

# IMPROVED DAMAGE TOLERANCE OF Ti-6Al-4V AERO ENGINE BLADES AND VANES USING RESIDUAL COMPRESSION BY DESIGN

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## ABSTRACT

The deep stable layer of compressive residual stress produced by low plasticity burnishing (LPB) has been demonstrated in laboratory testing to improve damage tolerance in engine alloys IN718, Ti-6Al-4V, Ti-6-2-4-6, and 17-4PH. This paper describes the fatigue and FOD tolerance benefits afforded by LPB treatment of a Ti-6Al-4V first stage fan blade and vane. FOD sensitive blades and vanes removed from fielded engines were LPB processed to protect the leading edge of the blade and the trailing edge of the vane. Both components were fatigue tested in cantilever bending mode at  $R > 0$  using specially designed test fixtures. FOD was simulated with machined notches for the blade and electrical discharge machined (EDM) notches for the vane. Residual stress and cold work distributions were measured using x-ray diffraction mapping techniques.

LPB produced a zone of nominally  $-100$  ksi ( $-690$  MPa) through-thickness compression in the leading edge of the blade and trailing edge of the vane. The HCF strength for LPB processed blades was 125 ksi (860 MPa) without FOD, and equal or greater than the as-received blades for FOD up to 0.050 in. (1.3 mm) deep - an order of magnitude improvement in damage tolerance. For both vanes and vane simulation specimens with 0.020 in. (0.5 mm) deep FOD, the HCF strength after LPB was over 4 times higher than the unprocessed counterparts. The HCF performance was largely unaffected by FOD up to 0.030 in. (0.7 mm) deep. If the traditional design criterion of  $K_t = 3$  is used, both the LPB processed blade and vane could be considered tolerant of even 0.10 in. (2.5 mm) deep FOD.

Linear elastic fracture mechanics analysis using AFGROW including the residual stress fields confirms the HCF and FOD performance and the minimal effect of stress ratio,  $R$ , in the presence of high residual compression. A novel Haigh diagram based method of predicting the improvement in damage tolerance is described and demonstrated for the Ti-6-4 blade and vane application using the fatigue data developed in the IHPTET HCF program and from the current work. The method allows estimation of the minimum compression required to achieve a desired damage tolerance or the optimum tolerance possible for a given application in terms of  $R$ -ratio, applied stress and  $K_I$  for the damage mechanism. The method provides a means of improving the damage tolerance of engine components by design, potentially reducing operating costs and improving fleet readiness by reducing inspection and maintenance requirements.

## INTRODUCTION

Fan and compressor blades are prone to HCF failure because of high mean operating stresses and foreign object damage (FOD). High cycle fatigue (HCF) accounts for 56% of major aircraft engine failures<sup>1</sup> and ultimately limits the service life of most critical rotating components. FOD creates crack initiation sites and reduces the HCF strength by nominally one-half. Extensive inspection and maintenance programs have been developed to detect, rework and replace damaged blades, to avoid catastrophic engine failure. An

estimated \$400M<sup>1</sup> 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. In this paper, examples of complete mitigation of FOD and HCF damage in a Ti-6Al-4V compressor vane and blade by LPB treatment of the damage prone edges are presented. The design methodologies utilized to achieve the correct level and shape of compression to accomplish damage tolerance are also described.

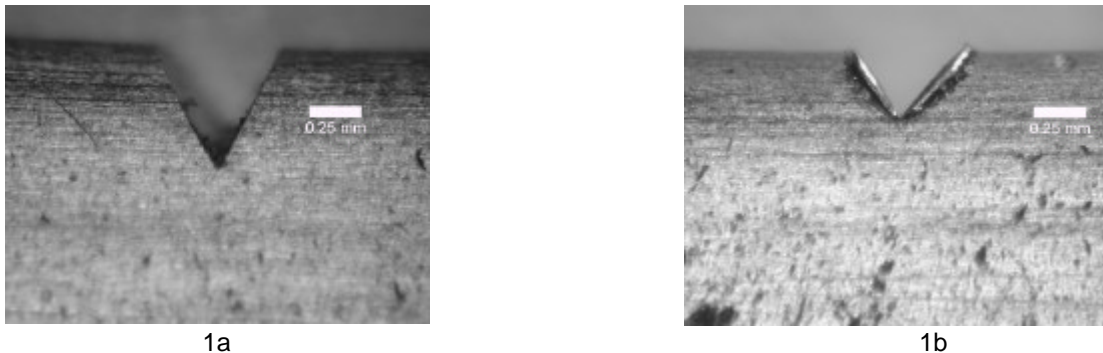
Deep compression has been shown to dramatically improve both the damage tolerance and fatigue strength of steels,<sup>2</sup> titanium,<sup>3</sup> nickel,<sup>4,5</sup> and aluminum<sup>6</sup> alloys. LPB<sup>7</sup> produces a layer of compressive residual stress in Ti-6Al-4V approaching the alloy yield strength and extending to depths exceeding 0.050 in. (1.3 mm). LPB is performed using conventional CNC machine tools in a machine shop environment, and can be easily incorporated into existing manufacturing and overhaul operations

## EXPERIMENTAL PROCEDURE

1<sup>ST</sup> stage Ti-6Al-4V fan blades and vanes were chosen as typical of FOD limited components in NAVAIR service. Blades and vanes removed from service during engine overhaul were obtained from the Cherry Point NAVAIR Naval Engine Airfoil Center (NEAC) and the Jacksonville NAVAIR Depot.

### ***Simulated Blade Edge FOD***

Blade edge 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 “worst case” service generated FOD and was also amenable to fracture mechanics based fatigue life modeling. Simulated FOD of 0.020, 0.050 and 0.100 in. (0.5, 1.25, and 2.5 mm) depths were produced to determine the maximum FOD tolerance. Photographs of the machined FOD are shown viewed from the concave and convex sides of a blade at 60X in Figure 1.



**Figure 1** – Simulated FOD created as a 50-degree “V” notch on the convex (entrance) side in Figure 1a and the concave (exit) side Figure 1b.

### ***Simulated Vane Edge FOD***

Vane edge FOD was simulated by an EDM notch made with a 0.005 in. (0.13 mm) thick graphite electrode with depths ranging from 0.020 to 0.100 in. (0.5 mm to 2.5 mm). Vane FOD was located at the point of maximum applied stress in cantilever loading. EDM produces yield strength tension in the re-cast layer that is typically cracked at the bottom of the notch and has the advantage of accurate control and repeatability to minimize scatter of the fatigue data.

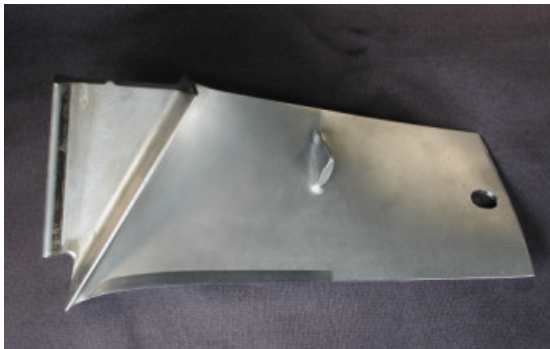
### ***LPB Processing***

The LPB parameters including ball size, material, pressure, feed, etc. were determined empirically through a series of trial runs. Standard xray diffraction ( $\sin^2\psi$  method) was used for measurement of the residual stress and cold work distributions. The processing was then fixed in the code used for CNC machine tool positioning and pressure regulation in the LPB control system. The pressures actually achieved for each position of the tool were recorded to files by the LPB control system. This allows the monitoring of the process at every step of the operation and documentation and assessment of the process parameters for each component. LPB processing can therefore meet the quality assurance (QA) standards that are internationally accepted as well as those standards that are unique to individual OEM or repair/maintenance depots.

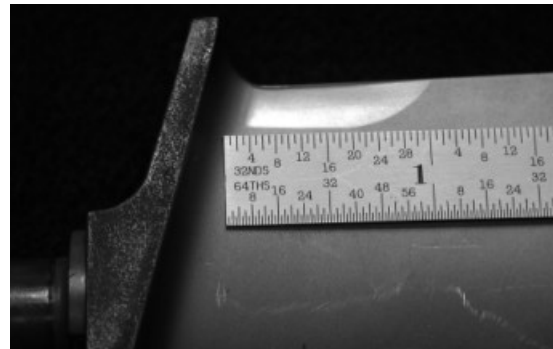
#### ***LPB Processing of Ti-6Al-4V Blades and Vanes***

A region nominally 0.25 in. (6 mm) wide along half the length of the blade leading edge, from the platform to the mid-span damper, was selected for burnishing. This blade-edge region is reportedly prone to FOD in actual service. 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, 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.

Both vanes and vane-edge simulation samples were also LPB processed in a CNC mill. Again, a caliper tool was used to burnish opposing sides of the vane-edge simultaneously, achieving through-thickness compression in the nominally 0.030 in. (0.7 mm) thick trailing edge. The processing parameters were selected to produce substantial compression on the order of at least  $-50$  ksi (344 MPa) through the thickness of the vane trailing edge, with high compression on the surface. All vanes and samples were then processed essentially identically within the reproducibility of CNC machining practices. The fine surface finish produced on the leading and trailing edges is evident in the photograph of the finished blade and vane in Figure 2.



Ti-6Al-4V 1<sup>st</sup> Stage Fan Blade



Ti-6Al-4V Vane

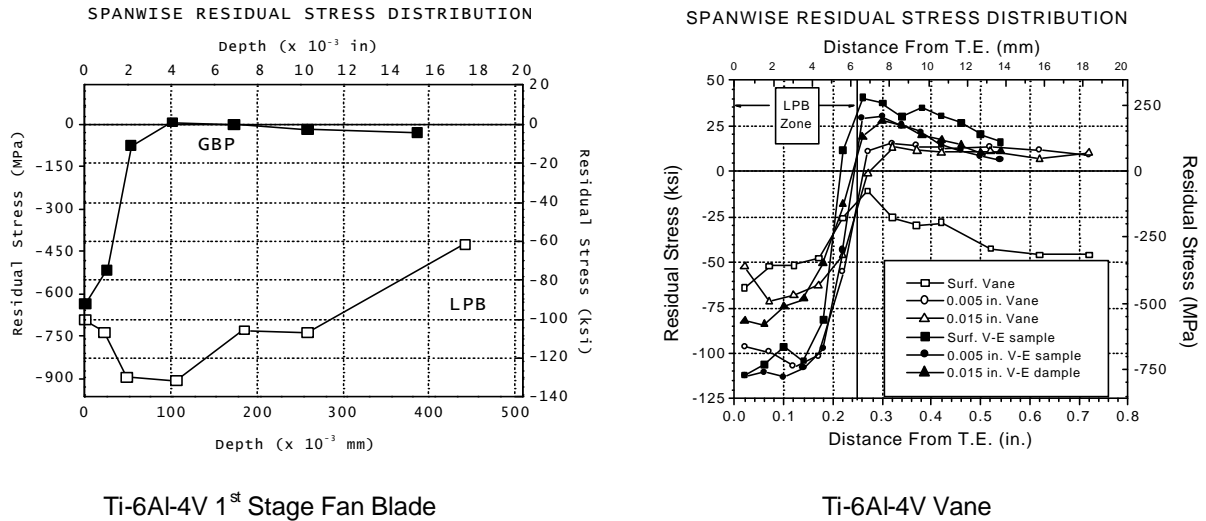
**Figure 2** – Photographs of finished Ti-6Al-4V first stage fan blade (left) showing the LPB region spanning the lower half of the leading edge (The hole near the tip of the blade is used for loading during fatigue testing) and vane (right) showing the LPB region on the trailing edge near the platform.

#### ***Residual Stress Measurement***

The span wise residual stress distribution produced by LPB to a depth equal to the blade mid-thickness is shown in Figure 3. Through-thickness compression was achieved, ranging from  $-100$  ksi ( $-690$  MPa) at the surface, to approximately  $-60$  ksi ( $-410$  MPa) at mid-thickness. Surface roughness of the blades with service was on the order of  $2.1\mu\text{m}$  as-received and  $0.5\mu\text{m}$  after LPB.

The residual stress distributions achieved by LPB in the trailing edge of both the actual vane and the vane-edge samples are shown in Figure 3. The span-wise (longitudinal) residual stress distribution is shown as a function of distance chord-wise moving from the trailing edge back along the chord of the vane. For both the

vane and vane-edge simulation sample, the stresses are shown at the surface and at depths 0.005 in. (0.13 mm) and 0.015 in (2.5 mm), the nominal mid-thickness of the trailing edge. Compression on the order of –110 to –100 ksi (-757 to –689 MPa) was achieved at a depth of 0.005 in. (0.13 mm) on the vane simulation samples for a distance of nominally 0.2 in. (5 mm) chord-wise from the trailing edge. Interior compression was lower, on the order of –80 to –50 ksi (-550 to –344 MPa), at mid-thickness of the vane-edge specimens. Compression on the vanes was lower at the surface, on the order of –50 ksi (-344 MPa), from the trailing edge to 0.2 in. (5 mm), which is attributed to the presence of cold work on the order of 35% due to previous glass bead peening of the vanes. The vanes were not stress relieved before LPB processing. Compression at 0.005 in. (0.13 mm) and at the 0.015 in (2.5 mm) mid-thickness depths are quite comparable to that achieved in the vane-edge sample using the same LPB processing parameters and CNC tool control code.

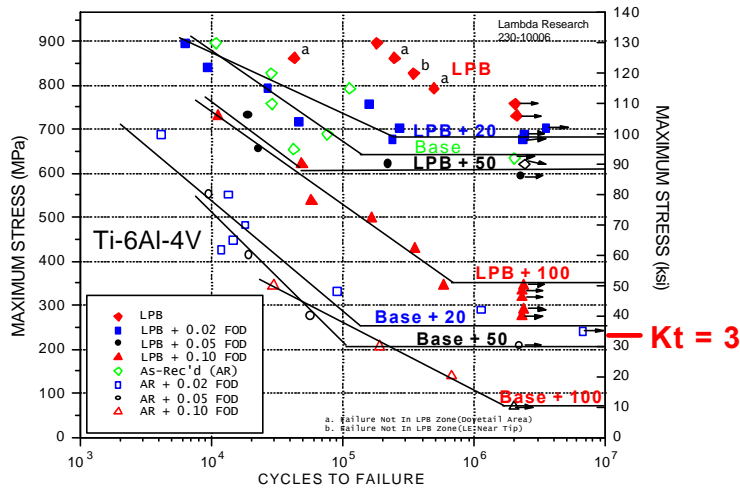


**Figure 3** – Span-wise residual stress distributions plotted as a function of depth produced by glass bead peening (GBP) and LPB on the leading edge of a Ti-6Al-4V first stage fan blade (left) and for LPB treated trailing edge of a Ti-6Al-4V first stage vane (right)

The compensating (equilibrating) tension behind the compressive leading edge is higher in the vane-edge samples than in the actual vanes, reaching 20 to 30 ksi (137 to 206 MPa) at chord-wise distances beyond the LPB processed 0.25 in. (6 mm), before falling off to nominally 10 ksi (70 MPa) at a distance of 0.55 in. (14 mm). In contrast, the actual vane reaches only nominally 12 ksi (83 MPa) behind the highly compressive trailing edge. The tension in the vane then extends to greater depths providing equilibration for the compressive edge. This difference in the equilibrating tensile stress distribution behind the compressive edge produced by LPB is attributed to the differences in the geometry of the actual vane and the vane-edge specimen. The greater chord-wise width of the vane provides more material to support the tensile stresses, and lower tensile magnitude is required for equilibrium.

**Blade Fatigue Testing**

Fatigue tests were performed in cantilever bending with a positive mean stress ( $R = S_{min} / S_{max} = +0.1$ ) to maintain the leading edge in tension and simulate the first bending mode of the blade with the high centrifugal mean stress seen in service. 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 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. The HCF results are shown in Figure 4.

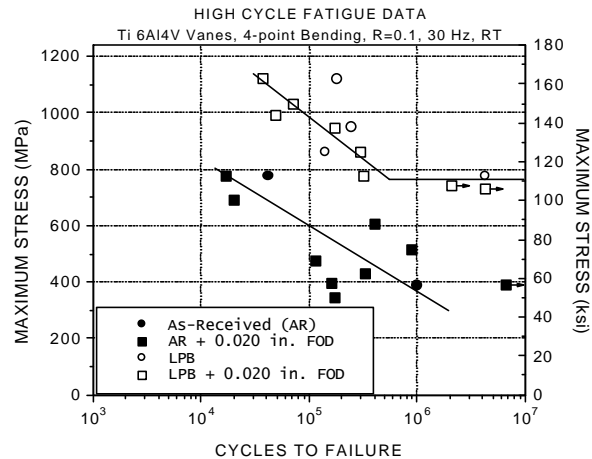


Both the location of maximum applied stress in cantilever bending and a load calibration curve were determined using a blade instrumented with a series of ten strain gages along the leading edge. Simulated FOD was machined at the maximum stress location, 2.12 in. (53.4 mm) above the platform. The dynamic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

**Figure 4** - HCF S-N curves for Ti-6Al-4V first stage fan blades showing the fatigue strength lost due to FOD depths from 0.020 to 0.10 in. (0.5 to 2.5 mm), and the improvement in fatigue strength afforded by LPB treatment of the leading edge.

**Fatigue Testing of Vanes and Vane-edge Simulation Specimens**

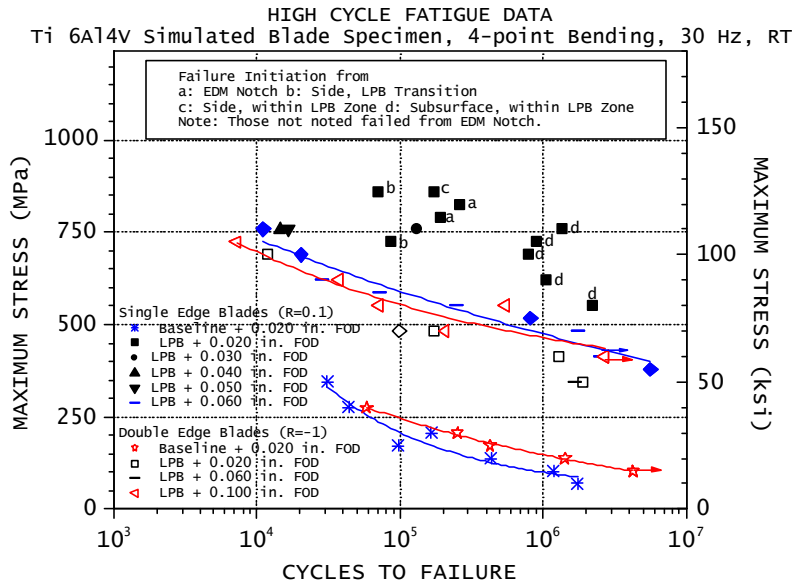
A limited number (32) of Ti-6-4 out of service vanes were utilized for developing the LPB processing parameters and fatigue testing. The vanes had been removed from an engine damaged by an unrelated failure causing a number of the vanes to be slightly deformed and damaged near the outboard end. It was recognized at the outset that fatigue testing of this set of atypical vanes, the only actual components available, might not be representative of production vanes. The HCF results shown in Figure 4 show considerable scatter that is attributed to the variability of the blade geometries and to the limited region placed under uniform stress in cantilever loading. The HCF results for the vanes processed with LPB, with or without 0.020 in. (0.5 mm) FOD, tended to overlap within the scatter band. However, a significant benefit in endurance limit, on the order of nominally 40 ksi (275 MPa), nearly double the endurance limit of the untreated vanes, is evident for the LPB processed vanes. All of the LPB processed vanes failed from the end of the LPB processed zone rather than the FOD introduced at the location of maximum stress. The unprocessed vanes failed from the EDM simulated FOD at lower applied stress, as seen in Figure 5.



**Figure 5** – The effect of trailing edge LPB processing on the HCF performance of Ti-6-4 vanes tested at R=0.1 with and without 0.020 in. (0.5 mm) deep FOD. The scatter is attributed to the variability of the out-of-service vanes used in the experiment.

Testing of fielded vanes provided an important demonstration of the effect of LPB on the fatigue performance of actual components. However, the complications of the complex loading, unknown field history, and the limited number of vanes justified the use of a vane-edge feature sample to generate additional data. Vane-edge feature samples manufactured from the equivalent material with the same radius and taper as the actual vane trailing edge were LPB processed identically producing the residual stress distributions shown in Figure 3 as functions of distance from the trailing edge. Testing in four-point bending provided a large uniformly stressed vane-edge under simple constant stress loading. Tests were conducted with various FOD depths ranging from 0.020 in. (0.5 mm) to a maximum of 0.060 in. (1.5 mm).

Because the static vane is loaded at an R ratio of  $-1.9$  during engine service, the possibility existed that the already highly compressive trailing edge would yield in compression during the compressive portion of the loading cycle, reducing or eliminating the compressive residual stresses and the resulting benefit in fatigue performance. Testing at  $R=-1.9$  was not feasible in bending, and axial testing was not possible for the sample dimensions required for equilibrium below the deep LPB compressive layer. Therefore, a double edge four-point bend specimen with symmetrical opposing trailing edge geometries was fabricated. The double edge specimen was tested in fully reversed bending ( $R=-1$ ) so that the compressive LPB processed zone was driven to the same magnitude of compression as tension on each cycle.



**Figure 6** – S-N curves for single-edge and double-edge vane-edge feature samples tested with and without LPB and FOD depths from 0.020 to 0.100 in. (2.5 mm).

The results of both the single-edge and double-edge tests are summarized in Figure 6. FOD of 0.020 in. (0.5 mm) drastically reduced the fatigue life of both single-edge (R=0.1) and double-edged (R=-1) specimens to nominally 10 ksi (70 MPa), with slightly higher performance for the fully reversed bending. It proved extremely difficult to achieve failure from the smaller FOD dimensions in the LPB processed double-edge sample, as fatigue cracking typically initiated from the boundaries of the LPB zone.

Fatigue results for the vane-edge feature samples indicate no significant reduction in fatigue performance as a result of testing in fully reverse bending (R=-1) as compared to tension-only testing (R=0.1). The data further indicate that damage tolerance for the vane could be increased to as much as 0.060 in. (1.5 mm) or even 0.10 in. (2.5 mm) from the current 0.002 in. (0.05 mm) limit, and still achieve fatigue performance in excess of the  $Kt=3$  criteria typically employed in HCF limited design.

#### **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, 3.58 in. (91 mm) wide and 0.03 in. (0.75 mm) 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.<sup>8</sup> 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 140 ksi (965 MPa) was assumed.

The trailing edge of the vane was modeled assuming a simple edge notched plate of uniform 0.030 in. (0.7 mm) thickness. Even with the limitations imposed by the simple geometric models for which closed form stress intensity factor solutions are available, the effect of LPB on fatigue performance is reasonably predicted and shown to be due to the effect of the mean compressive stress induced into the vane edge ahead of the crack.

## **RESULTS AND DISCUSSION**

### **Blade Damage Tolerance**

The fatigue strength (HCF endurance limit) of the as-received blades was nominally 95 ksi (655 MPa). With one exception, fatigue cracks initiated from small service generated FOD impressions on leading edges, 0.005 in. (0.13 mm) and less in depth. Typically, origins were not 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 2.2 in. (56 mm) to 2.9 in. (74 mm) from the platform, whereas the maximum applied stress occurred at 2.1 in (53 mm).

FOD 0.02 in (0.5 mm) deep reduced the fatigue strength of as-received blades to nominally 34.8 ksi (240 MPa), one-third the strength without FOD. FOD 0.05 in (1.25 mm) deep reduced the fatigue strength nominally the same amount. (It should be noted that the 0.02 in (0.5 mm) FOD was not of uniform depth and exceeded 0.75 mm on the convex side of several samples.) The deepest 0.10 in. (2.5 mm) FOD further reduced the HCF strength to less than 14.5 ksi (100 MPa). 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.

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 130 ksi (895 MPa), 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 115 ksi (790 MPa). 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.

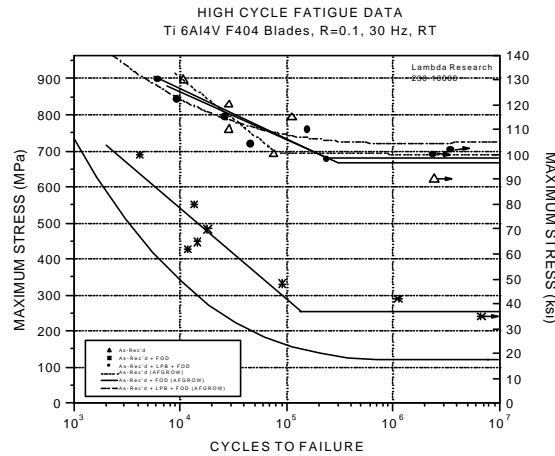
LPB processed blades with 0.02 in (0.5 mm) FOD had both HCF strength and fatigue life at stresses above the endurance limit generally better than the original blades without FOD. The fatigue strength of blades with FOD 0.05 in (1.25 mm) deep introduced after LPB was virtually identical to that of as-received blades without FOD. This is an order of magnitude improvement in the current 0.005 in. (0.13 mm) limit for FOD on the critical lower third of the leading edge. FOD 0.10 in. (2.5 mm) deep reduced the endurance limit to nominally 345 MPa (50.1 ksi), still a smaller fatigue debit than 0.02 in (0.5 mm) FOD without LPB. The LPB compressive layer retarded crack growth, providing nearly an order of magnitude fatigue life improvement regardless of FOD depth from 0.5 to 0.10 in. (2.5 mm). Fatigue initiation in blades with LPB always occurred from the notch root at mid-thickness of the blade cross-section. Compressive residual stresses from LPB always produced normal-mode crack progression within the LPB zone, transforming to slant-mode progression beyond.

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 0.10 in. (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.

Predicted HCF S-N curves for 0.02 in (0.5 mm) leading edge FOD in a highly compressive (-100 ksi, -690 MPa) LPB zone and in a stress-free blade are shown superimposed on the actual fatigue data in Figure 8. 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 105 ksi (725 MPa) is within 5% of the nominal 100 ksi (690 MPa) value obtained from testing. However, the predicted S-N curve for 0.02 in (0.5 mm) FOD without LPB is consistently 20 ksi (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 0.02 in (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 0.02 in (0.5 mm) FOD with 100 ksi (690 MPa) maximum applied stress, in agreement with the experimental results. Infinite life is predicted for FOD up to 0.15 in. (3.8 mm) deep if the maximum stress is less than 95 ksi (655 MPa). Even FOD of 0.20 in (5 mm) should be tolerated for stress levels below 90 ksi (620 MPa), well above the design stress for the fan blade.



**Figure 8** – Ti-6Al-4V first stage fan blade fatigue life prediction assuming -100 ksi (-690 MPa) compression through the thickness with 0.02 in (0.5 mm) FOD.

Predicted and test fatigue lives for the LPB processed blades with FOD of 0.05 in (1.25 mm) and less agree well, but the fatigue strength for 0.10 in. (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 0.005 in. (0.13 mm), and at the depth of mid-thickness, 0.015 in (2.5 mm). Figure 9 reveals that, although the LPB processed zone extended back 0.25 in. (6 mm) from the leading edge at the surface, uniform -100 ksi (-690 MPa) compression was actually achieved only 0.10 in. (2.5 mm) back from the leading edge, and then diminished linearly to zero at 0.20 in. (5 mm). FOD 0.015 in (2.5 mm) deep penetrated entirely through the uniform compressive layer assumed for life calculation. The ability to tolerate 0.02 in (0.5 mm) and 0.05 in (1.25 mm) FOD without loss of fatigue strength and fatigue debit for 0.10 in. (2.5 mm) deep damage appears to be explained by the residual stress distributions actually achieved.

Table I  
AFGROW Life Predictions

LPB Treated Ti-6Al-4V 1<sup>st</sup> 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<sup>3</sup> cycles

Figure 9 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.

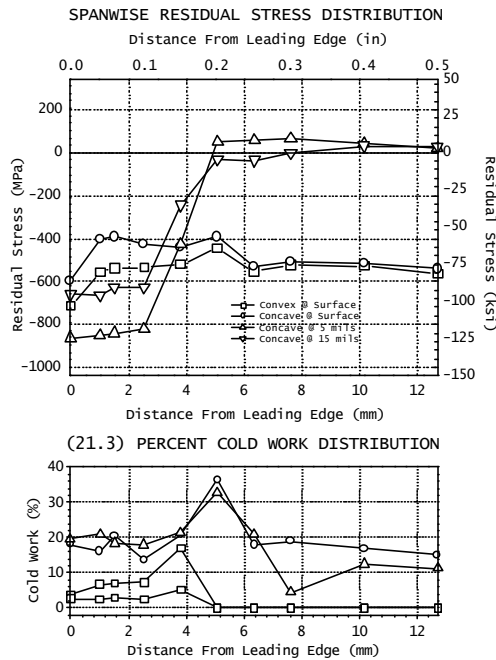
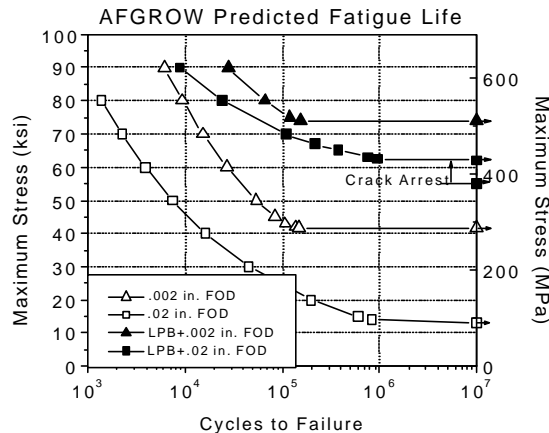


Figure 9 – Span wise (longitudinal) residual stress distributions in the Ti-6Al-4V first stage fan blade after LPB, showing extent of through thickness compression.

### Vane Damage Tolerance

Linear elastic fracture mechanics modeling was undertaken using the AFGROW code assuming a simple edge notched plate of uniform 0.030 in. (0.7 mm) thickness. As discussed earlier with the limitations imposed by the simple geometric models for which closed form stress intensity factor solutions are available, the effect of LPB on fatigue performance is reasonably predicted and shown to be due to the effect of the mean compressive stress induced into the vane edge ahead of the crack. Figure 10 shows the predicted S-N curves for the simple edge notch plate assuming a uniform compressive stress of -100 ksi throughout the thickness. Results are shown for both 0.002 in. (0.05 mm) deep FOD, the current FOD limit for the vane, and the 0.020 in. (0.5 mm) deep FOD used for vane testing. Assuming that the smaller FOD might be considered characteristic of surface damage found on vanes removed from service, the predicted fatigue lives for LPB processed vanes, regardless of FOD size, and out-of-service vanes with the smaller FOD are in reasonable agreement with the fatigue data shown in Figure 5. AFGROW predicts a much lower life for the vanes with larger FOD than was actually observed in testing. This may be attributable to deformation that occurred within this high stressed area as a result of the engine failure that lead to the vane removal. The engine failure may have left the region in a state of compressive stress that enhances fatigue performance beyond that predicted for a stress-free model. Further, simple axial loading was assumed in the model. The complex bending and twisting actually imposed on the vane trailing edge by the single point cantilever loading could not be modeled with AFGROW.



**Figure 10** – AFGROW linear-elastic fracture mechanics predictions of high cycle fatigue performance assuming -100 ksi (-690 MPa) compression in a 0.030 in. (0.7 mm) thick plate with an edge notch equal to the FOD depths indicated.

### Fatigue Design Diagram

The fatigue design diagram (FDD) is a novel adaptation of conventional Haigh/Goodman diagram to include the region of compressive mean stresses.<sup>9</sup> Conventionally, the Goodman line is drawn assuming a linear relationship between mean and alternating stresses. Here, the Smith-Watson-Topper (SWT) model is used to model the effects of varying mean stress on the fatigue strength at a given fatigue life. With the introduction of Neuber's stress concentration factor ( $k_t$  or  $k_f$ ) a series of SWT lines can be drawn. This leads to the identification of a "SAFE" region in which the stresses are always in compression and hence the component is protected from mode I cracking. If the damage state (be it a crack tip, corrosion pit, or FOD tip) is under this compression, the component can be completely safe from fatigue-related failure. This is demonstrated in Figures 11A and B for Ti-6Al-4V. This method has been shown to predict the component behavior accurately after LPB treatment.<sup>9</sup>

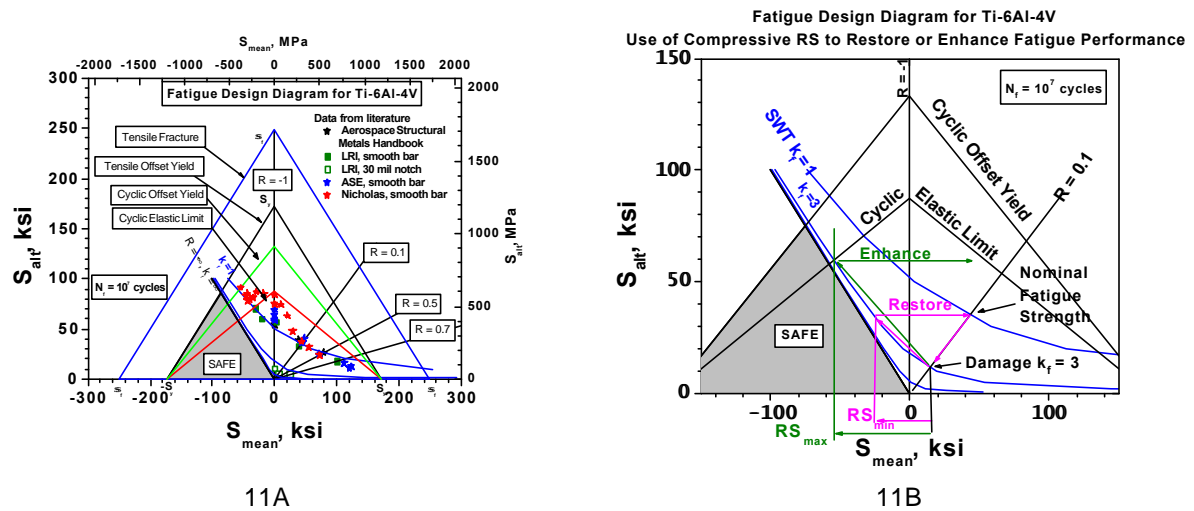


Figure 11 – A. Fatigue Design Diagram for Ti-6Al-4V. B. Methods to determine residual stresses for restoring and enhancing fatigue performance.

## 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  $-100$  ksi ( $-690$  MPa) was achieved along the FOD sensitive lower third of the blade extending from the leading edge  $0.10$  in. ( $2.5$  mm) chord wise. 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  $95.1$  to  $114.7$  ksi ( $655$  to  $790$  MPa). LPB prior to  $0.02$  in. ( $0.5$  mm) deep FOD increased the endurance limit from nominally  $34.8$  to  $95.1$  ksi ( $240$  to  $655$  MPa), and for  $0.05$  in. ( $1.25$  mm) FOD, from  $29.9$  to  $90.0$  ksi ( $206$  to  $620$  MPa). 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.

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

LPB processing of a Ti-6Al-4V first stage vane, a static fatigue critical engine component has been demonstrated to improve damage tolerance by an order of magnitude and to withstand cyclic loading in compression in fully reversed bending. LPB processing of fielded Ti-6Al-4V vanes with a current trailing edge damage tolerance  $0.002$  in. ( $0.05$  mm) resulted in a ten-fold increase in damage tolerance to at least  $0.020$  in. ( $0.5$  mm) The fatigue strength of the trailing edge of LPB processed vanes doubled, from nominally  $40$  to  $80$  ksi ( $275$  to  $550$  MPa).

The beneficial compression and the fatigue benefit of LPB are not lost when the vane is cycled into compression at stress levels producing HCF failures, even in the high-stress low cycle fatigue regime. The minimal effect of R-ratio on fatigue life with high residual compression from LPB was confirmed with linear elastic fracture mechanics. FOD up to  $0.060$  in. ( $1.5$  mm) was tolerated with fatigue strength of  $60$  and  $50$  ksi ( $413$  and  $344$  MPa) for  $R=0.1$  and  $R=-1$ , respectively. The results were corroborated with linear elastic fracture mechanics modeling for the residual stress level and FOD sizes investigated.

A novel method of fatigue design diagram (FDD) has been developed to optimize the magnitude of compression needed to both restore and enhance the fatigue performance of damaged parts. FDD has been validated by test results from the 1<sup>st</sup> stage compressor Ti-6Al-4V vanes.

LPB has been successfully demonstrated to provide an order of magnitude improvement in the damage tolerance of titanium alloy fan blades and vanes. In addition, LPB provides significant damage tolerance in non-rotating components cycled into compression. The benefits of LPB processing FOD sensitive aero engine blades and vanes could significantly reduce the costs of turbine engine inspection and maintenance while improving fleet readiness and providing a significant reduction in the cost of aircraft ownership.

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