Experimental Verification of Analytically Determined Weld Overlay Residual Stress Distributions

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Abstract

Weld-overlayed specimens prepared using qualified field procedures were used in a test program to verify analytically predicted through-wall residual stresses. The distributions experimentally determined from a strain relief method showed that the predictions were conservative. Substantial compressive residual stresses were produced on the inside surface and through half of the pipe wall.

1.0 Introduction

The weld overlay as a repair technology for intergranular stress corrosion cracking (IGSCC) was first used in 1982 on a six-inch reactor water clean-up line at Unit 2 of Commonwealth Edison's Quad Cities Nuclear Power Plant. In the past three years, the increasing occurrence of IGSCC indications in BWR stainless steel piping has resulted in the application of over five hundred weld overlay repairs in U.S. nuclear power plants.

The first weld overlays were conservatively designed to replace the structural cross-section of the pipe and were considered technically as interim repairs. As more experience was gained with weld overlay design, application, and analysis, the very beneficial residual stress improvement effects of the weld overlay were considered. The current weld overlay design approach takes into account the flaw characterization by ultrasonic examination, the flaw growth due to fatigue and IGSCC, and the residual stress effects resulting from applying the weld metal. Conservative flaw growth analyses indicate a design life in excess of ten years.

In late 1983, a program was initiated to experimentally verify the analytical prediction of through-wall residual stress distributions with a weld overlay applied. Similar work on a test specimen with last pass heat sink welding (LPHSW) applied was included in the program. The main objective of this test program was to compare the experimentally determined residual stress distribution through the pipe wall to that calculated by analytical model. Two different weld overlay thicknesses were applied to pipe specimens using procedures that were qualified and in use for plant repairs in the U.S.

2.0 Conceptual Description of Weld Overlay Repair

The weld overlay is applied with the process fluid in the pipe to address flaws usually detected by ultrasonic examination in weld joint heat-affected zones. The weld overlay repair increases the local pipe wall thickness through deposit of weld metal 360° circumferentially and to either side of an existing butt weld.

The weld deposited band increases the local pipe wall thickness at the flawed location to meet or exceed the safety margins required by ASME Section XI. In addition, the through wall differential temperature from the welding process and the weld metal shrinkage produce a strongly compressive residual stress distribution on the inside portion of the pipe wall. This residual stress distribution limits further crack growth, and inhibits initiation of new flaws, thus limiting degradation of the repaired location.

The deposited weld metal is chosen so that a barrier of IGSCC-resistant material clads the outside of the flawed location. Weld overlays are normally applied using Type 308L duplex austenitic-ferritic weld material with delta ferrite content controlled between 5 FN and 20 FN. The as-deposited delta ferrite content is typically greater than 7.5 FN. Consequently, even if a flaw were to propagate by IGSCC through the original pipe wall, it would arrest in the weld metal.

3.0 Specimen Preparation

Three test specimens were prepared from 12-inch NPS schedule 100 type 304 pipe. The specimens were cut into specified lengths and weld ends machined. The weld preparation and counterbore geometries were consistent with those used during the construction of Georgia Power Company's Hatch units. Because the counterbore for the two units were slightly different, one half of the test specimen had a geometry for Unit 1, while the other half of the same specimen had a counterbore consistent with that used in Unit 2.

Removable end plates were fabricated with inlet and outlet connections for each end of the specimen to allow water flow through the specimen during the application of the weld overlay and the LPHSW. Strain gages and thermocouples were applied on the ID and OD surface of each specimen and prepared for the appropriate environmental conditions that were to be encountered. The instrumentation was connected to a multichannel continuous read-out recorder.

The outside surface of the pipe was then prepared for overlay and LPHSW in accordance with procedures used for the field application in actual nuclear power plants. Under this procedure overlay thicknesses were recorded, interpass temperatures were checked, surfaces were liquid penetrant tested, and delta ferrite content was measured. In addition, external measurements for axial and diametrical shrinkage were recorded after the completion of each layer. Intermittently, the test assemblies were disassembled sufficiently to take internal shrinkage data. Welding was performed using a automatic GTAW welding machine. All consumables (weld wire, argon, etc.) and interpass temperature requirements were the same as those used for field overlays. Welding parameters and the corresponding heat inputs were monitored and maintained within the same range as required during field application. For the overlays, the average calculated heat input applied during the welding was 23 kilojoules per inch of circumference (KJ/in). During the application of the LPHS weld, the heat input was 83 KJ/in.

The 0.20" overlay was made with two initial layers for intermediate layer measurement purposes. This was followed with a final layer of approximately 0.1" thickness. The length across the top of the completed overlay was 3.5" while the toe-to-toe measurement was 4". The 0.23" overlay was applied in three consecutive layers, each approximately .08" thick. For this overlay, the final length across the top was 4", while the toe-to-toe measurement was approximately 4.6". Both overlays were centered over the butt weld.

The LPHSW specimen was generated in two stages. On top of the existing surface flush butt weld, two parallel circumferential guard passes of weld metal were applied approximately .56" apart, and equal distance from the butt weld centerline. These passes served as small levies for the fluid last passes. Once the guard passes were in place the LPHSW was applied, using a high heat input of 83 KJ/in. This high heat was obtained by combining high amperage and voltage welding parameters with a very low machine travel speed.

4.0 Results

The program required input from three basic areas for overall evaluation.

4.1 Field Results

Several strain gage readings went off scale (>0.005 in/in) indicating that weld overlays produce high compressive axial and hoop stresses on the inside surface of the pipe, others confirmed the predicted high tensile axial and small compressive hoop stresses on the outside diameter near the toe of each overlay. This same general observation is true for LPHSW. It was interesting to note that the greatest portion of the residual stress shift occurred with the first overlay layer. Subsequent layers may add structural margin but do little to further increase the residual stress benefit.

Axial and diametrical shrinkage measurements recorded during the test indicated that moderate amounts of axial and diametrical shrinkages occur. The final axial shrinkages for the 0.20" thick overlay, 0.22" thick overlay, and LPHSW are .057", .080", and .073", respectively. The diametrical shrinkages were .049", .072", and .068".

4.2 Analytical Residual Stress Predictions

Using the temperatures from thermocouple readings taken during the application of weld overlays and LPHSW, through-wall residual stresses were computed using the WELDS II computer program.

Residual stresses resulting from weld overlay repairs, IHSI, or similar processes must be determined to demonstrate the efficacy of the repair or mitigation. A sufficiently favorable residual stress distribution will arrest shallow existing cracks and inhibit future crack initiation.

Residual stresses are analytically determined using a finite element approach. A model of the unrepaired geometry is developed. The estimated initial residual stress distribution, which exists as a consequence of the original component butt weld, is determined and used as an initial condition in the model. The effects of the process in question (i.g., weld overlay) are imposed on the model in a thermal transient analysis. The temperature history is iteratively calculated using an elastic-plastic thermal analysis in conjunction with the finite element model.

This temperature history is then used as input to a finite element stress calculation to iteratively calculate final residual stress distributions. The WELDS analysis predicted a distribution of compressive residual stress along the inside half of the pipe wall and a tensile residual stress on the outer half of each specimen. The beneficial ID compressive stress prediction ranged from 5 to 30 KSI.

4.3 Experimentally Determined Residual Stress Distribution

The physical measurements of through-wall residual stresses in these three specimens were performed at Argonne National Laboratory, near Chicago, IL. The approach to determining residual stress distributions consisted of instrumenting each specimen then removing full-thickness bars 63mm wide and 340mm long at four azimuthal positions. The strain changes produced by the removal of the bars indicated that the stress distributions were asymmetric. Therefore, other specimen through-wall stresses were determined from the bars cut from only one of the azimuths. Strain data was taken at each of several axial locations on either side of the butt weld within each specimen bar as material was removed by EDM and/or milling. The resultant strain relief data used to compute the through-wall stress distribution. The results of this data indicate a uniform distribution of residual stresses through the circumference of the butt weld. The interior half of the pipe wall is shown to be in significant compressive stress regime while the outer half is in tension. Representations of stress distributions are shown in Figures 1 and 2.

5.0 Discussion of Results

Both measured and predicted residual stresses from a weld overlay and LPHSW indicate that a compressive residual stress is produced on the pipe ID and through a substantial portion of the inner pipe wall. The magnitude and distribution of the residual stress can be affected by the welding process, the number of layers of overlay material, the pipe thickness, and weld joint geometry.

The differential temperature created across the pipe wall during the application of the weld overlay and LPHSW together with the normal shrinkage of the applied weld metal as it cools combine to provide a very substantial compressive residual stress on the pipe ID. The creation of a compressive residual stress at the pipe inside surface acts to inhibit the initiation of IGSCC. Further, if IGSCC should be present there is a substantial compressive residual stress field through a large portion of the inner pipe wall. This compressive residual stress field would act to inhibit further growth of IGSCC. Finally, for deep flaws, the tensile residual stress in the outer surface of the pipe is blanketed with a crack resistant material that stops any further crack growth. In those cases where crack length is short, the inner surface compressive field pins the crack such that circumferential growth is inhibited, even though some depth increase may be realized.

This test substantiated the analytical predictions of residual stress improvement for the application of weld overlays. Additionally, it showed that a major portion of the benefit achieved occurs with the initial layers of the weld overlay. Subsequent layers may add structural margin but do little to increase the benefit of residual stress.

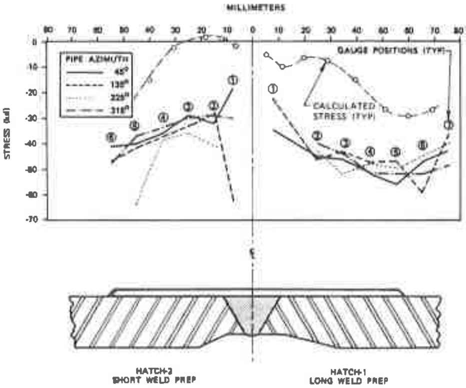

Figure 1: ID Surface Axial Residual Stress

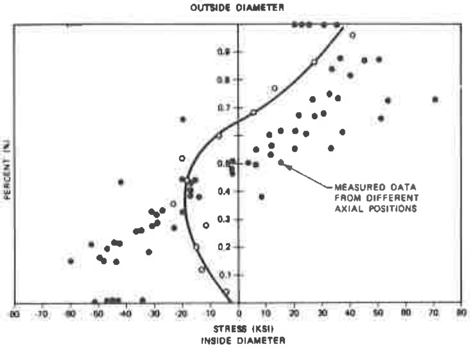

Figure 2: Through-wall Residual Stresses