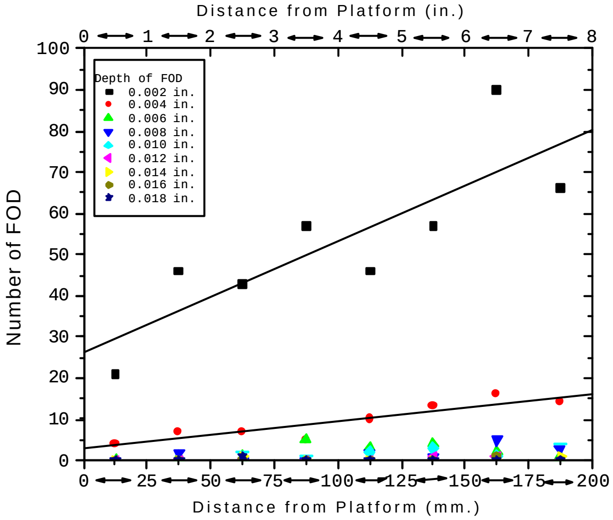

Figure 2 – Distribution of service generated leading edge FOD observed on ten (10) randomly selected Ti-6Al-4V first stage fan blades in terms of both depth and position along the leading edge above the platform.

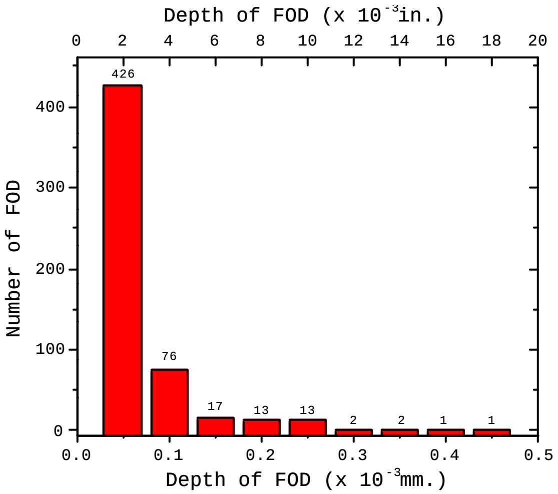

Figure 3 – Distribution of service generated FOD by depth regardless of position along the leading edge of the Ti-6Al-4V first stage fan blades based upon ten (10) randomly selected used blades.

Simulated FOD

Leading edge FOD has been simulated many ways for fatigue studies, including high-speed impact of spheres or cubes of silica glass material, indenting with chisel-shaped tools or pendulum driven cutters, and with machined or EDM notches.[8,9] Actual service generated FOD was found to consist of indentations with a wide array of shapes, sizes and orientations. No one type of impact-generated simulated FOD could be considered typical. Further, complex residual stress distributions generated in and around the impact zones would influence fatigue crack initiation and growth in a manner not necessarily representative of the random FOD that occurs in service.

Simulated FOD of 0.5 mm depth, deeper than any FOD found on the used blades, was chosen to assess the damage tolerance afforded by LPB. FOD was simulated with a 60-degree “V” notch machined into the leading edge with a thread cutting tool at the location of maximum applied stress in the cantilever loading mode used for fatigue testing. The “V”-notch was chosen as a reproducible simulation of service generated FOD, and was also amenable to fracture mechanics based fatigue life modeling. After initial HCF testing indicated LPB completely mitigated the effects of 0.5 mm FOD, depths of 1.25 mm and 2.5 mm were produced to assess the maximum FOD tolerance. The FOD notches were machined in a gentle fashion with a series of machining steps as the cutter advanced into the edge of the blade to minimize machining residual stresses. Photographs of the machined FOD are shown in Figure 5 viewed from the concave and convex sides of a blade.

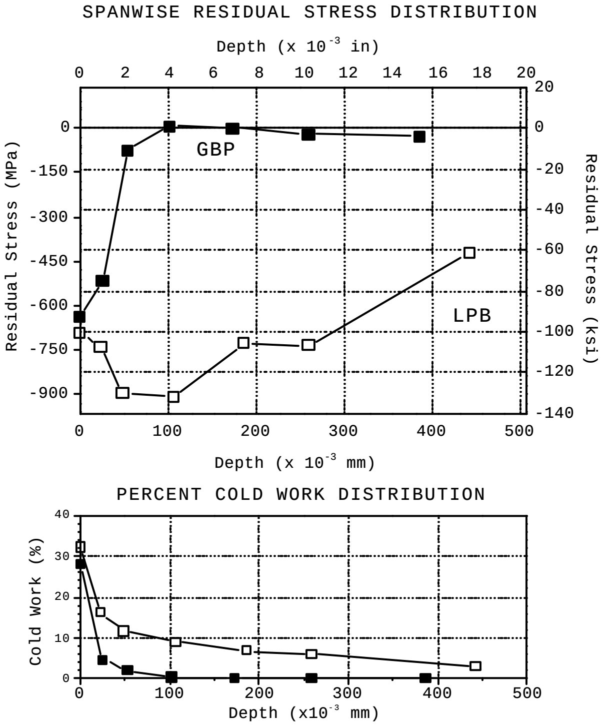

Figure 4 – Span-wise residual stress and cold work distributions as functions of depth produced by glass bead peening (GBP) and LPB on the leading edge of a Ti-6Al-4V first stage fan blade.

LPB Processing

Low plasticity burnishing (LPB) develops a deep layer of high compression, with improved surface finish and minimal cold work.[7] Unlike other burnishing or "deep rolling" methods, a single pass of a smooth free rolling spherical tool is used under a normal force just sufficient to deform the material, creating a compressive layer of residual stress with low controlled plastic deformation and surface cold working. Low cold working provides overload and thermal stability of the residual compression produced.[10] The LPB tool path is controlled in a CNC machine tool in a machine shop environment. Any surface topography that can be followed with a multi-axis CNC tool and allows tool access can be LPB processed. The form and magnitude of the compressive residual stress distribution produced can be engineered to cancel applied tensile stresses and optimize fatigue performance. The LPB tooling and process have been described previously.[4,11,12]

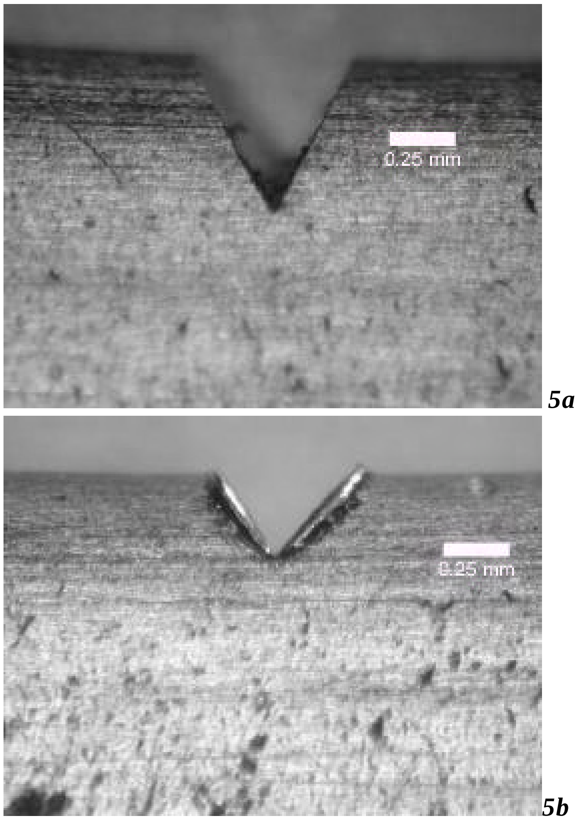

Figure 5 – Simulated FOD created as a 60-degree “V” notch on the convex (entrance) side in Figure 5A and the concave (exit) side Figure 5b.

The blades were held in a fixture by the dovetail during LPB processing on a four-axis CNC mill. A region nominally 6.3 mm wide along half the length of the leading edge, from the platform to the mid-span damper, was processed using an LPB caliper tool to burnish both sides simultaneously, as shown in Figure 6, developing compression through the thickness of the leading edge. To avoid a sharp transition at the end of the compressive region, the burnishing pressure was gradually reduced at the boundaries of the LPB zone. The fine surface finish produced on the leading edge is evident in the photograph of the finished blade in Figure 7.

Figure 4 shows the span-wise residual stress distribution produced by LPB to a depth equal to the blade mid-thickness. Through-thickness compression was achieved, ranging from –690 MPa (–100 ksi) at the surface, to approximately –410 MPa (–60 ksi) at mid-thickness. Surface roughness of the blades with service FOD was on the order of 2.1µm as-received and 0.5 µm after LPB.

Figure 6 – First stage Ti-6-4 fan blade being LPB processed in 4-axis CNC facility.

Figure 7 – Photograph of a finished Ti-6Al-4V first stage fan blade showing the LPB region spanning the lower half of the leading edge. (The hole near the tip of the blade is used for loading during fatigue testing.)

Fatigue Testing

Fatigue tests were performed in cantilever bending with a positive mean stress (R = Smin / Smax = +0.1) to maintain the leading edge in tension and simulate the first bending mode of the blade with the high centrifugal mean stress typical for fan blades. A dovetail gripping system was designed to avoid fretting induced dovetail failures by tightly clamping the base of the blade. Loading was applied through a linkage with two spherical tie-rod end bearings to accommodate the complex bending, twisting, and translational deformation of the blade under cantilever loading. The specimen mounted for testing is shown in Figure 8. The blade was aligned in a nearly vertical orientation so that the top edge was placed in maximum tension under cantilever bending. Fatigue tests were conducted at constant stress amplitude, 30 Hz, and at ambient temperature.

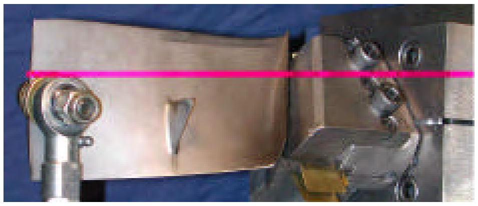

Figure 8 – Close-up of the first stage fan blade mounted in cantilever loading for fatigue testing. (Note the low plasticity burnished leading edge at the top of the blade.)

Both the location of maximum applied stress in cantilever bending and a load calibration curve were determined using a blade instrumented with a series of ten strain gages along the leading edge. Simulated FOD was machined at the maximum stress location, 53.4 mm (2.12 in.) above the platform. The dynamic load during testing was calculated from the calibration curve relating the stress at the maximum stress location to applied static load.

Fatigue Life Modeling

AFGROW, version 4.002.12.8, was used to perform fatigue crack growth and fatigue life modeling. The fan blade geometry was approximated as a thin plate, 91 mm (3.58 in.) wide and 0.75 mm (0.03 in.) thick; with FOD introduced as a single through-thickness edge crack. Crack growth data for mill annealed Ti-6Al-4V in bending at R=0.1 were not found, but data for remote tensile loading at R=0.1 was available.[13] Remote tension loading was assumed to adequately simulate cantilever loading for the small crack growth that dominates HCF life. A 0.2% yield strength of 965 MPa (140 ksi) was assumed.

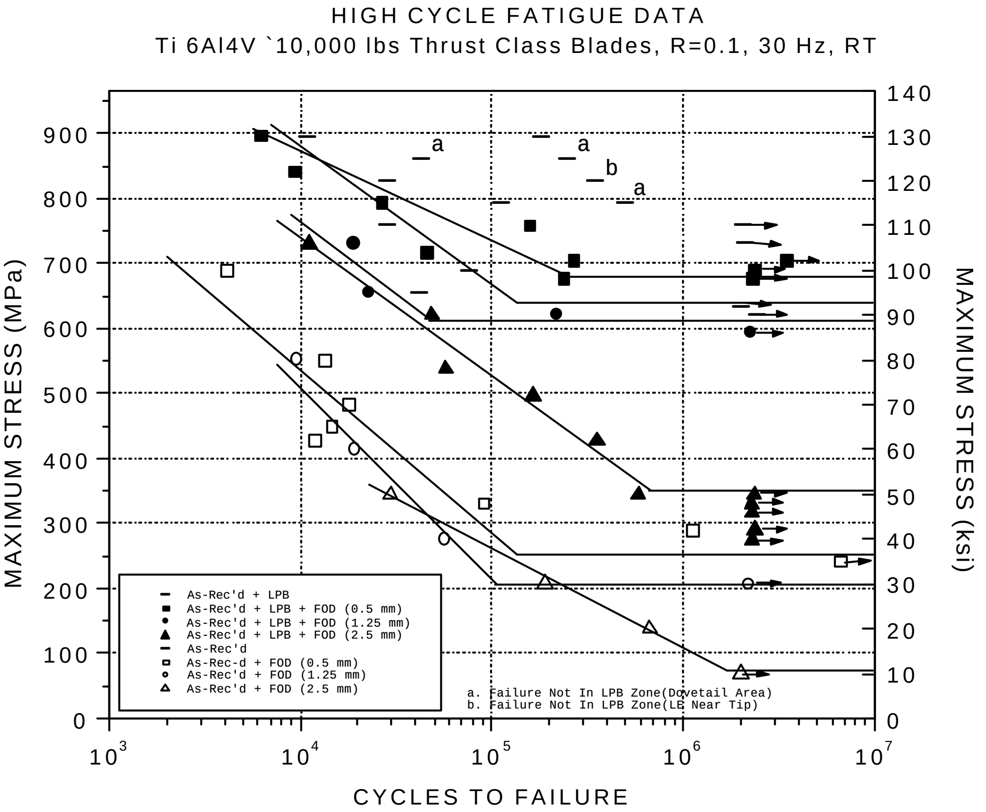

Figure 9 – S/N curves for the Ti-6Al-4V first stage fan blades as received (with service generated FOD) and with LPB for 0.5, 1.25 and 2.5 mm FOD.

RESULTS AND DISCUSSION

High Cycle Fatigue and Damage Tolerance

The high cycle fatigue S-N curves are presented in Figure 9 for four blade conditions and three FOD depths:

1. As-received blades (service FOD only)
2. As-received + 0.5, 1.25, or 2.5 mm simulated FOD
3. As-received (service FOD only) + LPB
4. As-received + LPB + 0.5, 1.25 or 2.5 mm FOD.

Typically, origins were not located at the highest stress location along the leading edge, demonstrating that small service FOD impressions were significant fatigue initiation sites. Fatigue origins associated with FOD were located from 56 mm (2.2 in.) to 74 mm (2.9 in.) from the platform, whereas the maximum applied stress occurred at 53 mm (2.1 in.). The fatigue strength (HCF endurance limit) of the as-received blades was nominally 655 MPa (95 ksi). With one exception, fatigue cracks initiated from small service generated FOD impressions on leading edges, 0.13 mm and less in depth. A typical fatigue initiation from service FOD on the concave side of the leading edge is shown in Figure 10.

Fatigue crack progression in the thin highly stressed as-received blades occurred primarily via shear, in slant-mode rather than normal-mode. The tendency for slant-mode propagation increased with the applied stress level, consistent with shear mode propagation. Visual observation of crack tunneling during failure, with surface deformation noted before observation of a physical crack, provided further evidence of slant-mode crack progression.

The fatigue strength of as-received blades was reduced to nominally 240 MPa (34.8 ksi) with FOD 0.5 mm deep, one-third the strength without FOD. FOD 1.25 mm deep reduced the fatigue strength nominally the same amount. (It should be noted that the 0.5 mm FOD was machined at an angle to the blade edge, and the depth exceeded 0.75 mm on the convex side of several samples.) The deepest 2.5 mm FOD further reduced the HCF strength to less than 100 MPa (14.5 ksi). At stress levels above the endurance limit, regardless of the FOD depth, fatigue life was reduced by an order of magnitude. Fatigue cracking initiated from the base of the FOD notch near mid-thickness of the blade cross-section, in all cases.

LPB effectively strengthened the leading edge, causing all but one failure to occur outside the LPB zone, generally in the dovetail. One failure did occur within the LPB zone at the point of maximum applied stress on the leading edge after 10^5 cycles with a maximum alternating stress of 895 MPa (129.9 ksi), near the yield strength. Assuming an S-N curve of comparable shape to that of the as-received blades, the one LPB zone failure indicates LPB increased the HCF endurance limit in the absence of FOD to nominally 790 MPa (115 ksi). Initiation occurred subsurface, beneath the leading edge, and shear, slant-mode fatigue cracking was inhibited within the LPB zone. Normal or flat-mode cracking predominated despite the high applied stress level. Slant-mode propagation immediately resumed, when the crack passed beyond the compressive LPB zone. This crack mode transition is considered direct evidence of the role of compressive residual stresses created by LPB in reducing the effect of the applied stress on the advancing fatigue crack.

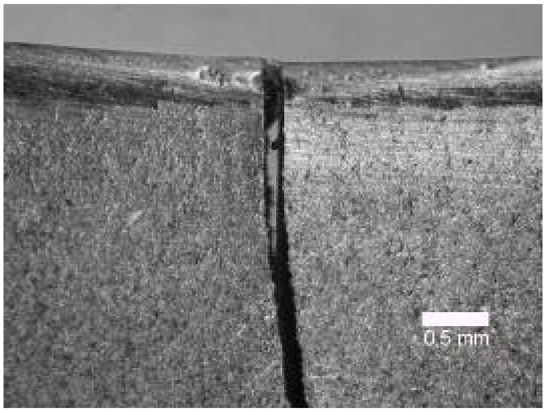

Figure 10 – Fatigue crack emanating from nominally 75 ìm deep FOD at the leading edge of a Ti-6Al-4V first stage fan blade in the as-received condition.

LPB processed blades with 0.5 mm FOD had both HCF strength and fatigue life at stresses above the endurance limit generally better than the original blades without FOD. The fatigue strength of blades with FOD 1.25 mm deep introduced after LPB was virtually identical to that of as-received blades. This is an order of magnitude improvement in the current 0.13 mm (.005 in.) limit for FOD on the critical lower third of the leading edge. FOD 2.5 mm deep reduced the endurance limit to nominally 345 MPa (50.1 ksi), still a smaller fatigue debit than 0.5 mm FOD without LPB. The LPB compressive layer retarded crack growth, providing nearly an order of magnitude fatigue life improvement with FOD from 0.5 to 2.5 mm deep. Fatigue initiation in blades with LPB always occurred from the notch root at mid-thickness of the blade cross-section, as shown in Figure 11. Compressive residual stresses from LPB always produced normal-mode crack progression within the LPB zone, transforming to slant-mode progression beyond.

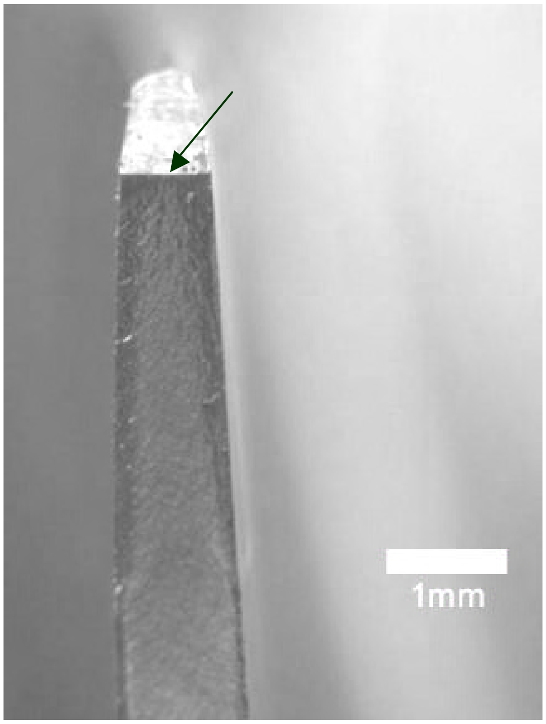

Figure 11 – Fatigue initiation at mid-thickness 1.25 mm FOD root in LPB processed blade.

Fatigue Life Prediction

As a fracture mechanics based code, AFGROW requires a finite initial crack size. FOD on the as-received blade was assumed equivalent to a crack depth of 0.01 mm, on the order of observed service FOD depths. Simulated FOD of 0.5, 1.25 and 2.5 mm depths was modeled as an initial crack of the same depth. The span-wise residual stress distributions (parallel to the axis of loading) produced by LPB processing were assumed for the fatigue life calculations to be uniform at –690 MPa through the entire thickness of the blade edge. No residual stresses were introduced for the as-received blade model.

Predicted HCF S-N curves for 0.5 mm leading edge FOD in a highly compressive (–690 MPa) LPB zone and in a stress-free blade are shown superimposed on the actual fatigue data in Figure 12. Even with the assumed simple geometry and stress field, the calculated S-N curves are

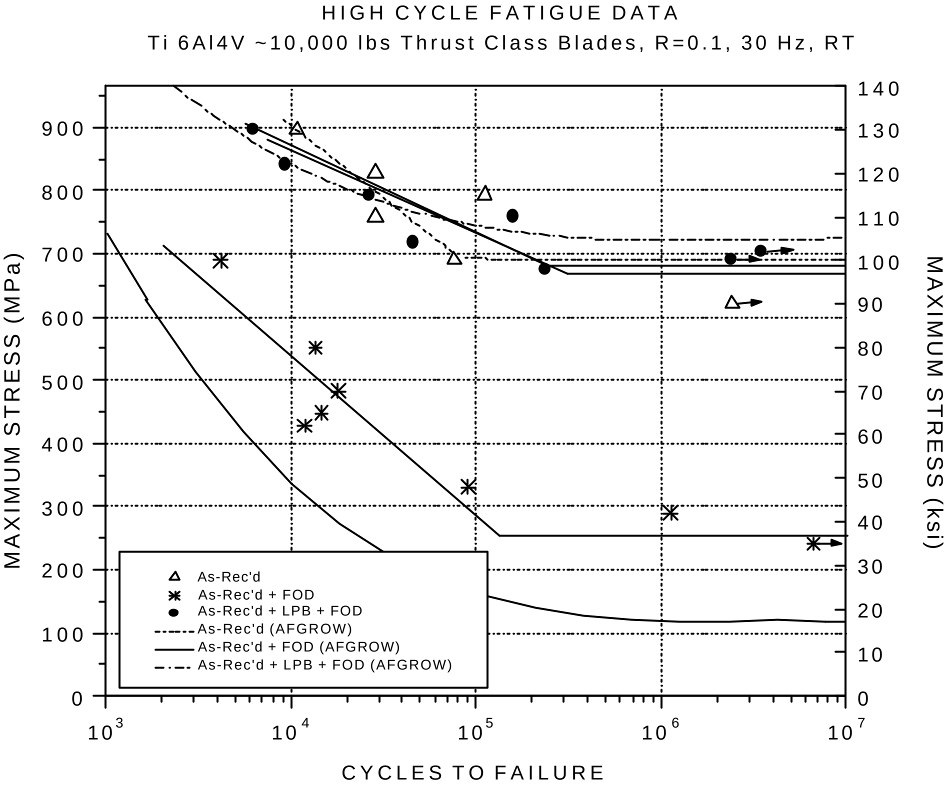

Figure 12 – Ti-6Al-4V first stage fan blade fatigue life predictions assuming –690 MPa (-100 ksi) compression through the thickness with 0.5 mm FOD.

in good agreement with the fatigue data for the LPB processed blades. The predicted endurance limit of 725 MPa is within 5% of the nominal 690 MPa value obtained from testing. However, the predicted S-N curve for 0.5 mm FOD without LPB is consistently 138 MPa lower than the as-received test data. Compressive residual stresses induced during machining of the FOD simulation notches may have increased fatigue life during testing.

AFGROW predicts that FOD deeper than 0.5 mm should be tolerated by the zone of compression produced by LPB. Predicted fatigue lives are shown in Table I for different maximum stress levels and FOD depths. Infinite life is predicted for 0.5 mm FOD with 690 MPa maximum applied stress, in agreement with the experimental results. Infinite life is predicted for FOD up to 3.8 mm (0.15 in.) deep if the maximum stress is less than 655 MPa (95 ksi). Even FOD of 5 mm (0.20 in) should be tolerated for stress levels below 620 MPa (90 ksi), well above the design stress for the fan blade.

Predicted and test fatigue lives for the LPB processed blades with FOD of 1.25 mm or smaller agree well, but the fatigue strength for 2.5 mm FOD was substantially less than predicted. To investigate this disparity, the span-wise residual stress was mapped as a function of the chord-wise distance from the leading edge on both surfaces, at depths of 0.127 mm , and at the depth of mid-thickness, 0.38 mm. Figure 13 reveals that, although the LPB processed zone extended back 6.3 mm from the leading edge at the surface, uniform –690 MPa compression was actually achieved only 2.5 mm back from the leading edge, and then diminished linearly to zero at 5 mm. FOD 2.5 mm deep penetrated entirely through the uniform compressive layer assumed for life calculation. The ability to tolerate 0.5 mm and 1.25 mm FOD without loss of fatigue strength and the fatigue debit for 2.5 mm deep damage appears to be explained by the residual stress distributions actually achieved.

Figure 13 also reveals that high tension does not exist behind the compressive edge. The tension needed to maintain equilibrium is of low magnitude extending on through the thick section of the blade (off of the figure to the right), rather than as a peak of high tension immediately adjacent to the compressive zone.

Table I
AFGROW Life Predictions

LPB Treated TI-6AL-4V 1st Stage Fan Blade

LE Notched to Various Depths 53 mm (2.1 in) above Platform
Constant Stress Amplitude, R=0.1

Notch Depth (mm.)

Max Stress (MPa)	0.002	0.050	0.13	0.25	0.51	1.27	1.90	2.54	3.81	5.08
896	11*	75	18	9	6	4	3	2	1	0.5
826	INF	INF	75	28	14	9	7	6	3	2
792			INF	66	28	15	11	9	5	3
758				213	76	29	21	16	10	5
723				INF	355	96	58	41	22	11
689					INF	94	47	28	104	28
654						INF	INF	INF	INF	136
620										INF

** Life in 10^3 cycles*

CONCLUSIONS

LPB produced a region of compressive residual stress approaching the yield strength and extending through the thickness of the leading edge of a titanium alloy fan blade. Through-thickness compression on the order of – 690 MPa (-100 ksi) was achieved along the FOD sensitive lower third of the blade extending from the leading edge 2.5 mm (0.10 in.) chord wise. LPB processing was performed in a machine shop environment on a conventional 4-axis CNC machining center.

At stresses above the endurance limit, the life of untreated blades with either depth FOD was less than 10% of the life of an undamaged or LPB treated blade. LPB increased the endurance limit in the absence of FOD from 655 to 790 MPa (95.1 to 114.7 ksi). LPB prior to 0.5 mm (0.02 in.) deep FOD increased the endurance limit from nominally 240 MPa to 655 MPa (34.8 to 95.1 ksi), and for 1.25 mm (0.050 in.) FOD, from 206 to 620 MPa (29.9 to 90.0 ksi).

Fatigue life prediction with AFGROW confirmed both the improved HCF strength and damage tolerance afforded by LPB. Modeling further predicted that any depth of FOD less than the extent of the chord-wise zone of through-thickness compression should be tolerated. Further, the HCF endurance limit should be nominally equal to the magnitude of the through-thickness compression achieved.

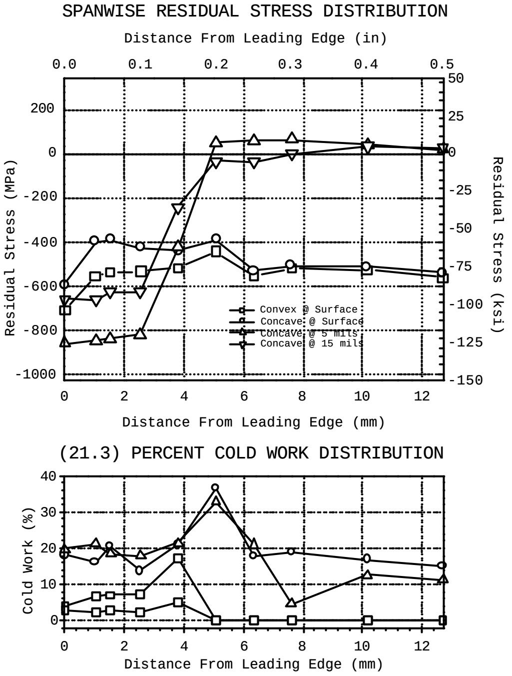

Figure 13 – Span-wise (longitudinal) residual stress distributions in the Ti-6Al-4V first stage fan blade after LPB, showing extent of through thickness compression.

The ability of low plasticity burnishing to provide an order of magnitude improvement in the damage tolerance of a titanium alloy fan blade has been successfully demonstrated. Application of LPB to the leading edges of FOD sensitive fan and compressor blades can significantly reduce the costs of turbine engine inspection and maintenance while improving fleet readiness.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge both funding and technical support for this work under Navy SBIR contract N68335-01-C-0274 and the contributions of the staff of Lambda Research for making this research possible.

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