Mitigation of Stress Corrosion Cracking Using an Engineered Residual Stress Solution

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Abstract

Stress corrosion cracking (SCC) is known to be the result of the combined influence of tensile stress and a corrosive environment on a susceptible material. Austenitic stainless steels such as types 304L and 316L are susceptible alloys often used in nuclear applications. Tensile residual stresses are developed in components by cold working, forming, prior machining, grinding and welding. In many cases tensile residual stresses in the heat affected zone of weldments can reach the yield strength of the material. SCC can be mitigated or eliminated by introduction of an engineered compressive residual stress field into components via low plasticity burnishing (LPB).

SCC testing results comparing LPB treated and un-treated 304L and 316L stainless steel weldments are presented. Residual stress results are shown for 304L and 316L stainless steels and Ni based Alloy 22. The results show conclusively that the deep, stable compression produced by LPB eliminates SCC in austenitic weldments, regardless of sensitization from welding. The successful application of LPB to mitigate SCC in Alloy 22 closure welds on full size nuclear waste containment vessels is discussed.

Keywords: Stress Corrosion Cracking, Low Plasticity Burnishing, Residual Stress, Weldments, Austenitic Stainless Steels

Introduction

SCC is one of the most serious metallurgical problems facing industries today. Studies have revealed that all grades and conditions of austenitic stainless steels and Ni based alloys are susceptible to SCC [1]. Material degradation problems due to SCC have cost the U.S. nuclear industry alone 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. An effective means of mitigating SCC would greatly reduce operational and maintenance costs.

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]. Surface enhancement techniques such as shot peening (SP), needle peening and cavitation peening are currently being used in 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.

High levels of cold work 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. 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. LPB is a unique, component specific process, which imparts a deep, engineered 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 304L and 316L stainless steel weldments, shown in this paper, indicates complete mitigation of SCC on the LPB processed surfaces.

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. Plates nominally 102 x 102 x 13 mm (4 x 4 x 0.5 in.) and schedule 40 pipe with an outside diameter of 89 mm (3.5 in.) 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. 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. Welded specimens of each material were processed identically; one used for XRD residual stress analysis and the others for SCC testing.

X-ray diffraction residual stress measurements were made on the specimens to characterize the residual stresses from welding and LPB at and below the surface. Measurements were made using a $\sin^2\psi$ technique [13-16]. 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 [17] and for stress relaxation caused by layer removal [18]. The values of the x-ray elastic constants were determined in accordance with ASTM E1426-91 [19]. Systematic errors were monitored per ASTM E915.

Following residual stress measurement specimens were subjected to up to 100 hours constant immersion in hot/boiling $MgCl_2$ at 150° 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 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 12.7 mm (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. Details of the actual closure lid weld geometry and mock up fabrication are discussed elsewhere [20]. 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 305 x 406 x 25 mm (12 x 16 x 1 in.) were evaluated using x-ray diffraction to determine the surface and subsurface residual stress distributions resulting from welding, laser shock peening (LSP) and LPB. X-ray diffraction measurements were performed using the same technique described earlier. Measurements were made as a function of distance from the fusion line at the surface and several depths on an as welded plate. Measurements were also made at 13 mm (0.5 in.) from the fusion line on an as welded, as welded + LSP, and as welded + LPB condition. Measurements were made in a parallel direction to the weld-line.

Experimental Results

Case 1 – 304L & 316L SS Weldments

Figure 1 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 +689 MPa (+100 ksi). The LPB treatment produced deep compression with a magnitude of greater than -827 MPa (–120 ksi). Photographs shown in Figure 2 depict a 304L specimen after 100 hours exposure to hot/boiling $MgCl_2$ above 120° C and a 316L pipe weld specimen 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 sides developed extensive SCC.

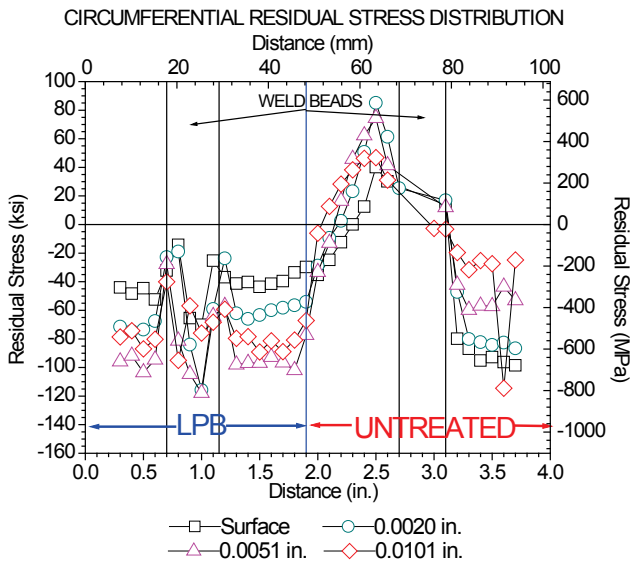

Figure 1. XRD residual stress measurements on half LPB treated welded 304L SS plate.

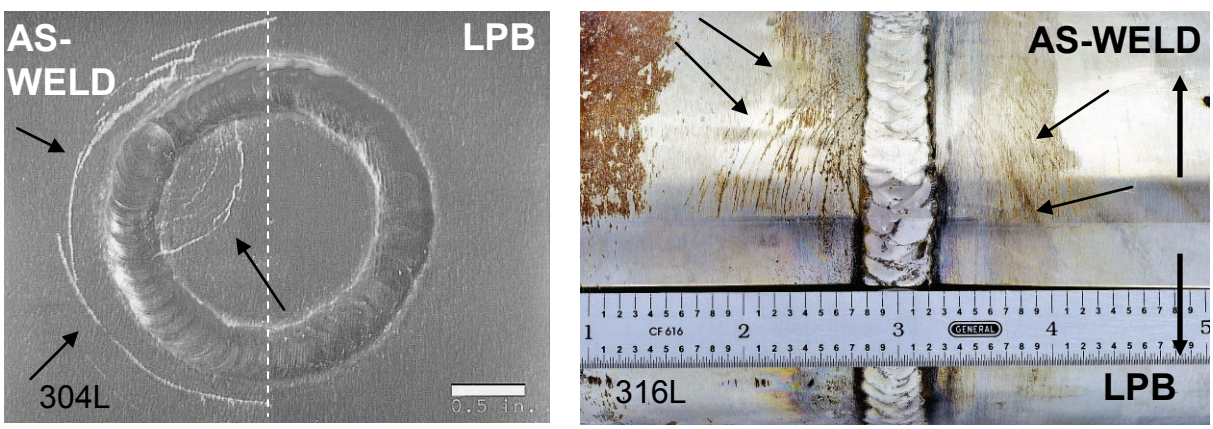

Figure 2. Macro photos of 304L SS sample and 316L pipe sample following $MgCl_2$ exposure. Arrows indicate SCC cracking on untreated side of samples.

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.

The surface roughness was 6.1 μm (241.4 μin) for the untreated material. The LPB process produced an improved surface roughness of 0.4 μm (14.4 μin). Surface roughness was reduced on average by 94%.

Alloy 22 Weld Mock Up

Figure 3 shows the residual stress distributions as a function of distance and depth. In the as-welded condition the highest tensile stress is located either adjacent to or near the fusion line. Tensile stresses are highest, approaching +1034 MPa (+150 ksi), at the surface. Stresses cross from tension to compression at distances greater than 19 mm (0.75 in.) from the fusion line. LPB treatment produced a maximum compressive stress of -563 MPa (–81.6 ksi) at a depth of 1 mm (0.039 in.) 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.

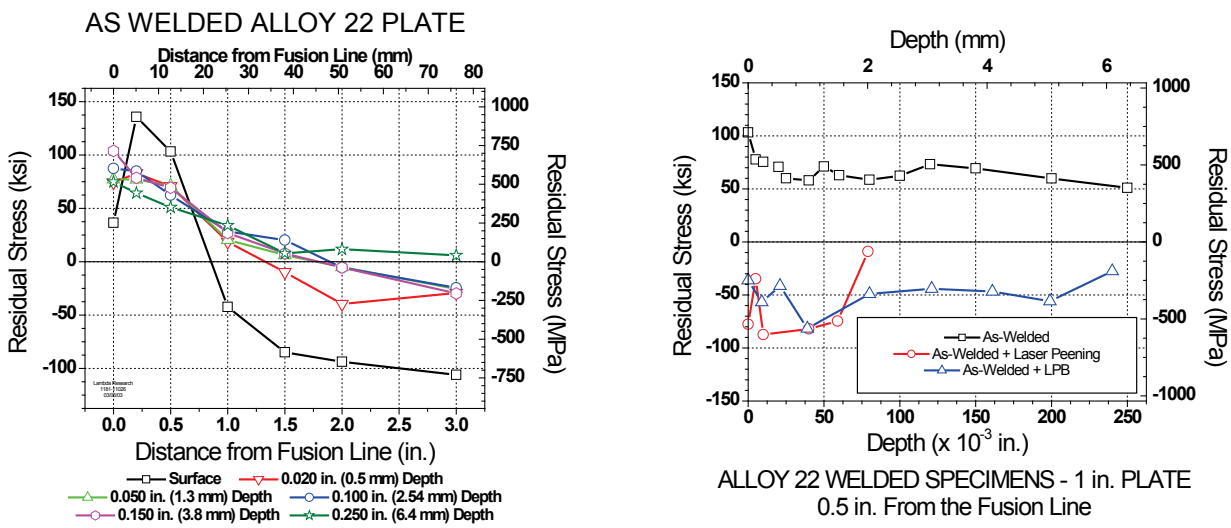

Figure 3. XRD residual stress results for welded, LSP, and LPB conditions of Alloy 22. Note the high tensile residual stress in the As-Welded condition and substantial increase in depth of compression with LPB treatment.

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 +689 MPa (+100 ksi) 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 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 an easily implemented technology, which is capable of producing a deep layer of stable compression in welded components to mitigate SCC.

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