Use of Engineered Compressive Residual Stresses to Mitigate Stress Corrosion Cracking and Corrosion Fatigue in Sensitized 5XXX Series Aluminum Alloys

Kyle A. Brandenburg, Douglas J. Hornbach, Perry W. Mason
Lambda Technologies
5521 Fair Lane
Cincinnati, Ohio, 45227
USA

ABSTRACT

A commonly used aluminum alloy in ship superstructures, AA5083-H116 is susceptible to sensitization from thermal exposure leading to beta-phase (Mg_2Al_3) precipitation. The precipitation that forms around the grain boundaries, caused by thermal exposure from sources such as solar, exhaust gas, or welding, increases the alloy's susceptibility to stress corrosion cracking (SCC) and corrosion fatigue (CF). The United States Navy has identified this issue as a significant problem as it dramatically affects operation and maintenance (O&M) costs and fleet availability.

It has been shown that minimizing tensile stresses can lower SCC susceptibility and improve CF performance. Furthermore, a means of reliably introducing a deep layer of compressive residual stresses in critical regions can reduce O&M costs by extending the service life of ship superstructures. Low plasticity burnishing (LPB) is an advanced surface enhancement process providing a means of introducing compressive residual stresses into metallic components for enhanced CF life and SCC performance.

Tests were conducted to characterize the effect of LPB on CF and SCC in sensitized and unsensitized AA5083-H116 test samples. Residual stress measurements were performed to quantify the magnitude and depth of the residual compression from the LPB process. Samples were high cycle fatigue tested while exposed to simulated seawater consisting of 3.5% weight NaCl in distilled water. Samples were exposed to accelerated corrosion damage via SCC and alternate immersion tests to introduce pitting and general corrosion damage prior to fatigue testing. LPB provided up to 100X improvement in fatigue life and up to 3.5X improvement in fatigue strength over the untreated condition.

Key words: Low plasticity burnishing (LPB), stress corrosion cracking (SCC), fatigue, corrosion fatigue (CF), residual stress, sensitized aluminum

INTRODUCTION

The introduction of engineered compressive residual stresses in metallic components has long been recognized[1-4] as a method to enhance fatigue performance and mitigate stress corrosion cracking (SCC). The fatigue performance of many engineered components is often improved by surface enhancement treatments such as shot peening. Modern surface enhancement treatments such as low plasticity burnishing (LPB),[5] laser shock peening (LSP),[6] and ultrasonic peening[7] have emerged that, in varying degrees, benefit fatigue and stress corrosion prone components.

AA5083 is commonly used in naval shipbuilding applications due to its high strength-to-weight ratio and excellent corrosion resistance. However, 5XXX aluminum alloys that contain more than 3% Mg are susceptible to sensitization from thermal exposure. With exposure to elevated temperatures, Mg precipitates from solution and forms a second phase (β Mg_2Al_3) that collects along the grain boundaries. The β phase is anodic to the matrix and, when subjected to a corrosive environment, this β phase is preferentially attacked. This dissolution from the grain boundaries can cause SCC in materials subjected to prolonged tensile stresses and can also significantly reduce fatigue performance. Sensitization can occur at temperatures as low as 70°C when exposed for many years. Higher temperatures, on the order of 175°C, can cause severe sensitization in only a few days.

Introducing compressive residual stresses into aluminum alloy components can mitigate SCC and improve corrosion fatigue performance.[8] LPB is a highly effective, reliable, and reproducible method of producing deep compressive residual stresses in complex geometric components. LPB produces a very smooth surface finish, which can aid in nondestructive inspection and examination. LPB tooling can often be integrated with existing CNC machines used for manufacture and repair of aluminum alloy components. LPB technology was developed in conjunction with NASA's SBIR program and is currently being used to treat components in the aerospace, medical, and nuclear industries.[9-12]

AA5083 and other marine-grade 5XXX series aluminum alloys are the materials of choice for many naval shipbuilding applications due to their high strength-to-weight ratios, good as-welded strength, and excellent corrosion resistance. However, their susceptibility to sensitization and, subsequently, intergranular corrosion leads to severely degraded performance and increased operation and maintenance (O&M) costs. In this work, the effect of the LPB treatment on SCC and CF of sensitized and unsensitized 5083-H116 material was evaluated.

EXPERIMENTAL PROCEDURE

Material and Sectioning

A one-inch thick plate section of 5083 aluminum was procured in the H116 condition. All test samples were removed from the plate so that the direction of loading was transverse to the rolling direction. Samples were removed such that the test surfaces were at mid-thickness of the plate. The chemistry and mechanical properties of the material are shown in Tables 1 and 2, respectively.

Table 1
Bulk Composition of the As-Received Alloy

Element	Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn	Other
Weight %	94.3	0.072	<0.04	0.21	4.68	0.65	0.092	0.023	0.017	Balance

Table 2
Mechanical Properties of the As-Received Alloy

Yield Strength	UTS
34.5 ksi (238 MPa)	49.4 ksi (341 MPa)
Elongation	**Reduction of Area**
19.0 %	37.8 %

Trapezoidal Sample Processing

A sample with a trapezoidal gage cross section was used for fatigue and SCC testing. The trapezoidal cross section sample was designed to force failures to initiate in the compressive gage section. Samples were either LPB treated following machining or left in the as-machined “Baseline” condition.

LPB process parameters were developed to impart a depth and magnitude of compression sufficient to mitigate the corrosion damage and sensitization effects with minimal cold work. Figure 1 shows fatigue samples in the process of being LPB treated in the four-axis manipulator on the CNC milling machine.

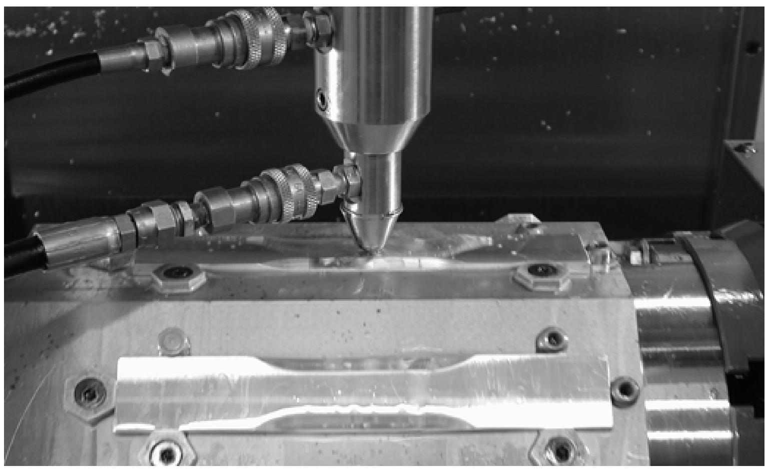

Figure 1: A set of fatigue samples being LPB processed on a CNC milling machine.

Sensitization and Nitric Acid Mass Loss Test

Nitric acid mass loss tests (NAMLT) per ASTM standard test method G67 were employed in order to quantify the degree to which the material was sensitized after each exposure process by providing a measure of the susceptibility to intergranular corrosion. The test method consisted of immersing rectangular test sample coupons in concentrated nitric acid at 30°C for 24 hours and then determining the resulting mass loss per unit area. Sensitization increases the formation of beta-phase precipitate. Therefore, material more severely sensitized will be more susceptible to intergranular corrosion and will exhibit greater mass loss than the same material sensitized to a lesser degree.

ASTM standard test method G67 states that, when subjected to NAMLT testing, a ‘susceptible material’ exhibits mean mass losses ranging from 30 to 44 mg/cm^2. Also, it has been shown[13] that a mass loss of 30 mg/cm^2 represents a threshold for corrosion fatigue degradation of 5083 aluminum. Therefore a mass loss value of 30 mg/cm^2 was used as a minimum target for sensitized material in this study.

Initial test coupons were sensitized at a range of temperatures between 50°C and 175°C for 240 hours to determine the desired sensitization temperature for testing. Select groups of LPB and Baseline samples were then sensitized at two different temperatures. A sensitization process of 175°C for 240 hours was chosen as the more severe exposure and a sensitization process of 90°C for 240 hours was chosen for a less severe exposure. Both processes produced a NAMLT reading of greater than the target value of 30 mg/cm^2.

Residual Stress

Surface and subsurface X-ray diffraction residual stress measurements were made in order to determine the depth and magnitude of residual stress distributions produced by the LPB process before and after sensitization exposure. Measurements were made in the direction of fatigue loading in the gage region employing a $\sin^2\psi$ technique and the diffraction of chromium Kα1 radiation from the (311) planes of the 5083 aluminum. 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.[14-18]

The residual stress measurements were corrected for both the penetration of the radiation into the subsurface stress gradient[19] and for stress relaxation caused by layer removal.[20] The value of the x-ray elastic constants required to calculate the macroscopic residual stress from the strain normal to the (311) planes were determined in accordance with ASTM E1426-98. Systematic errors were monitored per ASTM E915-96.

Stress Corrosion Cracking

SCC tests were performed, in part, per ASTM G44: Standard Practice for Exposure of Metals and Alloys by Alternate Immersion in Neutral 3.5% Sodium Chloride Solution. Trapezoidal gage samples were loaded in four-point bending to 90% of yield (31 ksi, 214 MPa). Load was applied using instrumented bolts that allowed monitoring of compliance throughout the duration of the test. The alternate immersion test utilized a 1-hour cycle that included a 10-minute period in an aqueous solution of 3.5% NaCl at ambient temperature (~22°C) followed by a 50-minute period out of the solution, during which the samples were allowed to dry. Samples were exposed for 1000 hours.

High Cycle Fatigue

HCF tests were performed under constant amplitude loading on a Sonntag SF-1U fatigue machine using a test setup and technique previously established in past studies.[11] Fatigue testing was conducted at ambient temperature (~22°C) in four-point bending mode. The cyclic frequency and stress ratio, R, were 30 Hz and 0.1 respectively.

Corrosion fatigue (CF) testing was performed in a neutral 3.5% wt. NaCl solution prepared with distilled water. Absorbent pads were soaked with the solution, applied to the gage section of the fatigue test samples, and sealed with a plastic film to inhibit evaporation for the duration of the testing. Several fatigue samples were tested with prior exposure to a 3.5% wt. NaCl solution via SCC testing, as described previously, to determine the effect on the subsequent fatigue life.

Tests were conducted to the event of sample fracture or until a “run-out” life of 1×10^7 cycles was attained, whichever occurred first. Partially fractured samples were subsequently broken by hand to permit direct observation of fracture surface details. All sample fracture faces were viewed on a Nikon stereoscopic microscope in order to verify that the fracture initiations were within the gage region.

Testing Scope

Table 3 lists the various sample processing and the tests that were completed. All tests run on sensitized conditions include both sensitizations of 90°C and 175°C for 240 hours.

Table 3
Sample Process and Testing Scope

Process	Test Procedure					
	Nitric Acid Mass Loss Test	X-Ray Diffraction	Stress Corrosion Cracking	High Cycle Fatigue (No Corrosion)	Corrosion Fatigue	SCC + Corrosion Fatigue
Baseline	X	X	X	X	X	X
Baseline+Sensitization	X	X	X		X	X
LPB		X	X	X	X	X
LPB+Sensitization	X	X	X		X	X
Sensitization+LPB	X		X		X	X

RESULTS

Sensitization and Nitric Acid Mass Loss Test

Figure 2 shows the mass loss results for the various sample processes. The red line indicates the critical mass loss value of 30 mg/cm^2.

The Baseline condition with no thermal exposure showed relatively low mass loss as would be expected. The 175°C exposure temperature produced a highly sensitized condition with mass loss between 43-47 mg/cm^2 in the LPB samples and about 61 mg/cm^2 in the Baseline condition. The lower temperature exposure of 90°C for 240 hours also produced a mass loss of greater than 30 mg/cm^2 with a value on the order of 34 mg/cm^2.

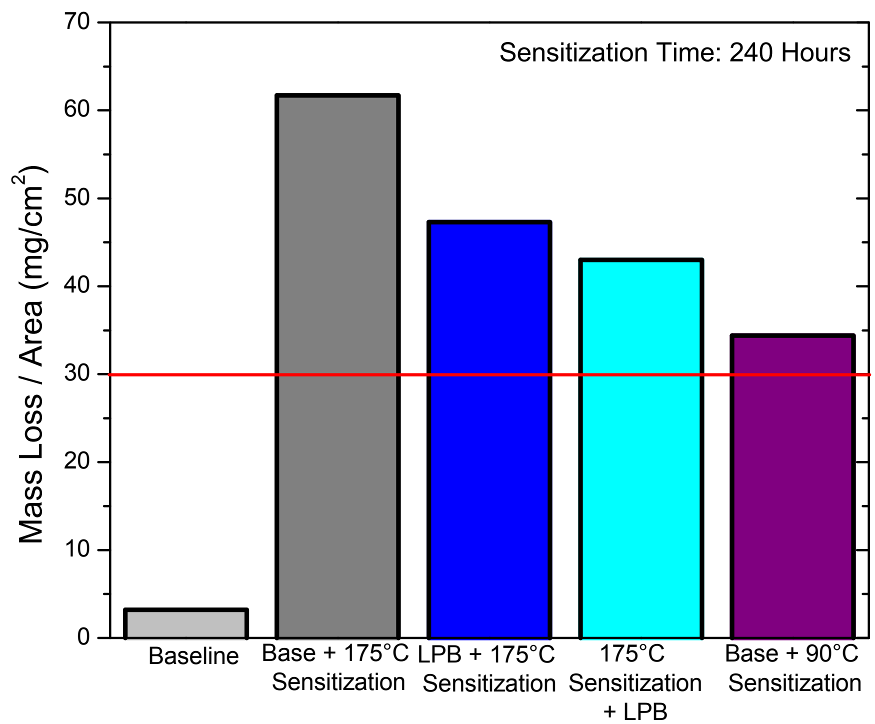

Figure 2: Nitric acid mass loss test results showing effects of sensitization and LPB processing.

Residual Stress

The residual stress distributions measured as functions of depth are shown graphically in Figure 3. Compressive stresses are shown as negative values, tensile as positive, in units of ksi (10^3 psi) and MPa (10^6 N/m^2).

The data in Figure 3 demonstrates the magnitude of compressive residual stress achieved by the LPB process. The optimized LPB parameters produced compressive stresses to a depth of approximately 0.050 in. (1.27 mm). Maximum compression was measured at the surface and was on the order of –35 ksi (-241 MPa). The relatively low magnitude compressive stress observed in the Baseline sample is due to the machining process. A slight reduction in the compression from LPB was observed as a result of the 90°C 240 hour exposure.

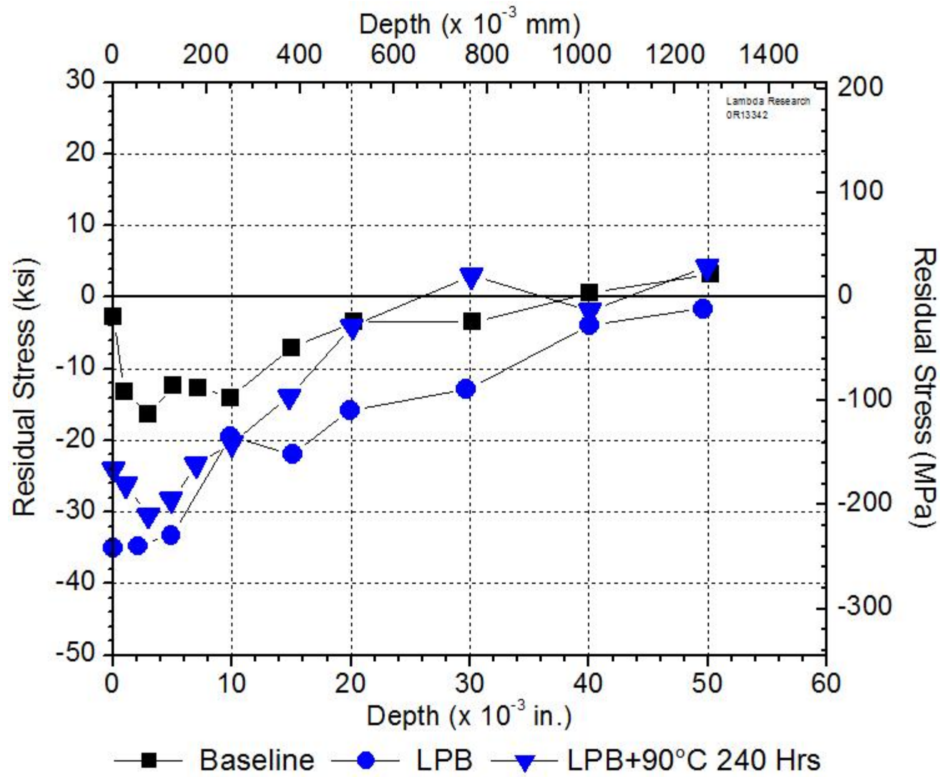

Figure 3: Residual stress profiles showing depth and magnitude of compressive residual stress achieved and retained due to LPB processing.

Stress Corrosion Cracking

No SCC failures were observed during the 1000-hour test. Figure 4 shows the surface conditions of a representative selection of samples following the test. Samples exhibited general corrosion with the sensitized samples showing significantly more corrosion and exfoliation along the grain boundaries compared to the unsensitized samples. The SCC samples were subsequently fatigue tested in order to determine the effect of the damage incurred from the SCC test on the remaining fatigue strength.

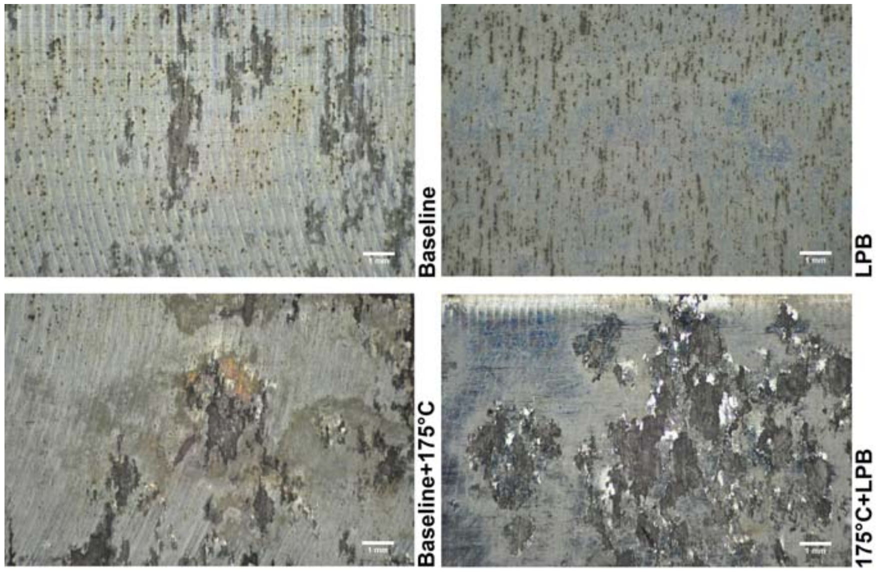

Figure 4: Sample surfaces resulting from SCC test.

High Cycle Fatigue

Results for the HCF fatigue tests are presented graphically in Figures 5 through 7. The data are shown in semi-log plots of maximum stress in units of ksi (10^3 psi) and MPa vs. number of cycles to failure. Arrows indicate run-outs.

The unsensitized sample results are shown in Figure 5. The results show that LPB processing improved the fatigue strength over 50% compared to the baseline samples with no active corrosion and about 50% for the samples tested with active corrosion. The LPB + Corrosion Fatigue condition also had a slightly higher fatigue strength than the Baseline with no active corrosion. LPB improved the fatigue life by nearly 100X over Baseline for both with and without active corrosion conditions.

The fatigue results for the sensitized samples are shown in Figure 6. Results show more than a 3X improvement in fatigue strength from LPB when used to treat sensitized material. When applied prior to sensitization the LPB process improves fatigue strength by approximately 70%. LPB improved fatigue life by 10X or greater over untreated samples.

Figure 7 compares the fatigue results for the pre-corroded SCC exposed samples along with the corresponding conditions with no prior SCC exposure. Results are shown in the form of a bar chart with a run out life of 10^7 cycles. Baseline samples with sensitization have a significantly lower fatigue life than the unsensitized baseline samples. At the 35 ksi stress level, LPB completely mitigated the CF life debit due to sensitization, returning CF life back to the level of the Baseline condition. At the 25 ksi stress level, the sensitization + LPB samples ran out, indicating LPB increased the CF life of the sensitized samples to a level significantly greater than that of the Baseline unsensitized condition.

Fracture initiations were not well defined or easily visible in this alloy, yet it was determined that the majority of the samples examined did show a single initiation at the gage surface.

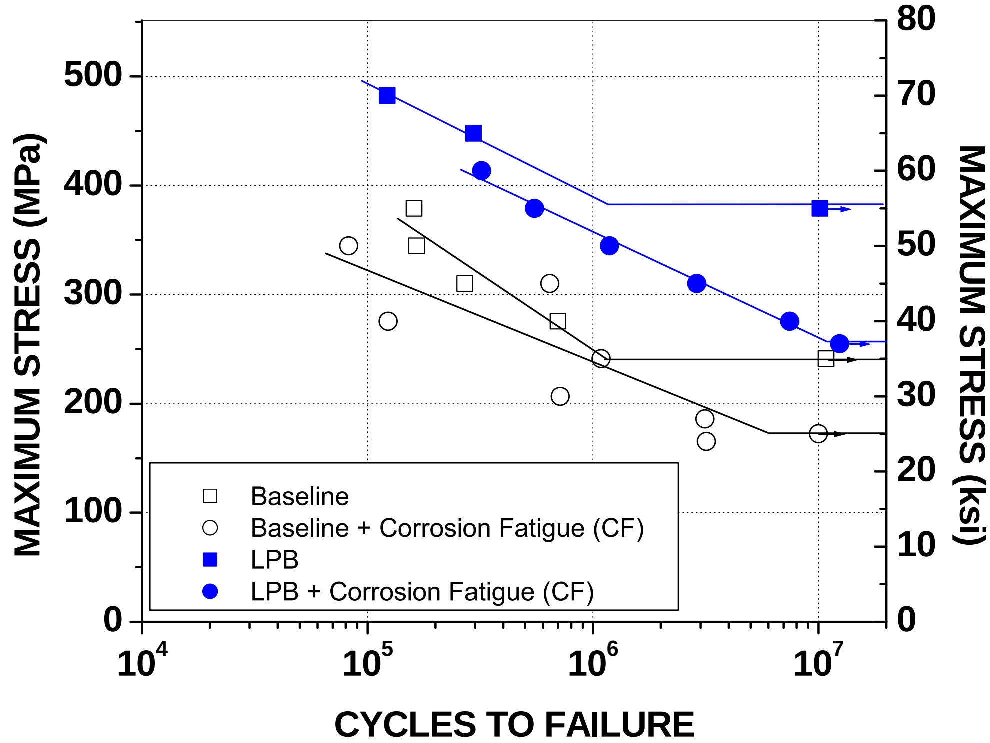

Figure 5: High cycle fatigue results for unsensitized samples.

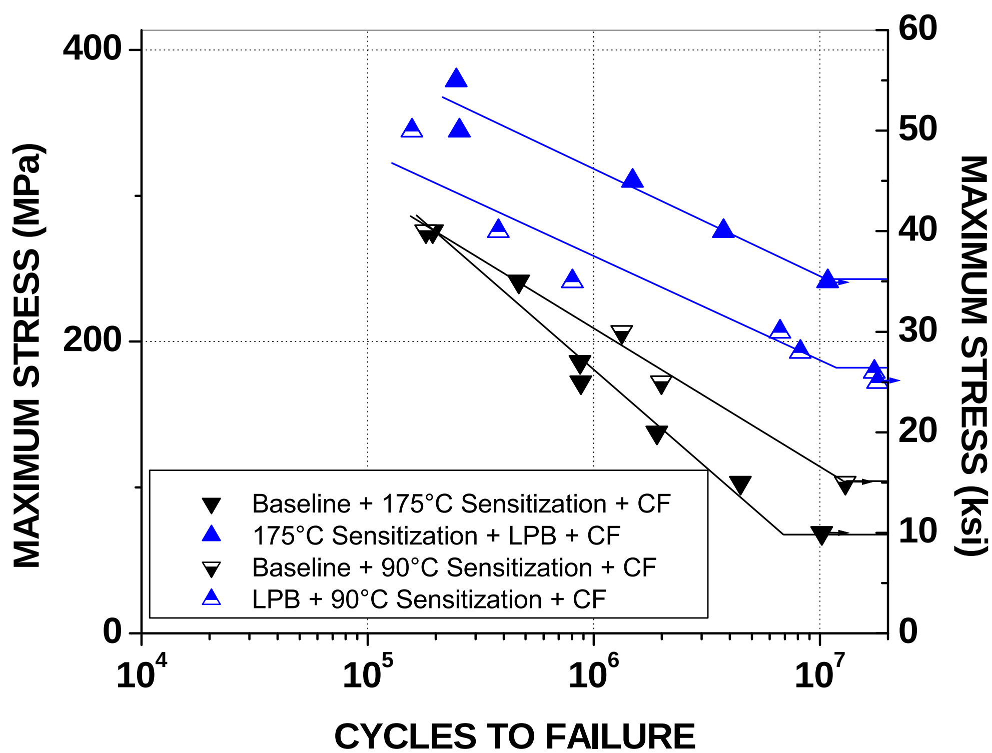

Figure 6: High cycle fatigue results for sensitized samples.

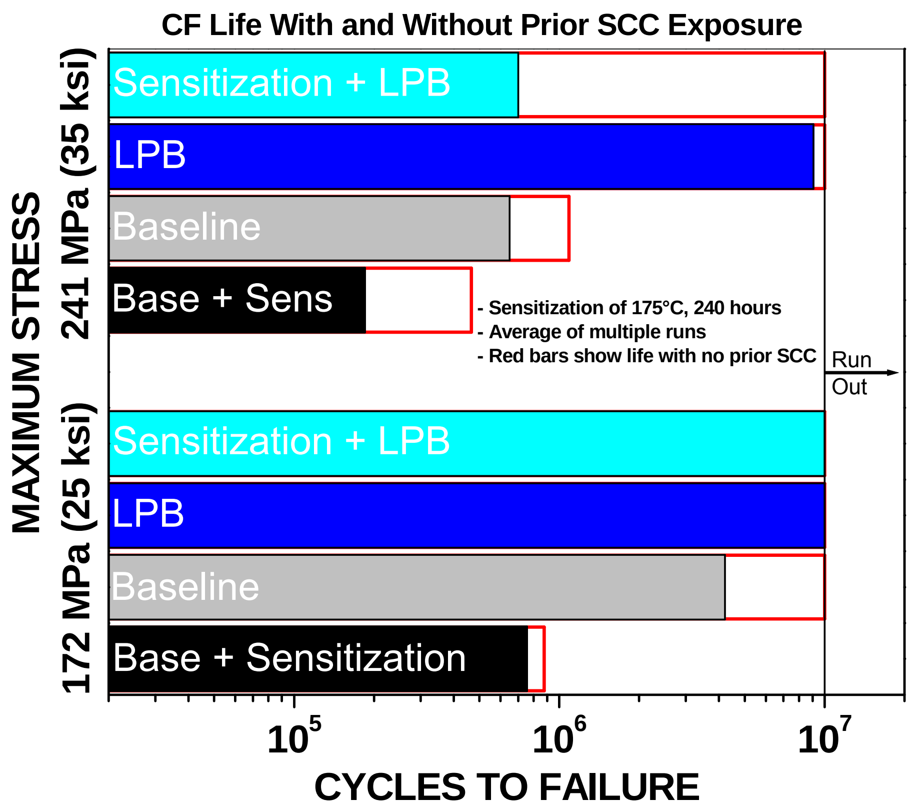

Figure 7: High cycle fatigue results for samples with and without SCC exposure.

CONCLUSIONS

It was shown that sensitization causes up to a 60% decrease in fatigue strength of AA5083. LPB was successfully applied to produce significant compressive residual stress in 5083-H116 aluminum alloy. LPB produced a depth of compression of approximately 0.050 in. (1.27 mm), which is deeper than any expected corrosion damage.

The LPB process improved CF life by up to 100X over untreated samples. Results show more than a 3X improvement in CF strength from LPB when applied after sensitization. LPB treatment following sensitization may be necessary as a repair process of existing structures that have already been exposed to thermal loads as well as in weld heat affected zones. The data shows that when applied prior to sensitization, such as in preventive applications of new structures that will be exposed to solar or engine thermal loads, the LPB process improves CF strength by approximately 70%.

This study has shown that LPB can be applied on pre or post-sensitized AA5083-H116 components to improve corrosion fatigue life and SCC performance. This improvement could ultimately provide a significant reduction in operation and maintenance costs of naval ship superstructures that rely on 5XXX series aluminum alloys.

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