Improved Damage Tolerance in Titanium Alloy Fan Blades with Low Plasticity Burnishing

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ABSTRACT

Low Plasticity Burnishing (LPB) has been applied to produce a layer of deep high magnitude compressive residual stress in the leading edge of Ti-6Al-4V first stage fan blades. The goal was to improve damage tolerance from 0.13 to 0.5 mm (0.005 to 0.02 in.). LPB processing of the airfoil surface was performed on a conventional four-axis CNC mill. The LPB control system, tooling, and process are described. A zone of through-thickness compression on the order of −690 MPa (-100 ksi) was achieved extending 2.5 mm (0.10 in.) cord-wise from the leading edge and along the lower half of the blade from the platform to mid-span damper. Cantilever fatigue testing was performed at R=0.1 using FOD simulated by a 60 degree "V" notch. The processing provided complete tolerance of FOD up to nominally 1.3 mm (0.05 in.) in depth, an order of magnitude improvement in damage tolerance. The benefits of the deep layer of surface compression were confirmed through fatigue performance modeling.

INTRODUCTION

Turbine engine fan and compressor blades are prone to HCF failure because of high mean operating stresses and foreign object damage (FOD). FOD creates crack initiation sites and reduces the HCF strength by nominally one-half. High cycle fatigue (HCF) accounts for 56% of major aircraft engine failures[1]. To avoid catastrophic engine failure, extensive inspection and maintenance programs have been developed to detect, rework and replace damaged blades. An estimated $400M[1] is expended annually for HCF related inspection and maintenance of military aircraft alone, greatly increasing the total cost of aircraft ownership. As the fleet continues to age, the costs for engine inspection and maintenance are projected to increase exponentially. The associated reduction in time on-wing increasingly impacts fleet readiness.

Low Plasticity Burnishing (LPB) can produce 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). Deep compression from LPB has been shown to dramatically improve both the damage tolerance and fatigue strength of steels[2], titanium[3], nickel[4,5], and aluminum[6] alloys. LPB is performed in a machine shop environment using conventional CNC machine tools, and can be 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 highly compressive residual stress on leading edges of FOD prone Ti-6Al-4V fan blade.

Blade Selection and Initial Characterization

The first-stage fan blade of the F404 engine used in the F18 fighter was chosen as typical of FOD limited Ti-6Al-4V fan blades. Blades removed from service during engine overhaul, and containing service generated FOD, were obtained from the Cherry Point Naval Engine Airfoil Center (NEAC) and the Jacksonville Depot.

Ten blades were examined in detail using low power optical microscopy to determine both the depth and spatial distributions of the service generated FOD. 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. 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. Grit loosened from the anti-skid surface coating used on aircraft carriers was reported to be a primary source of FOD particles. The distribution of FOD along the leading edge is plotted for 50 μm depth increments in Figure 2. 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. More than 400 examples of 50 μm FOD were found, and none larger than 0.5 mm.
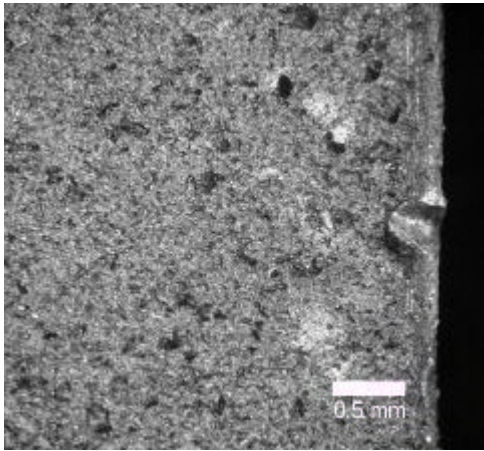

Figure 1 – Typical FOD, consisting of numerous small impact zones and including a single large impact on the leading edge, concave side, of the Ti-6Al-4V first stage fan blade.

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.
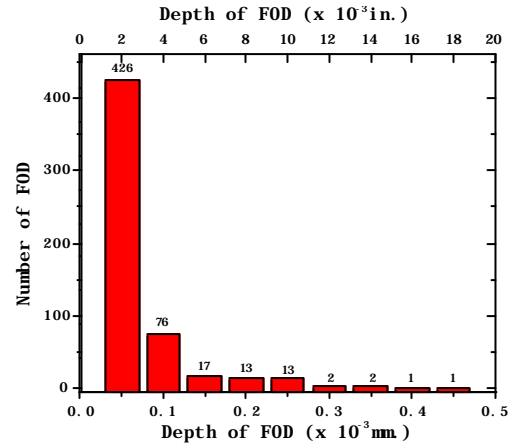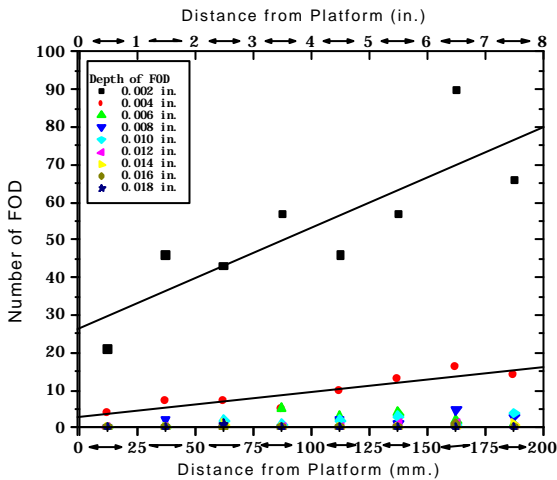

Figure 3 – Distribution of service generated FOD by depth regardless of position along the leading edge of the Ti-6Al-4V first stage fan blade based upon ten (10) randomly selected used blades.

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 -80 to -90 ksi (-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.

Simulated FOD

Leading edge FOD has been simulated many ways, including high-speed impact of spheres or cubes of silica glass material, by indenting the leading edge with chisel-shaped tools, pendulum driven cutters, and with machined or EDM notches.[9,10] Service generated FOD consisted 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. A "worst case" FOD was selected as appropriate for the purpose of assessing the effect of LPB on damage tolerance.

SPANWISE RESIDUAL STRESS DISTRIBUTION

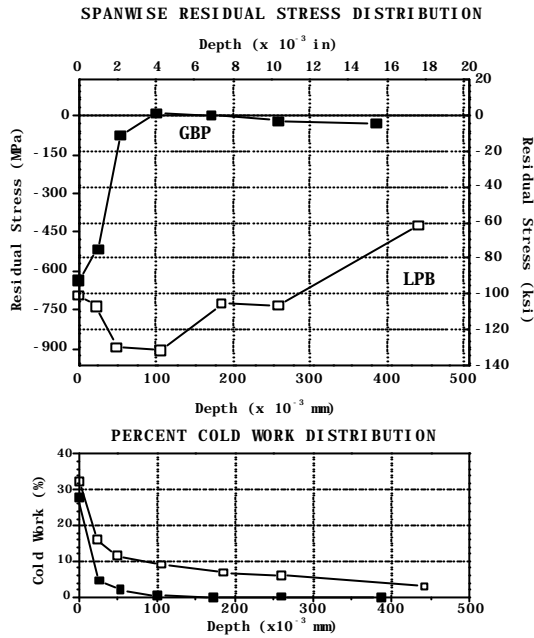**PERCENT COLD WORK DISTRIBUTION**

5a

5b

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.

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. 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. 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.

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 surface of the material, creating a compressive layer of residual
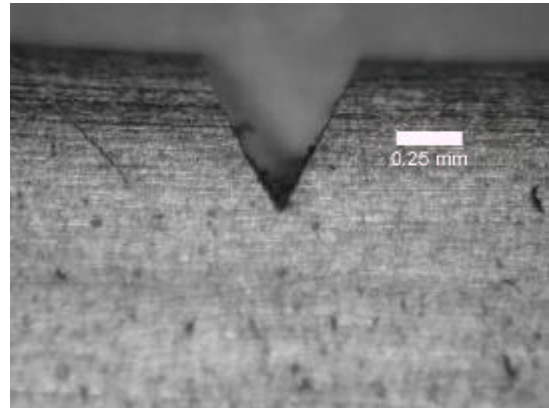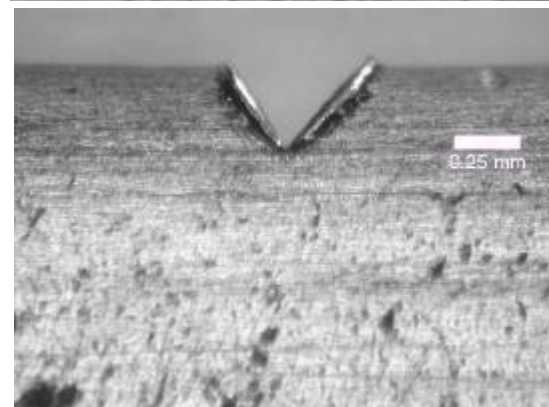
Figure 5 – Simulated FOD created as a 60-degree "V" notch on the convex (entrance) side in Figure 5A and the concave (exit) side Figure 5b.

stress with low controlled plastic deformation and surface cold working. Low cold working provides overload and thermal stability of the residual compression produced.[8] 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 process has been described in an earlier paper.[4]

A region nominally 6.3 mm wide along half the length of the leading edge, from the platform to the mid-span damper, was selected for burnishing. The blades were held in a fixture by the dovetail during LPB processing on a four-axis CNC mill. A caliper tool was used to burnish both sides simultaneously, as shown in Figure 6, developing compression through the thickness of the leading edge. LPB processing parameters were developed with a series of trials, adjusting the LPB pressure and tool path until suitable levels of surface and through-thickness compression were achieved. 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. LPB processing was completed in nominally 15 min. per blade.

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.)

The span-wise residual stress distribution produced by LPB to a depth equal to the blade mid-thickness is shown in Figure 4. 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.

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 rotor 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

Fatigue crack growth and fatigue life modeling were performed using AFGROW, version 4.002.12.8. 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.[11] 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.
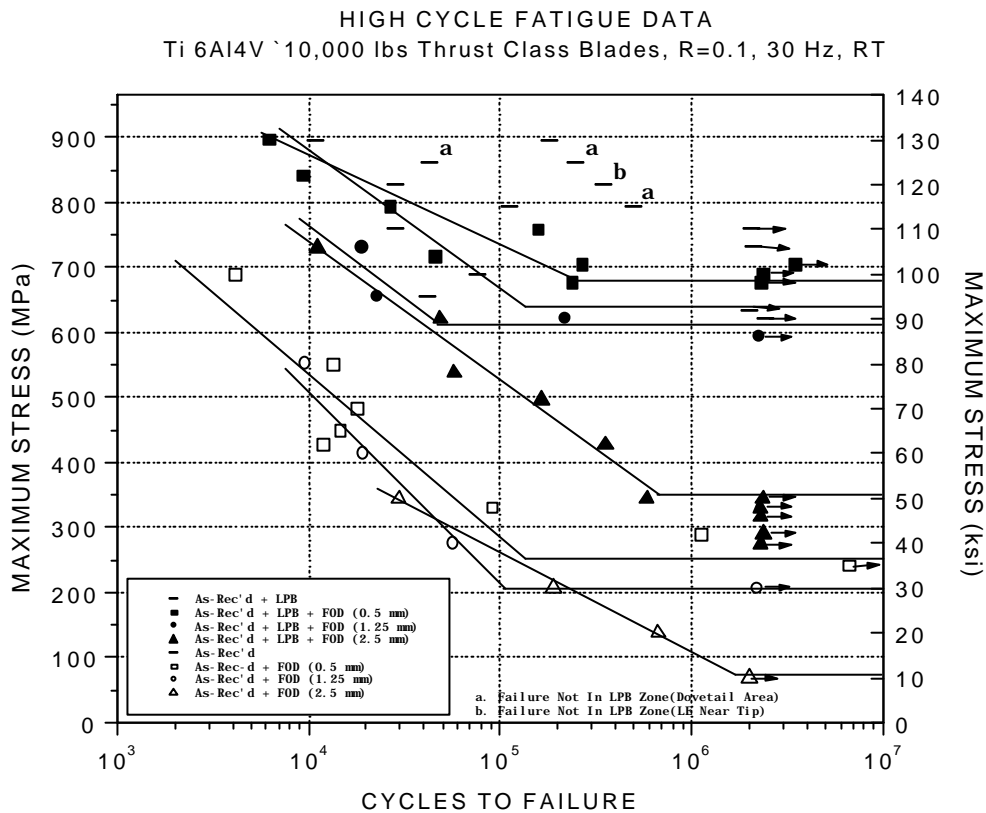
HIGH CYCLE FATIGUE DATA
Ti 6Al4V `10,000 lbs Thrust Class Blades, R=0.1, 30 Hz, RT

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.
5.

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. Figure 10 shows such a typical fatigue initiation from service FOD on the concave side of the leading edge. 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.).

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 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.

FOD 0.5 mm deep reduced the fatigue strength of as-received blades to nominally 240 MPa (34.8 ksi), 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). FOD also reduced the fatigue life at stress levels above the endurance limit by an order of magnitude, regardless of the FOD depth. In all cases fatigue cracking initiated from the base of the notch near mid-thickness of the blade cross-section.
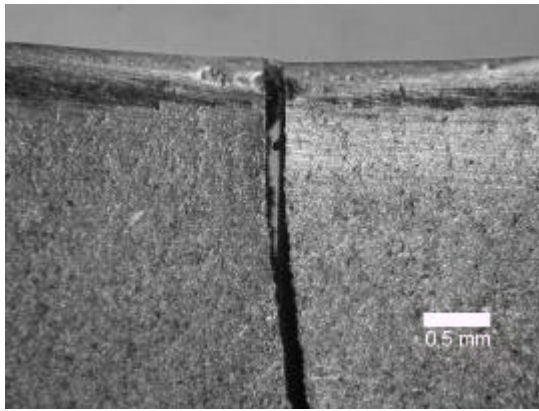
Figure 10 – Fatigue crack emanating from nominally 75 ìm deep FOD at the leading edge of a Ti-6Al-4V first stage fan blade in the as-received condition.

LPB 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. When the crack passed beyond the compressive LPB zone, slant-mode propagation immediately resumed. 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.

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 without FOD. 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.
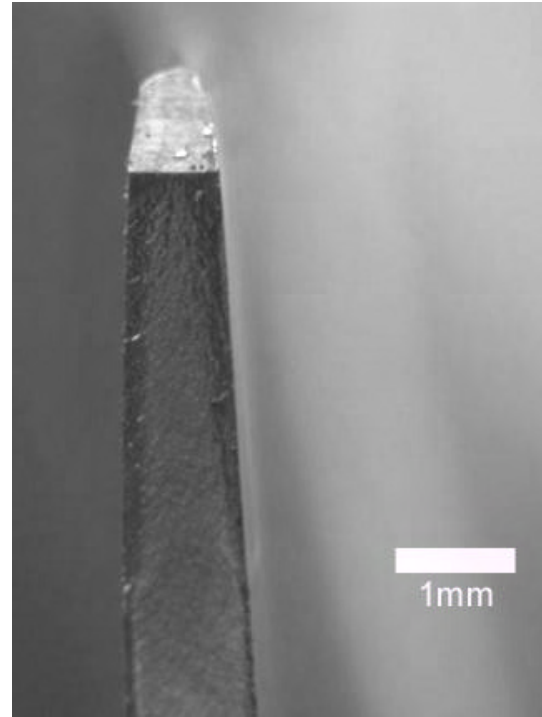

Figure 11 – Fatigue initiation at mid-thickness 1.25 mm FOD root in LPB processed blade.

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 (–100 ksi) through the entire thickness of the blade edge. No residual stresses were introduced for the as-received blade model.

HIGH CYCLE FATIGUE DATA
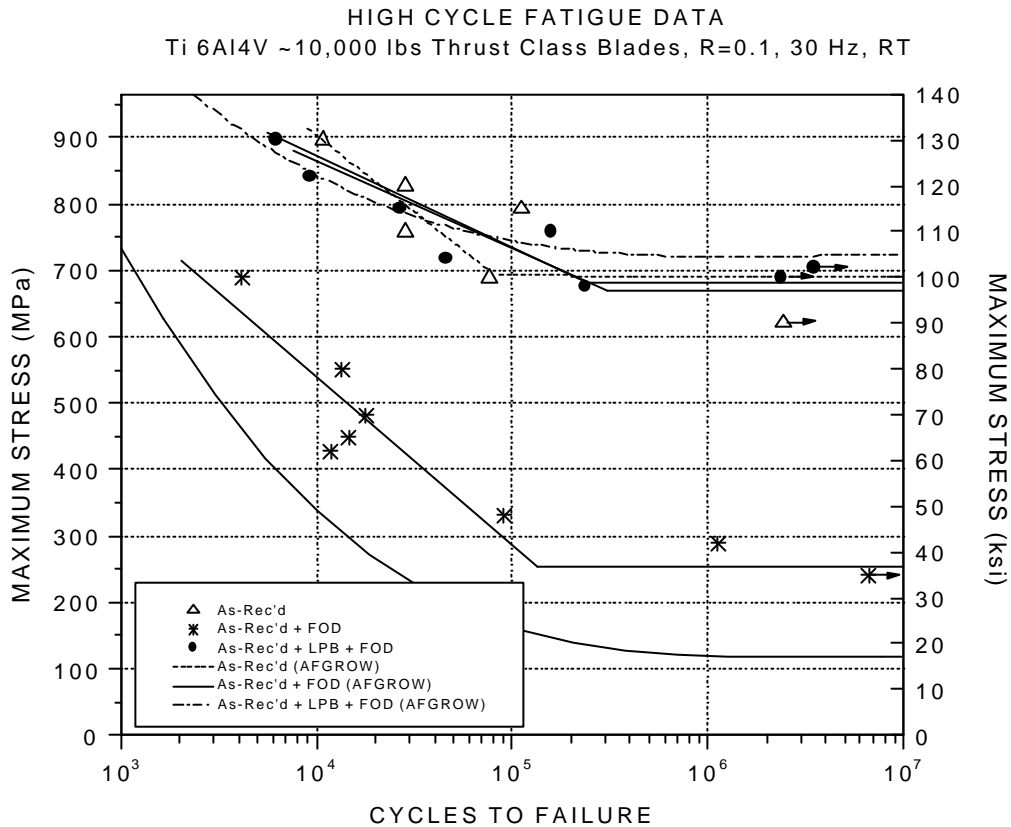Ti 6Al4V ~10,000 lbs Thrust Class Blades, R=0.1, 30 Hz, RT

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.

Predicted HCF S-N curves for 0.5 mm leading edge FOD in a highly compressive (–690 MPa, -100 ksi) 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 in good agreement with the fatigue data for the LPB processed blades. The predicted endurance limit of 725 MPa (105.2 ksi) is within 5% of the nominal 690 MPa (100 ksi) value obtained from testing. However, the predicted S-N curve for 0.5 mm FOD without LPB is consistently 138 MPa (20.0 ksi) 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 (0.02 in.) FOD with 690 MPa (100 ksi) 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 (0.05 in.) or smaller agree well, but the fatigue strength for 2.5 mm (0.10 in.) 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 (0.005 in.), and at the depth of mid-thickness, 0.38 mm (0.015 in.). Figure 13 reveals that, although the LPB processed zone extended back 6.3 mm (0.25 in.) 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 (0.20 in.). FOD 2.5 mm (0.015 in.) deep penetrated entirely through the uniform compressive layer assumed for life calculation. The ability to tolerate 0.5 mm (0.02 in.) and 1.25 mm (0.05 in.) FOD without loss of fatigue

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

Max Stress (MPa)	Notch Depth (mm.)									
	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

strength and the fatigue debit for 2.5 mm (0.1 in.) deep damage appears to be explained by the residual stress distributions actually achieved.
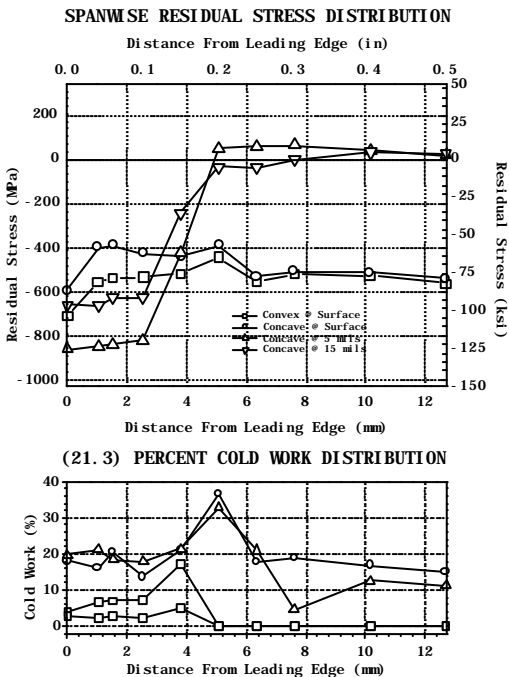

Figure 13 – Span-wise (longitudinal) residual stress distributions in the Ti-6Al-4V first stage fan blade after LPB, showing extent of through thickness compression.

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.

CONCLUSIONS

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 has been produced with LPB. 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 a rate of 15 minutes per blade.

The effect of LPB on fatigue strength and damage tolerance was tested using actual fan blades in cantilever bending with a mean stress to simulate engine service. The endurance limit in the absence of FOD was increased 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). 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.

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.

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

ACKNOWLEDGEMENTS

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