AN OVERVIEW OF THE USE OF ENGINEERED COMPRESSIVE RESIDUAL STRESSES TO MITIGATE SCC AND CORROSION FATIGUE

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ABSTRACT

Mechanical suppression of corrosion fatigue and stress corrosion cracking (SCC) through low plasticity burnishing (LPB) has been demonstrated in several systems. LPB can be used to impart controlled compressive residual stresses of desired depth, magnitude and location in structural components. For example, in 300M aircraft landing gear steel, LPB produced over 1.2 mm of compression and in turn completely mitigated corrosion fatigue and SCC, even in the presence of simulated foreign object damage (FOD). In precipitation hardenable stainless steels used for turbine engine compressor blade applications, full mitigation of corrosion fatigue damage and FOD has been achieved. In friction stir processed (FSP) aluminum alloys, LPB mitigated the corrosion fatigue damage by completely suppressing the tensile residual stresses associated with the FSP. A comprehensive design procedure has been developed to determine the optimum location and magnitude of compression. Effects of compensatory tension and part distortion are analyzed with the use of several design tools like Fatigue Design Diagram and finite element analysis (FEA). Actual measurements of residual stresses and corrosion fatigue tests are used to validate the initial design.

LPB has been applied to successfully mitigate FOD and/or SCC in 300M landing gear steels, corrosion fatigue in turbine engine compressor blade 17-4PH and Custom450 stainless steels, and aircraft structural aluminum alloys AA7075-T6 and AA2219-T8751. In this paper, selected examples demonstrating the mitigation of active corrosion fatigue, restoration of fatigue performance after severe pitting due to prior corrosion exposure, and complete prevention of SCC by LPB treatment are presented.

INTRODUCTION

Stress corrosion cracking (SCC), corrosion fatigue and foreign object damage (FOD) are generally recognized as significant degradation processes that affect naval aircraft components. For example, ultrahigh strength steels such as 4340, Aeromet 100, AF1410 and 300M are widely used in landing gear 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.[1,2,3,4]

Salt spray corrosion pits are common sites of fatigue crack initiation in aluminum alloy structures. Salt 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 salt pit corrosion is well established for both steels[5] and aluminum alloys,[6] and typically reduces the endurance limit to nominally half of the uncorroded value.

Precipitation hardened martensitic stainless steels are widely used in applications where a combination of high strength and resistance to corrosion is needed. 17-4PH stainless steel is probably the most used alloy steel of this kind. Components made of precipitation hardened martensitic stainless steels have been known to be prone to corrosion fatigue and) SCC.[7,8,9,10] Much of the earlier research on this topic focused on preventing or minimizing corrosion fatigue damage and SCC through alloy chemistry, microstructure control through heat treatment, and surface treatment.

The phenomenon of SCC is generally understood to be the result of a combination of a material susceptible to SCC, exposed to corrosive environment, which is also subjected to a tensile stress above certain a threshold level. This is succinctly illustrated in Figure 1. Earlier solutions to this problem include the attempts to reduce the susceptibility to corrosion by modifying the material through alloy chemistry, microstructure by heat treatment, or protect the material from the environment by protective coatings.

Mechanical Suppression of SCC and corrosion fatigue by the introduction of deep residual compressive stresses at the surface has been very successful. SCC promotes tensile stresses above a certain threshold. Therefore, full mitigation of SCC is possible if the net stress on the SCC prone surface is kept below the threshold value through the introduction of deep surface residual compressive stresses by LPB.

Introduction of residual compressive stresses in metallic components has long been recognized[11,12,13,14] to lead to enhanced fatigue strength. For example, many engineering components have been shot-peened or cold worked with the fatigue strength enhancement as the primary objective or as a by-product of a surface hardening treatment like carburizing/nitriding, physical vapor deposition, etc. Over the last decade, other examples of the former type of treatments like LPB[15], laser shock peening (LSP)[16], and ultrasonic peening[17] have emerged. In all the surface treatment processes, key benefits are obtained when deep compression is achieved with no or minimal cold work of the surface. All of these surface treatment methods have been shown to benefit fatigue prone engineering components to different degrees.

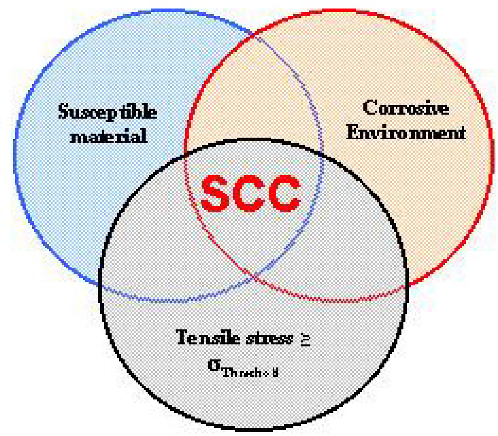

Figure 1 – SCC susceptibility diagram illustrating the need for the combination of a susceptible material, corrosive environment, and threshold tensile stress to cause SCC.

Low plasticity burnishing (LPB) has been demonstrated to provide a deep surface layer of high magnitude compression in various aluminum, titanium, nickel based alloys and steels. The deep compressive residual stress state on the surface of these materials mitigates fatigue damage including FOD[18,19,20] fretting fatigue damage,[21,22] and corrosion fatigue damage.[23,24,25,26] The LPB process can be performed on conventional CNC machine tools at costs and speeds comparable to conventional machining operations such as surface milling.

An overview of test results from several studies on various materials including 300M HSLA landing gear steel, AISI4340 high strength steel, 17-4PH stainless steel, Custom450 stainless steel, AA7075-T6, and AA2219-T8751 are presented in this paper. The effects of surface treatments like shot peening (SP) and LPB on active corrosion fatigue, fatigue performance after salt fog exposure, SCC, and/or FOD were examined. Effects of varying depth of compression from the different surface treatment processes in mitigating different damage conditions are discussed.

LOW PLASTICITY BURNISHING

The LPB process produces a layer of compressive residual stress of high magnitude and depth with minimal cold work.[27] The process has been described in detail previously,[28] characterized by a single pass of a smooth free rolling ball under a normal force sufficient to plastically deform the surface of the material. While hertzian loading from LPB treatment has been shown to create a layer of compressive residual stress to depths deeper than 10 mm (0.4 in.), in typical applications compression to a depth of 1 mm (0.04 in.) has been found to be adequate. The ball is supported in a fluid bearing with sufficient pressure to lift the ball off the surface of the retaining spherical socket. 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. In comparison, typical shot peening process produces compression to depths of 0.1 to 0.2 mm (0.005 to 0.010 in.) However, typical damage conditions like corrosion pits, SCC and FOD can be deeper than the compression afforded by shot peening and will not protect the components from cracking and fracture.

Using CNC positioning, the tool path is controlled in 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 depicted in Figure 2.

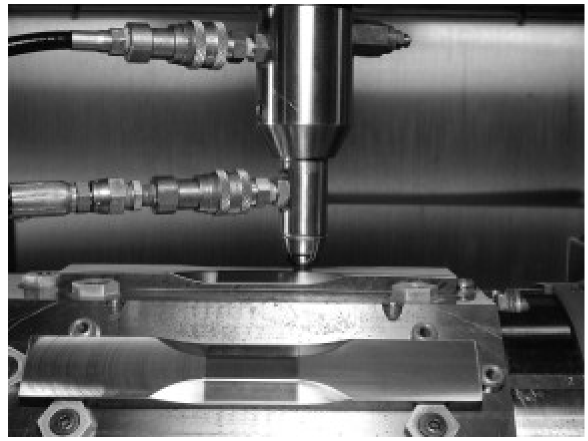

Figure 2 – LPB processing of fatigue samples with at single point contact LPB tool in a 4-axis CNC mill.

X-RAY DIFFRACTION SURFACE CHARACTERIZATION

Surface residual stresses were measured by standard x-ray diffraction ($Sin^2\psi$) method. Subsurface residual stresses were measured by the same method after sequential electropolishing of the surface. The appropriate corrections were applied to the measured residual stresses to account for redistribution of stresses from layer removal. Diffraction peak broadening, measured along 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.[29] 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.[30] 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.[31,32,33]

HCF AND SCC TESTING

Four-point bending was the HCF testing mode selected to provide maximum sensitivity to the surface condition.[34] 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 was 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 condition, 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, any 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. SCC testing was done on C-ring specimens with the gage section machined similar to the thick section specimen. The C-ring specimens were loaded with bolt and the load was monitored with instrumented washers. SCC testing was done 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 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 to the required depth on the gage section of the thick section specimens by electrical discharge machining (EDM) method.

In the following sections, results of residual stress depth profiles due to LPB treatment and corrosion fatigue test results from various studies will be presented.

HIGH STRENGTH 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. In this section, the effectiveness of LPB to mitigate corrosion fatigue and SCC is presented.

Figure 3 shows the residual stress profiles in LPB treated 4340 steel. 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 seen. The corresponding % cold work is well below 3% even at the surface of the specimens. Figures 4 and 5 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 both Figures 4 and 5 that prior corrosion damage leads to substantial debit in fatigue performance. LPB treatment is seen to result in significantly better fatigue performance for the as-machined condition. Also, both the S-N data and the bar chart indicate complete mitigation of damage from salt-fog exposure in LPB treated material.

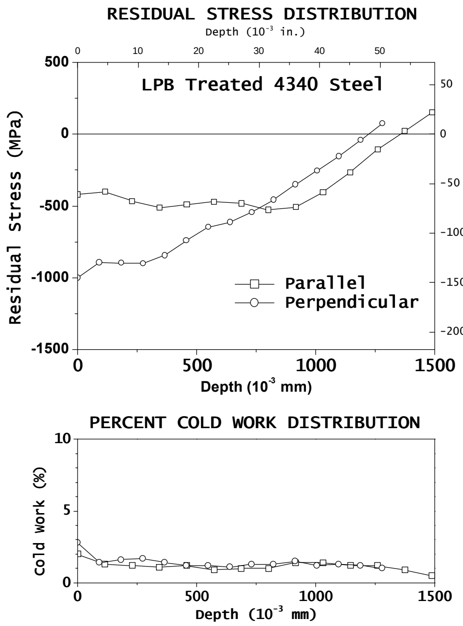

Figure 3 - Plots of residual stress and % cold work distribution in LPB treated 4340 Steel

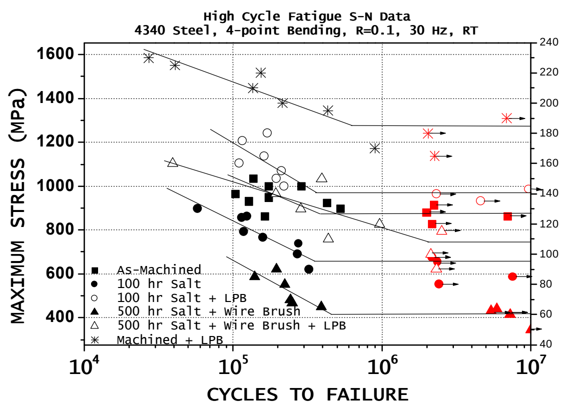

Figure 4 – S-N plots of salt fog exposed 4340 steel.

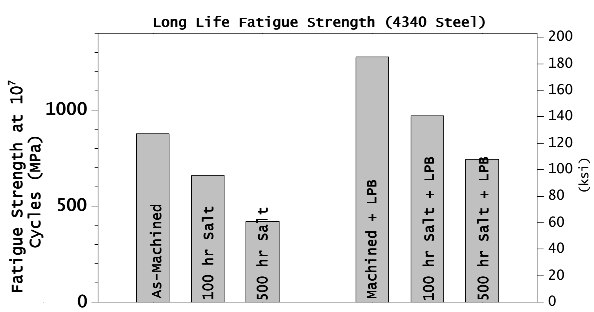

Figure 5 - Bar chart showing the relative fatigue strengths salt-fog exposed 4340 steel)

Figure 6 shows a comparison of residual stress profiles from SP and LPB treated 300M HSLA steel specimens. LPB treated specimens show compression to a depth of over 0.04 in. (1.2 mm) while the shot peening treatment 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. Figure 7 shows 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. Both active salt corrosion and FOD have the effects of decreasing the fatigue strengths by a factor of 5, while the combined effects of FOD and active corrosion are even worse. Shot peening (SP) has some marginal beneficial effects when only active corrosion is considered, while no benefit is seen with the presence of FOD and combined presence of FOD and active corrosion. Even Ni-Cr plating had no benefit in mitigating corrosion fatigue damage. With LPB treatment, almost all the damage from active salt corrosion, FOD, and the combined damage conditions are fully mitigated. The Ni-Cr plating on top of LPB treated surface performed better than with the SP 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 stopped by the deep compressive residual stresses. The Ni-Cr plating was found to have numerous plating cracks, and again the corrosion pitting and SCC were not stopped by the plating process.

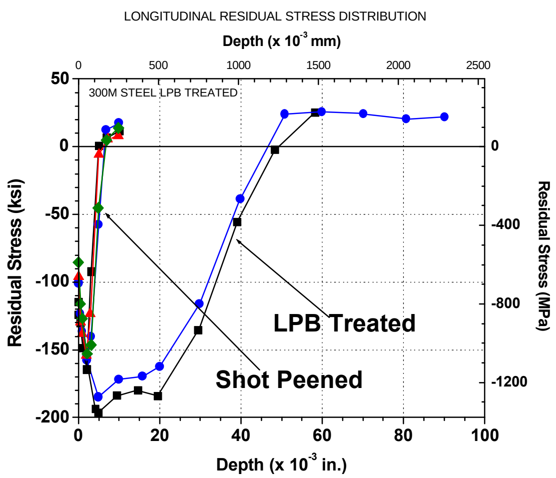

Figure 6 - RS profiles of shot peened and LPB treated 300MHSLA steel specimens
before and after 48 hours of thermal exposure to 400F

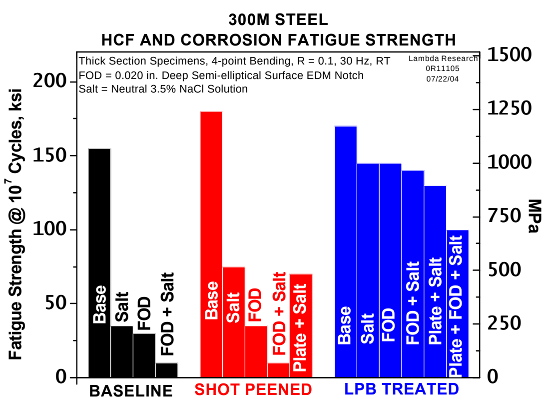

Figure 7 – Bar chart showing the fatigue strength of 300M HSLA steel.

SCC studies on LPB treated 300M HSLA steel showed similar benefits. Figure 8 shows a bar chart of time to failure at different constant applied stresses on c-ring specimens. 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 of alternate immersion in neutral salt solution, while LPB treated specimens did not fail after 1,500 hrs of exposure. Efforts to increase the stresses to beyond 180 ksi resulted in permanent bending of the LPB treated specimens, rather than failure. Thus it is evident that LPB processing helps to completely mitigate the SCC damage conditions in 300M HSLA landing gear steel.

STRUCTURAL ALUMINUM ALLOYS

The pronounced fatigue strength reduction caused by salt pit corrosion or corrosion fatigue in a marine environment is well established for aluminum alloys. The fatigue strength debit for either mechanism is typically on the order of half the long-life, high cycle fatigue endurance limit. Corrosion pits are a common site of fatigue crack initiation in the aluminum alloy 7075-T6, which is 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. The total cost of ownership and fleet readiness are adversely affected. A means of mitigating corrosion and corrosion-related fatigue damage is needed.

Figure 9 shows the residual stress profiles of AA7075-T6 fatigue specimens in the as-machined condition and in the LPB treated condition. A depth of compression of nearly 0.035 in. (0.9 mm) was achieved with LPB treatment. Figure 10 shows the S-N 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 so that the fatigue strength at 10^7 cycles drops by a factor of 2 from about 32 ksi to 16 ksi. With LPB treatment the HCF properties at all the cycle ranges are superior to even the as-machined condition. Evidently, the compressive residual stresses from LPB helped to not only mitigate the corrosion pitting damage, but also far exceed the baseline performance.

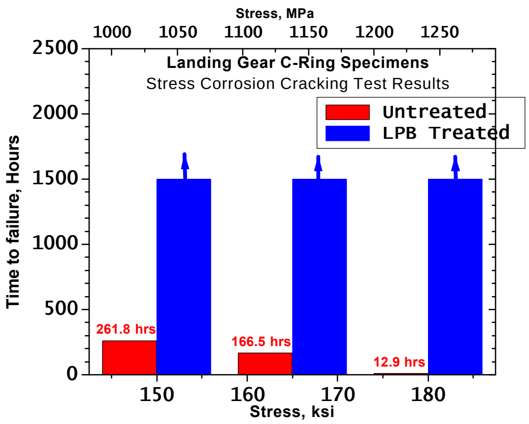

Figure 8 – SCC test results for 300M Steel

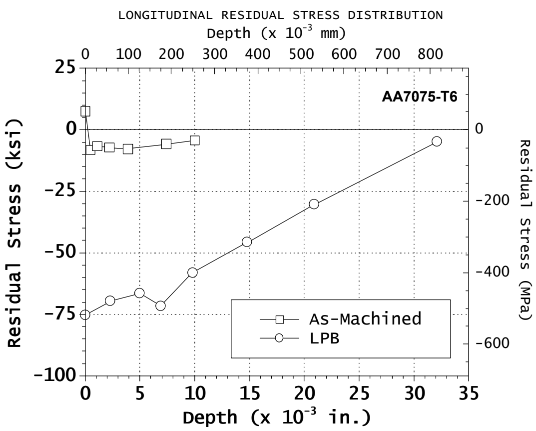

Figure 9 – RS distribution in AA7075-T6

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. LPB has proven to be an excellent cure by way of eliminating the tensile residual stresses, smoothing the surface to a mirror finish, and improving the fatigue performance significantly.

Figures 11 and 12 show the residual stress distribution around the weld on the surface and mid-thickness of a friction stir welded plate of AA2219-T8751. As seen in Figure 11, the surface tensile residual stresses created by the FSW process is completely eliminated and in place a compressive residual stress state is introduced by the LPB treatment. The LPB treatment did not affect the residual stresses in the mid-thickness plane.

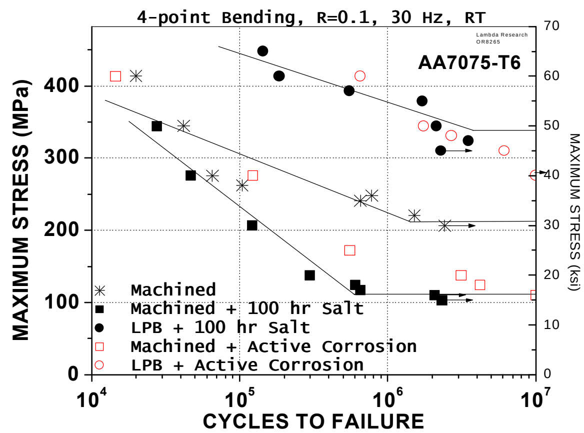

Figure 10 – S-N data for AA7075-T6

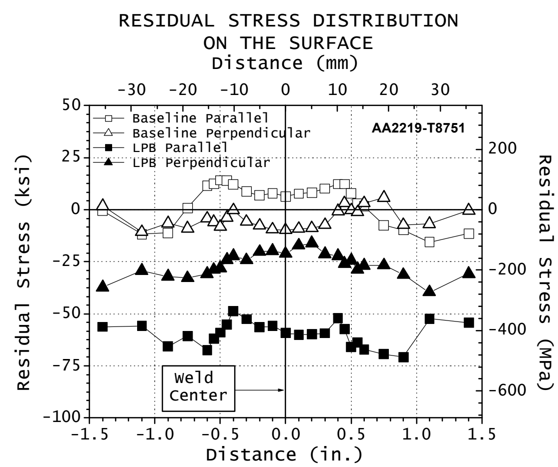

Figure 11 – Surface RS distribution in FSW plate AA2219-T8751.

As indicated earlier, since corrosion fatigue is a surface phenomenon, subsurface tensile stresses, although not desirable, are not excessively harmful. Figure 13 compares the S-N plots of baseline FSW vs LPB treated FSW both with and without active corrosion.

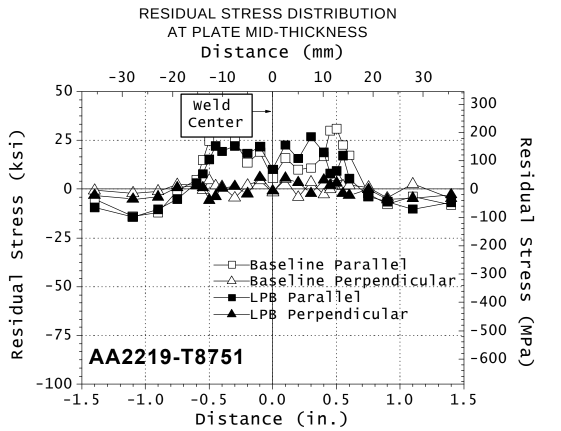

Figure 12 – Mid-thickness RS distribution in FSW AA2219-T8751

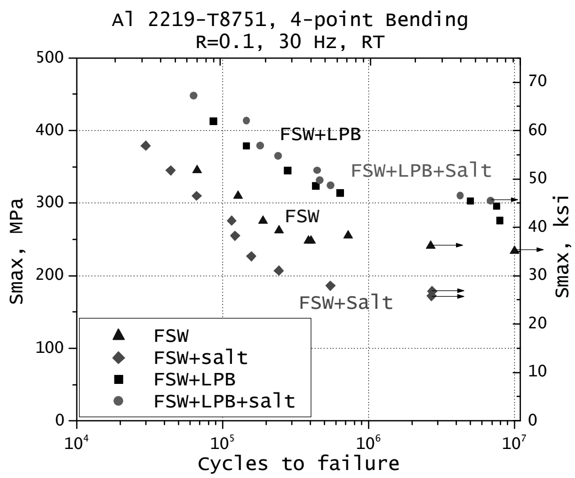

Figure 13 – S-N plots for AA2219-T8751

The fatigue strength of baseline FSW is seen Figure 13 to drop from about 35 ksi to about 25 ksi in the presence of active corrosion. Both LPB treated FSW in baseline condition and in active corrosion conditions performed equally well and surpassed the performance of even the baseline FSW. At about 45 ksi, an improvement in the fatigue performance is evident. This improvement is attributed to the surface compressive residual seen in Figure 11.

TURBINE COMPRESSOR BLADE STAINLESS STEELS

Precipitation hardened martensitic stainless steels are widely used in applications where a combination of high strength and resistance to corrosion is needed. 17-4PH stainless steel and Custom 450 stainless steel are probably the most used alloy steels of this kind. Components made of precipitation hardened martensitic stainless steels have been known to be prone to corrosion fatigue and SCC.

Figure 14 shows the residual stress profiles in low stress ground (LSG), SP, and LPB treated specimens. LPB treatment leads to a depth of compression of 0.040 in. (1 mm), while SP yields compression to a depth of 0.010 in. and LSG even less. The fatigue endurance strength for 10^7 cycles for the different treatments, active corrosion conditions, and FOD conditions reflect the effects of compression as seen in Figure 15. The baseline LSG material showed a fatigue strength of 150 ksi, which reduced to 100 ksi in active corrosion, and further degraded to less than 20 ksi in the presence of a 0.010 in. deep notch. The shot peened condition yielded similar results.

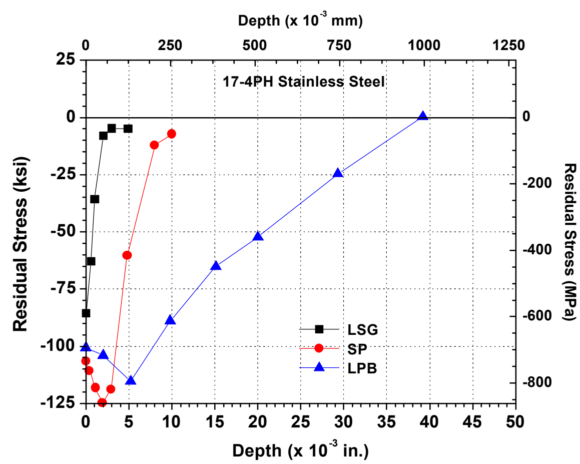

Figure 14 – RS profiles for surface treated 17-4PH SS

In contrast, LPB showed a baseline fatigue strength of 175 ksi, which dropped to about 145 ksi in active corrosion, and experienced only nominal degradation in the presence of FOD. Even FOD of 0.040 in. depth only dropped the fatigue strength to 50 ksi. The improved performance of the LPB treated specimens is attributed to the deep compression imparted by the LPB process.

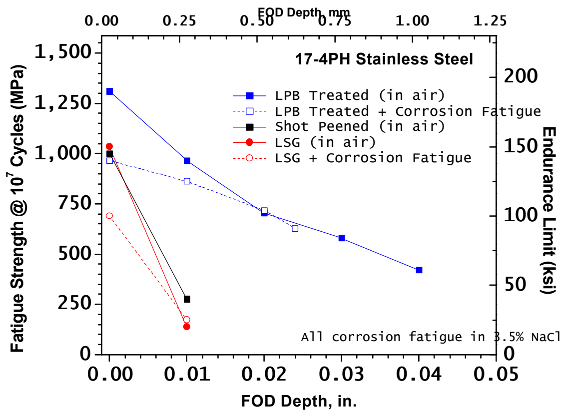

Figure 15 – Fatigue strength of 17-4PH stainless steel

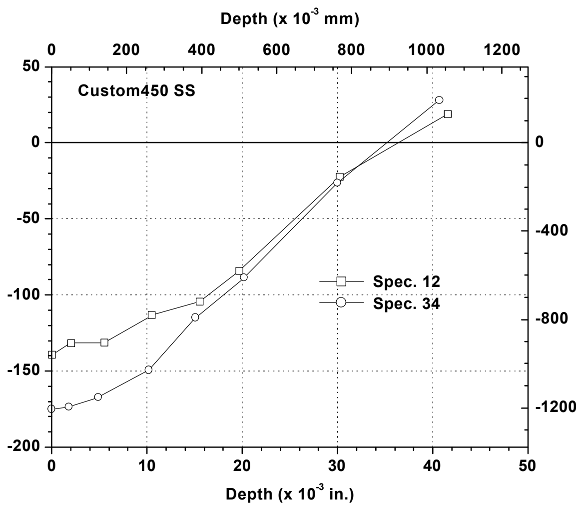

Figure 16 - Residual stress distribution for two LPB processed (and fatigue tested) specimens. Specimen #12 (LPB - no notch): Smax = 195 ksi (~1,345 MPa); Nf = 141,191 cycles. Specimen #34 (LPB + notch): Smax = 160 ksi (~1,100 MPa); Nf = 159,941 cycles

Similar to 17-4PH stainless steel, Custom450 stainless steel is a precipitation hardenable stainless steel. Figures 16 and 17 show the RS distribution from LPB and S-N plots for baseline (low stress ground – LSG) and LPB conditions. In Figure 16, residual stresses from fatigue tested LPB specimens are plotted as a function of depth. Very little differences are seen in both magnitude and depth of compression between the two specimens. The fatigue properties of the LSG specimens in active corrosion in acid salt environment is affected by a factor of 10 in the presence of a 0.010 in. deep FOD. However, through the LPB process the fatigue strength is fully restored and exceeded even in the presence of 0.010 in. FOD. Figure 17 shows that even in the presence of 0.020 in. or 0.030 in. FOD, the fatigue lives are favorably comparable to the LSG unnotched condition.

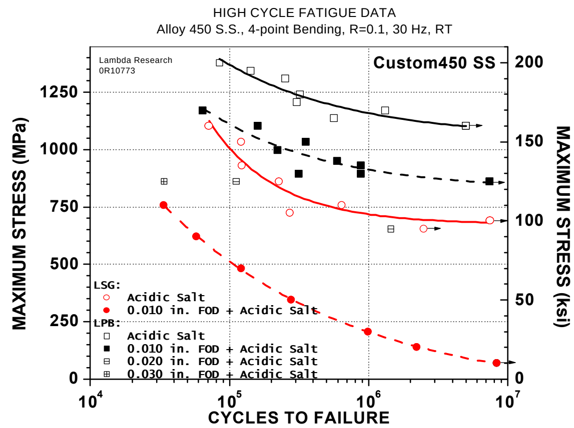

Figure 17 – S-N data for Custom 450 stainless steel.

SUMMARY

Low plasticity burnishing is shown to completely mitigate the damage conditions associated with active corrosion, prior exposure to salt fog corrosion, pitting corrosion, FOD, and SCC. The deep compressive residual stress from LPB effectively eliminates the damage growth process, although normal corrosion mechanisms like pitting, rusting, etc., are still active. The effectiveness of LPB to mitigate damage in a broad range of materials including different classes of steels, aluminum alloys, etc., has been demonstrated.

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