CASE STUDIES OF MITIGATION OF FOD, FRETTING FATIGUE, CORROSION FATIGUE AND SCC DAMAGE BY LOW PLASTICITY BURNISHING IN AIRCRAFT STRUCTURAL ALLOYS

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ABSTRACT

Surface enhancement technologies such as shot peening (SP), laser shock peening (LSP) and low plasticity burnishing (LPB) can provide mitigation of foreign object damage (FOD), fretting fatigue, corrosion fatigue, and stress corrosion cracking (SCC) damage. However, to be effective, the compressive residual stresses must be retained in service for successful integration into aircraft structural design, and the process must be affordable and compatible with the manufacturing environment. LPB provides high magnitude deep thermally and mechanically stable compression, and is performed on CNC machine tools. LPB provides a means to extend the lives of both new and legacy aircraft structural components. Improving fatigue performance by introducing deep stable layers of compressive residual stress avoids the generally prohibitive cost of modifying either material or design.

The LPB process combined with an overview of current research programs is presented. Fatigue performance and residual stress data developed to date for several case studies conducted to apply LPB to a variety of aircraft components include:

- Improved fretting fatigue and corrosion fatigue performance with LPB in 4340 high strength steel
- LPB treatment to mitigate FOD, corrosion fatigue and SCC in 300M HSLA landing gear steel
- Corrosion pitting and corrosion fatigue mitigation with LPB in AA7075-T6
- Improved fatigue and corrosion fatigue performance of friction stir welded joints of AA2219-T8751

Where appropriate, the performance of LPB is compared to conventional shot peening.

INTRODUCTION

FOD, fretting, active corrosion fatigue, corrosion pitting, and SCC are generally recognized as degradation processes that affect aircraft structural components. These damage processes are usually divided into three stages, initiation, propagation, and failure. Damage is normally localized and limited to specific areas, while a major part of the structure remains unaffected. It is known that tensile stress above a threshold is necessary for damage propagation leading to failure. For example, a threshold stress intensity factor (SIF), ΔK_{th}, and a threshold SCC stress are commonly used in structural design. Similar thresholds exist for other damage processes such as fretting fatigue. Therefore, introducing residual compression of sufficient magnitude and depth in the damage-prone region will lead to a local net stress that is below the threshold, and hence achieve mitigation of the damage.

The classical approach to improve resistance to damage initiation and propagation is through alloy development and/or modification of microstructure through heat treatment. Protective coatings are also used to delay the onset of fretting and corrosion damage. Alloy development programs are time consuming and can be very expensive, while application of protective coatings could have serious environmental impact.

Introduction of residual compressive stresses in metallic components has long been recognized[1,2,3,4] to lead to enhanced fatigue strength. Many engineering components have been shot-peened or cold worked with fatigue strength enhancement as the primary objective or by-product of a surface hardening treatment such as carburizing/nitriding, physical vapor deposition, etc. Over the last decade, treatments such as LPB[5], LSP[6], and ultrasonic peening[7] have emerged. In all surface treatment processes, optimal benefits are obtained when deep compression is achieved with minimal cold work of the surface. All of these surface treatment methods have been shown to improve the life and performance of fatigue prone engineering components to different degrees.

Low Plasticity Burnishing

LPB has been demonstrated to provide a deep surface layer of high magnitude compression in various aluminum, titanium, and nickel based alloys and steels with minimal cold work.[8] The deep compressive residual stress state on the surface of these materials mitigates fatigue damage including FOD[9,10,11] fretting,[12,13] and corrosion.[14,15,16,17] The LPB process can be performed on conventional CNC machine tools at costs and speeds comparable to conventional machining operations such as surface milling.

The LPB process has been described in detail previously,[19] and is characterized by a single pass of a smooth free rolling ball under a normal force sufficient to plastically deform the surface of the material. The ball is supported by a constant volume flow of fluid in a spherical hydrostatic bearing as shown in Figure 1, and can be held in any CNC machine or robotic positioning apparatus. The patented constant volume support prevents the ball from contacting the bearing surface. The ball is in solid contact only with the surface to be burnished and is free to roll on the surface of the work piece.

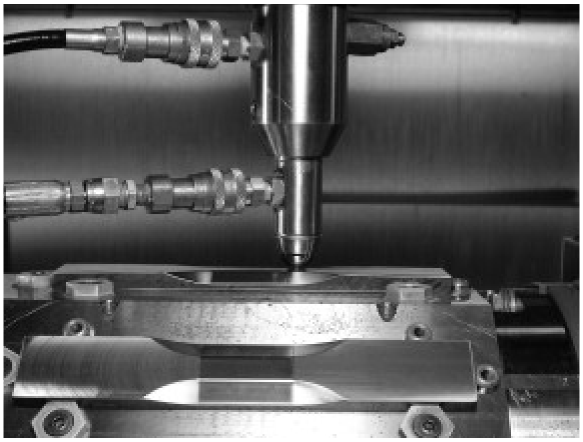

Figure 1 – LPB processing of fatigue samples with at single point contact LPB tool in a 4-axis CNC mill.

Using CNC positioning, the tool path is controlled during the LPB process so that the surface is covered with a series of passes at a separation maintained to achieve maximum compression with minimum cold working. The tool may be moved in any direction along the surface of a complex work piece, as in a typical multi-axis CNC machining operation. The LPB processing of fatigue specimens used in this investigation is also depicted in Figure 1.

EXPERIMENTAL TECHNIQUE

X-ray Diffraction Surface Characterization

Residual stresses were measured by standard x-ray diffraction method ($\mathrm{Sin}^2\psi$). Appropriate corrections were applied to the measured residual stresses to account for redistribution of stresses from layer removal. Diffraction peak broadening, measured in conjunction with the residual stress, allows the amount of plastic deformation developed by surface enhancement methods to be accurately assessed. The method of quantifying the degree of cold working of metals, by relating the x-ray diffraction peak broadening to the equivalent true plastic strain, has been described previously.[20] The distribution of cold work as a function of depth into the deformed surface can be expressed in terms of the equivalent true plastic strain. If the degree of cold work is taken to be the equivalent amount of true plastic strain, the degree of cold work is then cumulative and is independent of the mode of deformation. Thus, the subsurface yield strength distribution can then be estimated from true stress-strain curves.[21] The macroscopic residual stress, of primary interest in design and life prediction, is determined in the conventional manner from the shift in the diffraction peak position.[22,23,24]

Test Methods

The HCF testing mode selected to provide maximum sensitivity to the surface condition was four-point bending.[25] Fatigue testing was conducted on thick section specimens at room temperature under constant sinusoidal load amplitude at 30 Hz, R=0.1 using Sontag SF-1U fatigue testing machines. Fatigue data were developed as S/N curves of nominally eight samples each. HCF samples were all typically finish machined by low stress grinding. In order to minimize the surface residual stresses from machining, the specimens were subsequently stress relieve annealed or electropolished. In all cases, the surface residual stresses of the as-machined specimens were documented. S/N curves were prepared for various combinations of surface conditions, fretting damage, corrosion damage, corrosive environment, and/or FOD.

Salt fog corrosion samples were exposed at 35° C per ASTM B117 for a period of 100 hours. Following exposure to the salt fog, residual salt was removed by soaking and then rinsing the samples in tap water, followed with a distilled water rinse. Patches of corrosion product evident on the surface of the samples were examined by x-ray diffraction. The corrosion product was not removed prior to fatigue testing.

Active corrosion fatigue tests were conducted with the sample gage section wrapped in a chemical-free laboratory tissue saturated with 3.5-wt% NaCl solution (pH adjusted) and sealed with polyethylene film and vinyl to avoid evaporation. The saturated tissue served as a wick to maintain the salt solution in contact with the sample surface.

Fretting damage was produced in thick section specimens by pressing a cylindrical pad into the active gage section of the fatigue specimen during cyclic loading. The clamping fixture was instrumented with strain gages and calibrated to monitor the normal force during testing.

SCC testing was completed on C-ring specimens with the gage section machined similar to the thick section specimen. The C-ring specimens were loaded with a diametral bolt, and load was monitored with instrumented washers. SCC testing was completed in an alternate immersion set up with 3.5% NaCl neutral salt solution with the specimens immersed for 10 minutes and out of the solution for 50 minutes for a total of 1 hour per cycle. Tests were terminated upon failure or after 1500 hours of test time.

FOD was simulated by introducing a v-shaped surface notch on the gage section by electrical discharge machining (EDM).

RESULTS AND DISCUSSION

High Strength Structural Steels

Ultrahigh strength steels such as 4340 and 300M are widely used in applications where a combination of high strength and fracture toughness is needed. Most of these ultrahigh strength steels have been known to be prone to SCC and corrosion fatigue.

4340 Steel

The residual stress profiles in LPB treated 4340 steel are shown in Figure 2. Measurements made both parallel and perpendicular to the treatment directions are presented. In both orientations, compression to depths greater than 0.050 in. (1.25 mm) is observed. The corresponding % cold work is well below 3%, even at the surface of the specimens.

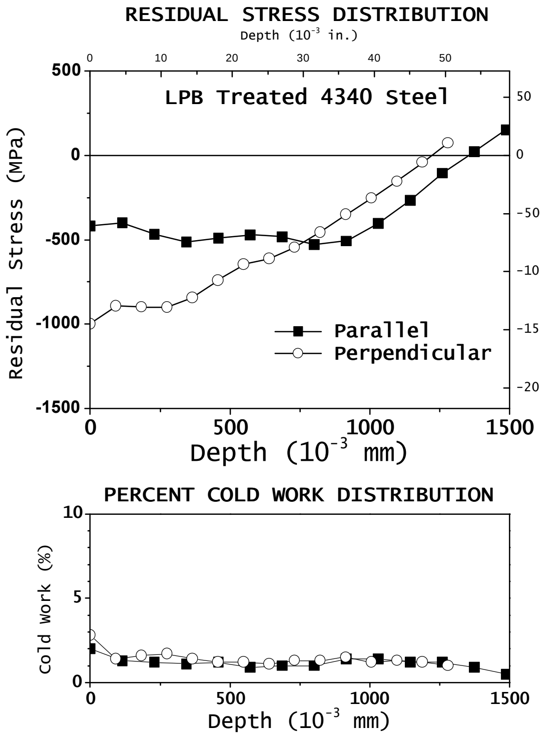

Figure 2 - Residual stress and % cold work distribution in LPB treated 4340 Steel

Figures 3 and 4 show the fatigue performance in the as-machined and LPB treated conditions before and after salt-fog exposure to 100 and 500 hours. It is evident from these figures that prior corrosion damage leads to a substantial debit in fatigue performance. LPB treatment results indicate significantly better fatigue performance than the as-machined condition. Also, both the S-N data and the bar chart indicate effective mitigation of damage from salt-fog exposure in LPB treated material.

Fretting of 4340 steel produced a fretting scar in the form of a narrow band of black oxidation on the surface nominally 1 mm (0.04 in.) wide, but varying with the applied stress and strain range. The depth of the fretting scar was shallow, insufficient to remove the surface marks left by grinding.

The width of the fretting scar was dependent upon the strain range of the test because the fretting was generated by a pad clamped to the surface of the cyclically strained fatigue sample. Fatigue cracks initiated from the edges of the scars at the point of maximum shear stress under contact loading.

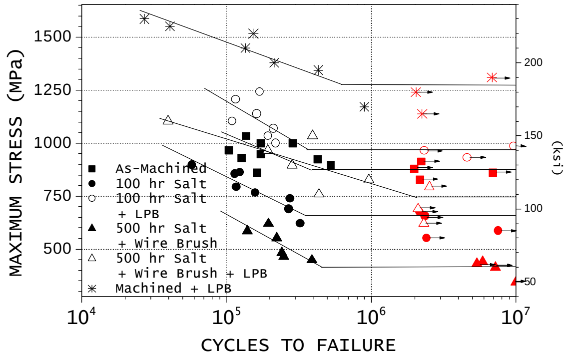

Figure 3 – HCF S-N plots of salt-fog exposed 4340 steel

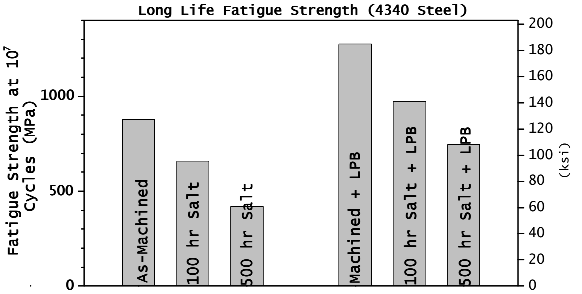

Figure 4 - Bar chart showing the relative fatigue strengths of salt-fog exposed 4340 steel

The fretting fatigue results are shown in Figure 5. The ground baseline samples produced an endurance limit of 827 MPa (120.0 ksi). Fretting of as-ground samples during fatigue testing reduced the endurance limit to nominally 758 MPa (110.0 ksi). Pre-fretting followed by fretting during fatigue testing (simulating returning a fretted part to continued service) reduced the HCF endurance limit further to nominally 620 MPa (90.0 ksi), a loss of 25% of the initial fatigue strength.

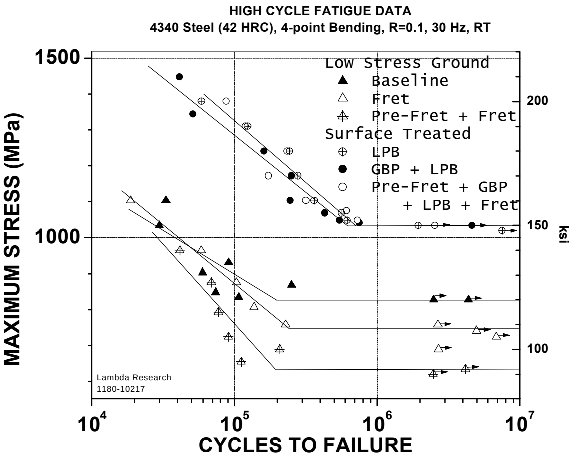

Figure 5 - 4340 steel fretting fatigue results

LPB, either before or after fretting, produced an endurance limit of nominally 1033 MPa (150.0 ksi), 25% higher than ground 4340 without fretting damage. Even with fretting, both before and after LPB, the LPB samples exhibited the same 25% endurance limit increase, indicating complete mitigation of the fretting fatigue debit.

Fatigue initiated from the edge of the fretting scar in all of the 4340 samples without LPB. Fatigue initiated in all LPB samples subsurface, just below the compressive layer, indicating a fatigue strength for the LPB surface even higher than indicated by the results achieved in bending. The subsurface failures are interpreted as a limitation of the test technique and sample design, which combined to allow the maximum tension to occur below the highly compressive test surface.

300M Steel

A comparison of residual stress profiles from shot-peened and LPB treated 300M HSLA steel specimens are shown in Figure 6. LPB treated specimens show compression to a depth of over 0.04 in. (1.2 mm) while the SP resulted in only 0.005 in. (0.1 mm) deep compression. In both cases, thermal exposure to 400ºF for 48 hours did not result in significant stress relaxation. A bar chart comparing the fatigue strengths of baseline material in the presence of a 0.01 in. (0.25 mm) deep FOD and/or active salt corrosion, with similar test conditions for shot peened and LPB treated specimens are shown in Figure 7. The results indicate both active salt corrosion and FOD decrease the fatigue strengths by a factor of 5, while the combined effects of FOD and active corrosion are even worse. SP has marginal beneficial effects when only active corrosion is considered, while no benefit is seen with the presence of FOD or with the combined presence of FOD and active corrosion. The results also indicate Ni-Cr plating had no benefit in mitigating corrosion fatigue damage. As seen in the LPB treated samples, almost all the damage from active salt corrosion, FOD, and the combined damage conditions are fully mitigated. The Ni-Cr plating on top of the LPB treated surface performed better than the shot-peened surface. Fractography indicated that all corrosion fatigue cracking damage initiated from corrosion pits. LPB did not stop the formation of corrosion pits, rather the crack initiation and growth processes were completely blocked by the deep compressive residual stresses. The Ni-Cr plating was found to have numerous plating cracks, and corrosion pitting and SCC were not prevented by the plating process.

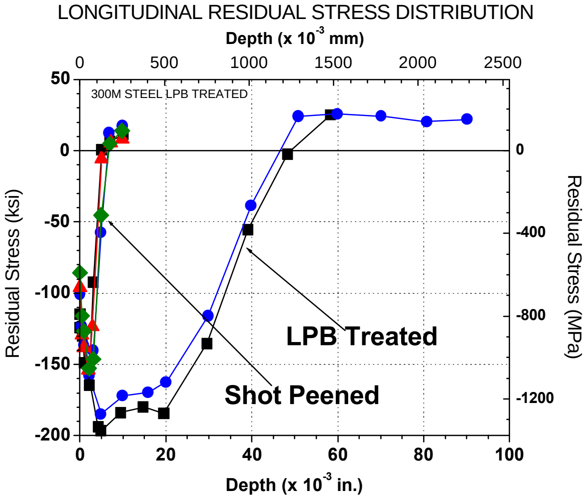

Figure 6 – Residual stress profiles of shot peened and LPB treated 300MHSLA steel specimens before and after 48 hours of thermal exposure to 400F

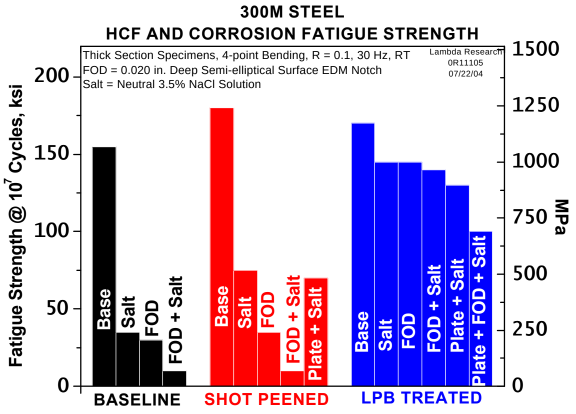

Figure 7 - Bar chart showing the fatigue strength of 300M HSLA steel

SCC studies on LPB treated 300M HSLA steel showed similar benefits. A bar chart of time to failure at different constant applied stresses on C-ring specimens is shown in Figure 7. Untreated baseline specimens, when stressed at 150 ksi, 165 ksi, and 180 ksi, failed after 261.8 hrs, 166.5 hrs, and 12.9 hrs respectively, of alternate immersion in neutral salt solution. The LPB treated specimens did not fail after 1,500 hrs of exposure. Efforts to increase the stresses beyond 180 ksi resulted in permanent bending of the LPB treated specimens, rather than failure. Thus, results indicate that LPB processing completely mitigated the SCC damage conditions in 300M HSLA landing gear steel.

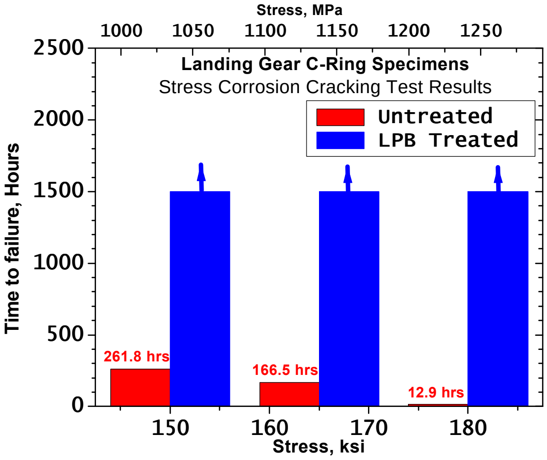

Figure 8 - SCC test results for 300M Steel

STRUCTURAL ALUMINUM ALLOYS

AA7075-T6

The pronounced fatigue strength reduction caused by salt pit corrosion or corrosion fatigue in a marine environment is well established for both steels[26,27] and aluminum alloys.[28] The fatigue strength debit for either mechanism is typically on the order of half the long-life, HCF endurance limit. Corrosion pits are a common site of fatigue crack initiation in the aluminum alloy 7075-T6 widely used for structural components of older aircraft. Pitting arises from intergranular corrosion to a depth dependent upon the service environment and the time of exposure, i.e., age of the aircraft. Current annual costs for corrosion inspection and repair of military aircraft alone are estimated to exceed one billion dollars. Currently, 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.[29] The total cost of ownership and fleet readiness are adversely affected. A means of mitigating corrosion and corrosion-related fatigue damage is needed.

The residual stress profiles of AA7075-T6 fatigue specimens in the as-machined and LPB treated condition are shown in Figure 9. A depth of compression of nearly 0.035 in. (0.9 mm) was achieved with LPB treatment. Figure 10 shows the HCF data for AA7075-T6 specimens tested in the as-machined and LPB treated conditions in both active corrosion mode as well as with prior salt-fog exposure. In the as-machined condition both active corrosion and prior salt-fog exposure results in a significant drop in the fatigue performance in that the fatigue strength at 10^7 cycles drop by 50% from about 32 ksi to 16 ksi. With LPB treatment the HCF properties are 50% higher than the as-machined condition. The results indicate the compressive residual stresses from LPB not only mitigated the corrosion pitting damage, but also far exceed the baseline performance.

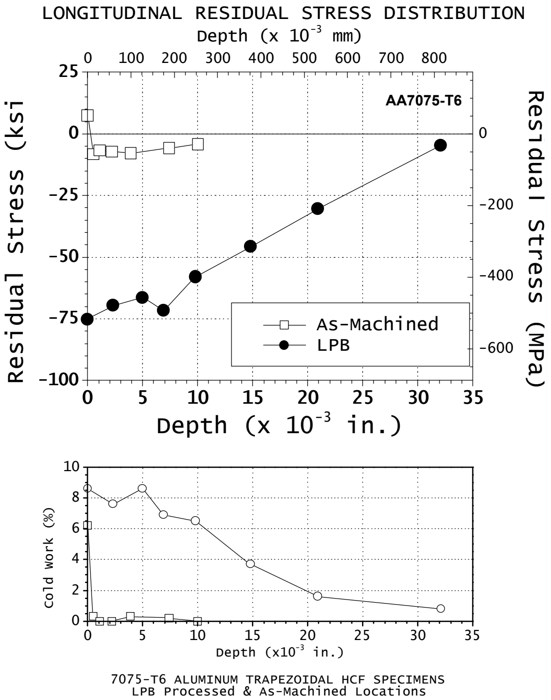

Figure 9 – Residual stress distribution in AA7075-T6 in the as-machined and LPB conditions

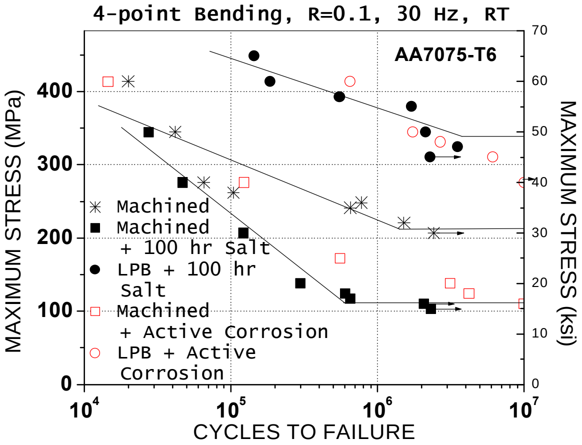

Figure 10 – HCF S-N data for AA7075-T6

AA2219-T8751

Friction stir welding (FSW) is emerging as a joining method for structural aluminum members. However, issues related to residual tensile stresses and surface finish lead to significant debit in fatigue performance. Test results indicate LPB has proven to be an excellent treatment by way of eliminating the tensile residual stresses, smoothing the surface to a mirror finish, and improving the fatigue performance, resulting in patented FSW applications.[30]

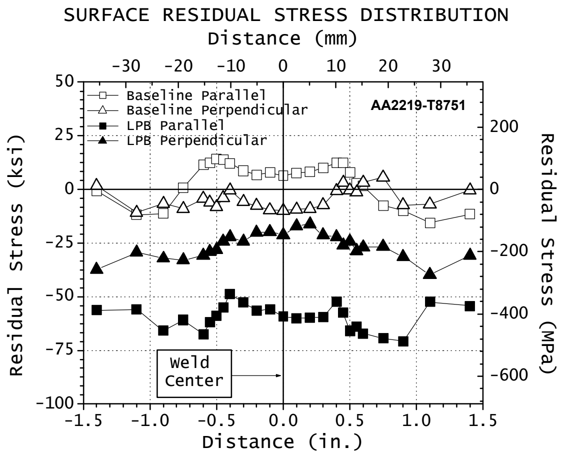

Figure 11 - Surface residual stress distribution in FSW plate AA2219-T8751

The residual stress distributions parallel and perpendicular to the weld on the surface of a friction stir welded plate of AA2219-T8751 are shown in Figure 11 for the as-welded condition and after LPB processing. As indicated in Figure 11, the surface tensile residual stresses created by the FSW process are completely eliminated and in place a compressive residual stress state is introduced by LPB treatment.

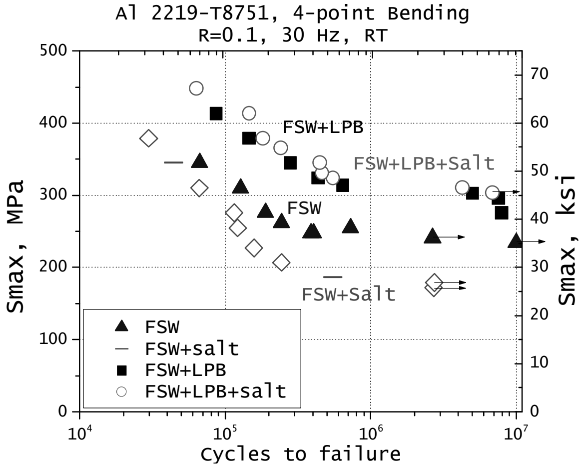

Figure 12 - HCF S-N plots for AA2219-T8751

A comparison of baseline FSW versus LPB treated FSW with and without active corrosion is shown in Figure 12. The fatigue strength of baseline FSW AA2219-T8751 is shown to decrease from nominally 35 ksi to 25 ksi in the presence of active corrosion. LPB treated FSW both in the baseline condition and the active corrosion conditions performed equally well and surpassed the performance of the baseline FSW. Improvement in the fatigue performance is evident at nominally 45 ksi. This improvement is attributed to the surface compressive residual stresses seen in Figure 11.

CONCLUSIONS

LPB is shown to completely mitigate the tensile stress threshold dependent mechanisms of SCC and corrosion fatigue. LPB effectively mitigates the damage associated with fretting, pitting corrosion, and FOD in laboratory testing of structural aluminum alloys and steels. The deep compressive residual stress afforded by LPB effectively eliminates the damage growth process, although normal damage initiation mechanisms like fretting, pitting, rusting, etc., are still active. The effectiveness of LPB to mitigate damage in aircraft structural steels and aluminum alloys has been demonstrated.

REFERENCES

1 Frost, N.E. Marsh, K.J. Pook, L.P., *Metal Fatigue*, Oxford University Press, 1974.

2 Fuchs, H.O. and Stephens, R.I., *Metal Fatigue In Engineering*, John Wiley & Sons, 1980.

3 Berns, H. and Weber, L., "Influence of Residual Stresses on Crack Growth," Impact Surface Treatment, edited by S.A. Meguid, Elsevier, 33-44, 1984.

4 Ferreira, J.A.M., Boorrego, L.F.P., and Costa, J.D.M., "Effects of Surface Treatments on the Fatigue of Notched Bend Specimens," Fatigue, Fract. Engng. Mater., Struct., Vol. 19 No.1, pp 111-117,1996.

5 Prevéy, P.S. Telesman, J. Gabb, T. and Kantzos, P., "FOD Resistance and Fatigue Crack Arrest in Low Plasticity Burnished IN718", Proc of the 5th National High Cycle Fatigue Conference, Chandler, AZ. March 7-9, 2000.

6 Clauer, A.H., "Laser Shock Peening for Fatigue Resistance," Surface Performance of Titanium, J.K. Gregory, et al, Editors, TMS Warrendale, PA (1996), pp 217-230.

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7 T. Watanabe, K. Hattori, et al, "Effect of Ultrasonic Shot Peening on Fatigue Strength of High Strength Steel," Proc. ICSP8, Garmisch-Partenkirchen, Germany, Ed. L. Wagner, pg 305-310.

8 U.S. Patent 5,826,453 (Oct. 1998) and 6,415,486 B1 (Jul. 2002), other patents pending.

9 P. Prevéy, N. Jayaraman, R. Ravindranath, "Effect of Surface Treatments on HCF Performance and FOD Tolerance of a Ti-6Al-4V Vane," Proceedings 8th National Turbine Engine HCF Conference, Monterey, CA, April 14-16, 2003

10 Paul S. Prevéy, Doug Hornbach, Terry Jacobs, and Ravi Ravindranath, "Improved Damage Tolerance in Titanium Alloy Fan Blades with Low Plasticity Burnishing," Proceedings of the ASM IFHTSE Conference, Columbus, OH, Oct. 7-10, 2002

11 Paul S. Prevéy, et. al., "The Effect of Low Plasticity Burnishing (LPB) on the HCF Performance and FOD Resistance of Ti-6Al-4V," Proceedings: 6th National Turbine Engine High Cycle Fatigue (HCF) Conference, Jacksonville, FL, March 5-8, 2001.

12 M. Shepard, P. Prevéy, N. Jayaraman, "Effect of Surface Treatments on Fretting Fatigue Performance of Ti-6Al-4V," Proceedings 8th National Turbine Engine HCF Conference, Monterey, CA, April 14-16, 2003

13 Paul S. Prevéy and John T. Cammett, "Restoring Fatigue Performance of Corrosion Damaged AA7075-T6 and Fretting in 4340 Steel with Low Plasticity Burnishing," Proceedings 6th Joint FAA/DoD/NASA Aging Aircraft Conference, San Francisco, CA, Sept 16-19, 2002

14 N. Jayaraman, Paul S. Prevéy, Murray Mahoney, "Fatigue Life Improvement of an Aluminum Alloy FSW with Low Plasticity Burnishing," Proceedings 132nd TMS Annual Meeting, San Diego, CA, Mar. 2-6, 2003.

15 Paul S. Prevéy and John T. Cammett, "The Influence of Surface Enhancement by Low Plasticity Burnishing on the Corrosion Fatigue Performance of AA7075-T6," Proceedings 5th International Aircraft Corrosion Workshop, Solomons, Maryland, Aug. 20-23, 2002.

16 John T. Cammett and Paul S. Prevéy, "Fatigue Strength Restoration in Corrosion Pitted 4340 Alloy Steel Via Low Plasticity Burnishing." Retrieved from www.lambda-research.com Sept. 5, 2003.

17 Paul S. Prevéy, "Low Cost Corrosion Damage Mitigation and Improved Fatigue Performance of Low Plasticity Burnished 7075-T6", Proceedings of the 4th International Aircraft Corrosion Workshop, Solomons, MD, Aug. 22-25, 2000.

18 U.S. Patent 5,826,453 (Oct. 1998) and 6,415,486 B1 (Jul. 2002), other patents pending.

19 P. Prevéy, "The Effect of Cold Work on the Thermal Stability of Residual Compression in Surface Enhanced IN718," Proc. 20th ASM

Materials Solutions Conf. & Expo, St. Louis, MO, Oct. 10-12, 2000.

20 P. Prevéy, “The Measurement of Subsurface Residual Stress and Cold Work Distributions in Nickel Base Alloys,” Residual Stress in Design, Process & Materials Selections, ed. W.B. Young, Metals Park, OH: Am. Soc. For Metals, 1987, p 11-19.

21 P. Prevéy, P. Mason, D. Hornbach, & J. Molkenthin, “Effect of Prior Machining Deformation Upon the Development of Tensile Residual Stresses in Weld Fabricated Nuclear Components,” *Journal of Materials Engineering and Performance*, Vol. 5, 1, February 1996, p. 51-56.

22 P.S. Prevéy, Metals Handbook, Vol 10, ASM, Metals Park, OH, (1986), p. 380-392.

23 M.E. Hilley, ed, Residual Stress Measurement by XRD, SAE J784a, SAE, Warrendale, PA (1971)

24 Noyan & Cohen, Residual Stress Measurement by Diffraction & Interpretation, Springer-Verlag, NY, (1987)

25 P. Prevéy, W.P Koster, “Effect of Surface Integrity on Fatigue of Standard Alloys at Elevated Temperatures,” Fatigue at Elevated Temperatures, ASTM STP561, ASTM, Phil., PA, (1972)pp. 522-531.

26 ASM Handbook, Vol. 19, Fatigue and Fracture, S.R. Lampman, ed., ASM International, Metals Park, OH, 1996, pp. 596-597.

27 Cammett, J. and Prevéy, P., “Fatigue Strength Restoration in Corrosion Pitted 4340 Alloy Steel via Low Plasticity Burnishing,” (2001), Retrieved July 19, 2002, from http://www.lambda-research.com/publica.htm.

28 Dowling, N., Mechanical Behavior of Materials, Prentice Hall, NJ, 1993, p. 365.

29 Agarawala, V., "Corrosion and Aging: Aircraft Concerns," presentation at 11th Annual AeroMat Conference, Bellevue, WA, June 26-29, 2000.

30 U.S. Patent 6,926,970 B2 (Aug. 2005)