Proceedings of the ASME 2012 International Mechanical Engineering Congress & Exposition
IMECE2012
November 9-15, 2012, Houston, Texas, USA

IMECE2012-87482

THE EFFECT OF SURFACE ENHANCEMENT ON IMPROVING THE FATIGUE AND SOUR SERVICE PERFORMANCE OF DOWNHOLE TUBULAR COMPONENTS

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ABSTRACT

Sulfide stress cracking (SSC) and hydrogen embrittlement (HE) prevent the use of high strength carbon steel alloys in the recovery of fossil fuels in H_2S containing 'sour' environments commonly experienced in deep well fossil fuel recovery efforts. Couplings are a common weak point in casing strings as high magnitude mean tensile stresses are generated by connection interferences created during power make-up of downhole tubular components. When subject to service loads both mean and alternating stresses are increased further providing the high tensile stresses necessary for SSC initiation. Since high strength carbon steel alloys are not typically suited for sour service environments, the current solution is to use or develop much more expensive alloys with increased corrosion-cracking resistance, or limit their use to significantly weaker sour environments, or higher operating temperatures.

Failure due to fatigue is another major problem in downhole tubular components. Likelihood of fatigue failure is further exacerbated in corrosive environments (such as H_2S and NaCl), commonly encountered in service. The cost for detecting the impending failure before final separation is dramatic at a factor 10X. A cost effective method of mitigating failure from SSC and corrosion fatigue would greatly reduce operational costs and extend component life.

Introduction of stable, high magnitude compressive residual stresses into less expensive carbon steel alloys alleviates the tensile stresses, and mitigates SSC, while also improving fatigue performance. Low plasticity burnishing (LPB) is an advanced surface enhancement process providing a means of introducing compressive residual stresses into metallic components for enhanced fatigue, damage tolerance, and SCC performance.

The effects of LPB on high cycle fatigue (HCF) and SSC were evaluated on quench and tempered API P110 grade steel. LPB processed specimens had an increase in fatigue life greater than an order of magnitude over untreated specimens. LPB was successful in completely mitigating SSC in all test specimens at tensile stresses up to 90% specified minimum yield strength (SMYS). The initial results indicate that LPB processing of P110 steel provides an economical means of SSC mitigation and fatigue strength improvement in sour environments.

KEYWORDS:
Low plasticity burnishing (LPB), sulfide stress cracking (SCC), fatigue, residual stress, sour service

INTRODUCTION

Surface enhancement of metals, inducing a layer of surface compressive residual stresses in metallic components, has long been recognized[1-4] to enhance fatigue performance and mitigate stress corrosion cracking (SCC). The fatigue performance of many engineering components is often improved by surface enhancement methods including rolling or 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. Maximum benefits are obtained when deep compression is achieved with minimal cold working of the surface.

Environmentally assisted cracking (EAC) in the form of Sulfide Stress Cracking (SSC), SCC, and Hydrogen Embrittlement (HE) prevent the use of less expensive high strength carbon steel alloys in the recovery of fossil fuels in corrosive-cracking environments commonly seen in offshore and deep well recovery efforts. Tensile residual stresses generated from straightening, machining and connection make-up, when added to applied stresses during downhole operations in high-pressure environments, are significant contributors to EAC and fatigue failure. The current solution is to develop new alloys with increased corrosion-cracking resistance in an attempt to mitigate the problems or limit their use to significantly weaker sour environments. This solution can be costly and can result in only a small benefit.

Introducing compressive residual stresses into less expensive carbon steel alloys can dramatically reduce the risk of failure, mitigate SSC, HE and SCC, and improve fatigue performance.[8] This would enable the use of less expensive alloys in harsh environments where they currently are unable to be used. Low plasticity burnishing (LPB) is highly effective, reliable and reproducible method of producing deep compressive residual stresses in complex geometric components. With advanced CNC control systems LPB can be applied using a closed loop feedback surface enhancement method capable of introducing a customized compressive residual stress field specifically tailored for each application. LPB so applied produces a very smooth surface finish, which aids in nondestructive inspection and examination. LPB tooling can be integrated with existing equipment used for manufacture and repair of downhole tubular components.

HCF and SSC susceptibility in high strength API P110 grade tubular products prevents their use in 100% H_2S sour environments. [9,10] As more deep wells and offshore resources are probed and recovered it is imperative to mitigate the problem of EAC and HCF failure in a cost effective manner. HCF and SSC tests conducted in a corrosive environment and with mechanical damage[11] has shown that the LPB process can provide a substantial increase in HCF life and mitigate SSC.[12, 13] In this work the LPB technology is being evaluated to determine if it can play a role in creating more reliable and efficient fossil fuel recovery systems that are capable of safely and reliably operating in aggressive environments. LPB processing has successfully been used to mitigate EAC in high strength steel, stainless steels, Ni based alloys and aluminums spanning many industries.[13] LPB technology was developed in conjunction with NASA's SBIR program and is currently being used to treat components in production for the aerospace, medical, and nuclear industries.[14-17]

EXPERIMENTAL TECHNIQUE

Material

C- ring specimens used for fatigue and SSC testing were taken from API P110 grade quench and tempered coupling stock with 4.5 in. (114.3 mm) ID and 0.25 in. (6.4 mm) wall thickness. C-ring samples were made per NACE TM0177-Method C. SSC tests were also conducted on full size coupling stock. An example of the coupling stock is shown in Figure 1. The chemistry and mechanical properties were verified and are shown in Tables I and II, respectively.

TABLE I: MATERIAL CHEMISTRY.

API P110 Chemistry				
Element (Weight Percent)				
C	Si	Mn	P	Ni
0.31	0.28	0.51	0.002	0.14
Cu	Mo	V	S	Fe
0.09	0.18	0.06	0.003	Balance

TABLE II: MATERIAL MECHANICAL PROPERTIES.

API P110 Mechanical Properties After Heat Treatment	
Yield Strength	UTS
125.6 ksi (866 MPa)	140.1 ksi (966 MPa)
Elongation	Reduction of Area
21.71 %	67.54 %

Specimen Processing

LPB process parameters were developed to impart a depth and magnitude of compression sufficient to mitigate SSC and the simulated damage during HCF testing with minimal cold work. Figure 2 shows a API-P110 coupling being LPB treated on a CNC lathe with a single point LPB tool.

FIGURE 2: API-P110 COUPLING BEING LPB PROCESSED ON A CNC LATHE

To simulate surface damage from any source (handling, tong marks, corrosion pitting or erosion), a surface notch with a depth of 0.02 in. (0.51 mm) was introduced in the center of the gage region of the HCF specimens by electrical discharge machining (EDM) following the LPB process. EDM leaves a cracked recast layer in residual tension at the bottom of the notch, producing a large fatigue debit. EDM notching is widely used for reproducible laboratory simulation of high k_f damage.

Residual Stress Evaluation

X-ray diffraction residual stress measurements were made at the surface and below the surface to determine the depth and magnitude of residual stress distributions of the untreated material and that produced by LPB. Measurements were employing a $\sin^2\psi$ technique and the diffraction of chromium Kα radiation from the (211) planes of P110 steel. 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.[18-20]

Material was removed electrolytically for subsurface measurement in order to minimize possible alteration of the subsurface residual stress distribution as a result of material removal. The residual stress 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 (211) planes of 410 stainless steel were determined in accordance with ASTM E1426-9. Systematic errors were monitored per ASTM specification E915.

High Cycle Fatigue Testing

HCF tests were performed under constant amplitude loading on a Sonntag SF-1U fatigue machine. A photo of the fatigue setup is shown in Figure 3. Specimens were tested in the untreated and LPB conditions with and without mechanical EDM or corrosive damage. Fatigue testing was conducted at ambient temperature (~72°F / 22°C) in four-point bending. The cyclic frequency and stress ratio, R ($\sigma_{min}/\sigma_{max}$), were 30 Hz and 0.1 respectively. Tests were conducted to specimen fracture or until "run-out" at 1 x 10^7 cycles. Specimens were subsequently broken open for optical and SEM fractographic analysis.

FIGURE 3: HIGH CYCLE FATIGUE TEST SET UP

Active corrosion (AC) fatigue testing was performed in a neutral 3.5% wt. NaCl solution prepared with de-ionized water. Filter papers were soaked with the solution, wrapped around the gage section of the fatigue test specimens, and sealed with a plastic film to avoid evaporation for the duration of the testing. Several fatigue samples were tested with prior exposure to a NaCl solution to determine the effect on the subsequent fatigue life. Sample exposure was conducted according to ASTM Standard G44-99. Specimens were exposed to 3.5% wt. NaCl solution by alternate immersion (10 minutes exposed and 50 minutes unexposed per hourly cycle). Specimens were exposed for 100 hours. Samples were then removed, cleaned with water, and tested in HCF.

Fractography

Following fatigue testing, each specimen fracture face was examined optically at magnifications up to 60x to identify fatigue origins relative to the specimen geometry. Photographs were taken through a Nikon Stereoscopic microscope at 15x. A representative photograph of a typical failure for each specimen group was obtained. A few selected specimens were also examined via SEM.

SSC Testing

SSC tests were conducted on untreated and LPB treated samples. All testing was performed in 100% NACE TM0177-Solution A at 1 bar H_2S at 25° C. The pH was monitored continuously throughout testing to ensure conformance to NACE TM0177.

C-ring specimens were initially tested at a tensile stress of 45% specified minimum yield strength (SMYS). After exposure to at least 720 hours the stress was increased to 80%, 85% and 90% of SMYS. Stress was monitored using strain gage rosettes placed on the inner diameter opposite the exposed location of maximum applied tension. The entire specimen, except the outer gage region, was coated in a polymer based stop-off coating prior to immersion in solution. Figure 4 shows a fully prepared C-ring specimen.

FIGURE 4: C-RING SPECIMEN PRIOR TO SSC TESTING.

Testing of full size coupling blanks was performed using a custom made holding fixture connected to a pressurizing test station. The full sized coupling blanks were internally pressurized hydraulically to impart the desired amount of applied hoop stress. Test solution was monitored for pH and refreshed as needed to conform to the NACE TM0177 standard. Testing was conducted until specimen failure or a run out life of 720 hours (30 days) or more was achieved per NACE TM0177 standard. Specimens were tested at 45%, 80%, and 85% of SMYS. The 85% SMYS stress level is regarded as an aggressive performance test for metal that is in direct contact with a 100% H_2S saturated environment. Pressure was monitored continuously throughout the test and the time to failure recorded. Figure 5 shows a coupling placed in the pressurized test apparatus.

FIGURE 5: FULL SIZE COUPLING BLANK PLACED IN PRESSURIZED TEST APPARATUS.

Surface Roughness

The surface roughness was measured for an LPB and untreated coupling. Surface roughness values were obtained using a Mitutoyo SJ-201 Tester. The arithmetic mean surface roughness, Ra, was determined over a 0.5 in. (12.7 mm) evaluation length in the axial direction. All reported values are the average of three measurements.

EXPERIMENTAL RESULTS

Residual Stress

The residual stress distributions, measured as functions of depth, are presented graphically in Figure 6. Compressive stresses are shown as negative values, tensile as positive, in units of ksi (10^3 psi) and MPa (10^6 N/m^2). LPB produces max compression of -105 ksi (~ -724 MPa), and gradually decreases to zero at a depth greater than 0.040 in. (~1 mm).

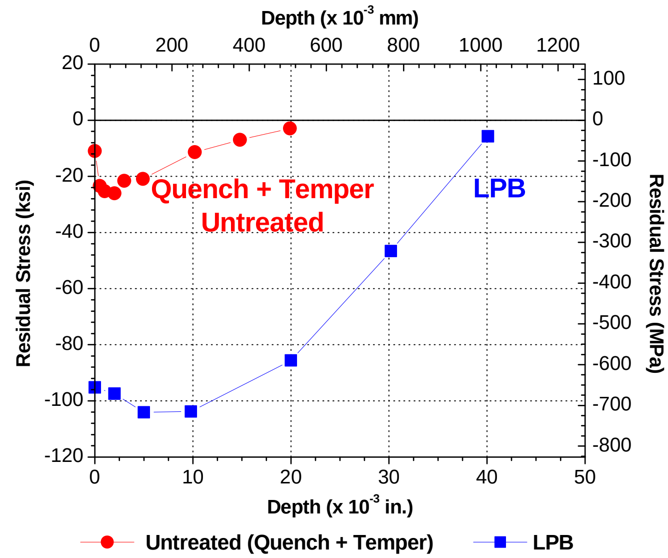

FIGURE 6: RESIDUAL STRESS PROFILES

High Cycle Fatigue Testing

Figure 7 shows stress vs. life (S-N) curves for the tested samples. The as-machined samples with a 0.020 in. (0.51 mm) deep EDM notch have a fatigue strength at 10^7 cycles of approximately 25 ksi (~170 MPa). LPB samples containing a 0.020 in. (0.51 mm) deep notch have a fatigue strength of 50 ksi (~345 MPa) at 10^7 cycles, nominally 2X the fatigue strength of the untreated samples with an increase in life of greater than a factor of 50X.

When subjected to corrosion damage the untreated samples have a fatigue strength of less than 20 ksi (~138 MPa). LPB samples subjected to active corrosion have a fatigue strength of 35 ksi (~241 MPa) approximately 1.75X greater than the untreated samples. Furthermore, LPB treated samples exhibit an increase in fatigue life of nominally an order of magnitude over the untreated samples.

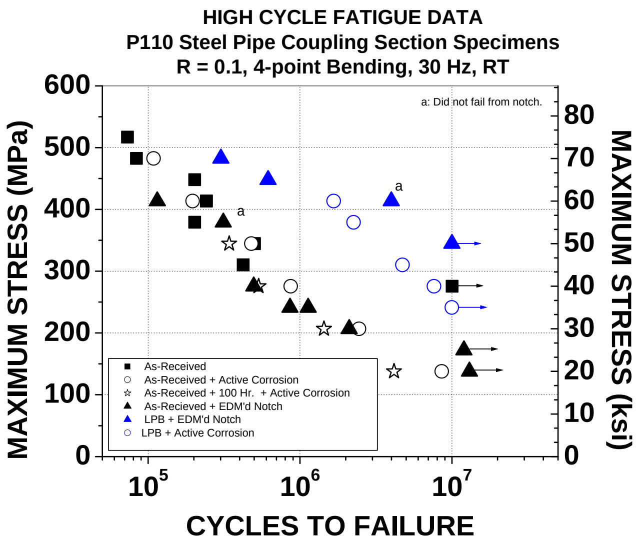

FIGURE 7: HIGH CYCLE FATIGUE RESULTS FOR API-P110 STEEL SPECIMENS

Fractography

Optical and SEM fractography indicated fatigue initiation from the bottom of the EDM notch on all of the notched samples tested. An example of a fracture face for an untreated + EDM Notch sample is shown in Figure 8. Samples tested with prior corrosion damage and active corrosion during testing contained surface initiations from the active gage region. An example of a fracture face for an untreated + active corrosion sample is shown in Figure 9.

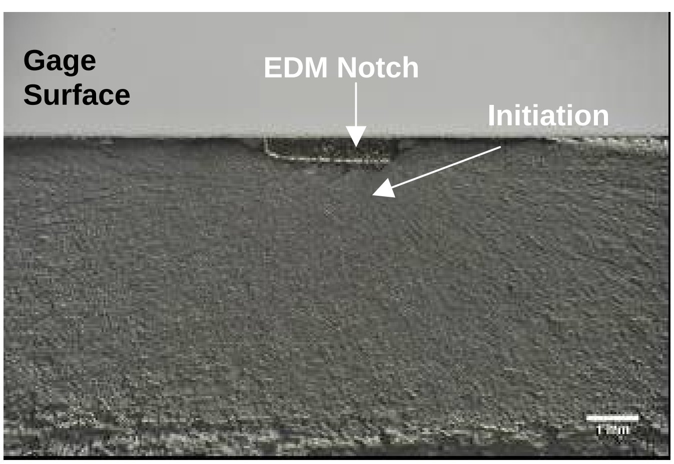

FIGURE 8: FRACTURE FACE OF UNTREATED + 0.020 IN. NOTCH SPECIMEN

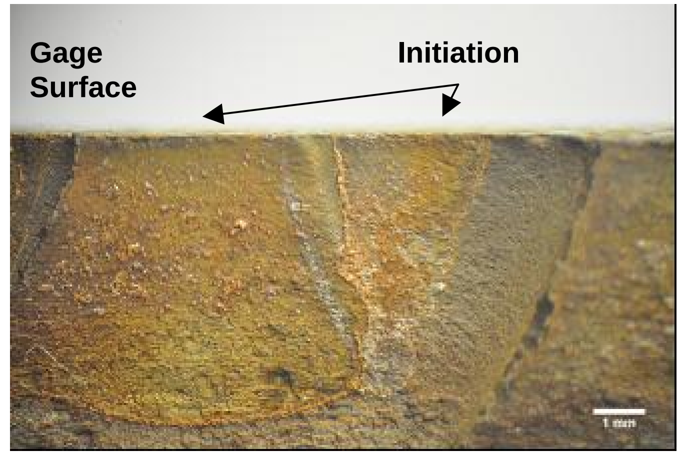

FIGURE 9: FRACTURE FACE OF UNTREATED + ACTIVE CORROSION SPECIMEN

SSC Testing

SSC results are presented graphically in Figures 10 and 11. The un-treated C-ring specimen failed in 10 hours at a stress of 45% SMYS. The LPB processed specimens exceeded the run-out life of 720 hours at 45%, 80%, 85% and 90% of SMYS exceeding typical hold-time requirements for testing in a sour service environment. The full sized pressurized coupling test results are very similar with the untreated coupling failing in 37.5 hours. The LPB processed specimens exceeded 720 hours at 45%, 80% and 85% SMYS stress levels while surpassing typical hold-time requirements for sour service testing. The second full sized LPB coupling blank ran for a total of 1454.75 hours in solution before testing was terminated and the specimen was removed from solution for dye inspection, which revealed no cracking. These test results demonstrate the dramatic improvement achieved by the LPB treatment..

A macro photo comparison of a failed untreated C-ring specimen and a run out LPB C-ring specimen is shown in Figure 12. Dye penetrent was used to reveal the axial SSC failure in the un-treated coupling blank shown in Figure 13. The SSC testing results show definitively that LPB is able to mitigate SSC cracking in common API P110 steel and dramatically increase the life.

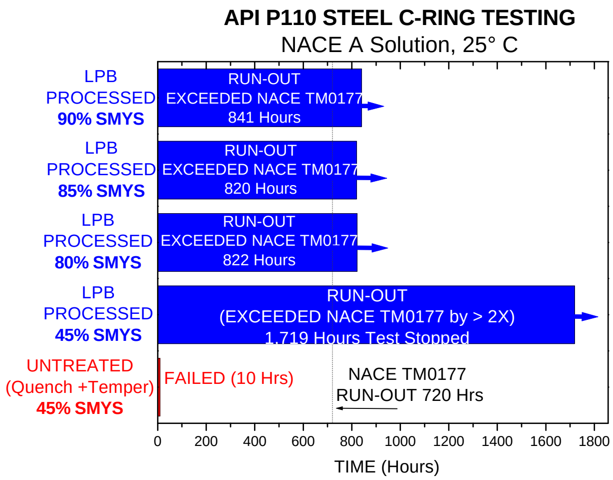

FIGURE 10: SSC C-RING TESTING RESULTS

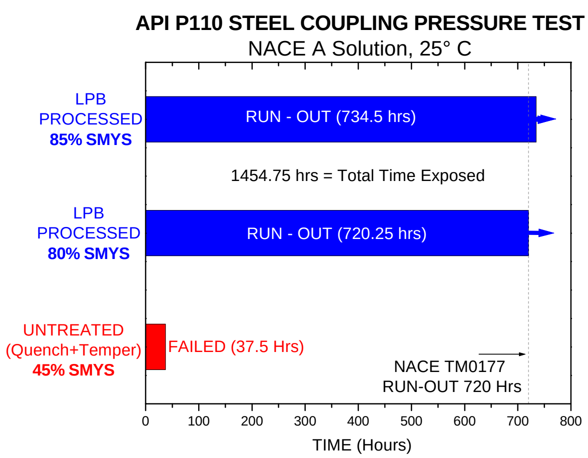

FIGURE 11: SSC FULL SIZED COUPLING BLANK TEST RESULTS

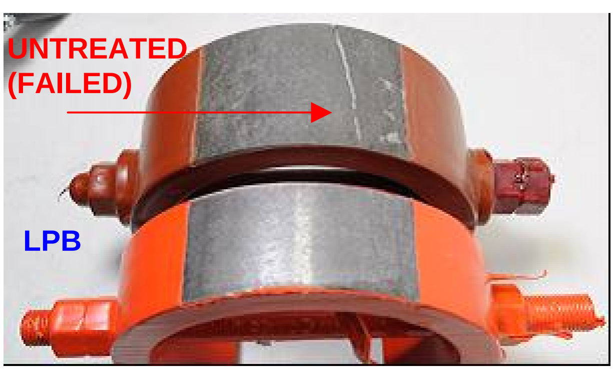

FIGURE 12: COMPARISON OF LPB TREATED AND UN-TREATED C-RING SPECIMENS AFTER SSC TESTING

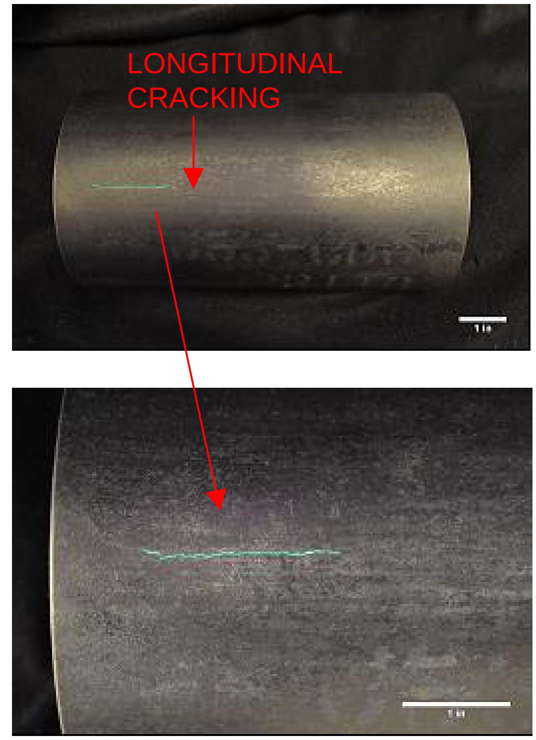

FIGURE 13: FDI INSPECTION OF FAILED UN-TREATED COUPLING REVEALING THROUGH WALL AXIAL SSC

Surface Roughness

The results of the surface roughness measurements are shown in Figure 14 in the form of a bar chart. The roughness value for the untreated condition is nominally 2.6X higher than that of LPB. LPB produces a smoothed surface finish by embossing the high hardness smooth balls surface into the couplings. The improved surface finish can aid in nondestructive inspection (NDI).

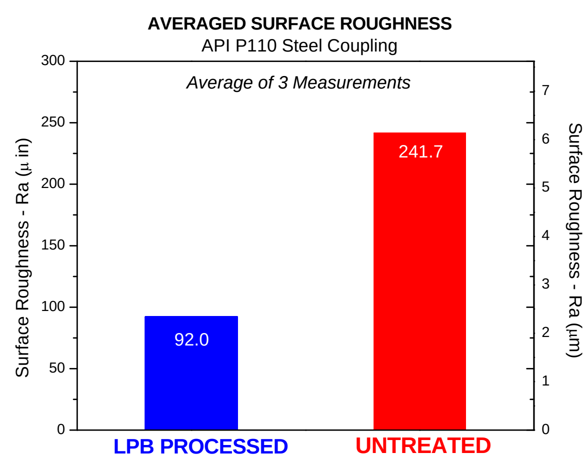

FIGURE 14: COMPARISON OF THE SURFACE ROUGHNESS OF UNTREATED AND LPB PROCESSED COUPLING SURFACES.

CONCLUSIONS

- LPB imparted a deep compressive layer of stable residual compression over 2X deeper and 10X greater in magnitude than the untreated couplings.
- LPB processing increased HCF life by 50X and fatigue strength by 2X over the untreated condition with 0.020 in. (0.51 mm) deep damage.
- When exposed to active corrosion LPB treated samples revealed a nominal 10X improvement in life and a 1.75X improvement in strength over untreated samples.
- LPB completely mitigated SSC failure. The LPB treated full sized coupling tests exceeded the NACE TM0177 720 hour NACE exposure time requirement at 45%, 80%, and 85% of the SMYS of 110 ksi (759 MPa) where the untreated coupling failed in 33 hrs. at a stress of 45% SMYS.
- The LPB processed C-ring tests exceeded NACE TM0177 time requirements at stress levels of 45%, 80%, 85%, and 90% of SMYS. The untreated C-ring failed in 10 hrs at a stress of 45% SMYS.
- Use of an engineered, deep compressive stress field via LPB to increase fatigue life under various damage conditions and to mitigate SSC was successful on API P110 quench and temper coupling specimens.

ACKNOWLEDGEMENTS

The authors wish to thank Peter Moore and Darrel Chelette of United States Steel for their assistance in providing testing equipment and material for SSC testing, as well as Mr. Thomas P. Lachtrupp and Mr. Perry W. Mason of Lambda Technologies for their help in overseeing the residual stress measurements and fatigue tests respectively.

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