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The Effect of Surface Enhancement on the
Corrosion Properties, Fatigue Strength, and Degradation of Aircraft Aluminum

Jeremy E. Scheel
Paul S. Prevéy III and Douglas J. Hornbach
Lambda Research
5521 Fair Lane
Cincinnati, Ohio 45227-3401
jscheel@lambdatechs.com

ABSTRACT

Corrosion, Stress Corrosion Cracking (SCC) and corrosion fatigue failures of high strength aircraft aluminums are costly and potentially catastrophic material problems affecting the aircraft fleet today. As the service lives of aircraft are extended, the increasing inspection and repair of corrosion in aging aircraft adversely affects fleet readiness, the cost of operation, and personnel safety.

Shot peening (SP) is a widely used surface enhancement and repair method that produces a shallow layer of compressive residual stress on the surface of components to improve fatigue life and corrosion resistance. The repeated random impact of shot subjects the treated surface to a high level of plastic deformation, or cold working. The high level of cold working reduces the thermal and mechanical stability of the beneficial compressive layer and creates a more chemically active surface that is prone to corrosive attack. Low Plasticity Burnishing (LPB) surface enhancement processing imparts a deep layer of stable compression with minimal cold working and has been shown to greatly improve fatigue and corrosion properties while avoiding the adverse effects of high cold working.

The corrosion fatigue and pitting corrosion performance of 7475-T7351 aluminum alloy is investigated for both SP and LPB treated test specimens. In all cases, LPB provided greater resistance to pitting and SCC damage. Corrosion fatigue life and damage tolerance were improved compared to the SP specimens. The depth of the shot peening compressive layer extends only a few thousandths of an inch into the surface. LPB imparts a much deeper layer of thermo-mechanically stable residual compression.

Corrosion pits, cracks, or other damage that exceed the depth of compression serve as the nucleation point(s) for corrosion induced fatigue cracking. Pit depths asymptotically approached a maximum depth dependent upon the surface treatment. The depth of compression from LPB greatly exceeds the maximum corrosion pit depth, therefore preventing corrosion related fatigue failure and ensuring safe-life operation.

INTRODUCTION

The operational life of many legacy aircraft is being extended well beyond the original design life. It is imperative that the existing fleet of aging aircraft continues to operate safely and at full capacity for this period of time while remaining cost effective. The current annual cost for corrosion inspection and repair of military aircraft alone is estimated to exceed one billion dollars annually. Presently, 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 2015. The total cost of ownership and fleet readiness are adversely affected at an increasing rate. A means of mitigating corrosion and corrosion-related fatigue damage is needed to prolong the service life of many structures and components as the fleet continues to age.

Surface enhancement of metals, inducing a layer of surface compressive residual stresses in metallic components, has long been recognized[1-4] to enhance fatigue strength. The fatigue strength of many engineering components is often improved by shot peening (SP). Surface enhancement treatments such as low plasticity burnishing (LPB)[5], laser shock peening (LSP)[6], and ultrasonic peening[7], have emerged that benefit fatigue and corrosion prone components to different degrees. Maximum benefits are obtained when deep compression is achieved with minimal cold working of the surface.

It is routine practice to grind out corrosion pits and other damage from components until clean metal is reached. A SP or blasting process is then typically used prior to painting and coating to restore the aircraft. While effective at removing damage and inducing a shallow layer of compressive residual stress, this practice removes material, limiting service life. Additionally, SP induces high levels of cold working into the material, as the surface is repeatedly deformed. The high levels of cold working generate an increased dislocation density providing for a highly unstable residual stress state[8]. A highly cold worked surface will relax during thermal exposure or mechanical overload, losing the beneficial compressive stresses from the surface enhancement process. Controlling the amount of cold working during surface enhancement allows for a stable, engineered compressive residual stress field that will not relax under thermal or mechanical stress.

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, steel, titanium, and nickel based super-alloys. LPB is currently used in production in multiple aerospace, nuclear and medical applications, including military gas turbine engine blades and vanes and the propeller taper bore for the P-3 Orion. LPB provides deep compression increasing fatigue performance for damage mechanisms including FOD[9-11], fretting[12-13], SCC, pitting and corrosion[13-17]. The LPB process is a 'turn key' technology performed on conventional CNC machine tools or robots, compatible with the overhaul or depot shop environment as well as production facilities. LPB has recently been approved by the FAA for commercial aircraft maintenance, repair and alteration to improve fatigue and SCC performance of aircraft components including engine, landing gear, and structural components.

Corrosion pits from salt spray are common sites of fatigue crack initiation in aircraft aluminum alloy structures. Corrosion pitting occurs during exposure to a marine atmosphere and results in intergranular corrosion to a depth depending on the time of exposure, temperature, and the service environment. The pronounced fatigue strength reduction caused by corrosion pitting is well established for aluminum alloys[18], and typically reduces the endurance limit to nominally half of the un-corroded value. The depth of residual compression is critical in preventing failure from corrosion pits. If the overall depth of compression exceeds the depth of pitting, then fatigue failure from pitting can be mitigated[19]. An overview of test results from studies on aluminum alloy AA7475-T7351 are presented. The effects of SP and LPB on active corrosion during fatigue testing and the fatigue performance after SCC exposure are discussed. SP and LPB and the resultant effect on the fatigue life and pitting depth of treated surfaces is presented and correlated with the depth of compression achieved by each surface treatment.

EXPERIMENTAL PROCEDURE

Material

AA7475-T7351 was acquired in plate form and machined into test specimens. Two specimen geometries were used. Specimen Type 1 consisted of rectangular bars with a trapezoidal gage region with maximum nominal dimensions of 8 x 1.25 x 0.375 in. (203 x 32 x 10 mm). Type 1 specimens were used for HCF, SCC and pit depth tests. The trapezoidal cross section HCF sample was designed to force the fatigue failures to initiate in the compressive gage region 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 immersion pit depth testing.

Specimen Processing

Low Plasticity Burnishing:

LPB process parameters were developed for both specimen types to achieve nominally 0.040 in. (1 mm) of compression. Samples were processed on a CNC mill to allow positioning of the LPB tool in a series of passes along the active gage region while controlling the burnishing pressure to develop the pre-determined magnitude of compressive stress with controlled low cold working. The LPB process has been described in detail previously[20].

Shot Peening (SP):

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

X-ray Diffraction Residual Stress

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 characterize the residual stress distributions. Measurements were made in the longitudinal direction in the fatigue specimens' gage region employing a $\sin^2\psi$ technique and the diffraction of chromium $K\alpha 1$ radiation from the (311) planes of aluminum.

Material was removed electrolytically for subsurface measurement in order to minimize possible alteration of the subsurface residual stress distribution. The measurements were corrected for both the penetration of the radiation into the subsurface stress gradient[21] and for stress relaxation caused by layer removal[22]. 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[23]. Systematic errors were monitored per ASTM specification E915.

Alternate Immersion Pit Depth Testing

Alternate immersion testing was conducted per ASTM G44 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. Specimen Types 1 and 2 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 1. Samples were immersed in solution for 10 minutes and exposed to air for 50 minutes of a 1-hour cycle. 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 measured 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.

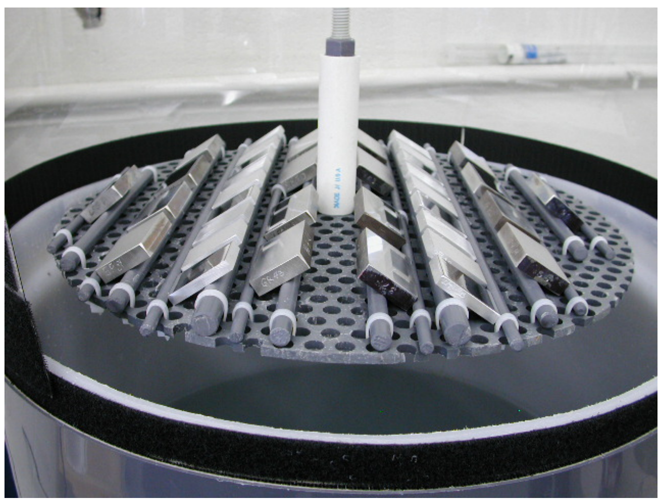

Figure 1 – Alternate immersion apparatus loaded with Type 2 samples.

High Cycle Fatigue Testing

High cycle fatigue (HCF) tests were performed under constant amplitude loading on a Sonntag SF-1U fatigue machine. Fatigue testing was conducted at ambient temperature (~72°F) in four-point bending mode. 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 a "run-out" life of 1 x 10^7 cycles was attained, whichever occurred first. Testing was terminated upon specimen failure. Specimens were subsequently broken fully open, if not cracked through entirely, to permit direct observation of fracture surface details using optical and SEM analysis. Several corrosive test methods were used to damage the specimens prior to and during HCF testing to fully evaluate the benefits of both surface treatments tested in a corrosive environment.

<u>Active Corrosion (AC)</u>

Active corrosion (AC) fatigue testing was performed in neutral 3.5% NaCl salt 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 2 shows a specimen with the salt solution soaked filter paper sealed around the gage section. Figure 3 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 2 - A Type 1 HCF specimen with 3.5% salt solution soaked tissue wrapped around the gage section to produce an 'active corrosion' environment during fatigue testing.

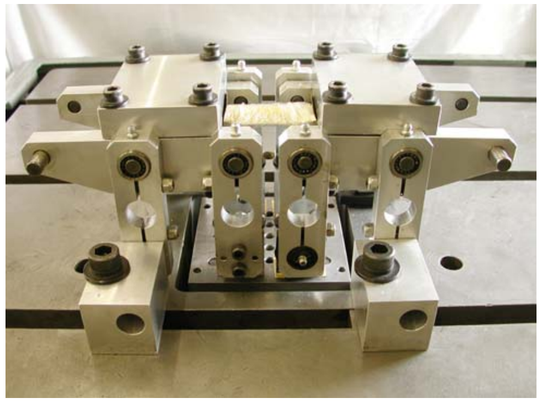

Figure 3 – Active corrosion fatigue testing set up.

Stress Corrosion Cracking

Specimens were tested in HCF with and without prior exposure to SCC damage to determine the effect on the fatigue life. Both SP and LPB processed samples were exposed to SCC damage. SCC exposure tests were conducted according to ASTM Standard G39 and G44-99. All exposed specimens were loaded in tension to 90% of the yield strength in 4-point bending using specially designed fixtures; the load on the specimen was monitored using instrumented bolts. Specimens were exposed to 3.5% NaCl salt solution by alternate immersion (10 minutes in and 50 minutes out per cycle) in a specially designed bath. SCC tests were conducted for 100 hours at which point the specimens were removed, cleaned with water, and tested in HCF.

LPB and SP Repair

As-machined fatigue specimens were exposed to SCC for 100 hours in the untreated condition at 90% of the yield strength. These specimens were subsequently treated with either SP or LPB and tested in fatigue with active corrosion during testing to determine the improvement in life when SP or LPB is used as a repair process on previously untreated material.

EXPERIMENTAL RESULTS

Alternate Immersion Pit Depth Testing

Photographs of the surfaces of specimens following alternate immersion salt exposure are shown in Figure 4. SP condition has a higher frequency of pitting compared to LPB. Figure 5 shows the maximum pit depth vs. exposure time. SP specimens have a greater overall number of pits compared to LPB processed specimens. SP specimens also had deeper pits compared to the LPB specimens.

It was observed from the pit depth vs. time plots that the pit depth asymptotically approaches a maximum for each surface condition. The maximum pit depth for the SP condition was nominally 17.4 x 10^{-3} in. (0.44 mm) compared to 6.8 x 10^{-3} in. (0.17 mm) for the LPB treatment. In all specimens tested the maximum pit depth was observed to be greater for the SP specimens. By introducing compression below the maximum pit depth the damage tolerance will be dramatically improved. Furthermore, if corrosion damage reaches a maximum, as these data indicate, a deep layer of residual compression well below the damage depth can, in principle, protect a structural component for the life of the aircraft. This would eliminate periodic grinding of corrosion and re-treatment of critical aircraft components.

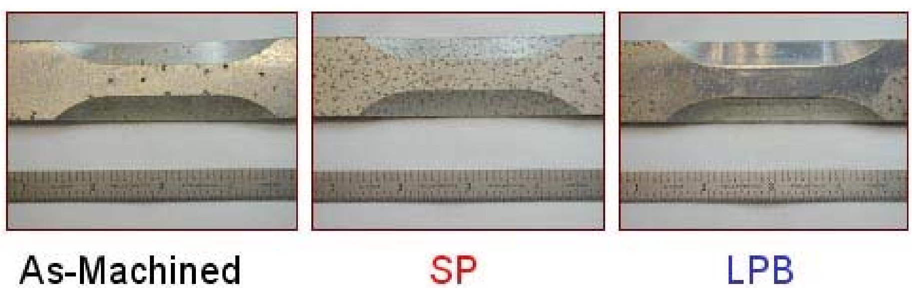

Figure 4 – AA7475-T7351 fatigue specimens after exposure. SP specimens exhibited greater corrosion damage than LPB and as machined specimens.

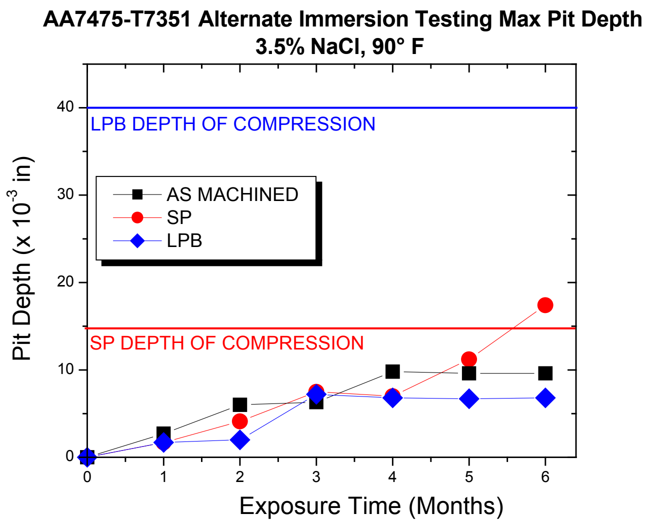

Figure 5 – Pit depth vs. exposure time for AA7475-T7351 revealing pit depth asymptotically approaches a maximum value that can be protected against with deep compression.

Residual Stress Distributions

X-ray diffraction results for AA7475-T7351 are presented graphically in Figure 6. Compressive stresses are shown as negative values, and tensile stresses as positive, in units of ksi (10^3 psi) and MPa (10^6 N/m^2). LPB produced maximum compression of nearly twice the magnitude as SP. SP has nominally half the compressive depth as LPB. Pit depths of the LPB sample are well below the maximum compression achieved by LPB providing for a substantial improvement in damage tolerance. Conversely, the depth of compression from SP is shallower than the maximum pit depth providing little to no damage tolerance.

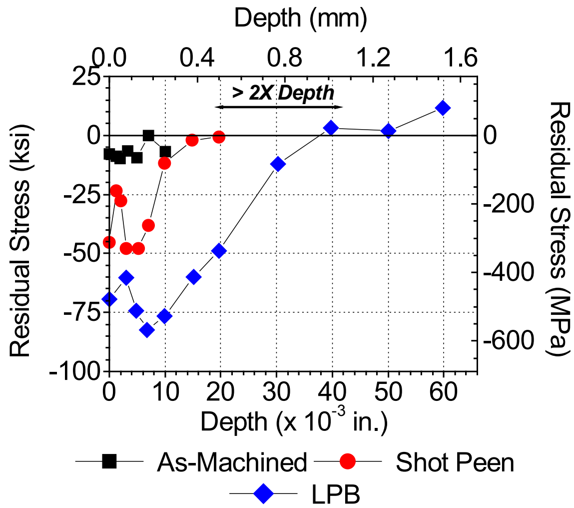

Figure 6 - Residual stress distributions for each surface treatment on AA7475-T7351. LPB processing provided greater magnitude and over 2X greater depth of compression than SP.

High Cycle Fatigue Testing

Figure 7 shows the S-N data for LPB, SP and untreated conditions with no prior active corrosion or SCC damage. SP provides a nominal 10 ksi improvement in fatigue strength at all applied stress levels tested. LPB provides a nominal 15 ksi improvement in fatigue strength over SP. The results indicate a nominal 10X improvement in fatigue life for LPB compared to SP.

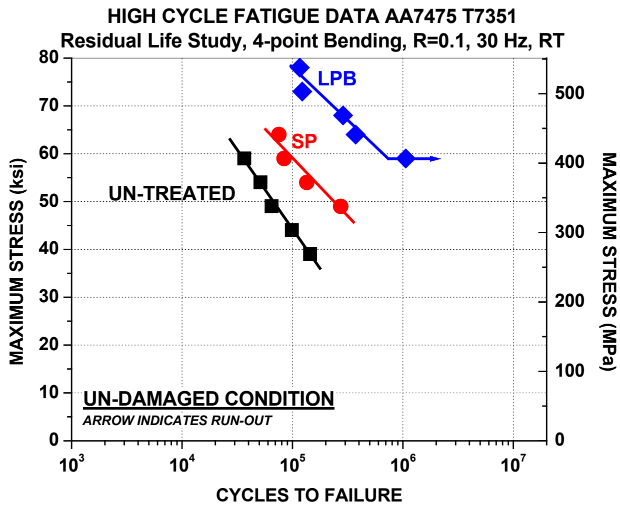

Figure 7 - S-N curve for AA7475-T7351 with no prior or active corrosion damage.

Figure 8 shows S-N data for LPB, SP and untreated conditions with prior SCC damage. Furthermore, the samples were fatigue tested with active corrosion. Damaged LPB specimens exhibited a fatigue life equal to, or greater than the untreated specimens with no damage. Fatigue strength of the SP condition is greatly reduced when exposed to SCC damage and active corrosion. This is a result of the corrosion pits penetrating through the shallow compression. The much deeper layer of compression from LPB prevents failure from pitting and other surface damage, greatly extending the fatigue life over the SP condition.

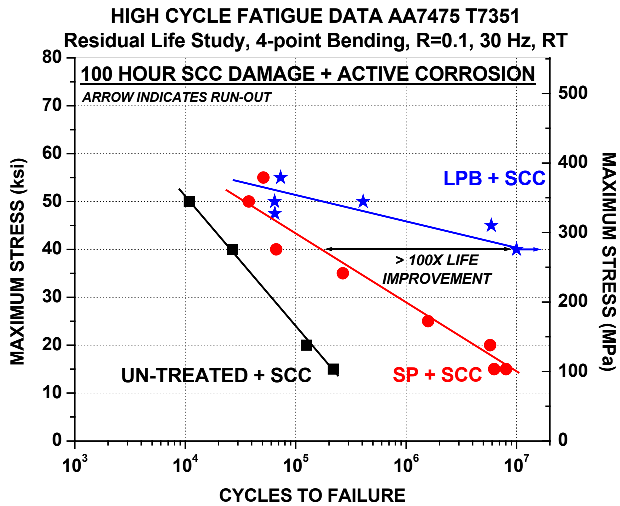

Figure 8 - S-N curve for AA7475-T7351 exposed to SCC and active corrosion during testing. LPB showed a life improvement greater than 100X that of SP.

Figure 9 shows S-N results on repair samples that were SP or LPB repaired following SCC damage. LPB repaired specimens had an order of magnitude increase in fatigue life over the SP repair specimens.

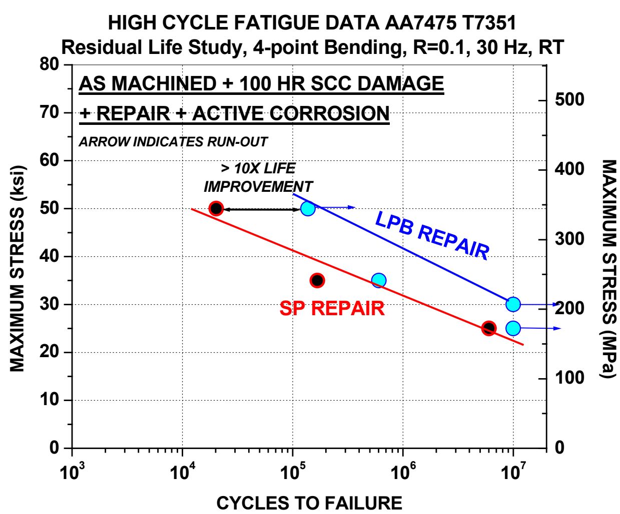

Figure 9 - S-N curve for AA7475-T7351 using SP and LPB as a repair method on pre-corroded specimens.

Fractography of failed HCF specimens was conducted using both optical and scanning electron microscopes. Fractographic analysis revealed that nearly all of the as-machined and SP processed specimens tested under corrosive conditions failed from one or more pits. Specimens tested at lower stresses generally exhibited failure initiation from a single deep pit while specimens tested at higher stress levels tended to have multiple nucleation sites. The LPB specimens failed both from the surface and below the surface. No failures from pits were observed in the LPB treated specimens.

CONCLUSIONS

- Corrosion pit depth vs. time results indicate the pit depth of 7475-T7351 asymptotically approaches a maximum depth for shot peen, LPB and as-machined conditions.
- Maximum pit depth results indicate that if a deep enough layer of residual compression is introduced the fatigue performance can be improved and sustained for the life of the component.
- XRD residual stress measurements show that LPB produces residual compression depth greater than 5 times the maximum pit depth.
- The maximum pit depth is greater than the SP depth of compression indicating little to no damage tolerance for the shallow compression from SP. Fatigue results obtained on 7475-T7351 samples show a nominal 10X improvement in life for LPB compared to SP condition for undamaged samples.
- A nominal 100X improvement was observed for LPB over SP for samples with significant corrosion damage.
- Fatigue life of 7475-T7351 aircraft aluminum alloy can be dramatically increased by use of engineered compressive residual stresses.
- The need for frequent inspections under retirement for cause can be reduced or eliminated through use of deep engineered compressive residual stress that extend well below the maximum corrosion damage depth. This engineered approach to safe life operation can greatly extend the operational service life of all aging aircraft, increase time-on-wing, and significantly reduce operational costs.

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