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STAINLESS STEEL PIPING (U)**

by

S. L. West 8/13/90

D.E. Rawl, Jr., S. L. West, D. A. Wheeler, and M.R. Louthan, Jr.

Westinghouse Savannah River Company
Savannah River Laboratory
Aiken, South Carolina 29808

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DEFECT CHARACTERIZATION IN PIPE-TO-PIPE WELDS IN LARGE DIAMETER STAINLESS STEEL PIPING

D. E. Rawl, Jr., S. L. West, D. A. Wheeler and M. R. Louthan, Jr.*

ABSTRACT

Metallurgical evaluation of pipe-to-pipe welds in large-diameter, Type 304 stainless steel piping used to construct the moderator/coolant water systems for Savannah River Site reactors has demonstrated that small weld defects found in this 1950-vintage system do not compromise the integrity of the system. The weld defects were too small for detection by the pre-service standard radiographic inspection, but were found through systematic ultrasonic testing (UT) and penetrant testing (PT) evaluations of piping that had been removed during upgrades to the piping system. The defects include lack of weld penetration, slag inclusions, and other weld metal discontinuities. These discontinuities typically did not propagate during more than 35 years of service. The defects examined were too small and isolated to degrade the mechanical properties of the pipe-to-pipe weldments and therefore did not compromise the integrity of the piping system.

INTRODUCTION

Nuclear reactors at the Savannah River Site (SRS) operate at relatively low temperatures (less than boiling) and low pressures (225 psig maximum) using heavy water (D_2O) as the moderator/coolant. These reactor systems were constructed in the 1950's using AISI Type 304 stainless steel. Thin-wall, large-diameter fabricated pipe sections were joined using multiple Type 308 weld filler passes. Typically, lengths of pipe were joined by a butt joint configuration with a single Vee groove using, predominantly, inert-gas-shielded welding processes. Branch pipe joints received a full penetration fillet weld. The root passes of butt welds were visually inspected on both the outer and inner surfaces, and the completed welds were volumetrically inspected by radiographic testing (RT). Pressure testing was also performed to assure the soundness of pipe material and welds.

Weld areas in the piping system were periodically inspected for defects by UT. This in-service inspection identified cracks in approximately 7 percent of the weld-heat-affected zones (HAZ). If the cracks were 50 percent through-wall or 20 percent of circumference, pipe sections were removed from service. Metallurgical evaluation of these cracks showed them to be predominantly intergranular stress corrosion cracks (IGSCC), resulting from tensile weld residual stresses, chloride ions in the water, and a sensitized microstructure. Cleaning procedures used for reactor fuel and target assemblies during early operation caused chloride ions in the

* Westinghouse Savannah River Company
Savannah River Laboratory
Aiken, SC 29808 USA

cooling water system. The pipe material contained up to 0.08 percent carbon, which was not stabilized, making the microstructure susceptible to sensitization by thermal treatments such as welding.

The microstructure of welds made with Type 308 filler metal consists of austenite with a small fraction of retained delta ferrite (five to ten volume percent) in the room temperature microstructure [1, 2]. Such welds solidified as primary ferrite with subsequent transformation of much of the ferrite to austenite on cooling [3, 4]. At elevated temperatures, this duplex structure resists solidification cracking [5]. An added benefit of the duplex microstructure is, in general, improved resistance to IGSCC because of differences in sensitization morphology and kinetics.

Studies of materials in Boiling Water Reactor (BWR) environments have shown that if the ferrite level in a duplex cast structure is 12 volume percent or higher, that structure is immune to IGSCC [6]. SRS operating experience and in-service inspections have not revealed any evidence of IGSCC in cast components but have produced an example of IGSCC in a weld fusion zone. This stress corrosion crack propagated into a weld fusion zone from the HAZ. This observation raised a concern that chloride accumulations in crevices or voids associated with weld defects might provide sites for crack development. Thus, additional evaluation of weld fusion zones was conducted.

This work focused on the examination of weld fusion zones in sections of process water piping removed from service because of IGSCC in the HAZ. Initially, the objective was to investigate the extent and location of fusion zone defects. Subsequently, defects were characterized to determine their morphology and mechanisms of formation. Most importantly, defects were evaluated for their tendency to propagate and to assess their impact on service life.

PROCEDURE

Pipe sections removed from service were examined for weld discontinuities using standard ultrasonic inspection procedures. Pipe inner surfaces were also examined using dye penetrant tests to locate defects that opened to the inner surface. Subsequently, bulk coupons that contained weld defects were cut from the pipe sections for metallography. The metallographic cross sections containing the defect areas were mounted in bakelite, mechanically polished through 0.03 μm Alumina, and electrolytically etched in ten percent oxalic acid solution to reveal the microstructure. Optical microscopy was used for much of the characterization with some additional examination by electron microscopy (SEM/EDS). Microhardness tests were also performed in the vicinity of some defects.

RESULTS

The results indicated that good welding and inspection practices were followed during construction in the 1950's. Numerous welds were examined, many (about 90 percent) of which showed no UT or PT indication of fusion zone discontinuities or defects. Only approximately ten percent of pipe sections investigated had defects, which were too small for detection by RT at the time of fabrication. Defects, located through the systematic UT and PT efforts included slight underfill at the inner surface of the weld root (first pass), incomplete weld penetration, small fissures, and slag inclusions.

Incomplete weld penetration results in a sharp, crack-like defect from failure of the weld root pass to penetrate to the pipe interior. A weld fissure, or hot crack (most appropriately termed a solidification crack [7]), is a fusion zone crack, usually intergranular, that results from segregation during weld solidification and the formation of low-melting-temperature liquid films. These liquid films exist to temperatures below the bulk solidus of the alloy and as the solidifying weld cools, shrinkage strains coupled with extrinsic mechanical restraint cause the liquid films to separate, resulting in cracks. A slag inclusion results from the entrapment of fluxing agents and deoxidizers in the molten weld pool. Solidification occurs before surface tension causes the slag to float to the surface.

A typical example of slight underfill (shrinkage cavity) with a small fissure (0.10 mm) in a pipe-to-pipe butt weld is shown in Figure 1. Visual examination of the pipe inner surface revealed the underfill and PT indicated the presence of the fissure (Figure 1c). Note the duplex structure of the weld metal with the major microstructural constituent of the columnar dendritic grains being austenite and the minor constituent being delta ferrite. The intergranular morphology of the fissure indicates that it is a hot crack present from the time of fabrication. There is no evidence of propagation of this defect by stress corrosion or any other mechanism over the 30-year service life.

Another defect associated with the root pass of a butt weld was incomplete penetration (Figure 2). The original joint preparation was a 75-degree, included-angle bevel (37.5 degrees at each pipe end) with short root faces (square edges) at the pipe inside diameter. The pipe sections were separated by a small gap to permit full penetration. Root faces left unwelded because of the lack of penetration were distorted by the deformation produced by subsequent weld passes. The lack of penetration appears to have been extended by a hot crack to a total length of 1.1 mm (Figure 2b). Although the crack tip was blunted by corrosive attack, there was no evidence of extension of the crack by stress corrosion.

Weld fissures not associated with underfill were also observed but did not exceed one millimeter in length. Dye penetrant testing of pipe inner surfaces located several hot cracks, two of which are shown in Figure 3. The hot crack in Figure 3a occurred in a butt weld, while that in Figure 3b occurred in a branch pipe weld. Again, no crack propagation during reactor service was observed, and general corrosion blunted the crack tips, thus lessening the severity of the defects.

In addition to crack-like defects, limited crevice corrosion occurred in weld fusion zones on the inner surfaces of pipe welds (Figure 4). The limited crevice corrosion occurred in both butt welds joining pipe sections (Figure 4a) and in branch pipe welds (Figure 4b). Such defects were no deeper than 0.5 mm and showed no tendency toward extension or toward the development of crack-like characteristics. Surfaces of these defects were well rounded.

Non-metallic inclusions were also observed, especially as subsurface discontinuities. No other subsurface discontinuities were observed. In one case, an inclusion was open to the inside surface of a pipe or extended to the surface by a fissure (Figure 5). Some form of corrosive attack appears to have enlarged the discontinuity, but no crack extension occurred. In another case, a subsurface inclusion was found with a circular cross section resulting from the effect of surface tension when the weld metal and inclusion were molten (Figure 6). This inclusion was observed at a region between two weld passes, a typical site for slag inclusions. The inclusion exhibited an unusually well developed structure, with distinct crystals

and dendrites in a dark matrix along with metallic particles (Figure 6b). Energy dispersion spectrography analysis of the inclusion composition showed concentrations of manganese, silicon, aluminum, and titanium, indicating an accumulation of deoxidizers and flux constituents and identifying this as a slag inclusion.

Another small slag inclusion with a maximum dimension of less than one millimeter exhibited a more representative elongated morphology at an interpass region (Figure 7). This inclusion also contained a high concentration of deoxidizing elements (manganese, silicon, aluminum, and titanium). These elements react with oxygen and each other to form hard, intermetallic compounds, principally silicates[8]. Hardness tests of the slag inclusions confirmed the high hardness and showed that the weld metal surrounding them was not significantly affected. None of these subsurface inclusions were extended by cracking or corrosion.

DISCUSSION

Stress-corrosion cracking was not associated with any weld defects, but the results indicate a need to review the crevice-corrosion behavior of weldments. Weld metal is generally considered to be more susceptible to crevice corrosion than its base metal equivalent, but experimental evidence supporting such a belief is limited. Defects such as hot cracks and slag inclusions create weld-metal crevices that are reported to be easily corroded, particularly in chloride-containing environments [9]. Crevice corrosion resulting from a lack-of-fusion defect in Type 304 material welded with Type 308 filler metal has been observed after exposure to even relatively pure water [9]. This situation is similar to the current situation involving Type 304 material welded with Type 308 weld filler; however, the observed crevice corrosion is not severe.

The character of crevice attack in weldments is similar to pitting caused by the morphology and size of the weld defects. The pitting resistance of weldments is also a subject of very limited experimental investigation [10]. Metallographic evaluations have shown that pit initiation in an austenitic matrix is primarily associated with non-metallic inclusions, and, in a duplex matrix (austenite and delta ferrite) such as a weld fusion zone, pit initiation occurs primarily in the austenite phase [11]. Other studies of stress corrosion and pitting of welded Type 304 stainless steel showed that both corrosion processes were more severe in parent material than in weld material [12]. The combined results of these studies demonstrate that defects in duplex weld fusion zones can serve as initiation sites for crevice corrosion. The results of this investigation are consistent with such observations and indicate that the propagation rate under SRS operating conditions is very slow.

The presence of defects in the weld fusion zone, especially those that are crack-like, also raised concern over their effect on mechanical properties. Tensile and fracture toughness tests performed at SRS operating temperatures on Type 304 SRS samples machined from pipe sections removed from service showed the weld material to have acceptable properties in comparison to pipe base material [13]. The lowest value of fracture toughness was found in a weld HAZ specimen, thus reducing the concern over the effect of fusion zone defects on mechanical behavior. A considerable margin of safety exists between actual weld metal properties, including fracture toughness, and those used in the fracture mechanics analysis to determine critical flaw sizes and demonstrate the integrity of the piping [14]. Hardness readings taken in the vicinity of the the hard, intermetallic slag inclusions found during the investigation suggested that the properties of the weld metal were not altered by thickness; thus minimizing concern over the initiation of a crack in that area.

The data obtained from this investigation demonstrates that small, inner surface weld-fusion-zone defects can act as initiation sites for crevice corrosion. Any enlargement of defects occurs slowly in a uniform manner, which tends to eliminate the crack-like character and reduce the tendency of the defects to concentrate stresses. Generally, the defects appear to have been present from the time of construction and any extension of the defect occurred at a very slow rate. Therefore, the weld fusion zone defects and discontinuities do not significantly affect the structural integrity of the piping system.

CONCLUSIONS

The metallurgical evaluation of pipe-to-pipe welds in large-diameter, Type 304 stainless steel pipe led to the following conclusions.

- The combination of UT and PT was an effective means to find and locate weld defects in process water pipe sections removed from service.
- Metallurgical examination showed that these defects occurred most frequently in near-inner-surface regions.
- Some defects in the duplex matrix fusion zones served as sites for the initiation of crevice corrosion that enlarged slightly but also blunted such defects. No propagation by stress corrosion cracking was observed.
- No original weld defect nor any defect enlarged by crevice corrosion approached the critical thresholds of 50 percent through-wall or 20 percent of circumference in pipe sections removed from service.
- Weld defects, generally present from the time of welding, did not impact the structural integrity or service life of the piping. Therefore, such defects do not constitute areas of major concern for in-service inspection, although these inspections should continue to include evaluation of weld discontinuities.

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a

b

c

Figure 1: Optical micrographs of underfill and hot crack at inner surface of butt weld: (a,b) root pass region where arrow indicates crack; and, (c) hot crack which shows no evidence of propagation. Etchant: 10% oxalic acid.

a

b

Figure 2: Optical micrographs of lack - of - penetration defect in butt weld: (a) weld penetration profile; and, (B) extension of lack - of - penetration by hot crack, with crack tip rounded by corrosion. Arrows indicate position of weld fusion boundary. Etchant: 10% oxalic acid.

a

b

Figure 3: Optical micrographs of hot cracks in: (a) butt weld; and, (b) branch pipe weld. Note that crack tips have been rounded by corrosive attack. Etchant: 10% oxalic acid.

a

b

Figure 4: Optical micrographs of crevice corrosion in (a) butt weld; and, (b) branch pipe weld. Irregular shapes have no sharp edges from which a crack could propagate. Etchant: 10% oxalic acid.

Figure 5: Optical micrograph of slag inclusion open to inner surface, with evidence of enlargement by crevice corrosion. Etchant: 10% oxalic acid.

a

b

Figure 6. Optical (a); and SEM (b) micrographs of subsurface inclusion with circular cross section. Arrows in (b) indicate crystals (A), metallic particles (B), and dendrites (C) in dark matrix. EDS indicated enrichment in Mn, Si, I, and Ti characteristic of slag inclusion. Etchant: 10% oxalic acid.

a

b

c

Figure 7: Optical (a); and, SEM (b,c) micrographs of subsurface inclusion at interpass region with typical elongated morphology. Arrows in (c) indicate crystals (A), metallic particles (B), and nonmetallic particle (C) in dark matrix. EDS indicated enrichment in Mn, Si and Al, characteristic of slag inclusion or accumulation of deoxidizers. Etchant: 10% oxalic acid.

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