

Safe Life Conversion of Aircraft Aluminum Structures via Low Plasticity Burnishing for Mitigation of Corrosion Related Failures

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ABSTRACT

Corrosion induced cracking, pitting, and the resultant failure of high strength aircraft aluminums are some of the most costly, and potentially catastrophic, material problems affecting the modern and aging aircraft fleet. Increased inspections, maintenance, and repair, due to corrosion of aging aircraft, adversely affect fleet readiness, personnel safety, and greatly increase cost of operation.

Shot peening (SP), has been used to produce a compressive layer of residual stress on the surface of components to improve fatigue life and stress corrosion cracking (SCC) resistance. The depth of the shot peening compressive layer extends only a few thousandths of an inch into the surface. Corrosion pits, cracks, or other damage that exceed the depth of compression serve as the nucleation point(s) for corrosion induced fatigue cracking. Low plasticity burnishing (LPB) imparts a much deeper layer of thermo-mechanically stable residual compression into the surface of a component. Pit depths asymptotically approached a maximum depth dependent upon the alloy and surface treatment. The depth of compression from LPB greatly exceeds the maximum corrosion pit depth in the studied materials, therefore preventing corrosion related fatigue failure and ensuring safe-life operation.

The effect of corrosion damage in the form of pitting, stress corrosion cracking, and salt fog exposure was evaluated on the high cycle fatigue (HCF) performance of several aircraft aluminum alloys processed using conventional SP or LPB. Results are shown for SP and LPB treated test specimens exposed to the various types of corrosion damage. Both surface treatments were also evaluated as repair treatments for pre-corrosion damaged surfaces. In all cases, the LPB treatment provided greater corrosion fatigue resistance and improved corrosion damage tolerance compared to SP.

Keywords: Corrosion Fatigue, Pitting, Stress Corrosion Cracking (SCC), High Cycle Fatigue (HCF), Low Plasticity Burnishing (LPB), Compressive Residual Stress, Safe Life.

INTRODUCTION

High cycle fatigue cracking, often initiating from corrosion pitting, along with SCC are a growing threat to the safety and performance of military aircraft. Maintenance requirements to inspect for fatigue damage and corrosion, replace parts, and rework to remove the corrosion damage dramatically increase the cost of operation. The down time required for inspections and repairs significantly impacts military readiness. Military budget pressures require aircraft to continue in operation for decades beyond the original design life. The existing fleet of aging aircraft must continue to operate safely and at full capacity while remaining cost effective. Estimated corrosion inspection and repair costs for Naval aircraft alone exceed one billion dollars annually. More than 30% of military aircraft are over 20 years old, and over 90% are expected to exceed a 20-year life by the year 2015¹. LPB is a proven, advanced surface enhancement process that is capable of greatly extending the service life of critical structural components while reducing the frequency of inspections and repair, thereby reducing costs while extending life.

Corrosion pits are a common site of fatigue crack initiation in aluminum alloy structural components of military aircraft. Pits result in intergranular corrosion to a finite depth depending upon the time of exposure, temperature, service environment, and surface treatment of the aircraft. The pronounced fatigue strength reduction caused by corrosion pitting is well established for aluminum alloys² and typically results in the reduction of the endurance limit to nominally half of the un-corroded value. Common repair and overhaul practice requires hand rework or machining to remove the pitted layer followed by SP to improve fatigue life by imparting a shallow layer of compressive residual stress. However, once a pit exceeds the depth of the compressive layer from SP, a fatigue crack can initiate and potentially propagate to failure. Both initiation and propagation can be avoided if the depth of compression exceeds the pitting depth. Compression produced by LPB is much deeper than a typical pit, and therefore the risk of fatigue failure from pitting is greatly reduced, if not eliminated for even the extended life of the aircraft.

Surface enhancement, inducing a layer of surface compressive residual stresses in metallic components, has long been recognized³⁻⁶ to enhance fatigue strength. The fatigue strength of many engineering components is improved by shot peening (SP). Treatments like LPB⁷, laser shock peening (LSP),⁸ and ultrasonic peening⁹ have emerged that benefit fatigue prone engineering components to different degrees. Additional benefits are obtained when deep compression is achieved with minimal cold working of the surface. Cold working is particularly critical in military aircraft aluminum alloys that will experience a corrosive environment. High levels of cold working create a more chemically active surface that is therefore more prone to corrosive attack. High cold working also has been shown to leave a surface in a thermo-mechanically unstable stress state¹⁰.

LPB has been demonstrated to provide a deep surface layer of stable, high magnitude compression with controlled, low cold working typically in the 3-5% range in aluminum, titanium, and nickel based alloys and steels. LPB is currently used in production in several aerospace, nuclear and medical applications, including military turbine engine blades and vanes and the propeller taper bore for the P-3 Orion. The deep compression mitigates fatigue damage including FOD,¹¹⁻¹³ fretting,¹²⁻¹⁵ SCC, and corrosion.¹⁶⁻¹⁹ The LPB process is performed on conventional CNC machine tools compatible with the overhaul shop

environment. LPB has recently been approved by the FAA for commercial aircraft maintenance.

The intent of this program was to study the effect of LPB as a process for safe life conversion of aircraft aluminum components in a corrosive environment. Knowledge of the materials stress state, operating conditions and damage characteristics are used to engineer a stable, compressive residual stress field that will greatly extend the life of the components in military aircraft. Corrosion fatigue, SCC, and alternate immersion pit depth testing were performed on four common aircraft structural alloys: 7075-T6, 7076-T6, 7475-T7351 and 2024-T351. SP was compared with LPB for each alloy to determine the improvement in service life and corrosion resistance, both as an initial manufacturing treatments, and as repair processes for surfaces damaged by prior SCC or salt fog exposure.

EXPERIMENTAL PROCEDURE

Material

Material was acquired in plate form and machined into test specimens. Alloy chemistry and mechanical properties were verified for each material tested. Two specimen geometries were used in testing. Specimen Type 1 consisted of rectangular bars with an undercut trapezoidal gage region nominally 8 x 1.25 x 0.375 in. (203 x 32 x 10 mm) used for HCF/SCC testing. The trapezoidal cross section HCF sample was designed to force the fatigue failures to initiate in the compressive gage section surface under 4-point bend loading. Specimen Type 2 was a rectangular or square coupon, no larger than 2 x 2 x 0.375 in. (51 x 51 x 10 mm) used for alternate exposure testing. Figure 1 shows an example of each specimen type.

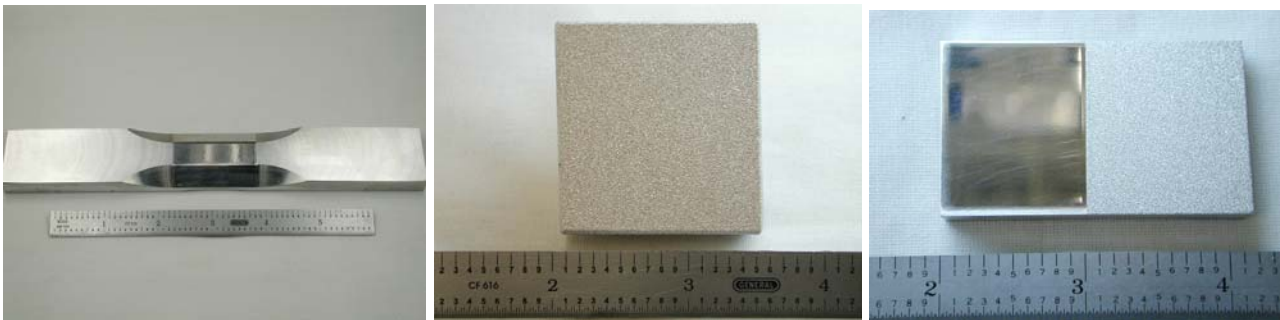


FIGURE 1 – Representative macro photos of specimen geometries tested

Specimen Processing

Test specimens were machined using conventional CNC machining methods and were subsequently LPB or SP processed as described below.

Low Plasticity Burnishing (LPB):

LPB process parameters were developed for each specimen type and alloy. The CNC control code was created to allow positioning of the LPB tool in a series of passes along the

region to be processed while controlling the burnishing pressure to develop the pre-determined magnitude of compressive stress with low cold working. The LPB tool operates in a closed loop, real-time feedback mode to ensure the proper pressures are applied to generate the compressive stress field desired and provides instant pass / fail response to the operator for each component processed.

Shot Peening (SP):

Shot peening was performed using a conventional air blast peening system equipped with a rotating table for both specimen types with the following process parameters: 6-8A intensity, 200% coverage, and CCW14 shot. Specimens were examined optically under low magnification to confirm coverage.

Alternate Immersion Pit Depth Testing

Alternate immersion testing was conducted in neutral 3.5 weight% NaCl solution at a constant temperature of 90°F (32°C) to determine the pit depth as a function of time. Type 2 coupons were tested in the following conditions: As-Machined 400 grit polish, SP, and LPB conditions. Testing was conducted using an automated alternate immersion tank shown in Figure 2 below. Samples were immersed in solution for 10 minutes and exposed to air for 50 minutes of a 1-hour cycle. All testing was performed under the guidelines and standards of ASTM G-44. A specimen of each surface treatment was removed and evaluated after 300, 500, 1000, 1500 and 2000 hours of exposure. Samples were cleaned and preserved in a sealed storage bag with silica gel desiccant to ensure no further corrosion in storage. Pit depths were using a Zeiss optical microscope at a magnification of 320X. Pit depths were plotted as a function of exposure time to determine the average pit depth for each surface treatment as a function of time.

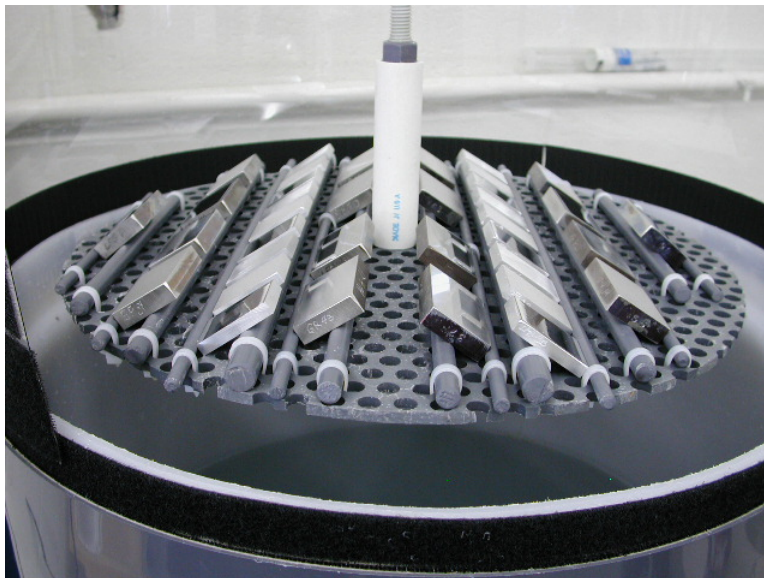


FIGURE 2 – Alternate immersion apparatus loaded with type 2 test samples

High Cycle Fatigue Testing

HCF tests were performed under constant amplitude loading on a Sonntag SF-1U fatigue machine. Fatigue testing was conducted at ambient temperature ($\sim 72^{\circ}\text{F}$ / 22°C) in four-point bending. The cyclic frequency and stress ratio, R ($\sigma_{\min}/\sigma_{\max}$), were 30 Hz and 0.1 respectively. Tests were conducted to specimen fracture or until "run-out" at 1×10^7 cycles. Specimens were subsequently broken fully open for optical and SEM fractographic analysis. Several corrosive test methods, described below, were used to damage the specimens prior to and during HCF testing to fully evaluate the benefits of SP and LPB.

Active Corrosion (AC):

Active corrosion (AC) fatigue testing was performed in a neutral 3.5% NaCl solution prepared with de-ionized water. Filter papers were soaked with the solution, wrapped around the gage section of the fatigue test specimen, and sealed with a plastic film to avoid evaporation. Figure 3 shows a specimen with the salt solution soaked filter paper sealed around the gage section. Figure 4 shows the specimen mounted in the four-point bend fixture assembled for fatigue testing in a Sonntag SF-1U HCF machine. In this manner specimens are exposed to a corrosive environment for the duration of the HCF test.



FIGURE 3 - A type 1 HCF specimen with 3.5% salt solution soaked tissue wrapped around the gage section to produce an 'active corrosion' environment during cycling

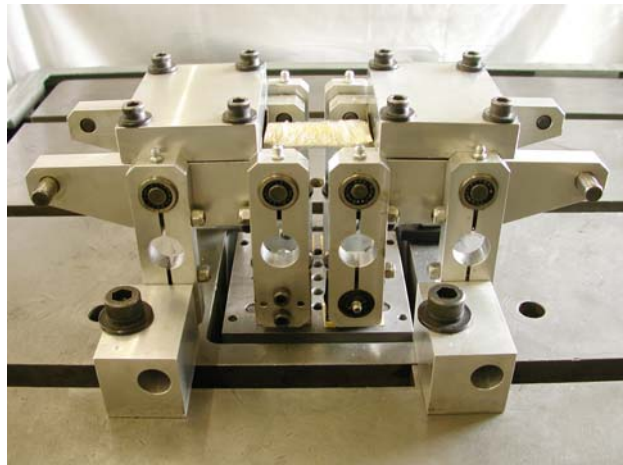


FIGURE 4 - Fatigue test set up

Salt Fog Corrosion Exposure:

A salt fog corrosion exposure was performed on the AA7075-T6 specimens at 95°F (35°C) per ASTM B117, Standard Practice for Operating Salt Spray (Fog) Apparatus. The fog deposited 1.0-2.0 ml/hr of 5 ± 1 mass percent NaCl aqueous solution on each 80 cm² of horizontal surface. The pH of the solution was maintained between 6.5 and 7.2. The salt fog exposure was performed at the Naval Air Depot at Cherry Point using a model TTC600 chamber manufactured by Q-Fog Corporation.

The specimens were exposed in two groups with the test surface horizontal for 100 and 500 hours. Following exposure to the salt fog, the samples were soaked and then rinsed in tap water, followed with a distilled water rinse to remove any salt solution remaining, and then dried. Patches of gray and white corrosion product evident on the surface of the samples were identified by x-ray diffraction as α - Al₂O₃. The corrosion product was not removed prior to testing or LPB processing.

Stress Corrosion Cracking (SCC) Damage Assessment:

Specimens were tested in HCF with and without prior exposure to SCC damage to determine the effect on the subsequent fatigue life of each material. The SP and LPB surface enhancement were compared for each material. Stress corrosion cracking exposure tests were conducted according to ASTM Standard G 39 and G44-99. All exposed specimens were loaded in tension to 90% of the alloy yield strength in 4-point bending. The load was monitored continuously with load cells to detect any change in compliance. Table 1 lists the maximum stress applied for each material during SCC exposure. A loaded SCC sample is shown in Figure 5. Specimens were exposed to 3.5% NaCl solution by alternate immersion (10 minutes in and 50 minutes out per cycle). The load history on each specimen was monitored for 100 hours. The specimens were then removed, cleaned with water, and tested in HCF. Specimens were tested in isolated baths specific to each material to avoid any possible galvanic effect during the SCC exposure. Table 2 describes the HCF test conditions studied for each material. A standard reaming process was performed after SP on the AA7076-T6 specimens to simulate an additional commonly used surface treatment.

TABLE 1 – SCC EXPOSURE LOADS

MATERIAL	MAX SCC STRESS (ksi)
<i>AA7075-T6</i>	<i>65.7</i>
<i>AA7076-T6</i>	<i>61</i>
<i>AA7475-T7351</i>	<i>55</i>
<i>AA2024-T351</i>	<i>42.3</i>



FIGURE 5 - Shot Peened SCC Sample in fixture after testing.

TABLE 2 – HCF TEST MATRIX

AA7075-T6	AA7076-T6	AA7475-T7351	AA2024-T351
<i>As-Machined</i>	<i>As-Machined</i>	<i>As-Machined</i>	<i>As-Machined</i>
<i>SP</i>	<i>SP+REAM</i>	<i>SP</i>	<i>SP</i>
<i>LPB</i>	<i>LPB</i>	<i>LPB</i>	<i>LPB</i>
<i>As-Mach. + 100 HRS SALT FOG + AC</i>	<i>As-Machined + AC</i>	<i>As-Mach. + 100 HRS SCC + AC</i>	<i>As-Mach. + 100 HRS SCC + AC</i>
<i>LPB + 100 HRS SALT FOG + AC</i>	<i>SP + REAM + AC</i>	<i>SP + 100 HRS SCC + AC</i>	<i>SP + 100 HRS SCC + AC</i>
<i>As-Mach. + 100 HRS SCC + AC</i>	<i>LPB + AC</i>	<i>LPB + 100 HRS SCC + AC</i>	<i>LPB + 100 HRS SCC + AC</i>
<i>SP + 100 HRS SCC + AC</i>	<i>SP + REAM + PITTED</i>	<i>As-Mach. + 100 HRS SCC + SP REPAIR + AC</i>	<i>As-Mach. + 100 HRS SCC + SP REPAIR + AC</i>
<i>LPB + 100 HRS SCC + AC</i>	<i>SP + REAM + PITTED + AC</i>	<i>As-Mach. + 100 HRS SCC + LPB REPAIR + AC</i>	<i>As-Mach. + 100 HRS SCC + LPB REPAIR + AC</i>
<i>As-Mach. + 100 HRS SCC + SP REPAIR + AC</i>	<i>SP + REAM + PITTED + LPB REPAIR</i>	-	-
<i>As-Mach. + 100 HRS SCC + LPB REPAIR + AC</i>	<i>SP + REAM + PITTED + LPB REPAIR + AC</i>	-	-

X-ray Diffraction Residual Stress Measurement

X-ray diffraction residual stress measurements were made at the surface and at several depths below the surface on LPB and SP treated fatigue specimens to determine the resulting residual stress distributions. Measurements were made employing a $\sin^2\psi$ technique and the diffraction of chromium $K\alpha_1$ radiation from the (311) crystallographic planes of the aluminum matrix phase. The lattice spacing was first verified to be a linear function of $\sin^2\psi$ as required for the plane stress linear elastic residual stress model.²⁰⁻²³

Material was removed electrolytically for subsurface measurement in order to minimize possible alteration of the subsurface residual stress distribution. The residual stress measurements were corrected for both the penetration of the radiation into the subsurface stress gradient²⁴ and for stress relaxation caused by layer removal.²⁵ The value of the x-ray elastic constants required to calculate the macroscopic residual stress from the strain normal to the (311) planes of aluminum were determined in accordance with ASTM E1426-9. Systematic errors were monitored per ASTM specification E915.

EXPERIMENTAL RESULTS

Alternate Immersion Pit Depth Testing

Photographs of the surfaces of AA7076-T6 specimens before and after testing are shown in Figure 6. Figure 7 shows the pit depth and Gaussian distributions for AA7076-T6 after the full 2000-hour exposure period. SP specimens tended to have a greater overall number of pits compared to LPB processed specimens. SP specimens also had deeper pits compared to the LPB specimens, which exhibited shallow surface damage with fewer deep pits.

It was observed from the pit depth vs. time plots that the rate of depth increase slowed as a function of time, asymptotically approaching a maximum pit depth for each alloy and condition. The maximum pit depth for the SP condition was nominally 9.5×10^{-3} in. (0.24 mm) compared to 5.7×10^{-3} in. (0.14 mm) for the LPB treatment. In all alloys tested the maximum pit depth was observed to be greater for the SP specimens. If the residual compression imparted from either SP or LPB exceeds the maximum pit depth so that the pit is held entirely in compression, then fatigue cracking cannot initiate, even with the high stress concentration due to the pit, and the likelihood of fatigue failure initiation from pitting is greatly reduced, or even eliminated if the compression is sufficient.

The pitting behavior was also plotted as histograms with a Gaussian function fit about the data. The histograms revealed the average depths for each condition as well as the minimum and maximum pit depth values for each distribution. The LPB treatment and as-machined conditions show similar behavior for all materials in alternate immersion testing. This is attributed to the lower cold working of the surface of the specimens. The LPB and as-machined conditions also both have much smoother and more uniform surface roughness than the SP specimen. The rough cold worked surface from the SP process provides a more chemically active surface that is more prone to corrosion.

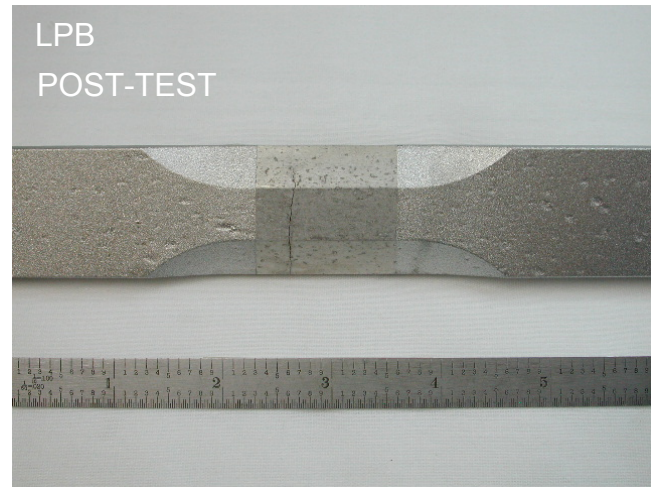
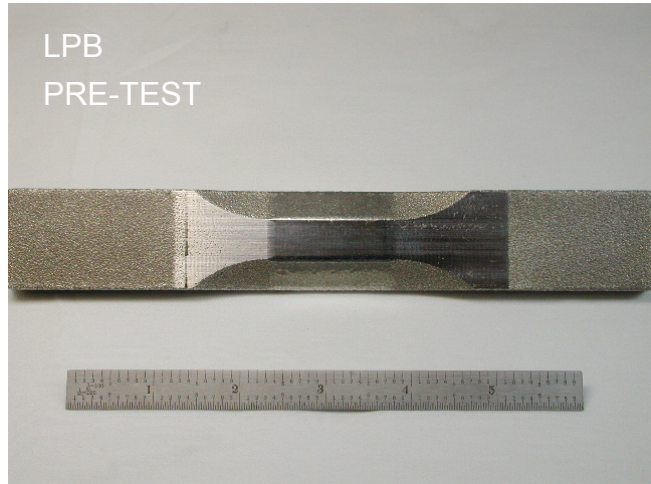
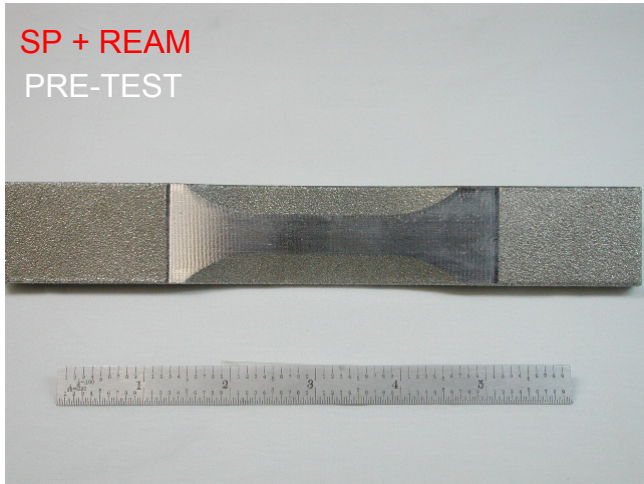


FIGURE 6 – Low magnification photos of specimens before and after exposure. SP specimens exhibited greater damage than LPB specimens.

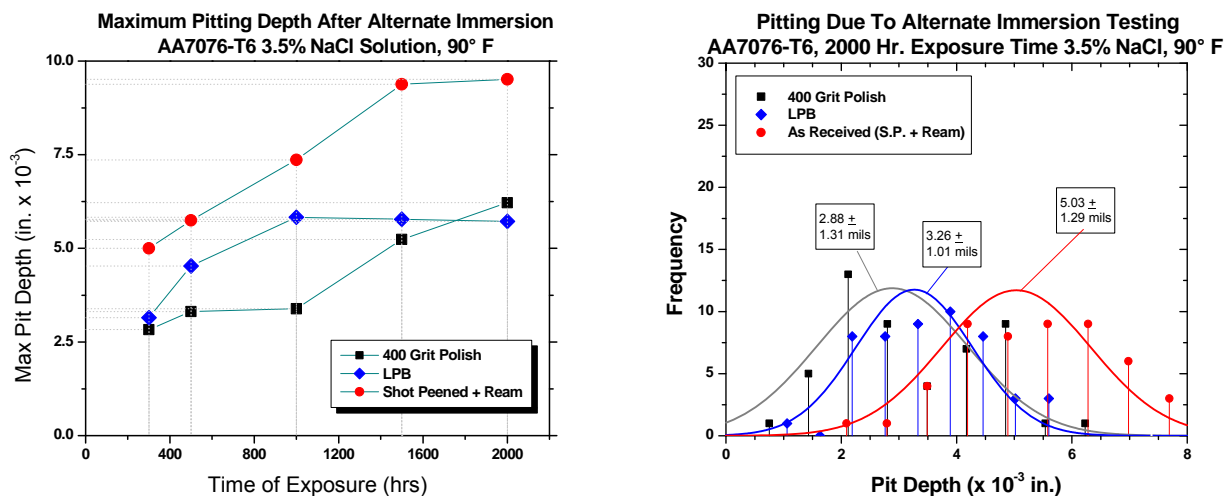


FIGURE 7 – Pit depth analysis for AA7076-T6. The plot on the left shows the pit depth as a function of time. The plot on the right is a histogram showing the distribution of pits after 2000 hrs. exposure.

High Cycle Fatigue Testing

Stress vs. Life (S-N) curves were generated for the four materials tested in the various corrosive conditions detailed in Table 2 above. To simulate both initial manufacture and repair, specimens underwent LPB or SP either before or after SCC exposure, respectively. The specimens were subsequently tested in HCF in active corrosion for the duration of the tests. To determine the full fatigue benefit of each treatment in the absence of a corrosive environment, ‘baseline’ tests were conducted with no prior corrosion or active corrosion during cycling. The pits resulting from the SCC exposure or salt fog chamber were consistent with the pit depths measured in the alternate immersion study.

The depth of compression in relation to the depth of the pits proved a critical factor. The greater depth of compression from the LPB process provided much longer fatigue life in all four alloys. Corroded LPB processed specimens exhibited fatigue life equal to, or greater than, the un-damaged as-machined specimens, and even the un-damaged SP processed specimens. The ‘baseline’ undamaged LPB curve, for all four alloys, produced the highest run-out stress and longest life of all the conditions.

LPB used as a repair process on as-machined + SCC exposed specimens was able to restore the fatigue life to greater than that of the SP + SCC specimens. In AA7075-T6 and AA2024-T351 the fatigue life was improved by greater than an order of magnitude over the SP repair specimens. The LPB repair processing was performed directly over the pre-corroded material with no prior cleaning other than a rinse in distilled water. Figures 8 and 9 show the full S-N curves for the alloys tested. Figure 10 shows the benefit of each surface treatment for a 7000 series alloy and 2000 series alloy when exposed to corrosion damage. The effectiveness of each treatment as a repair process is illustrated in Figure 11. The LPB process increased the fatigue life by nominally 10X over the SP treatment for all alloys tested and greater than 100X for the corrosion damaged alloys. Figure 12 is a bar chart showing the increase in fatigue strength at 1×10^7 cycles. The LPB process improved fatigue strength by 2-3X over the SP treatment under corrosive conditions.

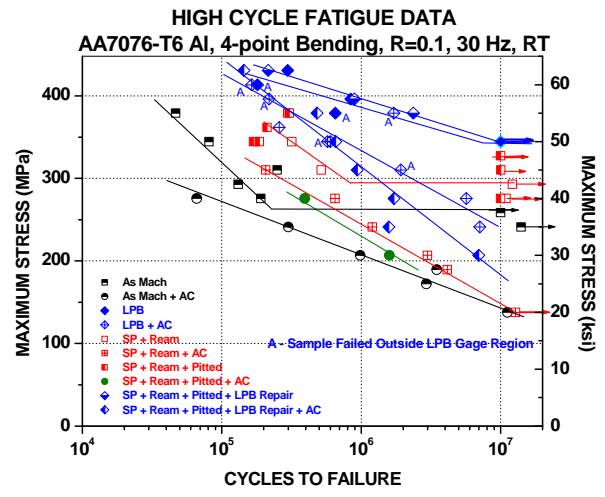
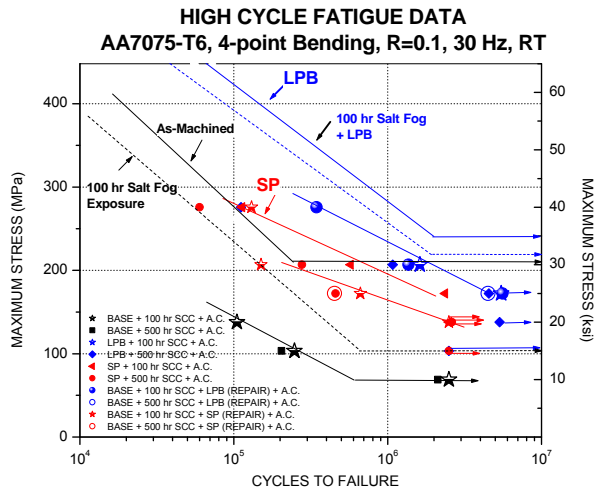


FIGURE 8 – S-N curves for AA7075-T6 (left) and AA7076-T6 (right). LPB processing showed greater than an order of magnitude improvement over the SP at most stress levels tested. LPB also increased the fatigue strength of both materials significantly.

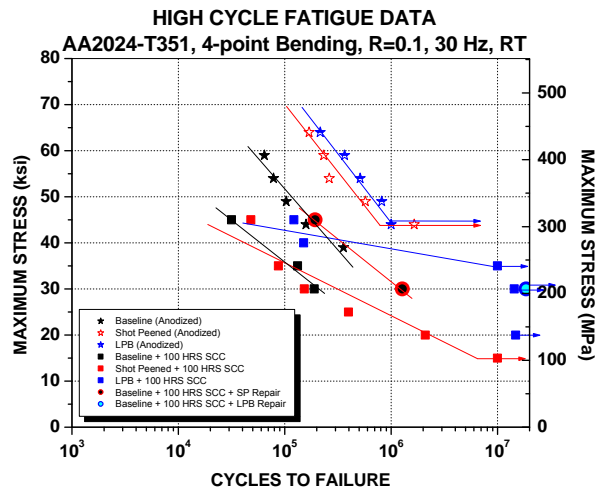
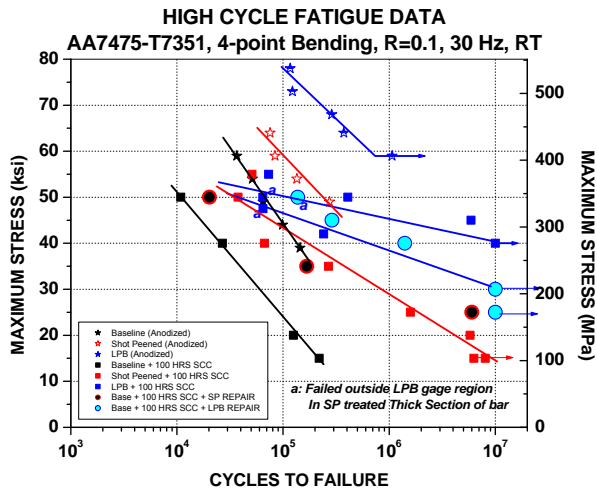


FIGURE 9 – S-N curves for AA7475-T7351 (left) and AA2024-T351 (right). The LPB process showed dramatic improvement in fatigue life and strength for both materials – particularly in the corrosion damaged conditions.

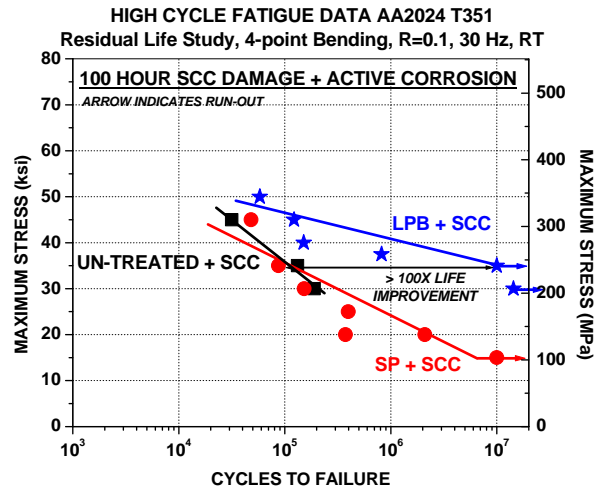
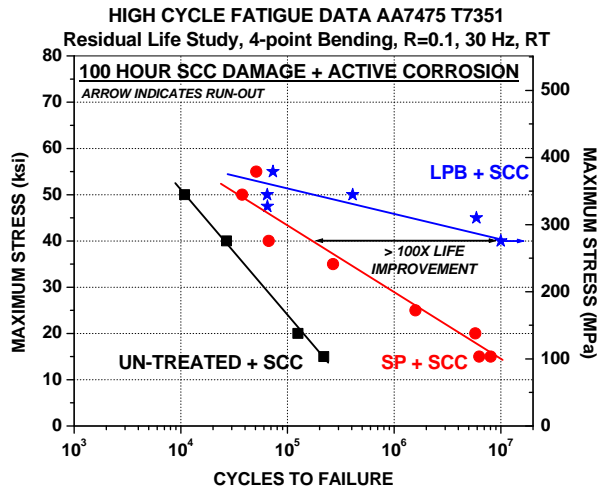


FIGURE 10 – Effect of corrosive environment on the fatigue life of 7000 and 2000 series Aluminum Alloys. The LPB treated specimens demonstrated greater than 100X increase in life over the SP treatment.

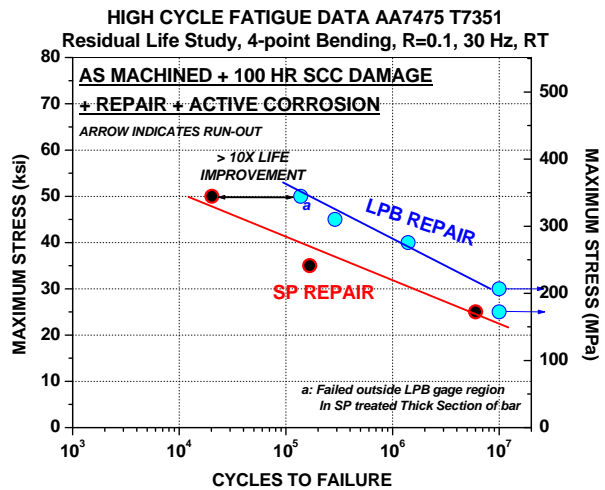
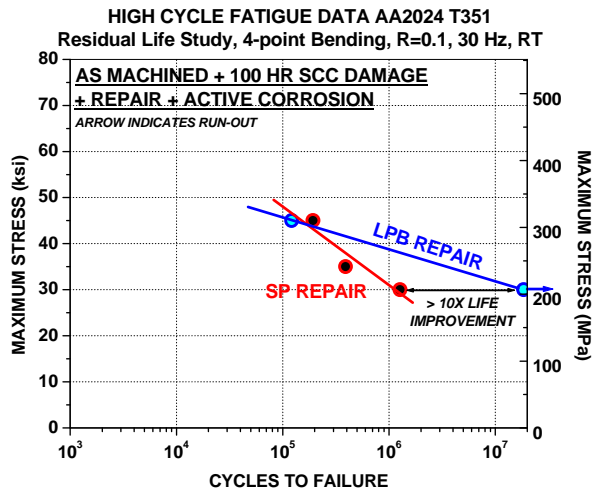


FIGURE 11 – Comparison of LPB and SP as repair processes for pre-corroded specimens. The LPB process improved the fatigue life by over an order of magnitude compared to the SP treatment.

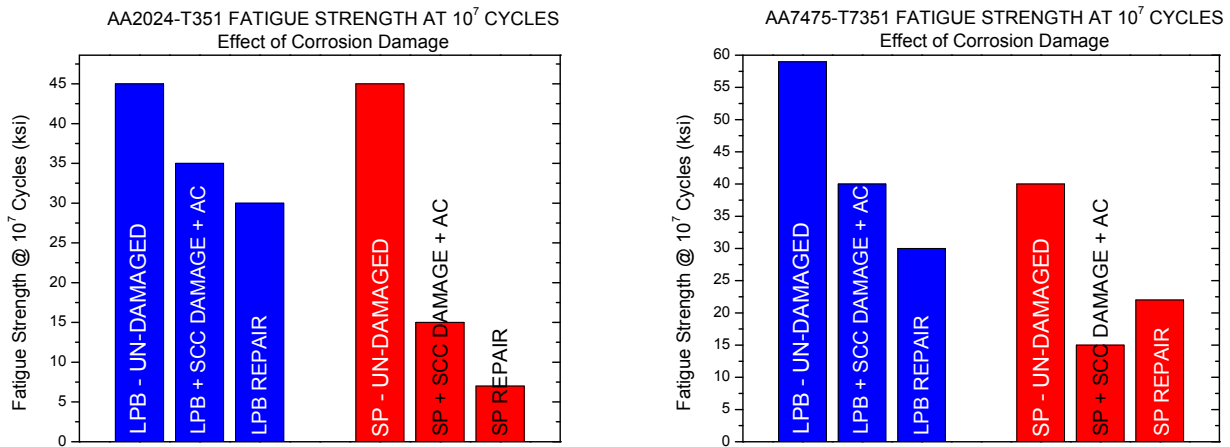


FIGURE 12 – Column plots comparing the fatigue strength at 10⁷ cycles. LPB processed specimens demonstrated an increase of 2-3X improvement over the SP treatment.

Residual Stress Distributions

X-ray diffraction residual stress results for AA7075-T6 and AA2024-T351 are presented graphically in Figure 14 and are representative of all four materials tested. Compressive stresses are shown as negative values, and tensile stresses as positive, in units of ksi (10^3 psi) and MPa (10^6 N/m²). Compared to SP, LPB produced a compressive residual stress field in each material with a greater magnitude of compression and over 3X the depth of compression. The random impact of shot during the SP process produces multiple impacts at the same location on the specimen. This repeated plastic deformation produces high cold working. LPB produced much less cold working of the treated specimens than SP ensuring the deep compression remains stable, even at high temperature or in the case of mechanical overload. The depth of compression from the LPB process greatly exceeds the maximum pit depth observed, preventing fatigue crack initiation from pits shallower than the compressive layer. This is reflected in the improved fatigue performance shown above.

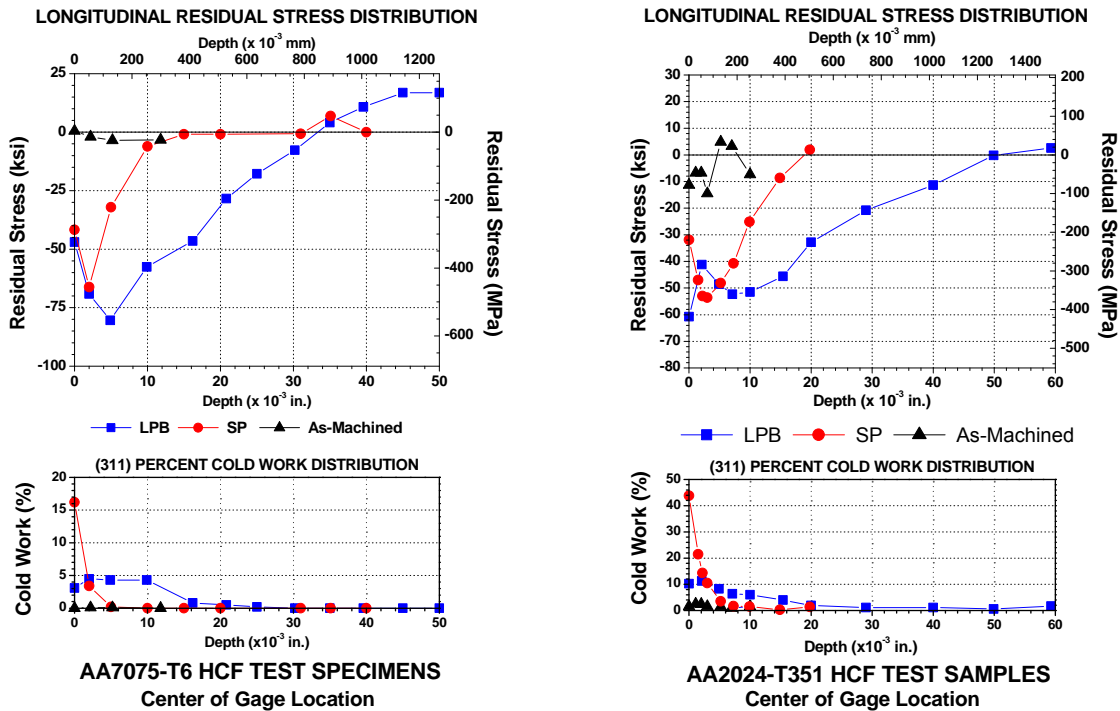


FIGURE 14 – Residual stress distributions for each surface treatment on AA7075-T6 and AA2024-T351. LPB processing provided greater magnitude and depth of compression than SP in all materials tested with low levels of cold working.

CONCLUSIONS

The corrosion fatigue performance of the four alloys tested was greatly improved by the LPB process relative to shot peening (SP). Whether used as a repair process or in initial manufacture, LPB increased the fatigue life of the specimens by up to an order of magnitude compared to 6-8A, 200% SP.

The results indicate a maximum pit depth is reached over time in 3.5% NaCl exposure of the 7000 and 2000 series alloys studied. Once a pit penetrates through the compressive layer, nucleation of fatigue cracking begins, and may progress to failure. By inducing compressive layer much deeper than the maximum pitting depth, fatigue cracking from pitting can be mitigated for the life of the structure.

LPB produced both greater depth and magnitude of residual compression than the 6-8A SP process. This difference in depth of compression was reflected in the improved corrosion fatigue performance of the LPB processed specimens.

Fractographic analysis revealed that SP and as-machined processed specimens failed predominately from single, or multiple, deep pits that exceeded the depth of compression. LPB processed specimens did not fail from pits and exhibited surface failures typical of non-corrosive fatigue failures where failure occurred simply due to reaching the fatigue limit for a particular stress.

As a repair process, LPB provided as much as an order of magnitude improvement in fatigue life over SP. LPB was able to restore, and even improve the fatigue life to exceed an un-corroded condition.

This investigation shows that the fatigue life of four commonly used aircraft aluminum alloys can be dramatically increased by use of engineered compressive residual stresses. Safe life operation of aircraft can be achieved by inducing a layer of compression exceeding the maximum pit depth for the alloy with LPB. The need for frequent inspections under retirement for cause can be eliminated. This engineered approach to safe life operation can greatly extend the operational service life of all aging aircraft, increase time-on-wing, and reduce operational costs.

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