PREVENTING STRESS CORROSION CRACKING OF NUCLEAR WELDMENTS VIA LOW PLASTICITY BURNISHING

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ABSTRACT

Stress corrosion cracking (SCC) has been observed for decades in austenitic alloy weldments such as types 304 and 316 stainless steel as well as in Ni based alloy weldments including Alloy 600 and 690. SCC continues to be a primary maintenance concern for many components in both pressurized water reactors (PWR) and boiling water reactors (BWR). SCC is understood to be the result of a combination of susceptible material, exposure to a corrosive environment, and tensile stress above a threshold. Tensile residual stresses developed by prior machining and welding can accelerate SCC. A surface treatment is needed that can reliably produce deep compressive residual stresses in austenitic and Ni based alloy weldments in order to prevent SCC.

Post-weld surface enhancement processing via low plasticity burnishing (LPB) can be used to introduce deep compression into tensile fusion welds thereby mitigating SCC. LPB has been developed as a rapid and inexpensive surface enhancement method adaptable to existing CNC machine tools or robots. Deep compressive residual stresses produced by LPB are designed to reduce the surface, and near surface stress state to well below the SCC threshold. Residual stress results are shown for 304L stainless steel, Alloy 22 and Alloy 718. SCC test results comparing LPB treated and un-treated 304L and 316L stainless steel weldments are presented. Results show that the deep compression produced by LPB eliminates SCC in austenitic weldments.

INTRODUCTION

SCC is one of the most serious metallurgical problems facing the nuclear industry today. Studies have revealed that all grades and conditions of austenitic stainless steels and Ni based alloys are in fact susceptible to SCC given the right environment and conditions, namely either applied or residual tensile stress [1]. Material degradation problems due to SCC have cost the U.S. nuclear industry over 10 billion dollars in the last thirty years [2]. SCC is a direct cause of increased inspection requirements and extensive component repairs and/or replacements. A cost effective means of mitigating SCC would greatly reduce operational and maintenance costs.

A combination of a susceptible material, corrosive environment and tensile stress over a threshold limit will result in SCC. Machining, welding and other fabrication processes can produce high tensile residual stresses and cold working in the surface and near surface material of critical nuclear reactor components. [3,4] Furthermore, SCC can occur at stresses well within the range of typical design stress thus presenting an obvious concern [5]. The conventional approach to mitigate the problem has been to develop new alloys more resistant to SCC. A more cost effective method is to induce a compressive residual stress into the critical regions of the weldment. Surface enhancement techniques such as needle peening and cavitation peening are currently being used in the nuclear industry to mitigate or impede SCC by inducing compressive residual stresses into the surface material [6,7].

Conventional forms of shot peening and other similar surface treatments are beneficial due to the compressive residual stresses generated at the surface of the material being processed. However, the depth of compression achieved by these methods is typically shallow. Furthermore, these operations cause a considerable amount of cold working that can exceed 50%. High levels of cold work further increase the susceptibility for SCC initiation and produce a thermally unstable residual stress state. Stability of the residual compression is particularly significant in high temperature applications seen in BWR or PWR systems.

Surface enhancement methods including laser peening (LP) [8] and LPB have been shown to more effectively mitigate SCC by producing a deeper layer of residual compression than conventional peening technologies. The ability to produce a deep layer of stable compression is paramount in preventing SCC. LPB is a cost effective, unique, component specific process, which imparts a deep layer of stable residual compressive stress with characteristic controlled low cold working on the order of 3-5%.

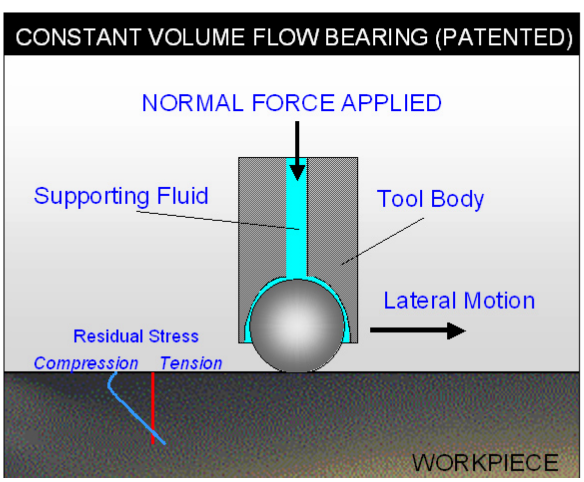
LPB has been successfully applied to mitigate SCC in 300M HSLA steel used in aircraft landing gear [9,10]; AA7076-T6 propeller taper bores, and closure lid welds on Alloy 22 nuclear waste containment canisters. An investigation into LPB treatment of 304 and 316 stainless steel weldments, shown in this paper, was also successful in completely mitigating SCC on the LPB processed surfaces.

LPB PROCESS & DESIGN METHODOLOGY

The basic LPB tool is comprised of a ball that is supported in a spherical, hydrostatic bearing as shown in Figure 1. Figures 2 through 4 show various types of LPB tooling currently being used in production. Tooling can be held and manipulated in any CNC lathe or mill as shown in Figures 3 and 4. Tooling can also be controlled robotically or with a customized fixture. Figure 5 shows a dual LPB tool simultaneously processing a closure weld on an alloy 22 nuclear waste containment vessel. LPB is cost effective, and can be easily implemented into existing processes. Standard cutting fluid is typically used to support the ball in a fluid bearing allowing the ball to roll in any direction with no resistance. The cutting fluid used depends largely on the application and a range of fluids is possible for use including distilled water for operations sensitive to contamination. The ball does not contact the bearing seat, even under load. Load is controlled with a hydraulic cylinder contained within the body of the tool.

As the ball rolls over the component, the pressure from the ball causes plastic deformation to occur in the surface of the material just under the ball. Because the adjacent material to the ball path is constraining the deformed area, the deformed material springs back into a compressive state after the ball pass is complete. No material is removed during the process. Material is displaced inward by a few ten-thousandths of an inch (0.0001-0.0006 in. (0.003 mm – 0.015 mm)) during processing. The LPB process also greatly enhances the surface finish, generally enhancing NDI detection limits. A near-mirror finish can be produced with roughness values on the order of 5 μin achievable.

Figure 1. LPB tool schematic



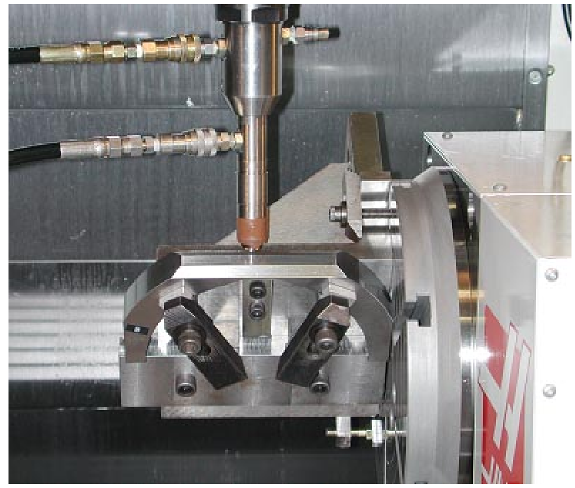


Figure 2. Single Point LPB tool burnishing

Figure 3. LPB processing of a welded plate

Figure 4.: LPB treatment of a nuclear waste containment vessel.

LPB produces low levels of cold work that results in a more thermally stable residual compressive stress distribution [11]. As an example, Figure 5 shows the residual stress and cold work vs. depth measured by X-ray diffraction (XRD) on thermally exposed shot peened and LPB treated Inconel 718. Compression produced by shot peening is dramatically reduced, at and near the surface, as a result of the 525°C and 600°C thermal exposure for 10 hrs. The deep compression produced by LPB is retained even after thermal exposure. The bottom graph illustrates the significant differences in cold working between the two processes. Shot peening produced cold working that approaches 60% while the LPB treatment produced less than 5% cold working. The high level of near surface cold work in the shot peened material produced a thermally unstable residual stress state.

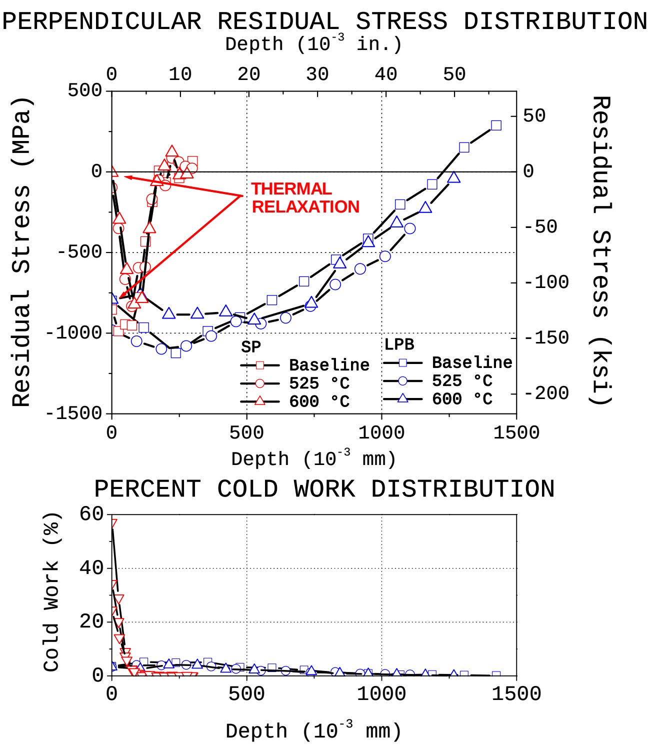


Figure 5.: Inconel 718 X-ray diffraction residual stress and cold work distributions showing a more thermally stable compressive stress for LPB vs. shot peening.

The LPB process is custom designed [12] for each specific component and operating condition. Compression is engineered based upon several aspects of the component including applied stress state, alloy, damage mechanism, and operating environment. The final LPB solution is validated through a series of applicable tests such as fatigue or SCC on the actual component or mock-up.

EXPERIMENTAL PROCEDURE

304L & 316L STAINLESS STEEL WELDMENTS

An investigation was undertaken to characterize the influence of the LPB treatment on SCC in 304L and 316L SS weldments. Specimens were manufactured of each material. Plates nominally 4 x 4 x 0.5 in. (102 x 102 x 13 mm) and schedule 40 pipe with an outside diameter of 3.5 in. (89 mm) were used for this investigation. A single circular weld bead was deposited about the center of the square plate specimens. The plate specimens were LPB processed along half of the plate as shown in Figure 6. Sections of schedule 40 pipe were welded together using a typical butt weld and then LPB processed on both the inside and outside diameters of half of the welded pipe as shown in Figure 7.

Figure 6.: 304L SS welded plate specimen.

Figure 7.: 316LSS welded pipe specimen; half LPB processed

X-ray diffraction residual stress measurements were made on the specimens to characterize the residual stresses from welding and LPB. X-ray diffraction measurements were performed using a $Sin^2\psi$ method, in accordance with SAE J784a [13]. X-ray diffraction residual stress measurements were made at the surface and at several depths below the surface on the specimens. 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 [13] and for stress relaxation caused by layer removal [14-17]. Measurements were performed as a function of depth and distance across the LPB surface over the weld and into the untreated material.

Following residual stress measurement the specimens were subjected to up to 100 hours constant immersion in hot/boiling MgCl2 above 120° C. Specimens were removed from solution and observed following exposure. Optical microscopy and fluorescent dye penetrent were used to inspect for, and reveal SCC on the specimens.

Surface roughness measurements were performed on both the untreated and LPB treated sides of the plate respectively using a Mitutoyo SJ-201 surface roughness tester. The Ra surface roughness, was calculated over a 0.50 in. evaluation length parallel and perpendicular to the longitudinal axis of the plate.

ALLOY 22 WELD MOCKUP

Alloy 22 welded plate mockups were fabricated to simulate the closure lid weld on spent-fuel nuclear waste containment canisters. A schematic of the closure lid weld is shown in Figure 8. The closure lid weld is the final weld which seals the spent radioactive fuel in the canister. The entire canister is thermally stress relieved prior to the final closure weld. Thermal stress relief of the final closure weld is not practical and therefore LPB treatment was implemented to prevent SCC of the closure lid welds and surrounding material.

Welded plate mockups of nominally 12 x 16 x 1 in. (305 x 406 x 25.4 mm) were evaluated using x-ray diffraction [13] to determine the surface and subsurface residual stress distributions resulting from welding, LSP and LPB. X-ray diffraction measurements were performed using the $sin^2\psi$ method [13]. Measurements were made as a function of depth at three locations on the specimen: Adjacent to the fusion line; 0.5 in. (13 mm) from the fusion line; and 1.5 in. (38 mm) from the fusion line. Measurements were made in a parallel direction to the weld-line. Figure 9 shows a representative welded specimen with the x-ray measurement locations identified.

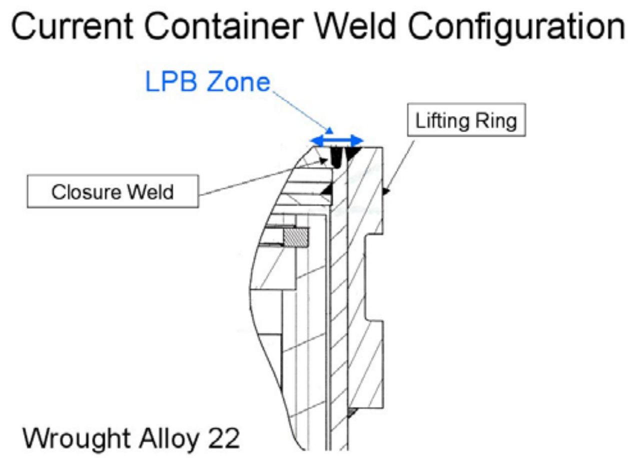


Figure 8.: Alloy 22 closure weld and LPB treatment region

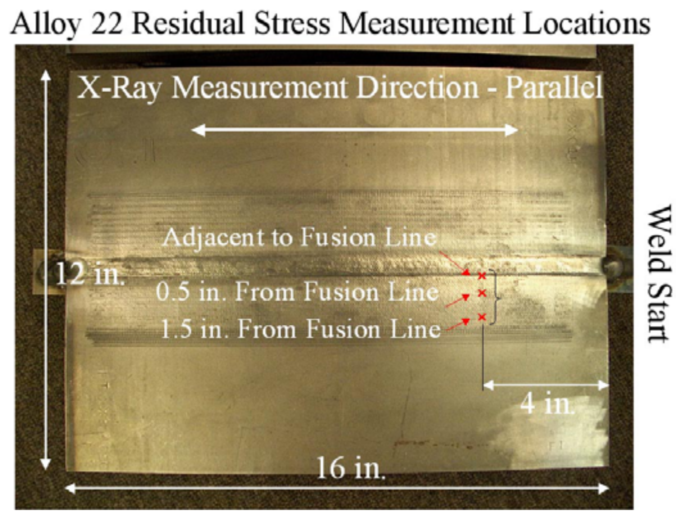


Figure 9. Representative Alloy 22 welded specimen with post welding surface enhancement.

RESULTS

CASE 1 – 304SS WELD

Specimens were examined via optical microscopy up to 60X magnification and a fluorescent dye penetrent was used to reveal SCC. Figure 10 shows XRD residual stress data for the welded plate in both the LPB treated and un-treated regions. Tensile residual stresses on the as-welded side of the sample approach +100 ksi (+689 MPa). The LPB treatment produced deep compression with a magnitude of greater than –120 ksi (-827 MPa).

Photographs shown in Figures 11 & 12 show a 304L and 316L SS specimen after 100 hours exposure to hot/boiling $MgCl_2$ above 120° C. Figures 13 & 14 show pipe weld specimens after 24 hours of $MgCl_2$ exposure. Examination of the welded plates and pipe weld specimens revealed no evidence of SCC on the compressive LPB processed side. The un-processed side, as expected, developed extensive SCC. Two welded plates of each material were processed identically; one plate was used for XRD residual stress analysis and the other for SCC testing. There is likely some variation between the location of the SCC cracks and the location of the high-tension region adjacent to the weld between the plate used for SCC testing and the plate used for X-ray stress analysis. The compressive residual stresses produced by LPB prevented SCC from initiating in all cases.

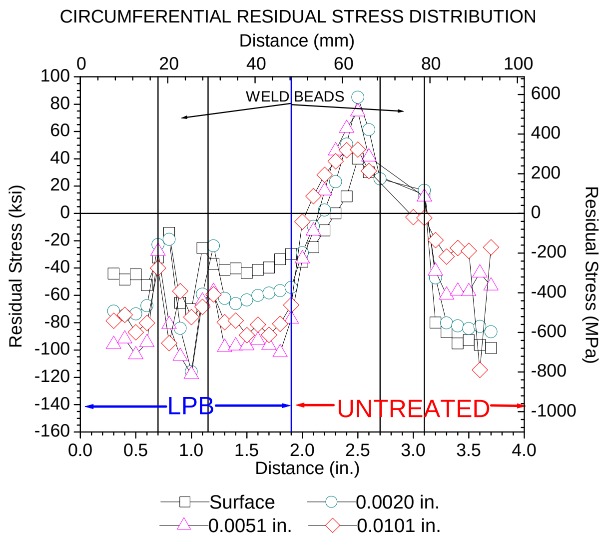


Figure 10. XRD residual stress measurements on half LPB treated welded 304L SS plate.

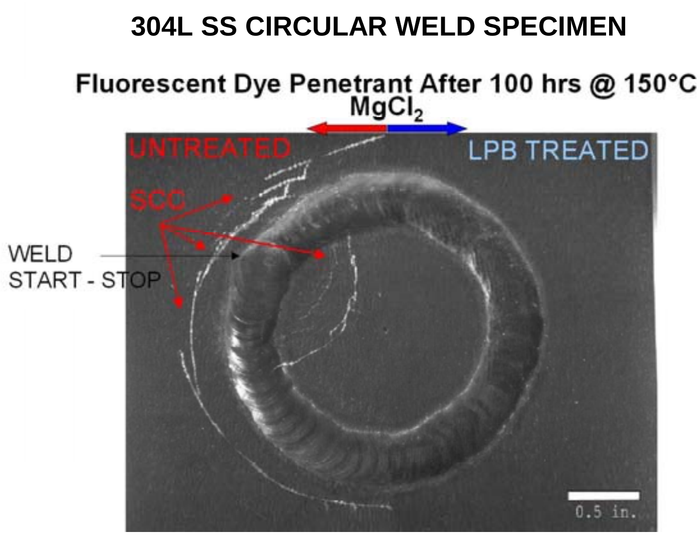


Figure 11. Fluorescent dye defines SCC cracking on un-treated side of 304SS specimen.

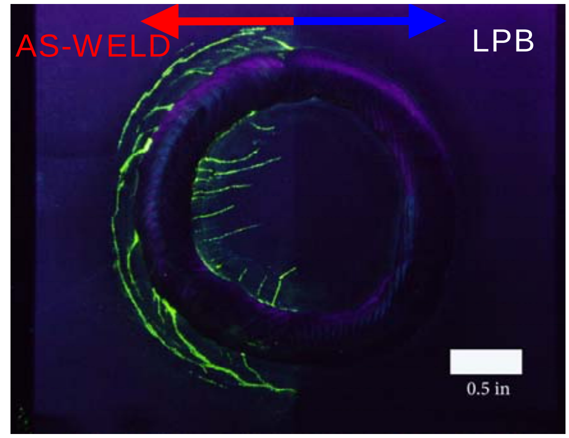


Figure 12. Black light fluorescent dye defines severe SCC cracking on un-treated side of a 316L SS specimen.

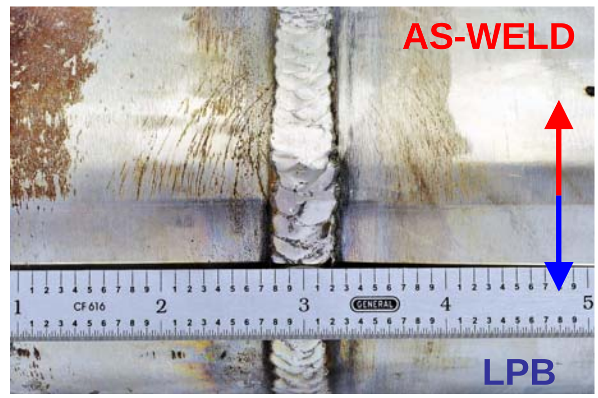


Figure 13. SCC cracking on un-treated side of a 304L SS pipe weld specimen.

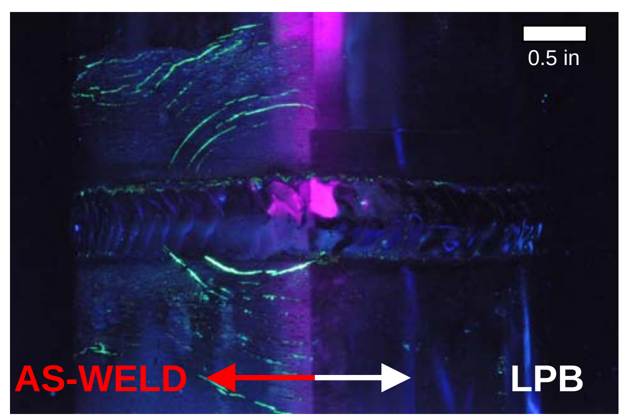


Figure 14. Black light fluorescent dye defines severe SCC cracking on un-treated side of a 316L SS pipe weld specimen.

Cracking on the un-processed sides of the welds and base material was characteristic of SCC with cracks running near perpendicular to the directions of maximum residual tensile stresses. The majority of cracking was observed in the region 0.5 in. to 1.25 in. (13 to 38 mm) from the fusion line of the weld.

Surface roughness results are presented graphically in Figure 15. The LPB treatment improved the surface finish. Surface roughness in the parallel direction was reduced by nominally 70% due to LPB.

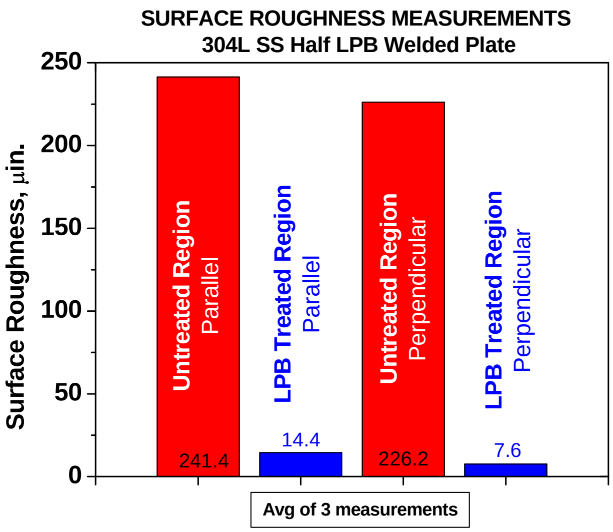


Figure 15. Average Ra surface roughness of specimen on un-treated and LPB treated regions.

ALLOY 22 WELD MOCK UP

Figure 16 shows the residual stress distribution as a function of distance and depth for the as-welded specimen. In the as-welded condition for any given depth the highest tensile stress is located adjacent to or at 0.2 in. (5 mm) from the fusion line. Tensile stresses are highest, approaching +150 ksi (+1034 MPa) at the previously highly cold worked surface and at the 0.005 in. (0.127 mm) depth. Stresses cross from tension to compression at distances greater than 0.75 in. (19 mm) from the fusion line.

Figure 17 shows the residual stress distribution for the as-welded, LSP and LPB treated plates as a function of depth at a location 0.5 in. (12.7 mm) from the fusion line. LSP introduced a maximum compressive stress of –87.4 ksi (-603 MPa) at a depth of 0.010 in. (0.254 mm) below the surface. LSP produced a depth of compression on the order of 0.08 in. (2 mm). LPB treatment produced a maximum compressive stress of –81.6 ksi (-563 MPa) at a depth of 0.039 in. (1 mm) from the surface. The residual compression imparted by LPB is significantly deeper than that of LSP. This greatly increased depth of compression over LSP further ensures complete mitigation of SCC.

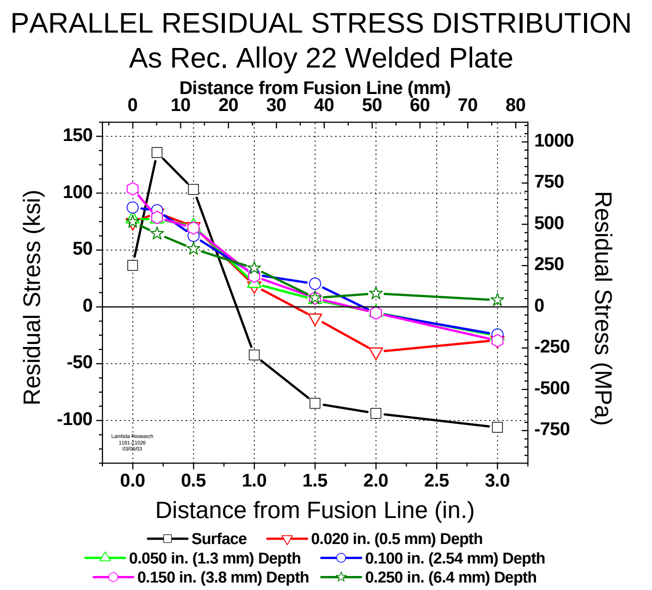


Figure 16. XRD residual stress data for the as received welded Alloy 22 plate. Stress vs. distance & depth

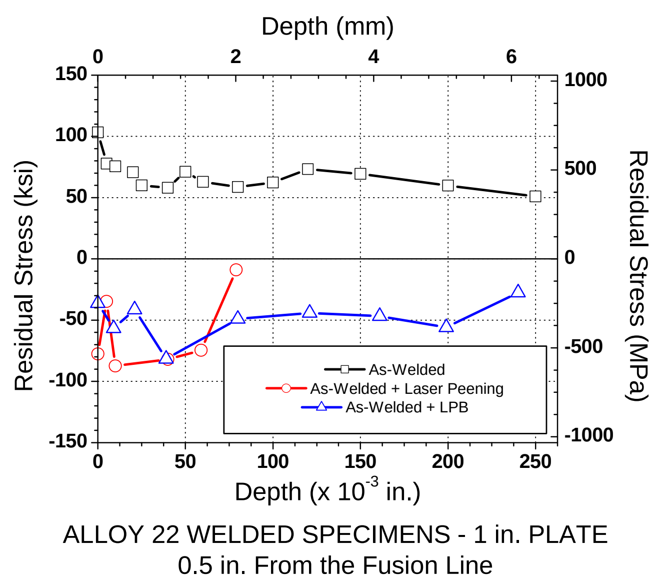


Figure 17. XRD residual stress results for welded, Laser Peened (LP), and LPB conditions of Alloy 22. Note the high tensile residual stress in the As-Welded condition and substantial increase in depth of compression with LPB treatment.

CONCLUSIONS

- The use of compressive residual stress on 304L and 316L SS and Alloy 22 is a viable method of preventing/mitigating SCC.
- Welding produces high tensile residual stresses of greater than +100 ksi (+689 MPa) at the surface and into the near surface material of both 304L and 316L SS and Alloy 22.
- LPB processing provides greater depth of compression than LSP or conventional shot peening protecting surfaces against SCC with the added benefit of low of cold working for thermally stable residual compression.
- SCC testing of LPB treated 304L and 316L SS weldments showed a complete mitigation of SCC.
- LPB is a cost efficient, easily implemented technology, which is capable of producing a deep layer of stable compression in nuclear weldments.

ACKNOWLEDGEMENTS

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