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Mitigation of Sulfide Stress Cracking in Down Hole P110 Components via Low Plasticity Burnishing

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ABSTRACT

Sulfide stress cracking (SSC) along with hydrogen embrittlement (HE) prevents the use of less expensive high strength carbon steel alloys in the recovery of fossil fuels in H_2S containing 'sour' service environments that are commonly seen in deep well fossil fuel recovery efforts. High magnitude tensile stresses are generated by connection interferences created during power make-up of down hole tubular components. When subject to service loads the stresses are increased further providing the high tensile stresses necessary for SSC initiation. Because these alloys processed into high strength grades are not suited for fully saturated 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.

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 strength. This could allow the potential of using less expensive alloys in sour environments. Low plasticity burnishing (LPB) is highly effective when applied to metallic components using a proven reproducible process of producing deep, high magnitude compressive residual stresses in complex geometric components without altering the geometry, design or chemistry.

The LPB process, applied with advanced control systems, is presently being employed to treat components resulting in a substantial increase in service life through SSC mitigation and improved fatigue life. The benefits of LPB have been evaluated on full size specimens of uni-axial hoop stress loaded coupling blanks and C-ring specimens manufactured from quench and tempered API P110 grade steel with a yield strength of 132 ksi (910 MPa). Specimens were exposed to 100% NACE TM0177-Solution A at 1 bara H_2S in both the LPB treated and untreated condition. The time to failure was documented along with the increase in life resulting from LPB treatment. LPB was successful in completely mitigating SSC in each test specimen up to 85% SMYS hoop tension; and in each case met or exceeded the 720-hour exposure time defined in NACE TM0177. At an applied fiber stress of 90% SMYS, the C-ring samples have exceeded exposures of 840 hours without failure. The initial results indicate that LPB processing of down hole tubular components may provide an alternative economical means of SSC mitigation and greatly reducing risk of component failure in sour environments.

Key Words: low plasticity burnishing, sulfide stress cracking, 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 strength and mitigate stress cracking. The fatigue strength of many engineering components is often improved by 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), Stress Corrosion Cracking (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 down hole operations in high-pressure environments are significant contributors to EAC and fatigue failure. Because these alloys at high strength levels are not suited for sulfide or chloride environments, the current solution is to use or create much more expensive alloys with increased corrosion-cracking resistance to mitigate the problems or limit their use to significantly weaker sour environments.

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 strength.[8] This could allow the potential of using 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 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 down hole tubular products.

SSC susceptibility in high strength API P110 grade tubular products prevents their use in 100% H_2S sour environments at temperatures less than 79°C (175 °F).[9,10] As more deep wells and offshore resources are probed and recovered it is imperative to mitigate the problem of EAC in a cost effective manner. Laboratory testing in standard 100% NACE TM0177-Solution A [11] at 1 bara H_2S liquid environment has shown that the LPB process can be employed to treat components with the effect of providing a substantial increase in service life, and SSC mitigation. The LPB technology is now being evaluated to determine if it can play a pivotal 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 and aluminums used in both the aerospace and nuclear industries. LPB technology was developed in conjunction with NASA's SBIR program and is currently used in production of parts used in the aerospace, medical, and nuclear industries and on many different metal alloys.[12-16]

EXPERIMENTAL PROCEDURE

Material

C- ring specimens and full size coupling blank specimens were sectioned from a length of API P110 grade quench and tempered coupling stock. Figure 1 shows the coupling stock used to manufacture the specimens. Figure 2 shows an example of each of the 2 geometries tested in this investigation.

Figure 1: API P110 Quench + Temper coupling stock.

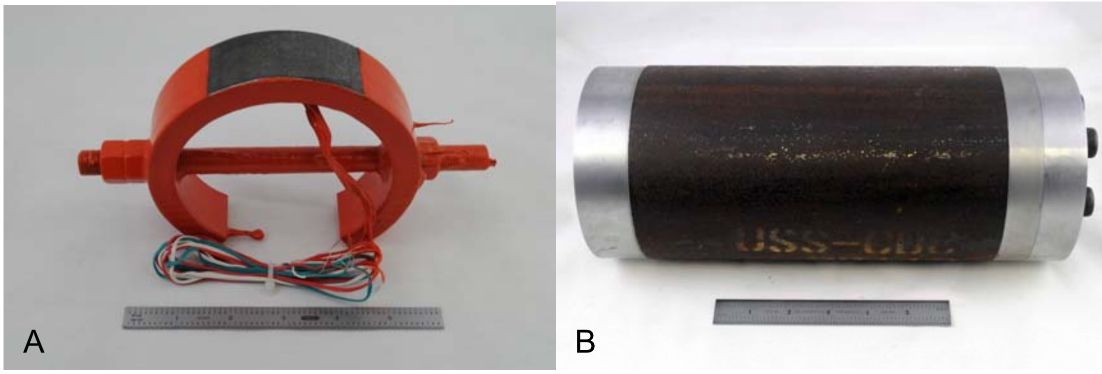

Figure 2: Examples of tested geometries: (A) C-ring specimen, and (B) full sized coupling blank in test fixture.

Specimen Processing

LPB process parameters were developed to achieve nominally 0.040 in. (1 mm) depth of compression. Samples were processed on a CNC mill or lathe to allow positioning of the LPB tool in a series of passes along the region to be processed while controlling the burnishing pressure to develop the pre-determined magnitude of compressive stress with controlled low cold working. The full lengths of the outer diameter of the full sized coupling blanks were LPB processed. The C-ring specimens were processed on the exposed section of the outside diameter. The LPB process has been previously documented in detail.[17]

X-ray Diffraction Residual Stress Analysis

X-ray diffraction residual stress measurements were made at the surface and at several depths below the surface on the outside diameter of both LPB and untreated specimens to characterize the residual stress distributions. Measurements were made in the axial direction employing a $\sin^2\psi$ technique and the diffraction of chromium Kα1 radiation from the (211) planes of steel.

Material was removed electrolytically for subsurface measurement in order to minimize possible alteration of the subsurface residual stress distribution. The measurements were corrected for both the penetration of the radiation into the subsurface stress gradient and for stress relaxation caused by layer removal. The value of the x-ray elastic constants required to calculate the macroscopic residual stress from the strain normal to the (211) planes of steel were determined in accordance with ASTM E1426-9.[18,19] Systematic errors were monitored per ASTM specification E915.[20]

Surface Roughness

The improvement in surface roughness was documented for LPB vs. un-treated coupling material. Surface roughness measurements were performed on both the untreated and LPB treated coupling blanks using a standard surface roughness tester. The Ra surface roughness was calculated over a 0.50 in. (12.7 mm) evaluation length in the axial direction.

SSC Testing

SSC Testing was conducted on 4 ½ in. (114.3 mm) API P110 quench and temper coupling stock (5 in. (127 mm) outside diameter). The coupling stock was sectioned into C-Ring specimens per NACE TM0177-Method C for testing and the full sized coupling stock blanks were machined to create an inside diameter of 4.375 in (111.1 mm) and provide a sealing surface for the internal pressure seals. Specimens were tested in both the un-treated condition as well as after LPB processing to determine the differential effects resulting from LPB treatment.

C-ring Testing:

Testing was performed on LPB treated and un-treated C-ring specimens per NACE TM0177-Method C. All testing was performed in 100% NACE TM0177-Solution A at 1 bara H_2S at 25° C, the pH was monitored continuously throughout testing to ensure conformance to NACE TM0177. Specimens were sectioned from a length of API P110 coupling stock. The specimens were loaded initially to nominally 45% of SMYS. After exposure to at least 720 hours the specimens were tested at 80%, 85% and 90% of SMYS. Stress on the specimens was monitored continuously 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 after loading and prior to immersion in solution. Figure 3 shows a C-ring specimen ready for testing.

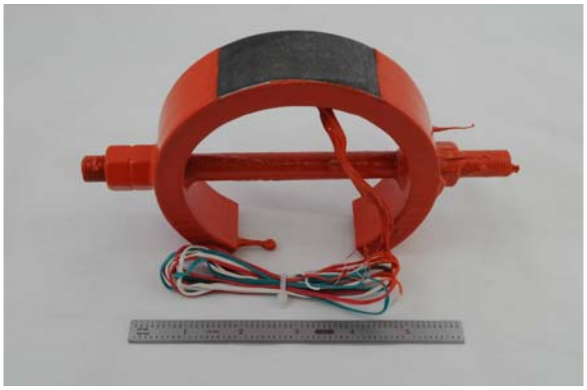

Figure 3: C-ring specimen prior to testing.

Full Sized Pressurized Coupling blank Testing:

Testing of full size coupling blanks was performed using a custom made holding fixture connected to a pressurizing test station. Specimens were tested in both the LPB treated and un-treated conditions. All tests were performed in 100% NACE TM0177-Solution A at 1 bara H_2S at room temperature with the pH continuously monitored. 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. Pressure was monitored continuously throughout the test and a timer was placed in the circuit to trip upon sample failure.

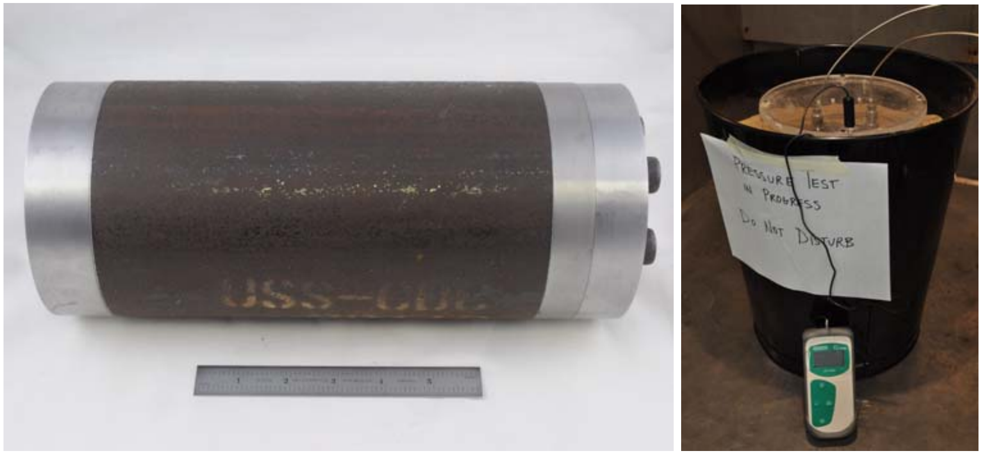

Figure 4: Full size coupling blank pressurized test apparatus and setup.

RESULTS AND DISCUSSION

X-ray Diffraction Residual Stress Analysis

X-ray diffraction residual stress vs. depth results for untreated and LPB processed API P110 coupling blanks are presented graphically in Figure 5. Compressive stresses are shown as negative values, and tensile stresses as positive, in units of ksi (10^3 psi) and MPa (10^6 N/m^2). Compared to the untreated condition, LPB produced a compressive residual stress field with a much greater magnitude of compression (>10X) and over 2X the depth of compression. The magnitude of compression is near the SMYS of 110 ksi (759 MPa) at the surface. LPB produces much less cold working than conventional processes and ensures the deep fiber layers remain in stable compression, even at high temperature or in the case of mechanical overload as has been demonstrated in prior work.[21]

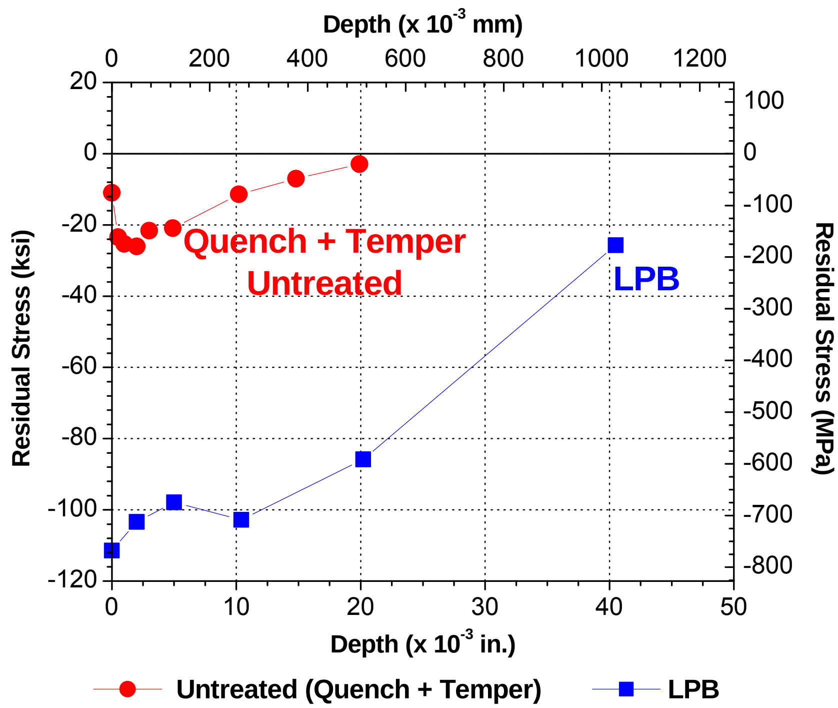

Figure 5: Residual stress comparison for LPB processed and un-treated material.

Surface Roughness

The improvement in surface roughness after LPB processing was quantified using the Ra surface roughness. LPB improved the surface finish by a factor of 2.6X. This can aid in NDI examination as well as reduce friction in service. Figure 6 displays the results graphically. Each value is an average of three repeat measurements.

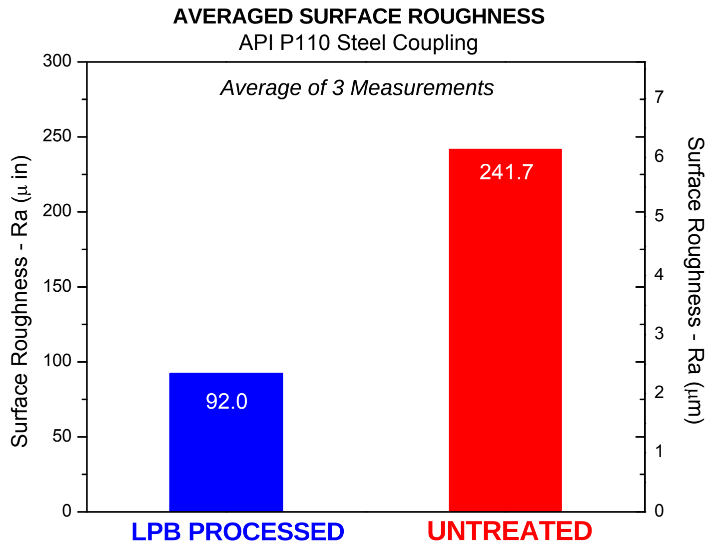

Figure 6: Surface roughness for LPB processed and un-treated API P110 coupling blank.

SSC Testing

The SSC testing data is presented graphically below in Figures 7 & 8. The un-treated C-ring specimen with an OD exposed surface 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 coupling blank test results are very similar with the un-treated coupling blank failing after the entire OD surface was exposed for 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 compared to the un-treated P110 material.

A macro photo comparison of a failed untreated C-ring specimen and a run out LPB C-ring specimen is shown in Figure 9. Dye penetrent was used to reveal the axial SSC failure in the un-treated coupling blank shown in Figure 10. Figure 11 shows the LPB coupling blank after timed run out at 85% SMYS, with and without FDI developer, documenting that there are no cracks of any size beginning to initiate on the specimen. The SSC testing results show definitively that LPB is able to mitigate SSC cracking in common API P110 steel and dramatically increase the life. 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. API Specification 5CT uses 80% SMYS stress levels for C90 and T95 tensile specimens and the next edition will likely add 85% SMYS stress level for a new C110 grade.

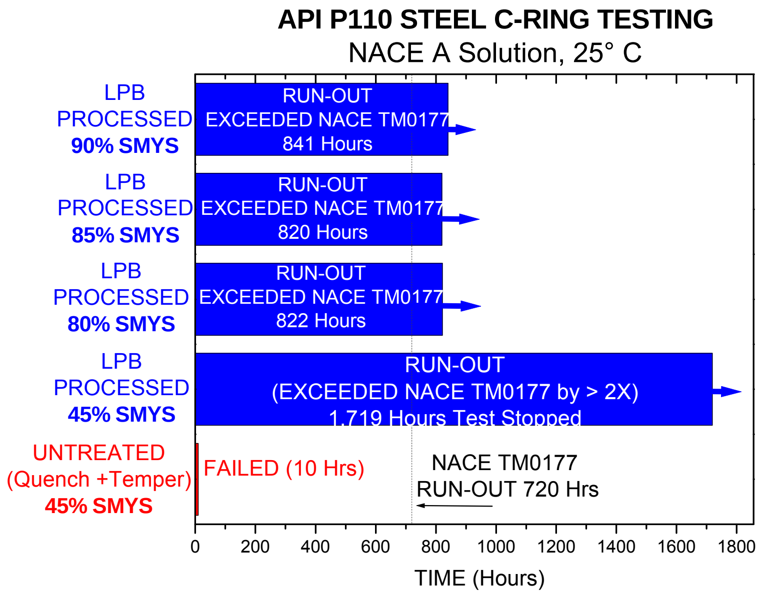

Figure 7: C-ring testing results.

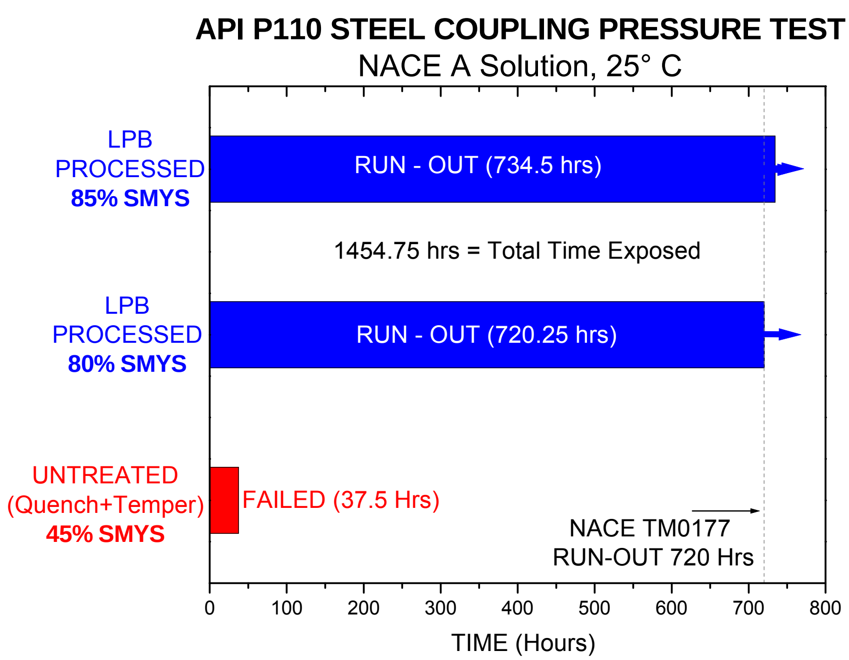

Figure 8: Full Sized Coupling blank Test Results.

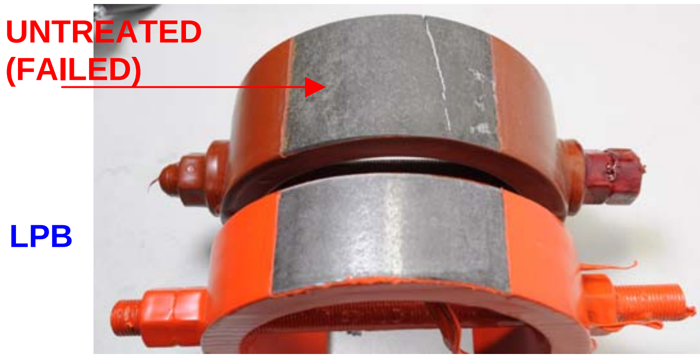

Figure 9: Comparison of LPB treated and un-treated C-ring specimens after testing. The un-treated specimen failed in 10 hours at 45% of SMYS. The LPB specimens ran-out at 45%, 80%, 85%, and 90% SMYS with no cracking.

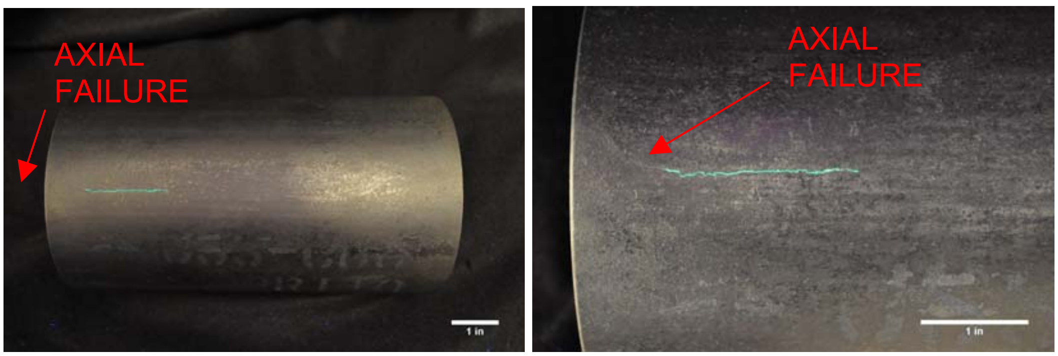

Figure 10: FDI inspection of failed un-treated coupling blank revealing thru wall axial SSC.

Figure 11: LPB processed coupling blank and test fixture after run-out at 85% SMYS. FDI developer showing no signs of crack initiation.

CONCLUSIONS

- LPB imparted a deep compressive layer of stable residual compression over 2X deeper and 10X greater in magnitude than the untreated coupling blanks.
- LPB was able to completely mitigate SSC failure in all tested specimens. The full sized coupling blank test exceeded the NACE TM0177 720 hour NACE A exposure time requirement at 45%, 80%, and 85% of the SMYS of 110 ksi (759 MPa).
- The LPB processed C-ring tests exceeded NACE TM0177 time requirements at stresses levels equal to 45%, 80%, 85%, and 90% of SMYS.
- The untreated coupling blanks and c-ring specimens failed in 33 hrs and 10 hrs respectively at a stress load of 45% SMYS.
- Use of an engineered deep compressive stress field using LPB to mitigate SSC was successful on API P110 quench and temper coupling blank specimens.

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