Mitigation of Fatigue and Pre-Cracking Damage in Aircraft Structures Through Low Plasticity Burnishing (LPB)

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ABSTRACT

A test program was set up by AFRL-VASM to study the effect of low plasticity burnishing (LPB) to mitigate fatigue debit due to pre-cracking damage in two feature specimens made of AA2024-T851 and designed to simulate features of aircraft structures. The LPB solution consisted of (a) designing the compressive residual stress field using Lambda's Fatigue Design Diagram (FDD) method, (b) introducing the compression via LPB tools and fixtures into the parts, (c) verifying the achieved residual stress distribution by measurements, and (d) validating the predictions through fatigue tests conducted by AFRL-VASM group.

Keywords: Residual Stresses, Surface Enhancement, Low Plasticity Burnishing (LPB), Fatigue Damage, Pre-cracking, Fatigue Crack Growth, Fatigue Design Diagram (FDD), Damage Mitigation

INTRODUCTION

Aircraft structures are made of many aluminum, titanium and iron-based alloys, and the structures are prone to a variety of damage conditions including fatigue, foreign object damage (FOD), corrosion fatigue, fretting fatigue, and prior corrosion pitting. Damage tolerant design approaches including the DoD's Aircraft Structural Integrity Program (ASIP) demand that the damage initiation and progression be monitored well before catastrophic failure could ensue. Issues such as the frequency of inspection, location, size and type of damage could lead to prohibitive costs, need for premature replacement of parts, aircraft downtime, etc. Most materials have very low threshold stresses below which such damage will not propagate. Invariably, a majority of structures are designed above threshold stresses with the idea that any damage progression can be monitored. Developing new materials and processing conditions to improve the threshold stresses can be very costly. Similarly, changing component design to minimize the stresses on the parts can prove to be very difficult. However, introduction of compressive residual stresses at critical regions of the part through a surface enhancement technology such as Lambda's LPB can help mitigate the failure due to different damage conditions, without changing either the material or the design.

The goal of this paper is to demonstrate the mitigation of pre-cracking and fatigue damage in AA2024-T851 parts simulating two different features of airframe structure through LPB treatment. The program consisted of comparing the effects of LPB by Lambda and laser shock peening (LSP) by two other vendors to mitigate the fatigue debit due to pre-cracking in the feature specimens. Here, only the benefits due to LPB are presented.

The LPB solution consisted of designing the compressive residual stress field using Lambda's FDD, introducing the compression through LPB tools and fixtures, verifying the achieved residual stress distribution by measurements, and validating the predictions through fatigue tests conducted by AFRL-VASM group.

PART DESIGN, FATIGUE TEST ARTICLES AND TEST VARIABLES

Two features of aircraft structures were simulated by specimens made of AA2024-T851. The specimens are Part A (Complex Geometry) and Part B (Simple Geometry) shown in Figures 1 and 2. Both sets of specimens were fatigue tested under a uniaxial load (from the ends) using standard MTS machines with friction grips. The clamped length at each end is about 2 inches. Part A was tested at a stress ratio, R (= S_{min}/S_{max}) of 0.01 and Part B was tested at an R of –1. The loads of 4,550 lbs and 5,500 lbs were chosen as maximum axial loads, respectively for the two parts. These loads were chosen after initial trials to achieve about 30,000 cycles to failure in undamaged parts corresponding to the baseline smooth condition. In both cases, finite element analysis showed that these loads corresponded to a far-field stress of about 11.5 ksi. Regions of stress concentration in each specimen were also identified, as shown in Figures 1 and 2.

In order to understand the fatigue life debit due to pre-cracking, a notch was introduced at the high stress location, as shown in Figures 1 and 2, and were cycled at a maximum load of 3,600 lbs (R = 0.01) to obtain a nominal pre-crack length of 0.05 in. Subsequently, the pre-cracked specimens were fatigue tested at the nominal loads of 4,550 and 5,500 lbs, respectively for Parts A and B. These tests revealed the fatigue life debit due to pre-cracking.

Fatigue tests were repeated on LPB treated parts both in the smooth condition to show that LPB does no harm, and in pre-cracked specimens to show that LPB mitigates the pre-crack damage.

The entire set of tests were repeated at a 10% higher applied load of 5,000 and 6,000 lbs, respectively for Parts A and B. The higher loads corresponded to nominal stress of 12.5 ksi in both parts.

3 to 6 replicate tests were performed at each test condition to assure repeatability of test results.

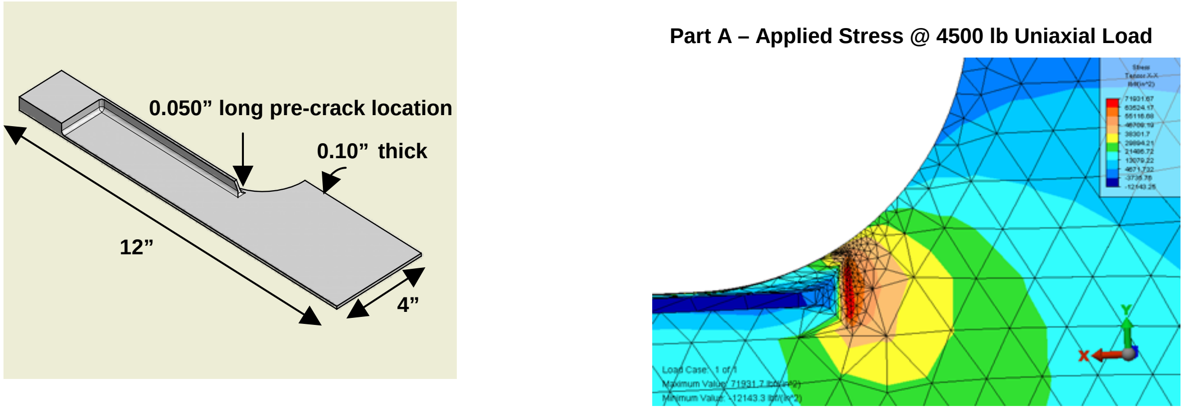

Figure 1. Part A (Complex) geometry and stress contours from finite element analysis (FEA) showing the high stress areas

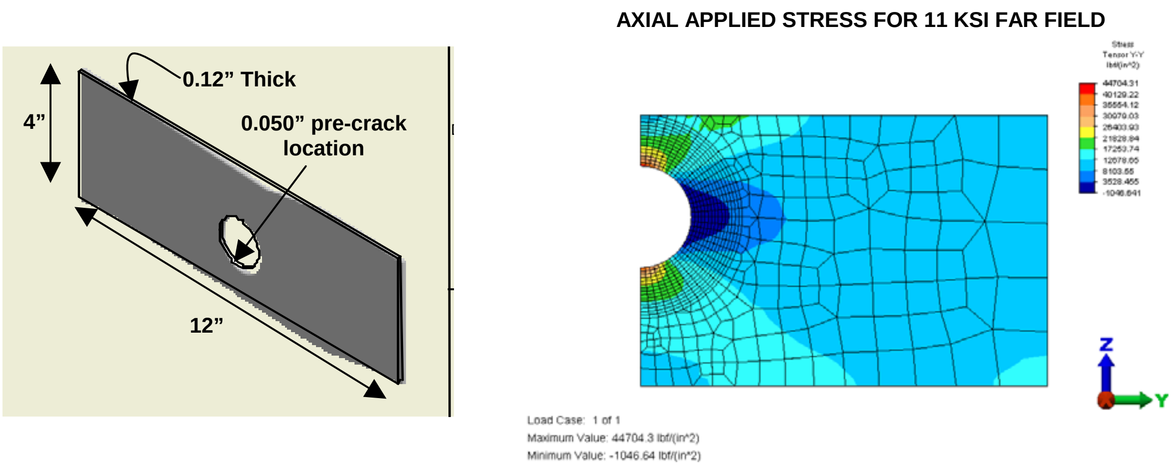

Figure 2. Part B (Simple) geometry and stress contours from finite element analysis (FEA) showing the high stress areas

RS DESIGN

Based on the baseline fatigue performance, material properties available in literature, and the fatigue life debit data obtained in this study, a Fatigue Design Diagram for AA2024-T851 was constructed. Compressive RS magnitude & locations to mitigate damage were designed using Lambda’s FDD method, as shown in Figure 3.

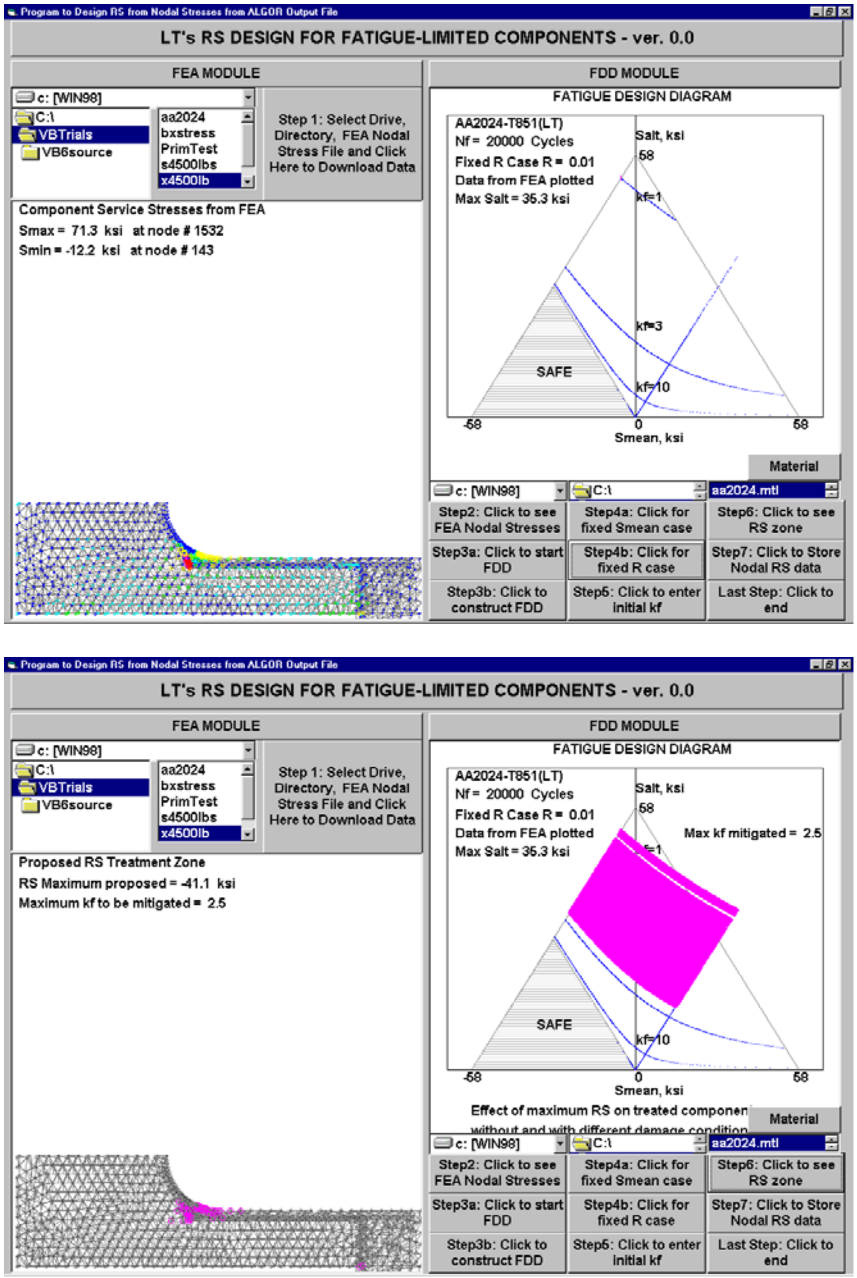

Figure 3. Computer screen images showing the steps involved in the use the FDD code to determine the maximum compressive RS distribution for the damage prone region of a component.

FDD is a novel adaptation of the well known Goodman or Haigh diagram, to extend into compressive mean stress range. The Smith-Watson-Topper (SWT) model is used to describe the fatigue behavior over the entire range of mean stress from tension to compression. A fatigue damage parameter, k_f (ratio of fatigue strengths of undamaged over damaged condition) is used in conjunction with SWT to account for damage. A series of fatigue performance lines at a constant fatigue life (for example, in Figure 3, N_f = 20,000 cycles) for different k_f values are drawn in a plot of S_{mean} vs. S_{alt}. So, at a given stress ratio (say, R = 0.01), the fatigue performance as indicated by the allowable S_{mean} and S_{alt} are reduced under any damage condition of $k_f > 1$. Knowing the k_f, the FDD facilitates the determination of the minimum compression needed to restore the fatigue performance and the additional compression needed to enhance fatigue performance.

As seen in Figure 3, there is a “safe” region signified by the highlighted triangle, in which the S_{max} (combined S_{mean} and S_{alt}) never exceeds zero, and hence mode I crack growth is not possible, when operated in this “safe” region.

Lambda’s FDD code takes nodal/elemental data from the FEA of the part and run that through the FDD module to generate an output file with information on the proposed distribution of compressive residual stresses. This FDD design procedure used for mitigating the damage due to precracking in Part A is presented in Figure 3.

Residual Stress Implementation:

Both controlled magnitude and depth of compression can be introduced at critical locations through LPB treatment. LPB is a surface treatment that develops a deep layer of high compression on surfaces to mitigate fretting, corrosion pitting, or FOD. Through-thickness compression can be achieved in thin sections, such as blade edges, providing dramatically improved damage tolerance.[1] LPB tools are designed to allow access to the fatigue critical areas of the component. The LPB process itself has been described in detail previously.[2]

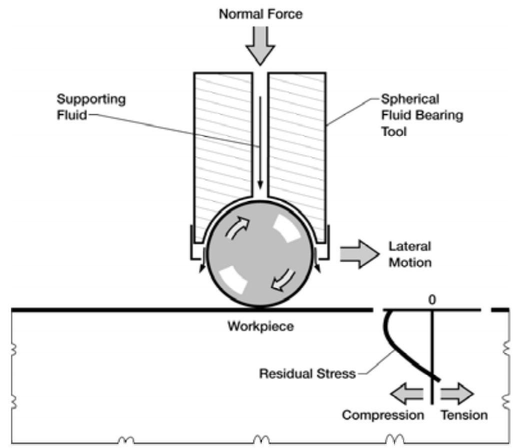

FIGURE 4 - LPB Schematic

Unlike other burnishing or "deep rolling" methods, a single pass of a smooth free rolling spherical ball tool, as shown in Figure 4, is used under a normal force just sufficient to deform the surface of the material, creating a compressive layer of residual stress with controlled plastic deformation. The LPB tool path and position are controlled in a CNC machine tool or robotically 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. LPB can produce high compression to a depth exceeding 1 mm in thick sections and entirely through thin sections such as structural sheet or the edges of titanium alloy fan blades in 4-axis or 5-axis CNC processing.[3,4] As the ball rolls over the component, the pressure from the ball causes plastic deformation to occur in the surface of the material under the ball. Since the bulk of the material constrains the deformed area, the deformed zone is left in compression after the ball passes. No material is removed during the process.

Compressive residual stresses can be introduced into components of very complex geometry and intricate locations by suitably designing the LPB tool and fixtures to hold the part. Various tools have been designed at Lambda to treat the bore of propeller bores, landing gears, turbine engine fan blades, blade dovetail regions, compressor disk post dovetail contact regions, etc. The specific shape and magnitude of the residual stress pattern can be sculpted in the part by appropriate CNC code to locate the tool and by applying the predetermined pressure conditions on the LPB tool. The LPB pattern thus applied for Parts A and B are shown in Figures 5 and 6.

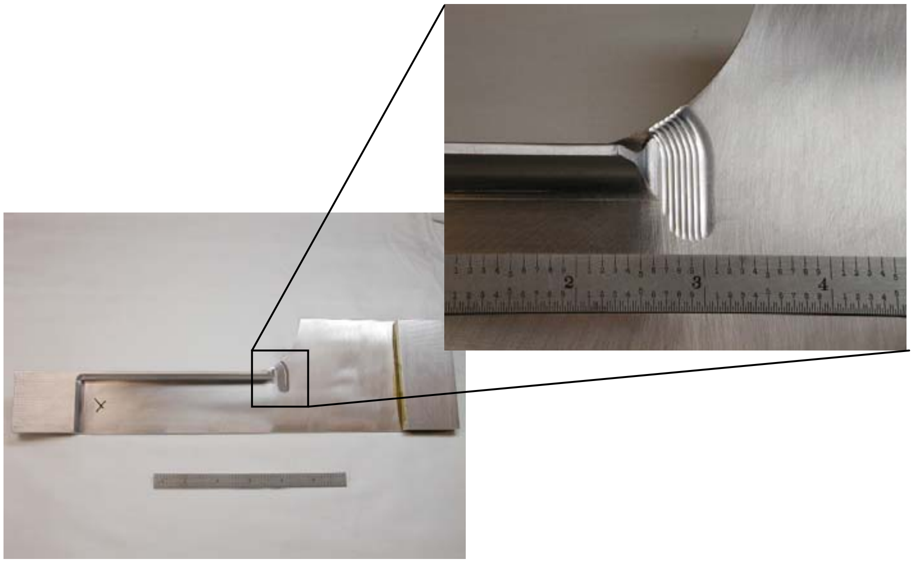

Figure 5. Photographs showing the LPB treated Parts A. Close-up view shows the exact region treated.

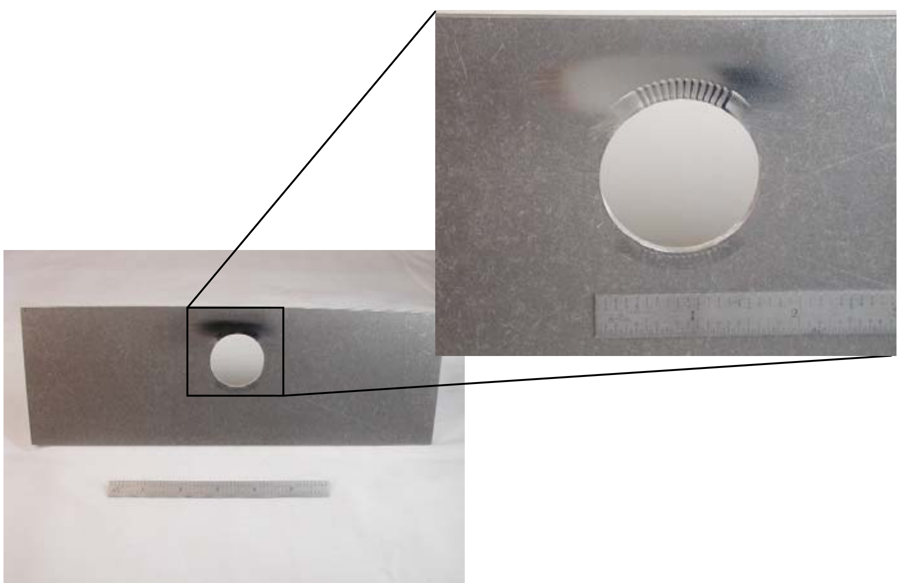

Figure 6. Photographs showing the LPB treated Part B. Close-up view shows the exact regions treated.

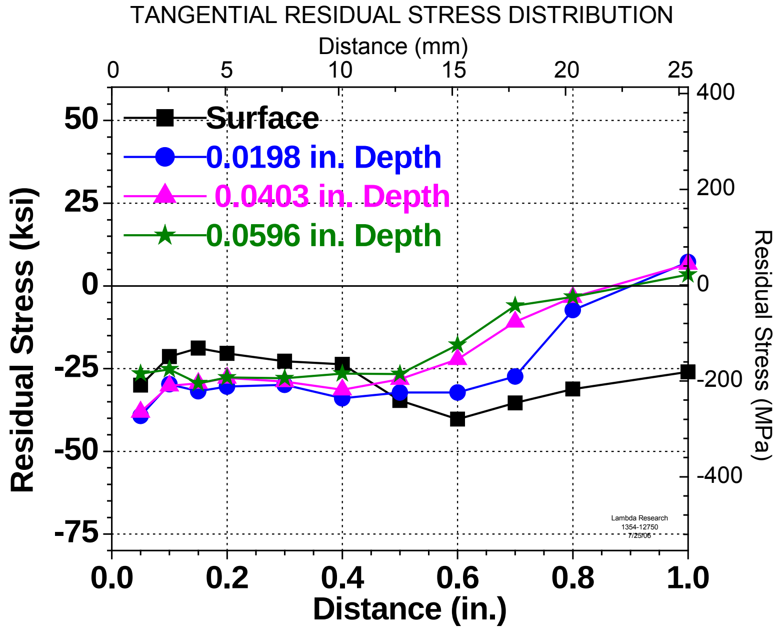

Figure 7. Residual stress distribution in LPB treated Part A.

RS Verification:

Verification of the residual stresses in treated parts was done by standard x-ray diffraction ($Sin^2\Psi$ method). Both surface and subsurface measurements were made, by sequentially electropolishing layers of material in the region of interest up to the mid- thickness plane. Residual stress measurements were made at each layer as a function of distance from the edge. Figure 7 and 8 show the residual stress distribution in LPB treated Parts A and B. In both parts, uniform compressive residual stresses of almost same magnitude are present through the thickness and up to the desired distance of nearly an inch in Part A and about 0.4 in. in Part B. The magnitudes and locations of residual stresses were verified to be the same as what was predicted by the FDD code and by the LPB process conditions.

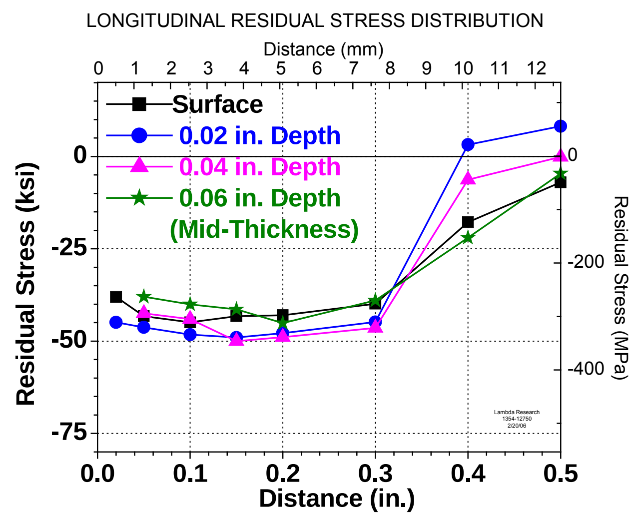

Figure 8. Residual stress distribution in LPB treated Part A.

Fatigue Performance Validation:

Validation of the residual stress design process was achieved through fatigue testing of LPB treated parts and comparing the results with untreated parts. The fatigue results are presented in the form of bar charts showing the fatigue lives for different treatment conditions in Figures 9 – 12.

Figure 9 shows the results for Part A (Complex geometry). Average fatigue life of the baseline smooth specimens tested at S_{max} of 11.4 ksi (R = 0.01) was 30,642 cycles. In the presence of a 0.05 in. pre-crack, the average fatigue life reduced to 1,583 cycles. Thus, the fatigue life debit was by nearly a factor of 20 in presence of a 0.05 in. pre-crack. However, after LPB treatment, the average fatigue life of smooth specimens was improved to 187,112 cycles, nearly a factor of 6 improvement over the baseline smooth condition. More importantly, in the pre-cracked specimens, the average fatigue of LPB treated specimens was 33,457 cycles, nearly the same as the untreated baseline smooth fatigue performance, thus showing that LPB completely mitigated the effects of the pre-crack damage on the fatigue performance. Figure 10 shows almost identical performance in Part A specimens tested at the higher nominal stress of 12.5 ksi.

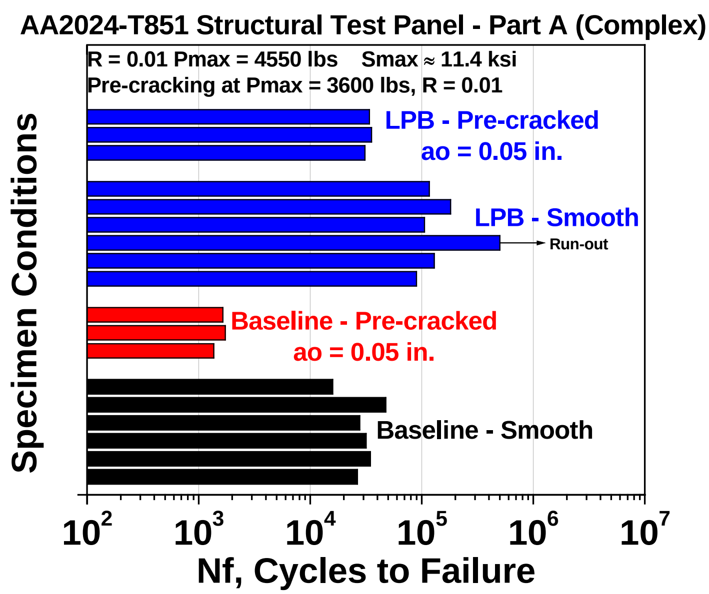

Figure 9. Fatigue life plots for untreated and LPB treated Part A (Complex geometry) tested at S_{max} = 11.4 ksi (R = 0.01)

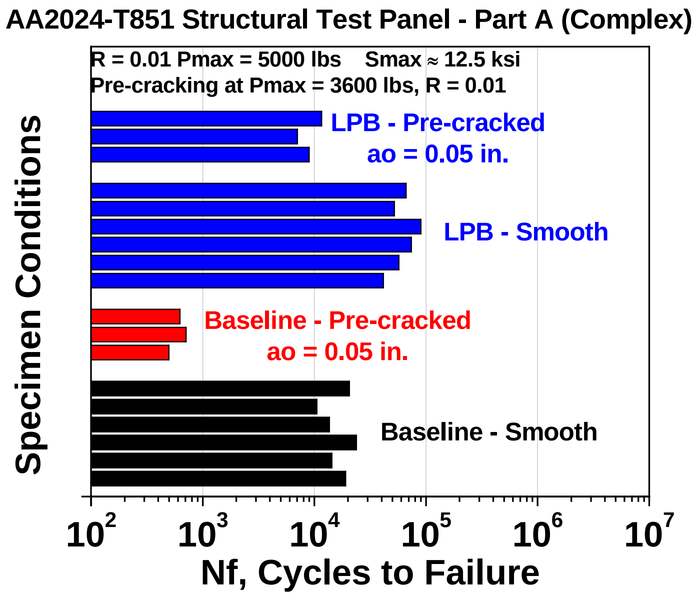

Figure 10. Fatigue life plots for untreated and LPB treated Part A (Complex geometry) tested at S_{max} = 12.5 ksi (R = 0.01)

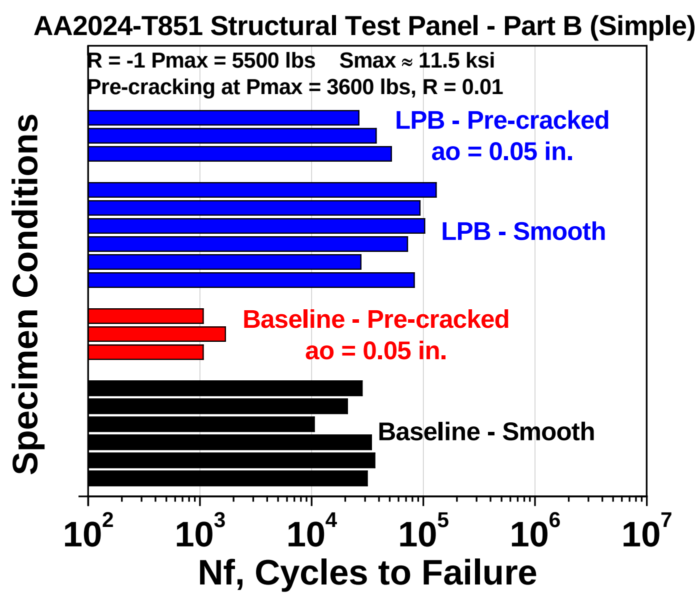

Figure 11. Fatigue life plots for untreated and LPB treated Part B (Simple geometry) tested at S_{max} = 11.4 ksi (R = -1)

Figures 11 and 12 also show that LPB improves the performance of smooth specimens, and completely mitigates the effects of pre-crack damage on the fatigue performance at R = -1.

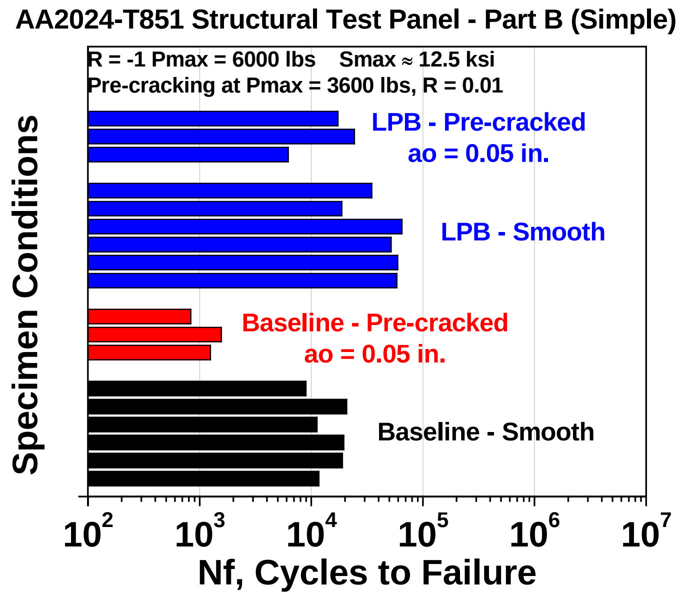

Figure 12. Fatigue life plots for untreated and LPB treated Part B (Simple geometry) tested at S_{max} = 12.5 ksi (R = -1)

Summary and Conclusions

In summary, a test program was set up by AFRL-VASM to study the effects of different surface treatments to mitigate the fatigue debit due to pre-cracking damage in two feature specimens designed to simulate aspects of aircraft structures. The entire program consisted of comparing the effects of LPB by Lambda and LSP by two other vendors. In this paper, only the benefits attributed to LPB are discussed. Following are the specific conclusions:

- The magnitude and location of compressive residual stresses needed to mitigate the damage conditions in two structural features were determined by the FDD method.

- LPB treatment was designed to introduce the intended compressive RS into the locations chosen for Parts A and B.

- RS distribution in the treated parts was verified by the x-ray diffraction method
    - In Part A (Complex) nominally uniform compressive RS of –30 ksi was achieved up to mid-thickness at critical locations.
    - In Part B (Simple) nominally uniform compressive RS of –45 ksi was achieved up to mid-thickness at critical locations.

- Fatigue test results validated predictions.
    - LPB significantly improved (by a factor of 6) the fatigue life of both smooth parts A & B.
    - In both Parts A & B, pre-cracks (0.05 in. long) reduced the fatigue life by nearly a factor of 20.
    - In both Parts A & B, LPB fully restored the fatigue life of the pre-cracked (of length 0.05 in.) parts to that of smooth baseline parts.

- The benefits of LPB were consistently evident at both stress levels of 11.5 and 12.5 ksi.

- The benefits of LPB were consistently evident at both stress ratios (R) of 0.01 and –1.

Reference:
1 U.S. Patent 5,826,453 (Oct. 1998), other US and Foreign patents pending.
2 P. Prevéy, (2000),"The Effect of Cold Work on the Thermal Stability of Residual Compression in Surface Enhanced IN718," Proc. 20th ASMI Conference.
3 Final Report (2001) N68335-01-C-0274 NAVAIR Phase I SBIR, “Affordable Compressor Blade Fatigue Life Extension Technology,” Nov. 29.
4 Air Force Phase II SBIR (2003), Contract F33615-03-C-5207, Component Surface Treatments for Engine Fatigue Enhancement