ELECTRIC POWER
RESEARCH INSTITUTE

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Vice President and
Chief Nuclear Officer

March 6, 2008

PROJ 669

Document Control Desk
Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

Subject: Request for Withholding of the Following Commercial Document:

Materials Reliability Program: Development of Preemptive Weld Overlay (PWOL) for Alloy 600.PWSCC Mitigation (MRP-208)
1016252

To Whom It May Concern:

This is a request under 10 C.F.R. §2.390(a)(4) that the U.S. Nuclear Regulatory Commission ("NRC") withhold from public disclosure the information identified in the enclosed Affidavit consisting of the commercial information owned by Electric Power Research Institute, Inc. ("EPRI") identified above (the "Report"). Copies of the Report and the Affidavit in support of this request are enclosed.

EPRI desires to disclose the Report in confidence as a means of exchanging technical information with the NRC. The Report is not to be divulged to anyone outside of the NRC nor shall any copies be made of the Report provided herein. The vertical bars mark the proprietary information that has been redacted from the non-proprietary version of this document. EPRI welcomes any discussions and/or questions relating to the information enclosed.

If you have any questions about the legal aspects of this request for withholding, please do not hesitate to contact me at (650) 855-2329. Questions on the content of the Report should be directed to Christine King of EPRI at (650) 855-2605.

Sincerely,

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ELECTRIC POWER
RESEARCH INSTITUTE

AFFIDAVIT

RE: Request for Withholding of the Following Commercial Document:

Materials Reliability Program: Development of Preemptive Weld Overlay (PWOL) for Alloy 600 PWSCC Mitigation (MRP-208)
1016252

I, CHRISTIAN B. LARSEN, being duly sworn, depose and state as follows:

I am a Vice President and the Chief Nuclear Officer of Electric Power Research Institute, Inc. whose principal office is located at 3420 Hillview Avenue, Palo Alto, California ("EPRI") and I have been specifically delegated responsibility for the above-listed Report that is sought under this Affidavit to be withheld (the "Report"). I am authorized to apply to the U.S. Nuclear Regulatory Commission ("NRC") for the withholding of the Report on behalf of EPRI.

EPRI requests that the Report be withheld from the public on the following bases:

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a. The Report is owned by EPRI and constitutes commercial information which has not been placed in the public domain by EPRI.

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c. EPRI made a substantial investment of both money and employee hours over an extended period of time in the development of the Report. As a result of such effort and cost, both in terms of dollars spent and dedicated employee time, the Report is highly valuable to EPRI.

d. A public disclosure of the Report would be highly likely to cause substantial harm to EPRI's competitive position and the ability of EPRI to sell the Report both domestically and internationally. If a party does not purchase the Report from EPRI, it would require an investment of money, time and effort equivalent to that expended by EPRI for the party to duplicate the Report.

I have read the foregoing and the matters stated herein are true and correct to the best of my knowledge, information and belief. I make this affidavit under penalty of perjury under the laws of the United States of America and under the laws of the State of California.

Executed at 3420 Hillview Avenue, Palo Alto, California being the premises and place of business of Electric Power Research Institute, Inc.

March 6, 2008

C. B. L

Christian B. Larsen

Subscribed and sworn before me this day: March 6, 2008

(Please see attached California Jurat form. Y.H.)

_____, Notary Public

State of California)
County of Santa Clara)

Subscribed and sworn to (or affirmed) before me on this 6th day of March, 2008, by Christian B. Larsen, proved to me on the basis of satisfactory evidence to be the person(s) who appeared before me.

Signature _____ (Seal)

YORK HUANG
COMM. # 1596774
NOTARY PUBLIC - CALIFORNIA
SANTA CLARA COUNTY
MY COMM. EXP. JULY 31, 2009

DESCRIPTION OF ATTACHED DOCUMENT

Request for Withholding of the Following Commercial Document
TITLE OR TYPE OF DOCUMENT

ELECTRIC POWER RESEARCH INSTITUTE

Non-Proprietary Version

Materials Reliability Program: Development of Preemptive Weld Overlay (PWOL) for Alloy 600 PWSCC Mitigation (MRP-208)

1016252

Materials Reliability Program: Development of Preemptive Weld Overlay (PWOL) for Alloy 600 PWSCC Mitigation (MRP-208)

1016252

Final Report, June 2006

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Structural Integrity Associates, Inc.

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This report describes research sponsored by EPRI.

The report is a corporate document that should be cited in the literature in the following manner:

"*Development of Preemptive Weld Overlay (PWOL) for Alloy 600 PWSCC Mitigation*", EPRI, Palo Alto, CA, Product ID 1016252.

PRODUCT DESCRIPTION

The EPRI PWR Materials Reliability Program (MRP), the Mitigation Working Group of the Alloy 600 Issue Task Group (ITG) has initiated this effort to evaluate the use of a weld overlay as an available mitigation technique as remedial measure to provide resistance to PWSCC in susceptible materials.

This tasks of the program involved: Finite Element Analysis, Mockup Fabrication, Application of Preemptive Weld Overlay (PWOL), XRD and hole drilling residual stress analyses to provide measurements to compare with the FEA results, Metallography, chemical analysis and hardness testing of the mockup section, Non-destructive Examination and Inspection of the Mockup, Reporting and Documentation of the program and its results and EPRI Topical Report for Submittal to the NRC.

Results & Findings

Findings of this program are: Residual Stresses predicted by the Finite Element Analysis (FEA) are consistent with those measured by the XRD residual stress measurements, FEA is a useful tool for designing preventive weld overlays in various size piping, satisfactory levels of Cr for PWSCC resistance are present to meet the criteria in Code Case N-740 for accepting the first layer in the design of an overlay, extreme care must be taken such as using test samples for demonstrations or mockups for field applications to verify the adequacy of the welding techniques for Alloy 52 and 52 MS, current PDI qualified UT procedures have been demonstrated as adequate for identifying and sizing fabrication flaws, and metallography and hardness testing results have shown that acceptable tempering of the heat affected zones was achieved by the ambient temperature temper bead welding.

The report includes recommendations for: additional work in verifying the adequacy of current PDI qualified UT procedures for configurations similar to mockup should be done using simulated stress corrosion cracks, the development of procedures and protocols to provide guidance on mockups to verify the adequacy of welding procedures and techniques prior to their implementation in actual field activities for repair and mitigation using overlays.

Challenges & Objectives

This report is of value to technical and management personnel tasked with finding solutions and evaluating costs for mitigating components susceptible to PWSCC.

Applications, Values & Use

The report provides information to aid an Owner in evaluating mitigation in lieu of costly repair and replacements of components subject to PWSCC.

EPRI Perspective

The report contains technical information for EPRI members that would not be available to the general public given its proprietary nature from an economic perspective.

Approach

The goal of the report was to demonstrate that a PWOL could provide a change in residual stresses in susceptible nickel based alloys such as Alloy 600 and its filler materials such as Alloy 182 to mitigate crack initiation. The program included: the verification of the results of finite element analysis by physical measurements of the residual stresses in a mockup, measurements of the chemistries of the deposited layers to assess if sufficient Cr was available to make the overlay resistant to PWSCC, and to assess that the deposited overlay had was sound and had suitable micro-structures in the overlay, the heat affected zone (HAZ) and the respective base materials. Those goals were met by the results and information included in the report.

Keywords

Mitigation
PWSCC Primary Water Stress Corrosion Cracking
Weld Overlay Stress Improvement
Residual Stress Measurements
Finite Element Analysis

ABSTRACT

Preemptive weld overlay was identified as a method of adapting today's available technology of repairing PWSCC in piping with weld overlay. This program was sponsored by the MRP/EPRI to validate the analytical finite element analysis (FEA) with experimental work by evaluating residual stresses, micro-structure, hardness and chemistry of an overlaid mockup. Residual Stresses predicted by the Finite Element Analysis (FEA) are consistent with those measured by the XRD and hole drilling residual stress measurements. The results discussed above clearly demonstrate FEA is a useful tool for designing preventive weld overlays in various size piping. The experimental verification of the FEA provides a basis for the use of analysis in applications of differing pipe sizes.

Using the welding techniques to deposit the overlay, satisfactory levels of Cr for PWSCC resistance are present to meet the criteria in Code Case N-740 for accepting the first layer in the design of the overlay. Alloy 52 and 52MS are difficult materials to weld. Extreme care must be taken such as using test samples for demonstrations or mockups for field applications to verify the adequacy of the welding procedures and techniques. Metallography and hardness testing results have shown that acceptable tempering of the heat affected zones was achieved by the ambient temperature temper bead welding.

Current PDI qualified UT procedures have been demonstrated as adequate for identifying and sizing fabrication flaws. The UT examinations performed indicate current PDI qualified UT procedures may be effective for finding stress corrosion cracking (SCC) for configurations like the mockup. However additional work on simulated SCC samples is needed.

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1
INTRODUCTION

1.1 Background

Alloy 82/182 butt welds were used extensively in PWR primary coolant piping to connect dissimilar metal components, generally between stainless steel piping and low alloy steel or carbon steel components. In recent years, the dissimilar metal Alloy 82/182 bimetallic pipe to nozzle butt-welds (DMWs) have experienced cracking due to primary water stress corrosion (PWSCC).

Volumetric inspections of large diameter butt weld locations (>4" NPS) are required by ASME Code, Section XI, generally at ten-year inspection intervals. This is a very difficult inspection, and until recently (after ASME Code, Section XI, 1992 edition) the inspection techniques were not subject to the rules for inspection of welds in piping that require the procedures, equipment, and personnel to be qualified by a performance demonstration in accordance with Appendix VIII. Recent inspections with performance demonstrated techniques in accordance with Appendix VIII, as implemented through the EPRI PDI program, are more sensitive than previous methods, and generally reveal more cracking than has historically been observed. In addition, when one considers the possible existence of inside diameter (ID) repair welds in these joints from original construction, coupled with weld metal primary water stress corrosion cracking (PWSCC) crack growth rates (which are large), continued use of the ten-year ASME Code, Section XI inspection interval for unmitigated, PWSCC susceptible welds is not considered viable. In fact, the Materials Reliability Program (MRP) developed Inspection and Evaluation Guidelines (MRP-139) that include more frequent inspections than those required by the ASME Code.

1.2 Objective

Preemptive weld overlay was identified as a method of adapting today's available technology of repairing PWSCC in piping with weld overlay. This program was sponsored by the MRP/EPRI to validate the analytical finite element analysis (FEA) with experimental work by evaluating residual stresses, micro-structure, hardness and chemistry of an overlaid mockup. This experimental verification of the FEA will provide a basis for the use of analysis in applications of differing pipe sizes.

1.3 Scope of Work

Sub-Task a - Finite Element Analysis

Sub-Task b – Mockup Fabrication

Sub-Task c - Application of Preemptive Weld Overlay (PWOL)

Sub-Task d – XRD residual stress analyses to provide measurements to compare with the FEA results (Supported by EPRI).

Sub-Task e Metallography, chemical analysis and hardness testing of the mockup section (Supported by EPRI).

Sub-Task f – Examination and Inspection of the Mockup (Supported by EPRI)

Sub-Task g- Reporting and Documentation of the program and its results.

Sub-Task h-Complete and Finalize EPRI/EPRI Topical Report for Submittal to the NRC

2
TECHNICAL DISCUSSION

SI with the aid of Welding Services Inc. (WSI) designed and fabricated a mockup representing a steel Pressurizer nozzle welded to a stainless steel pipe with Alloy 82/182 filler material containing a significant weld repair on the ID. SI performed finite element analyses to determine residual stresses distribution in the mock-up and to evaluate the satisfaction of Section III design allowables. The mockup was examined by surface and UT examinations to characterize the as built mock-up. Residual stresses in the mockup were characterized non-destructively by Proto Manufacturing Ltd. under contract to EPRI using the x-ray diffraction method before and after the application of the weld overlay. Residual stresses were measured on the OD and ID surfaces. Chemistry measurements of the mockup were performed by WSI. Chemistry for each deposited overlay layer was analyzed. The initial mock up and the overlaid mockup were examined by surface and UT methods by EPRI. EPRI sectioned, examined metallographically and took hardness measurements of the mockup. A residual stress measurement by EPRI was also performed by the hole drilling method.

2.1 Finite Element Analyses

SI performed a weld overlay sizing calculations plus finite element analyses (FEA) in accordance with the mockup design specification to identify and determine key weld overlay design details to optimize/guide experimental results. SI provided a PWOL design drawing for the mockup based on these analyses (Figure 2-1). The results from the FEA of the mockup were compared with those from a prior FEA of a generic surge nozzle and found similar.

The FEA was performed using the ANSYS general purpose finite element computer software. An axisymmetric model was used for both thermal and stress analyses, as illustrated in Figure 2-2. Thermal analysis was first performed to determine the temperature response of the model to a series of lumped weld passes as they are added in sequence, followed by elastic-plastic stress analysis to calculate the residual stresses due to the temperature cycling. Heat convective boundary conditions for the thermal analysis were assumed consistent with the anticipated weld process for the mockup (water flowing on the inside of the pipe). The stress analysis assumed temperature dependent material properties and an appropriate strain hardening model. Since residual stress is a function of the welding history, stress analysis of each lumped pass was performed sequentially on top of the residual stress fields from all previously applied weld passes.

To obtain a bounding assessment of the residual stresses following preemptive weld overlays, the residual stress assessment considered, as a starting point, potential residual stresses resulting from a severe ID-surface weld repair, assumed to simulate a worst-case

repair during plant construction (magenta and green shaded region in Figure 2-2). The actual mockup included such a repair over a 90° arc of the inside surface of the dissimilar metal butt weld (Figure 2-3)

Through-wall and surface residual stress distributions were determined under two states:

1) following completion of the ID surface repair (prior to application of the PWOL)

2) following completion of the weld overlay.

Stress contour plots of the analytically predicted hoop and axial stress results for the pre- and post-overlay conditions from the FEA are shown in Figures 2-4 and 2-5, respectively. In the pre-overlay case the stresses adjacent to the weld repair in both the hoop and axial directions are highly tensile, as indicated by the green and yellow regions in the upper plots of Figures 2-4 and 2-5. After application of the PWOL, the predicted stresses in and adjacent to weld repair and the original weld are seen to be compressive in both directions (blue regions in the bottom plots of Figures 2-4 and 2-5). Comparisons of the analytically predicted versus measured axial and circumferential residual stresses, before and after the overlay, are presented in paragraph 2.4 below.

2.2 Mockup Fabrication

Welding Services (WSI), with the support of SI and input from EPRI, fabricated the surge nozzle mockup as shown in Figure 2.1. The fabrication included the Carbon Steel (CS) pipe weld prep buttered with Alloy 182, PWHT and welding of the CS pipe to SS reducer with an 82 root and 82 fill. A fabrication defect repair, about 90 degrees circumferential and 50% through weld was included in the mockup. The drawing of the mockup shown in Figure 2.5 was modified from the original design by welding a 3 in (7.62mm) CS circular plate to the 14 in (35.56mm) CS pipe to increase the restraint better simulating actual field conditions. The application of the A-182 butter would be done prior to PWHT of the 14 in (35.56 mm) pipe to plate weld. The simulated fabrication weld repair was done after the initial CS to SS weld was completed. This limits PWHT to the CS pipe to plate weld. This again simulates exposing the butter to the PWHT and the manner in which nozzle to pipe welds were done during construction. Figure 2.6 is a picture showing the mock up prior to overlaying.

2.3 Application of the Preventive Weld Overlay

An overlay was made on a test pipe with the newly modified Alloy 52MS filler from Special Metals by welding 360 degrees to demonstrate the process. The test was successful.

The welding of the overlay safe end to nozzle mockup was done with Alloy 52MS by welding 360 degrees continuously. Welding for application of the overlay was in the 2G vertical position to simulate a repair on surge nozzle. The welding was performed with the pipe filled slightly circulating water. Particular attention was utilized with regard to weld parameters and technique.

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SI provided the design drawing and FEA results to EPRI and WSI to assist in application of the PWOL and to compare with the diametrical displacement measurements to be taken by WSI at 4 azimuths, with spacing at approximately ¼ in (6.4mm) from the edge of the overlay and at two additional locations spaced in 1 in (25.4mm) increments from the initial measurement point. Measurements were taken by WSI prior to the application of the overlay and at the conclusion of each layer.

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2.4 X-Ray Residual Stress Analyses

Under a contract from EPRI, Proto Manufacturing Ltd. measured residual stresses in the mockup prior to overlay and after the mockup was overlaid. The measurements were performed using the X-ray diffraction technique (XRD).

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In summary, the analytical predictions and measured residual stresses on the inside surface of the PWOL mockup were in reasonable agreement, both showing relatively high tensile stress prior to application of the overlay (primarily attributable to the ID surface repair) and high compression after application of the weld overlay. These results confirm the effectiveness of a PWOL in reversing unfavorable residual stresses suspected of contributing to PWSCC in dissimilar metal butt welds. They also confirm the ability of axisymmetric analyses to reasonably predict residual stresses, even in the non-axisymmetric case of a 90° inside surface repair.

2.5 Examination and Inspection

The component shown in Figure 2.14 was inspected three different times during the course of this project. The first inspection, described as the pre-overlay inspection, was designed to check the integrity and cleanliness of the similar and dissimilar metal welds in this component. The second examination, described as the post-overlay inspection, was primarily done to assess cleanliness of the weld overlay. The last inspection, called the post-EDM inspection, was designed to determine if EDM notches contained within the dissimilar metal weld (DM weld) could be accurately detected and sized from the outside surface of the component. The techniques used in inspecting the overlay configuration were similar to those outlined in the PDI Qualified Generic Procedure, PDI-UT-8 but were performed using an automated system.

The techniques described in PDI-UT-8 Revision B procedure were used and are as follows:

1) Zero degree scan-The purpose of this scan is to detect any fabrication related defects in the weld material and to assure that adequate bonding is achieved between the base material and the applied weld material.

2) 70 Degree RL-This search unit is scanned in both the axial and circumferential directions in an effort to detect any planar flaws in the weld overlay material such as inner bead lack of fusion or cracking.

3) Outside Surface Creeping wave search unit- This search unit is scanned in both the axial and circumferential directions for the same reason as the 70 degree RL but is designed to evaluate defects that may be very close to the outside surface.

4) 45 and 60 Degree RL search units- These search units is scanned in both the axial and circumferential direction in an effort detect and size flaws located in the original weld or base material.

2.5.1 Examination of the Mockup

The examination of the mockup was performed by EPRI. The main purpose of the examination was to evaluate the overall cleanliness of the weld to determine if any significant defects were present that would have made the sample unusable for its intended purpose, and if any defects were present to characterize them and provide a baseline prior to application of the overlay. EPRI conducted the examination using 45, 60 and 70 degree longitudinal search units in the axial direction looking for circumferential defects located within the weld or adjacent base material. The scans were limited due to the presence of the weld crown. EPRI determined that there is reasonable assurance the examinations would have detected any significant defects. In addition, examinations were conducted using 45 degree shear wave search units skewed into the weld from all accessible base material. Circumferential scanning was also limited due to the presence of the crown. The first exam of the component, without the overlay, showed that both the similar and dissimilar welds were free of any welding defects throughout the volume of the weld.

2.5.2 Examination of the Overlaid Mockup

After the overlay was applied to the mock-up EPRI performed detailed examination of both the weld overlay and the base material below the weld overlay to depth of at least the upper 50% of the original base material a weld. The techniques used were identical to the techniques described in the PDI Generic procedure PDI-UT-8 Revision B. Data was collected with an automated imaging system for ease of evaluation and to provide the original UT data for inclusion in the report.

The result of the examination is as follows:

The exam, after the overlay was in place, showed there to be numerous welding flaws throughout the volume of the overlay; but seemed to be more concentrated at the weld overlay interface. These indications greatly impacted the propagation of sound into the base material and weld of the original component.

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In addition one flaw was ultrasonically sized so that a comparison could be made with metallographic sizing. This planar flaw was sized as 0.14" high, 0.57" wide and 2.36" long. While this flaw was characterized to be planar, it could also be detected with the 0 degree search unit for at least a portion of the length. This search unit was used to estimate the width of the flaw and the angle beam search units were used to measure the depth and length. A comparison of the UT and physical sizing is found in Section 2.6.2 below.

2.5.3 Jagged EDM Notches

A set of jagged EDM notches were machined in the mockup after the overlay was applied to facilitate evaluation of the examination coverage and provide some reflectors to allow an evaluation of the technique for this thinner overlay and extended examination volume. All of the intended simulated defects were measured and the size accuracy was evaluated against Appendix VIII Supplement 11 acceptance criteria.

After the welding flaws were mapped EDM notches were placed into the mock-up avoiding areas that contained welding defects. The flaw layout is shown in Figure 2.17. Because of the density of the welding flaws the EDM notches were only placed in DM weld in areas that are known to be susceptible to stress corrosion cracking. The post EDM ultrasonic examination results indicated that the flaws were detected and sizing was possible. In Figure 2.18 the fingerprint sheet used to compare as built dimensions to the ultrasonic data is shown with the deviations shown at the bottom.

2.5.4 Summary

The results of evaluation indicate that the conventional techniques have been successful for detecting and sizing fabrication induced flaws in this configuration if corrections are made for curvature and the taper. The fabrication induced actual welding flaws were readily detected and sized. The UT sizing of the width of the flaw was somewhat larger than the actual flaw size due to the presence of other adjacent flaws in close proximity to this flaw that could not be separated in the ultrasonic image. Nonetheless the UT detection and sizing is considered adequate and conservative.

The results of this evaluation while promising should be considered a first step in determining if actual stress corrosion cracks can be reliably detected and sizing in this configuration at depths up to 50% of the original component thickness. Actual stress corrosion cracks are known to be much tighter and harder to detect and size than EDM notches and thus EDM notches should not be used to draw absolute conclusions. If research continues in this area, actual simulated stress corrosion cracks should be used to determine the actual capabilities of the technique for service induced stress corrosion cracks.

2.6 Chemical Analyses, Metallography and Micro-hardness Testing

2.6.1 Chemical Analyses

In order to obtain information regarding the (Cr) content of the overlay layers, X-ray fluorescence (XRF) measurements were taken with a Niton XLP-868 alloy analyzer at 16 points (4 different locations axially and azimuthally) of the first layer deposited. The Cr content of the first layer varied between 28.15 and 29.29 %. The chemistries over the carbon and stainless are shown by layer in Tables 2.1 and 2.2. The measured Cr content is sufficient to be resistive to PWSCC and would be acceptable to be counted as a first

layer of the overlay in accordance with the requirements of draft ASME Code Case N-740.

2.6.2 Metallography

The completed mockup in the as welded condition is shown in Figure 2.19. Figure 2.20 shows the mockup after final surface preparation prior to shipping. Samples were removed from the mockup for metallography at three locations containing: 1) The carbon steel/overlay interface, 2) The butter/overlay location and 3) The end of the overlay on the SS pipe. Figure 2.21 is a photo of a macro section of the 45 degree location showing the original weld, the weld overlay, the butter and the base materials. The microstructure observed at the 3 locations was as expected for the base materials, the overlay and the heat affected zones. The welding flaws identified by the ultrasonic examinations were confirmed by the metallography. Examples of two locations in the overlay showing lack of bond between beads in the overlay are shown in Figure 2.22. The extent of the welding defects was not sufficient to affect the residual stresses or to preclude implanting some UT reflectors in a portion of the mockup for future use.

Since some fabrication flaws were found in the mockup, one defect was evaluated metallographically for size to allow comparison with UT flaw characterization. The overlay mockup was sectioned at the similar weld location, shown in Figure 2.23 to determine the height, width and circumferential length of the defect. Five sections approximately .600 in (15.2 mm) wide were removed from this region starting at ~48^0 and ending at ~80^0. The samples were labeled 0, 1, 2, 3 and 4. Each cross section was mounted on the surfaces illustrated in Figure 2.24 and Figure 2.25. The specimens were polished to establish flaw locations and dimensions. The cross sections were incrementally ground and polished to a depth of 0.20 in (5.1 mm). Photographs were taken at the surface and at seven depths to 0.20 in (5.1mm). The width, height and distance from the SS substrate were measured at depth to allow the fluctuation in the flaw size to be recorded.

Flaw 1 shown in Figure 2.26 and Figure 2.27 was measured for height and width along the direction of weld travel. Figure 2.26 shows orientation of height and width of the defect at one location. Figure 2.27 shows the distance of the defect from the SS pipe substrate and overlay interface. Figure 2.28 and Figure 2.29 show the fluctuation of the flaw height and width vs. circumferential length of the flaw.

The maximum flaw height was determined by metallography to be 0.103 in (02.6 mm) at 75-degree azimuth location. The average height of this flaw was approximately 0.050 (01.3 mm) in. The overall length of the flaw was determined to be approximately 2.5 (63.5 mm) in. The defect initiated near the 48-degree azimuth and terminated at the 80-degree azimuth. The maximum flaw width was determined to be 0.054 (01.3 mm) in at the 50-degree azimuth location. The average width of the defect was approximately 0.024 (0.65 mm).

Table 2-8 contains the comparison of the metallographic measurements as compared to the UT measurements. With the exception of the width measurement, it appears that the ultrasonic techniques used provided an accurate assessment of the actual flaw dimensions. After further evaluation of the data, it appears that additional flaws were present in close proximity of the flaw measured, but a slightly different depths (±0.040'). The ultrasonic techniques used for evaluation do not have the resolution required to separate these closely spaced flaws from one another, so the width reported is believe to be the combination of more than one flaw.

2.6.3 Micro-Hardness Testing

Micro-hardness measurements were performed on the cross section of the weld overlay mockup. An Instron Model Tukon 2100 was used for all measurements with hardness values reported in Vickers (HV0.5). The hardness values were measured at the dissimilar weld location to encompass the weld root and OD at the 182 butter interface with the CS pipe material, and in an area below the 52 PWOL overlay interface with the CS pipe material.

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Hardness values in the 182 butter averaged around 210 Vickers. The hardness values demonstrate the HAZ is adequately tempered.

2.7 Hole Drilling Residual Stress Measurements

The effect of residual stresses due to application of a welded overlay was a primary focus for these tests. One of the key goals for this work was to prove the feasibility of establishing the inspectability while minimizing residual stress. Since tensile residual stress is one of the three factors in static component failures (the other two are accepted as material susceptibility and aggressive environment), cursory examinations were made to try and determine what level of residual stress is present or induced from welding.

An experimental technique was employed to obtain quantitative information regarding relative stresses of the original fabrication weld and weld overlay. The experimental technique utilized electrical resistance strain gages and a blind hole drilling technique described in ASTM-E837. This technique, in brief, is performed as follows:

- Prepare the surface area of interest, removing minimal material.
- Epoxy the strain gage rosette to the substrate.
- Calibrate the rosette output to zero strain.
- Drill a hole through the center of the rosette using a low stress technique.
- Read the change in strain caused by metal relaxation.

Principal stresses can then be calculated based on the change in strain.

The procedures used for the strain gage application are outlined by Measurements Group Inc. in their Technical Bulletins and were used consistently throughout the project. The drilling was done with a high speed "dentist drill" as opposed to using the air abrasive method. This method provided greater speed and required less preparation and cleanup. Previous "round robin" studies performed at the EPRI NDE Center have shown that more consistent results are obtained with the drill technique.

It was necessary to develop some means of ensuring proper alignment of the drill in relation to the rosette when working within the radiused component. The drill must be centered over the rosette and it also must be perpendicular to the rosette. This prevents "drilling under" one gage element and influencing the response of that element more than other gage elements. This requirement was accomplished by implementing an optical alignment system utilizing a Helium Neon LASER to ensure the requisite perpendicularities as shown in Figure 2-14.

The LASER is first positioned into the drilling fixture and illuminated. The incident beam that strikes the rosette is reflected back at some angle. The reflected beam then strikes the surface of the LASER fixture. While observing this reflected beam, adjustments can be made to the fixture until the incident and reflected beams are in alignment. This procedure is repeated until perpendicularity is assured.

Measurements were evaluated by monitoring the strain released from sectioning the mockup and by performing a hole drilling measurement. By applying a gage to the mockup prior to saw cutting we are able to monitor released strain once the piece has been fully parted. Then using the same gage we were able to perform a hole drilling measurement in the same location to acquire total combined stresses.

Sectioning and hole drilling strain measurements indicate a combined stress of -14.8 ksi in the hoop direction and -23.7 ksi in the axial direction. These values approximate the post overlay stresses as modeled via Finite Element Analysis and the previously reported XRD measurements.

These measurements are likely to be far more compressive if the overlay is applied to a component that has not been repaired. Past experience indicates that manual repair welds induce significantly higher stresses relative to machine welds.

Layer 1	Location
Chemistry	Content deleted – EPRI/MRP Proprietary Information
Cr	
Ni	
Fe	
Mn	
Nb	
Layer 2	**Location**
Chemistry	Content deleted – EPRI/MRP Proprietary Information
Cr	
Ni	
Fe	
Mn	
Nb	
Layer 3	**Location**
Chemistry	Content deleted – EPRI/MRP Proprietary Information
Cr	
Ni	
Fe	
Mn	
Nb	
Layer 4	**Location**
Chemistry	Content deleted – EPRI/MRP Proprietary Information
Cr	
Ni	
Fe	
Mn	
Nb	

Table 2-1
Weld Deposit Chemistries (Performed over the Carbon Steel) after each weld layer

Layer 1	Location
Chemistry	Content deleted – EPRI/MRP Proprietary Information
Cr	
Ni	
Fe	
Mn	
Nb	
Layer 2	**Location**
Chemistry	Content deleted – EPRI/MRP Proprietary Information
Cr	
Ni	
Fe	
Mn	
Nb	
Layer 3	**Location**
Chemistry	Content deleted – EPRI/MRP Proprietary Information
Cr	
Ni	
Fe	
Mn	
Nb	
Layer 4	**Location**
Chemistry	Content deleted – EPRI/MRP Proprietary Information
Cr	
Ni	
Fe	
Mn	
Nb	

Table 2-2
Weld Deposit Chemistries (Performed over the Stainless Steel) after each weld layer

Distance from top of flange (inch)	Circumferential Orientation	1st layer delta (inch)	2nd layer delta (inch)	3rd layer delta (inch)	4th layer delta (inch)	Final layer delta (inch)
at 3.25	Content deleted – EPRI/MRP Proprietary Information					
at 4.25						
at 5.25						
at 11.125						
at 12.125						
at 13.125						

Table 2-3
Inside Diameter Shrinkage Measurements (delta measurements) at Axial and Azimuth Locations Identified

Note: 1 in = 25.4 mm

Azimuth	1st layer delta (inch)	2nd layer delta (inch)	3rd layer delta (inch)	4th layer delta (inch)	Final layer delta (inch)
45	**Content deleted – EPRI/MRP Proprietary Information**				
135					
225					
315					

Table 2-4
Axial Shrinkage Measurements (delta measurements) on the OD at Azimuth Locations Identified.

Note: 1 in = 25.4mm

Distance from top of flange (inch)	Circumferential Orientation	1st layer delta (ksi)	2nd layer delta (ksi)	3rd layer delta (ksi)	4th layer delta (ksi)
at 3.25	0-180	Content deleted – EPRI/MRP Proprietary Information			
	45-225				
	90-270				
	135-315				
at 4.25	0-180				
	45-225				
	90-270				
	135-315				
at 5.25	0-180				
	45-225				
	90-270				
	135-315				
at 11.125	0-180				
	45-225				
	90-270				
	135-315				
at 12.125	0-180				
	45-225				
	90-270				
	135-315				
at 13.125	0-180				
	45-225				
	90-270				
	135-315				

Table 2-5 Residual Stresses Calculated from Shrinkage Measurements after Weld Overlay

Note: 1 in = 25.4 mm 1 KSI = 6.89 Mega Pascal

SS Location @ 90° OD				
	Axial Stress (KSI)		Hoop Stress (KSI)	
Location	Before (value;±)	After (value;±)	Before (value;±)	After (value;±)
(7.00")	**Content deleted – EPRI/MRP Proprietary Information**			
(7.20")				
(7.40")				
SS Location @ 270° OD				
Location	Before (value;±)	After (value;±)	Before (value;±)	After (value;±)
(7.00")	**Content deleted – EPRI/MRP Proprietary Information**			
(7.20")				
(7.40")				
Dissimilar Weld Location @ 45° OD				
Location	Before (value;±)	After (value;±)	Before (value;±)	After (value;±)
Weld Centerline	**Content deleted – EPRI/MRP Proprietary Information**			
Center of Butter				
0.4" from Butter				
Dissimilar Weld Location @ 135° OD				
Location	Before (value;±)	After (value;±)	Before (value;±)	After (value;±)
Weld Centerline	**Content deleted – EPRI/MRP Proprietary Information**			
Center of Butter				
0.4" from Butter				

Table 2-6 Measured OD Surface Residual Stresses (XRD Results) Pre- and Post-Overlay

Note: 1 in = 25.4 mm 1 KSI = 6.89 Mega Pascal

SS Location @ 90° ID				
	Axial Stress (KSI)		Hoop Stress (KSI)	
Location	Before (value;±)	After (value;±)	Before (value;±)	After (value;±)
(7.00")	**Content deleted – EPRI/MRP Proprietary Information**			
(7.20")				
(7.40")				
SS Location @ 270° ID				
Location	Before (value;±)	After (value;±)	Before (value;±)	After (value;±)
(7.00")	**Content deleted – EPRI/MRP Proprietary Information**			
(7.20")				
(7.40")				
Dissimilar Weld Location @ 0.015", 45°, ID				
Location	Before (value;±)	After (value;±)	Before (value;±)	After (value;±)
5.1	**Content deleted – EPRI/MRP Proprietary Information**			
5.5				
5.9				
6.32				
Dissimilar Weld Location @ 0.015", 135°, ID				
Location	Before (value;±)	After (value;±)	Before (value;±)	After (value;±)
5.1	**Content deleted – EPRI/MRP Proprietary Information**			
5.5				
5.9				
6.32				
Dissimilar Weld Location @ 0°, ID				
Location	Before (truncated)	Before (as meas.)	Before (truncated)	Before (as meas.)
5.1	**Content deleted – EPRI/MRP Proprietary Information**			
5.5				
5.9				
6.32				
Dissimilar Weld Location @ 90°, ID				
Location	Before (truncated)	Before (as meas.)	Before	After
5.1	**Content deleted – EPRI/MRP Proprietary Information**			
5.5				
5.9				
6.32				

Note: nm = not measured

Table 2-7 Measured ID Surface Residual Stresses (XRD Results) Pre- and Post-Overlay

Note: 1 in = 25.4 mm 1 KSI = 6.89 Mega Pascal

UT Measured Length	Metallographic Results (Length)	Delta	UT Measured (Depth)	Metallographic Results (Depth)	Delta	UT Measured (Width)	Metallographic Results (Width)	Delta
2.36"	2.5	-0.14"	0.14"	0.103"	0.037"	0.56"	0.054"	0.506"

Table 2-8 Comparison of Ultrasonic and Metallographic Measurements

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Figure 2-1
Drawing of Mockup and Overlay

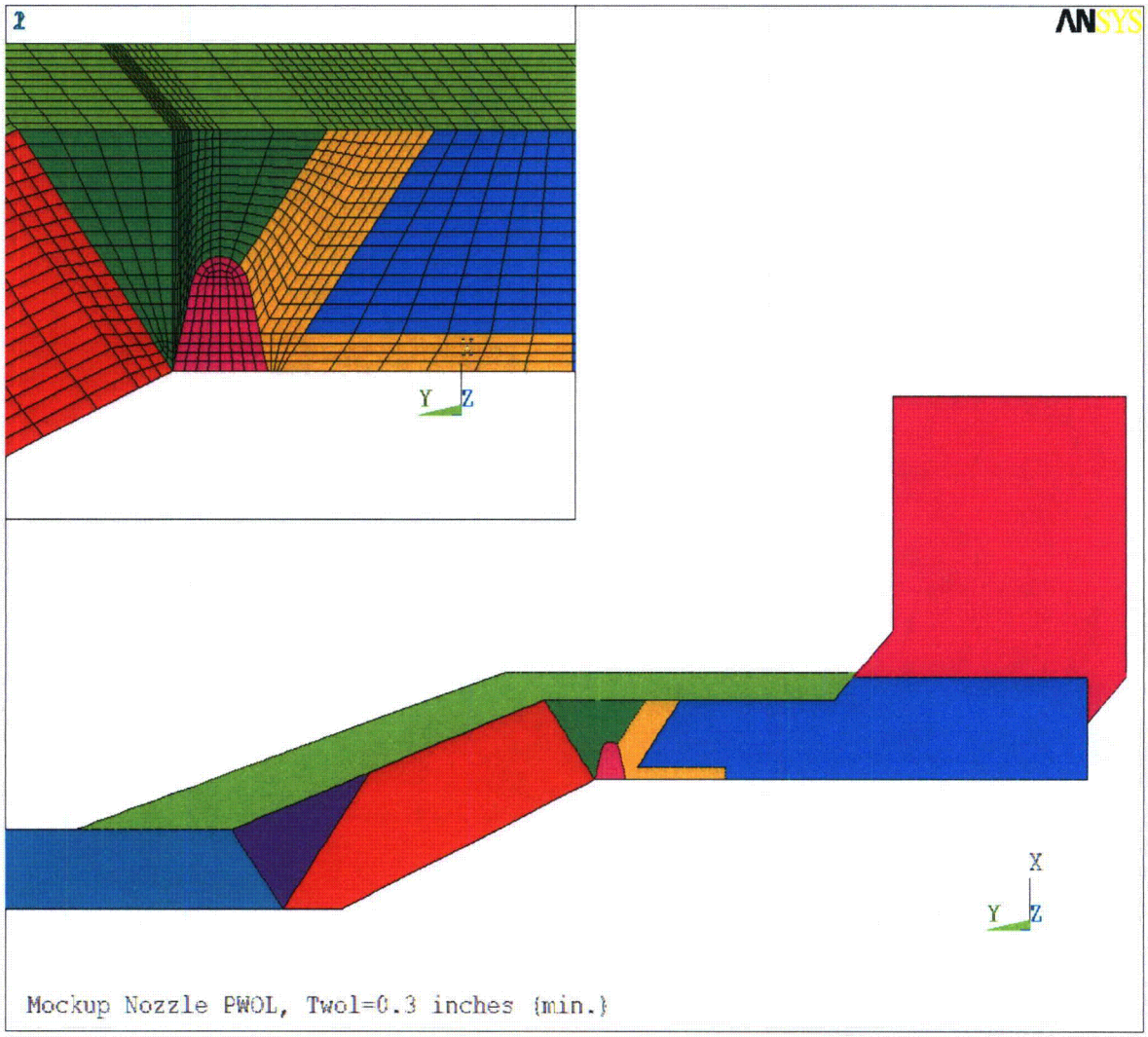


Figure 2-2
Actual FEA Model Initially used for the Mockup

Note: 1 in = 25.4 mm 1 KSI = 6.89 Mega Pascal

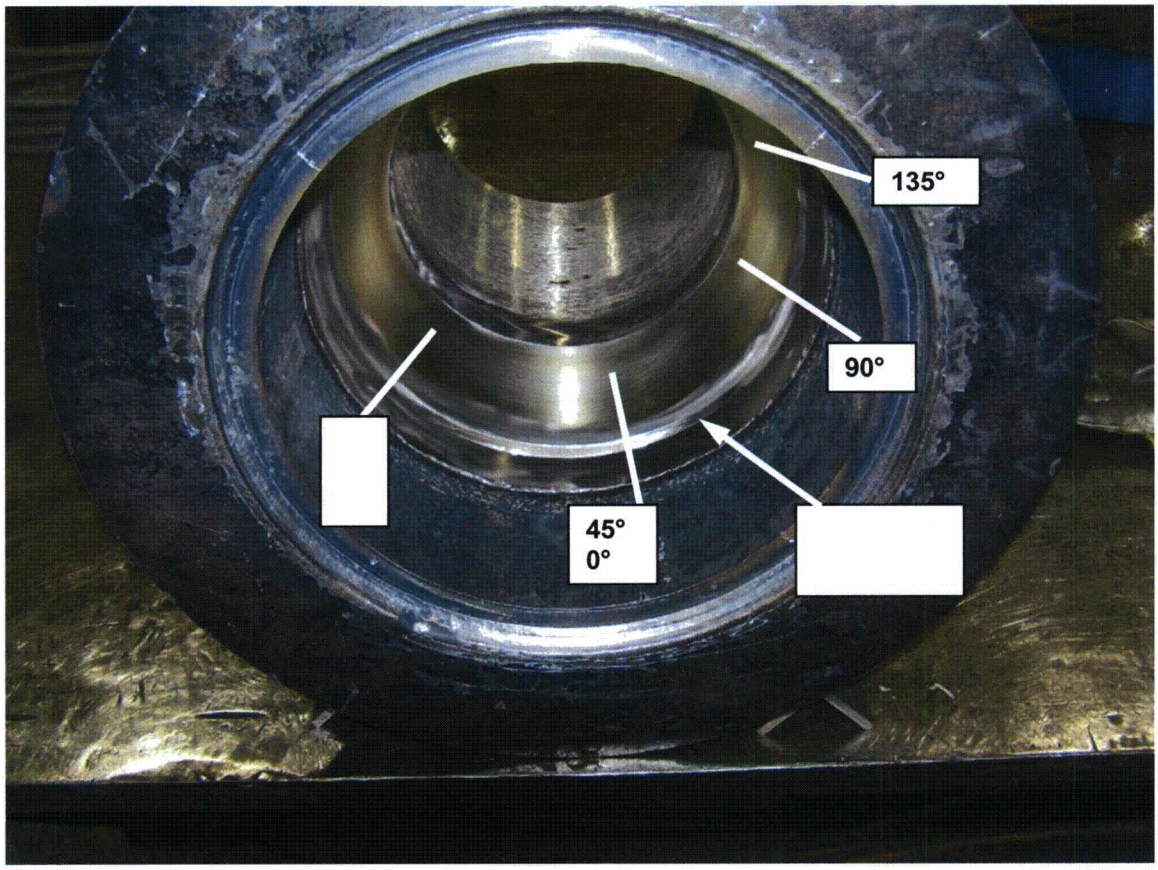
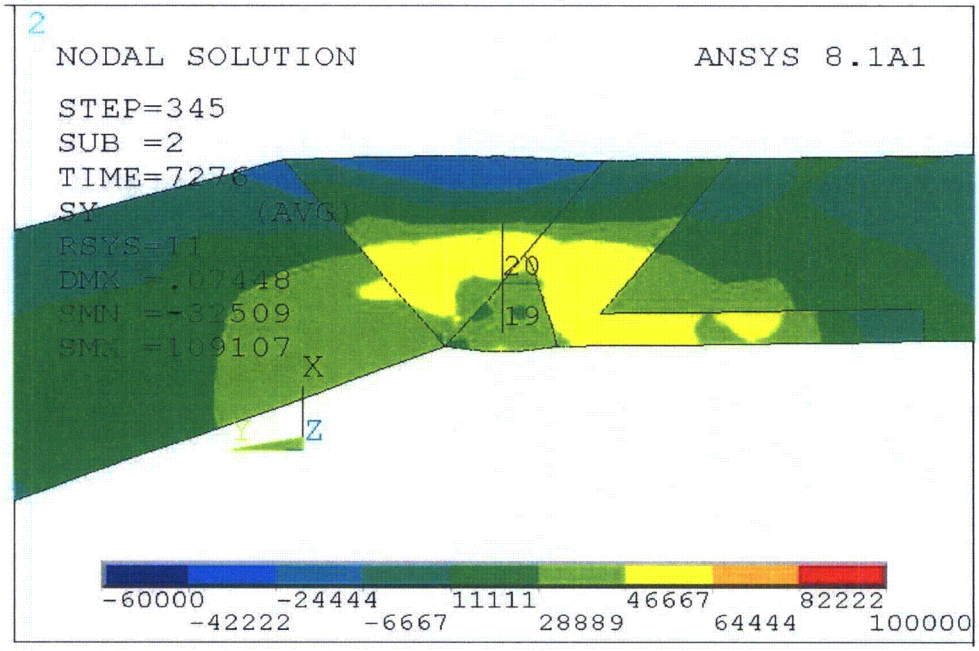
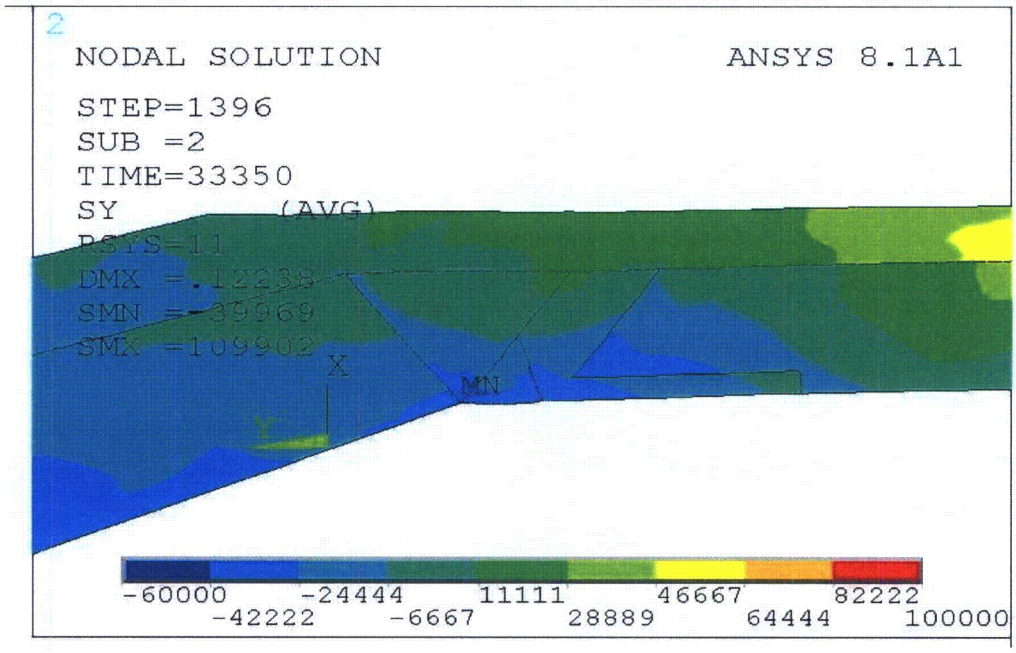


Figure 2-3
Photo of the Inside Surface of PWOL Mockup showing Simulated

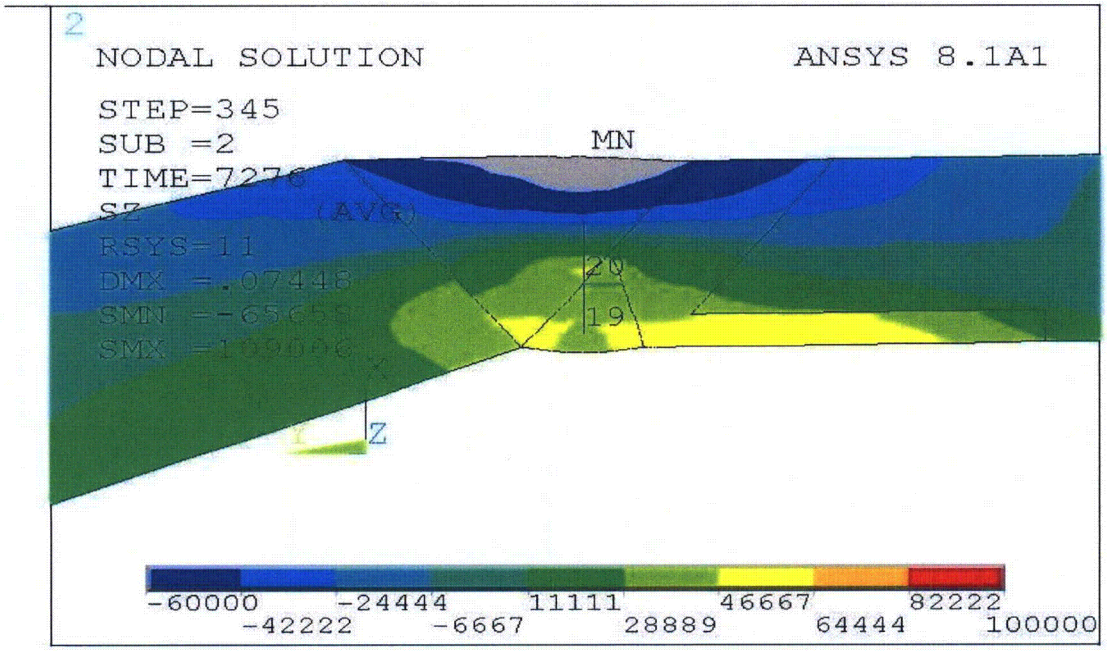


Pre-PWOL Note: 1 in = 25.4 mm 1 KSI = 6.89 Mega Pascal

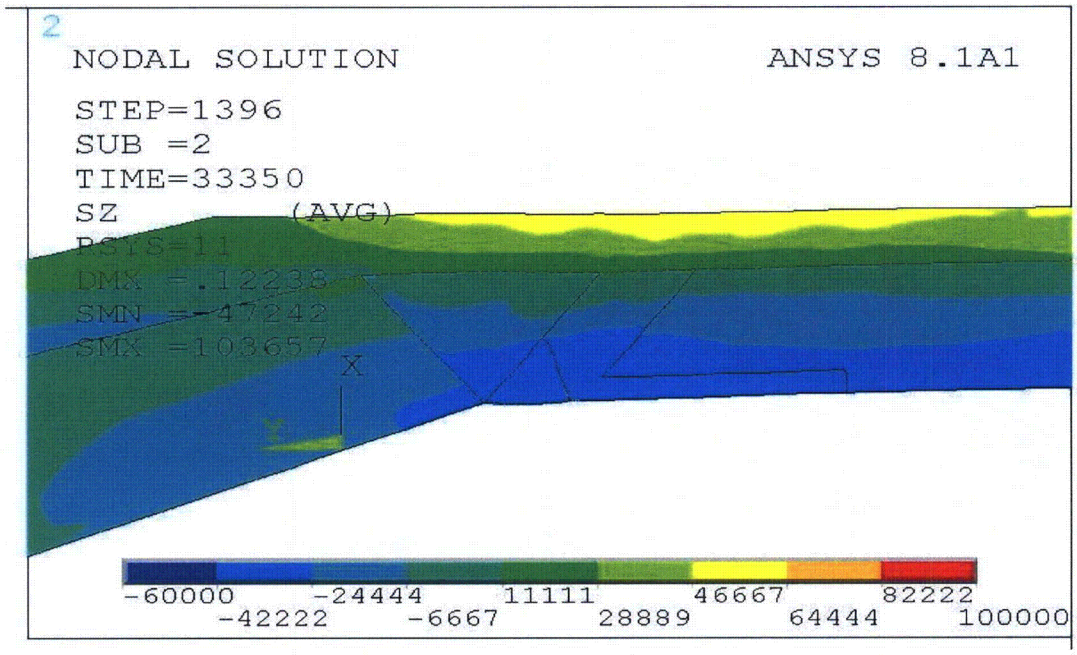


Post-PWOL Note: 1 in = 25.4 mm 1 KSI = 6.89 Mega Pascal

Figure 2-4
Hoop Stress Results



Pre-PWOL Note: 1 in = 25.4 mm 1 KSI = 6.89 Mega Pascal



Post-PWOL Note: 1 in = 25.4 mm 1 KSI = 6.89 Mega Pascal

Figure 2-5
Axial Stress Results

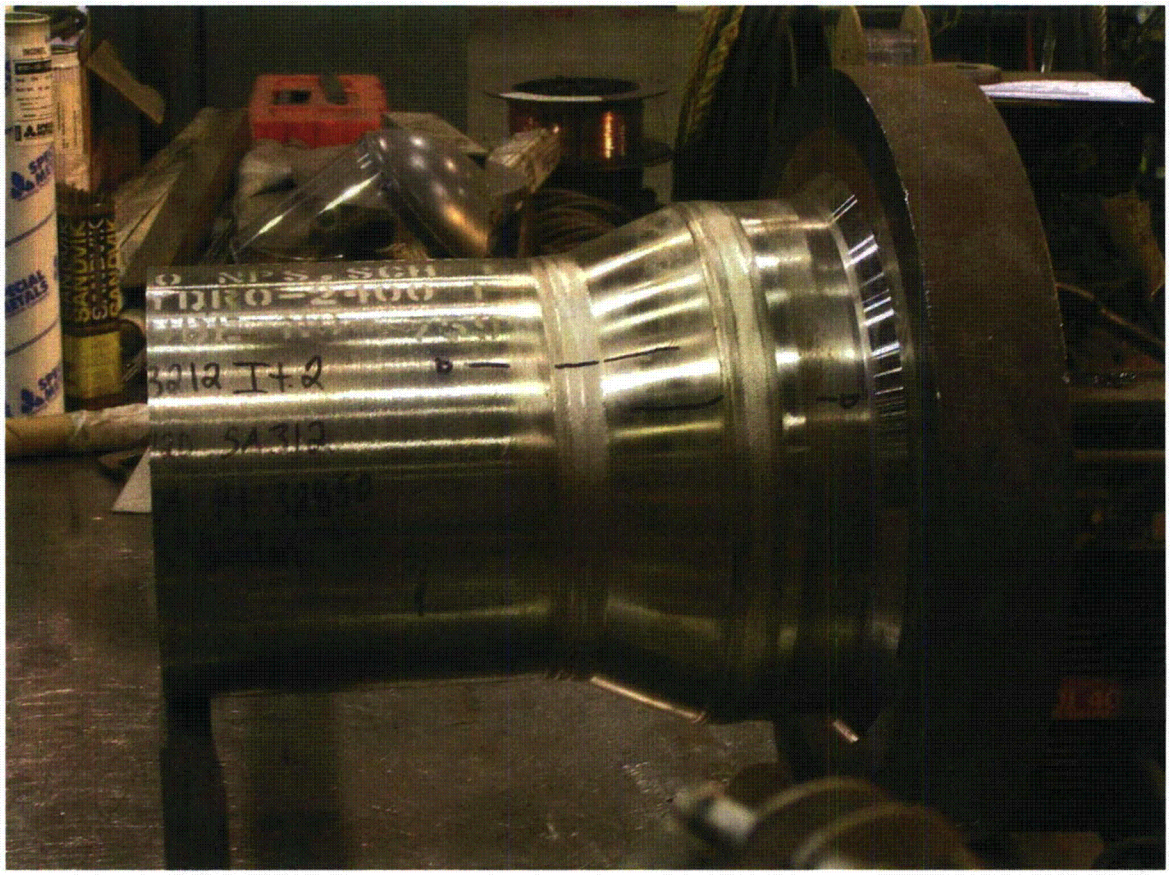


Figure 2-6
Photograph Showing the Actual Mockup Prior to Overlaying

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Figure 2-7
Sketch Showing Location of Residual Stress Measurements near the Dissimilar Weld Prior to Overlay Note: Measurements from end of CS pipe for ID and from end of CS Ring for OD. All measurements are approximate.

Note: 1 in = 25.4 mm

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Figure 2-8
Sketch Showing Location of Residual Stress Measurements near the Stainless Steel Weld Prior to Weld Overlay Note: Measurements from end of SS pipe for ID and OD

Note: 1 in = 25.4 mm

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Figure 2-9
Sketch Showing Azimuthal Locations of XRD Residual Stress Measurements

Note: 1 in = 25.4 mm

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Figure 2-10
Plot of the Inside Surface Axial Residual Stresses, Pre-Overlay - Analysis versus Measurements

Note: 1 in = 25.4 mm 1 KSI = 6.89 Mega Pascal

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Figure 2-11
Plot of the Inside Surface Axial Residual Stresses, Post-Overlay - Analysis versus Measurements

Note: 1 in = 25.4 mm 1 KSI = 6.89 Mega Pascal

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Figure 2-12
Plot of the Inside Surface Hoop Residual Stresses, Pre-Overlay - Analysis versus Measurements

Note: 1 in = 25.4 mm 1 KSI = 6.89 Mega Pascal

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Figure 2-13
Plot of the Inside Surface Hoop Residual Stresses, Post-Overlay - Analysis versus Measurements

Note: 1 in = 25.4 mm 1 KSI = 6.89 Mega Pascal

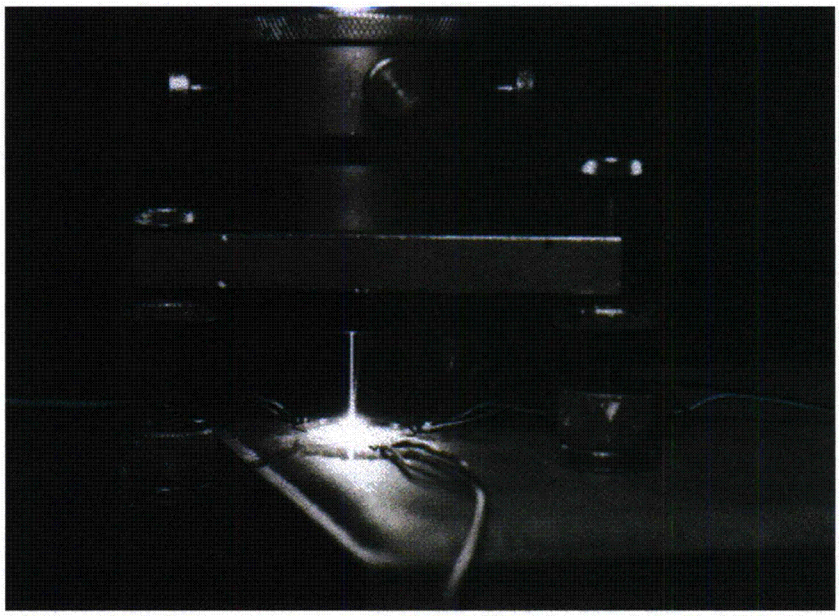

Figure 2-14
Laser alignment of strain gage drill

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Figure 2-15
Tomoview Data Showing the Weld Flaws

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Figure 2-16
Distribution of weld defects

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Figure 2-17
Flaw Layout for Jagged EDM Notches (As seen looking from Pipe to Nozzle)

Note: 1 in = 25.4 mm

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Figure 2-18
Fingerprint Data Sheet for post overlay notches.

Figure 2-19
Photo Showing the Finished Mockup in the As-Welded Condition

Figure 2-20
Photo Showing the Finished Mockup Ready for Shipment

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Figure 2-21
Photo of the Macro Section at the 45 Degree Location Showing the Buttering, Original Weld, the Weld Repair and the Base Materials

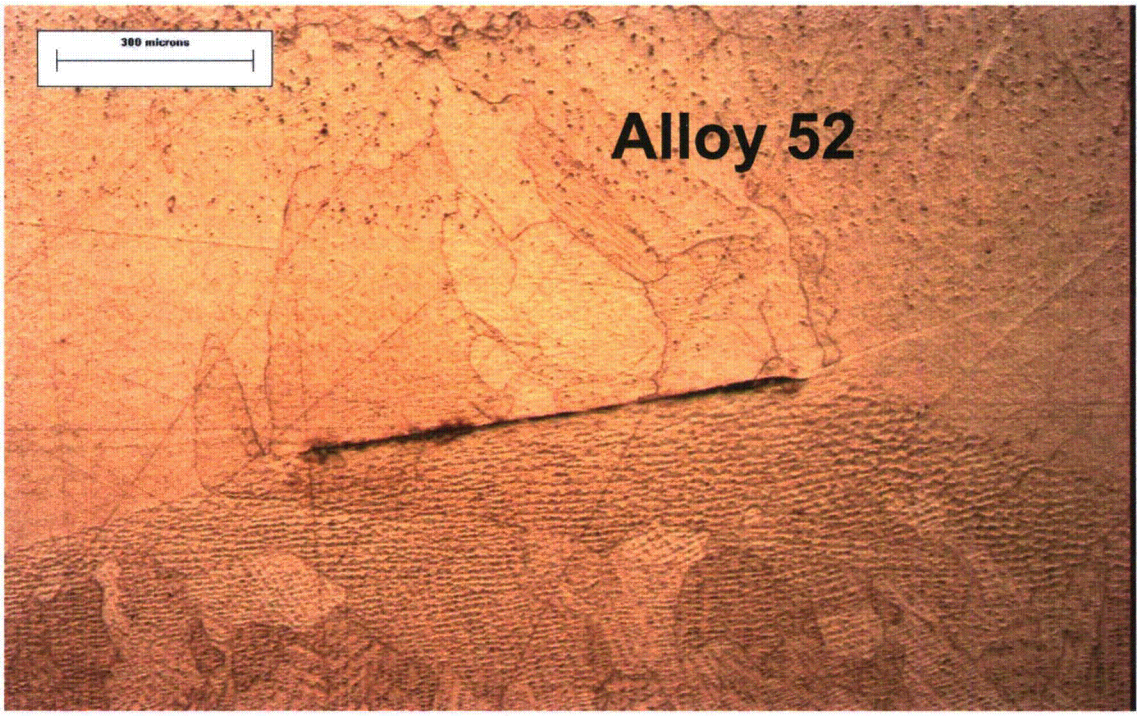

Figure 2-22
Photomicrographs Showing Examples of Lack of Bond Between the Deposited Layers

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Figure 2-23
Location of the Flaw Shown in the Hatched Area in the Overlay Directly above the Similar Metal Weld. (The approximate size of mounted cross section is designated by the green hatched area)

Note: 1 in = 25.4 mm

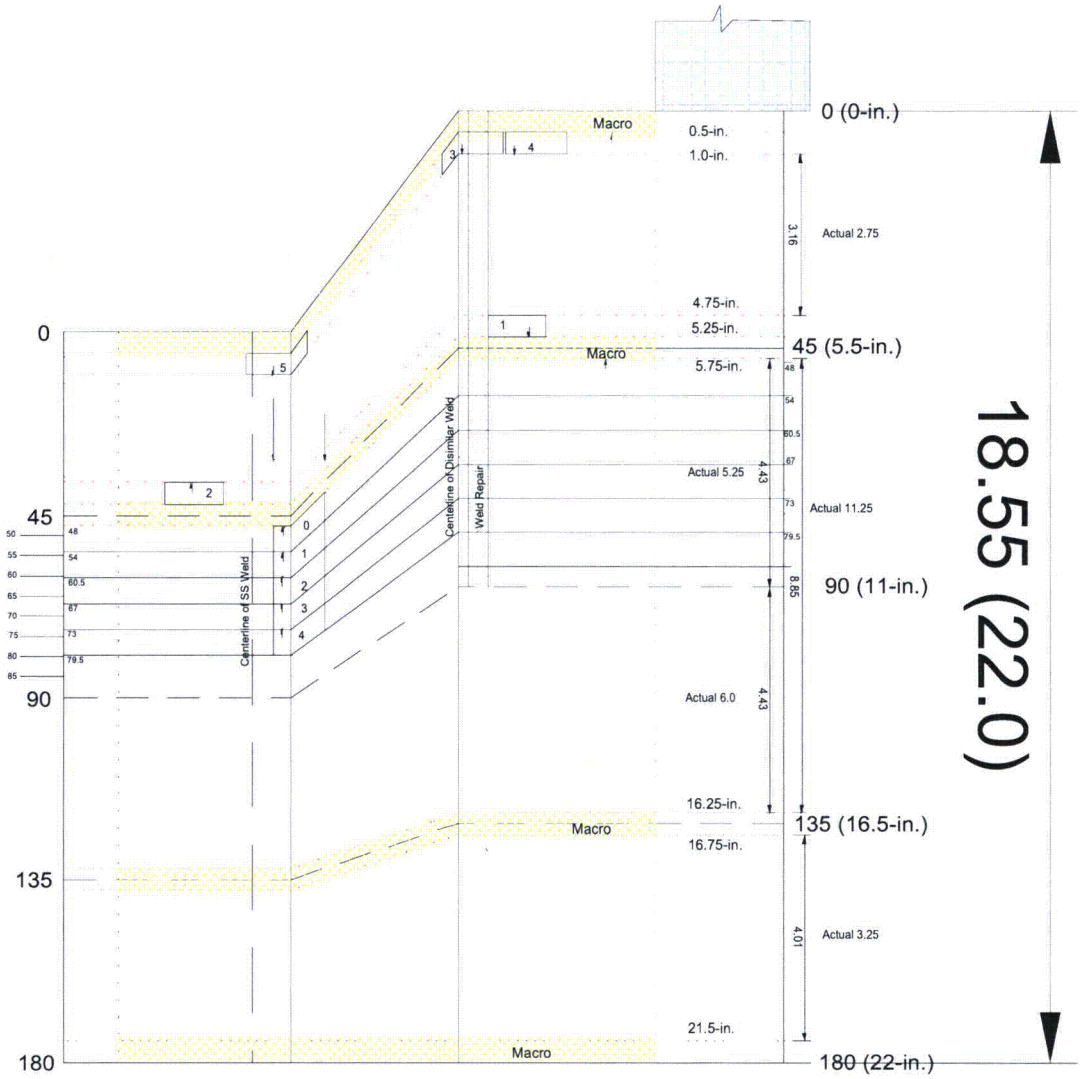

Figure 2-24
Roll Out of the 0 to 180 Degree Region of the Mockup (Flaw chase is shown as sample 0, 1, 2, 3, and 4, between the 45 and 90 azimuth)

Note: 1 in = 25.4 mm

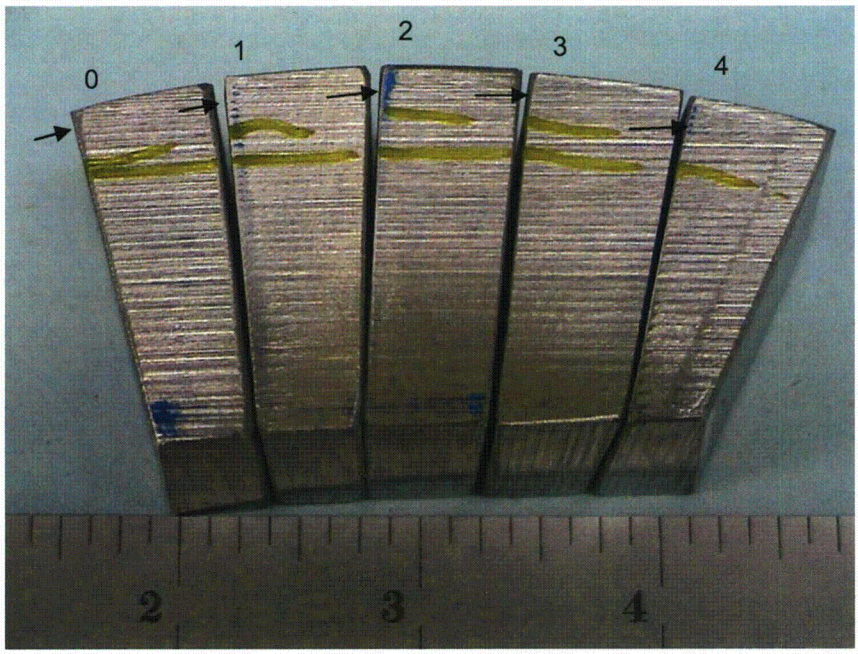

Figure 2-25
Specimens 0, 1,2,3,4 Removed from the PWOL Mockup (Arrows show the side mounted)

Note: 1 in = 25.4 mm

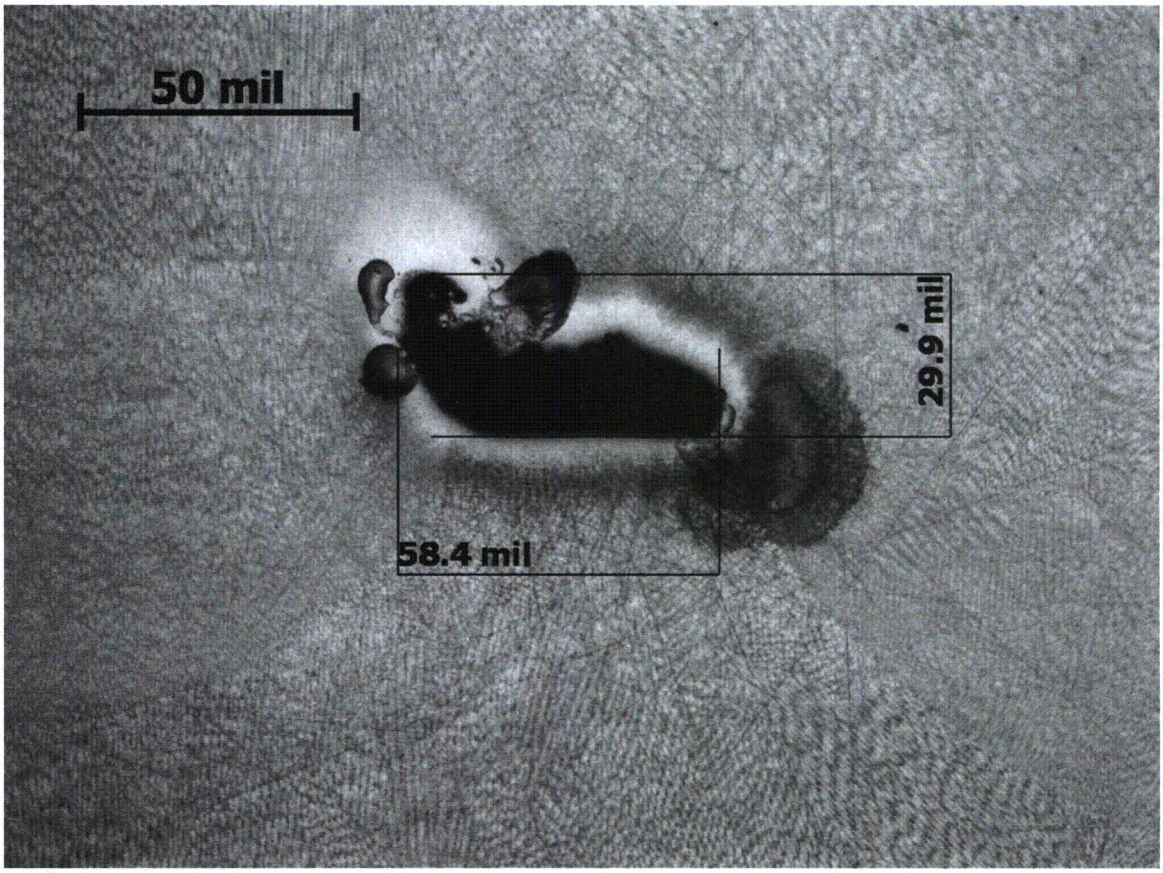

Figure 2-26
Example of Height and Width of Defect 1

Note: 1 in = 25.4 mm

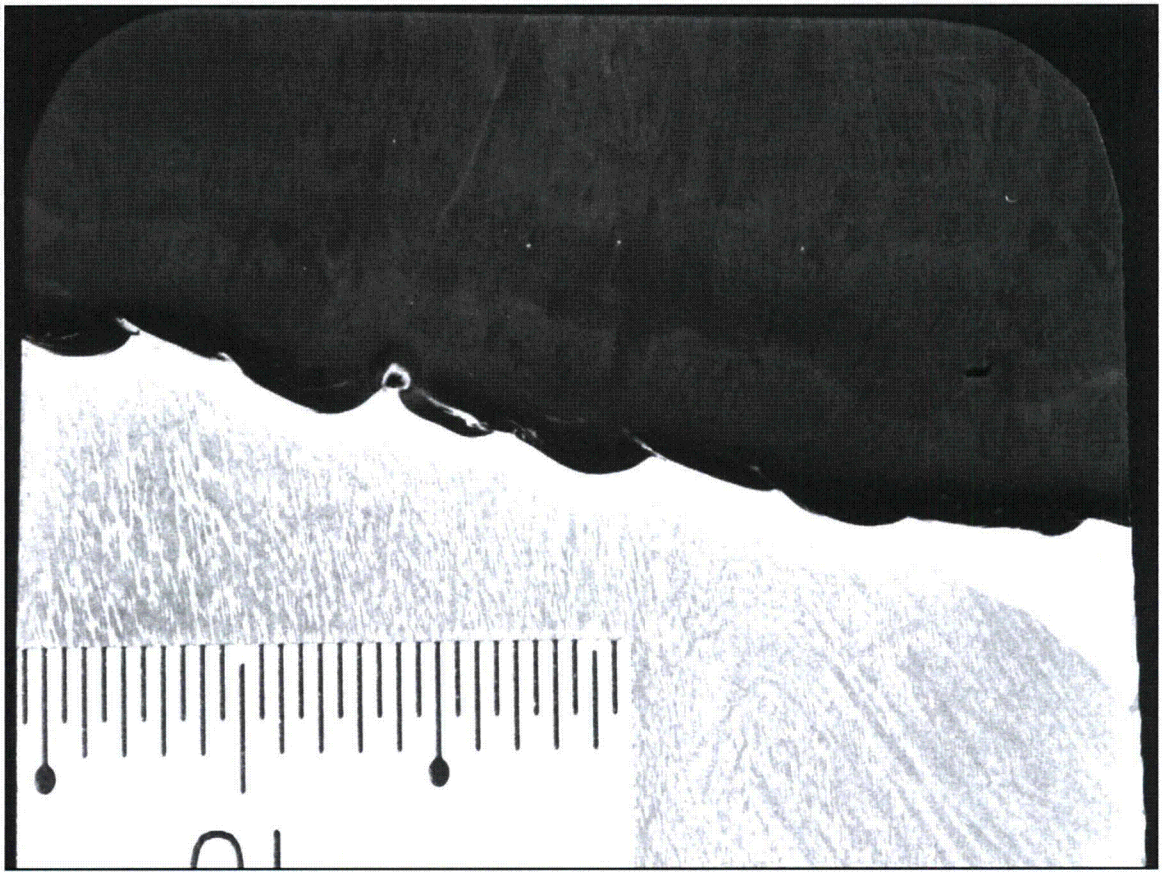

Figure 2-27
Example of Distance to Defect 1

Note: 1 in = 25.4 mm

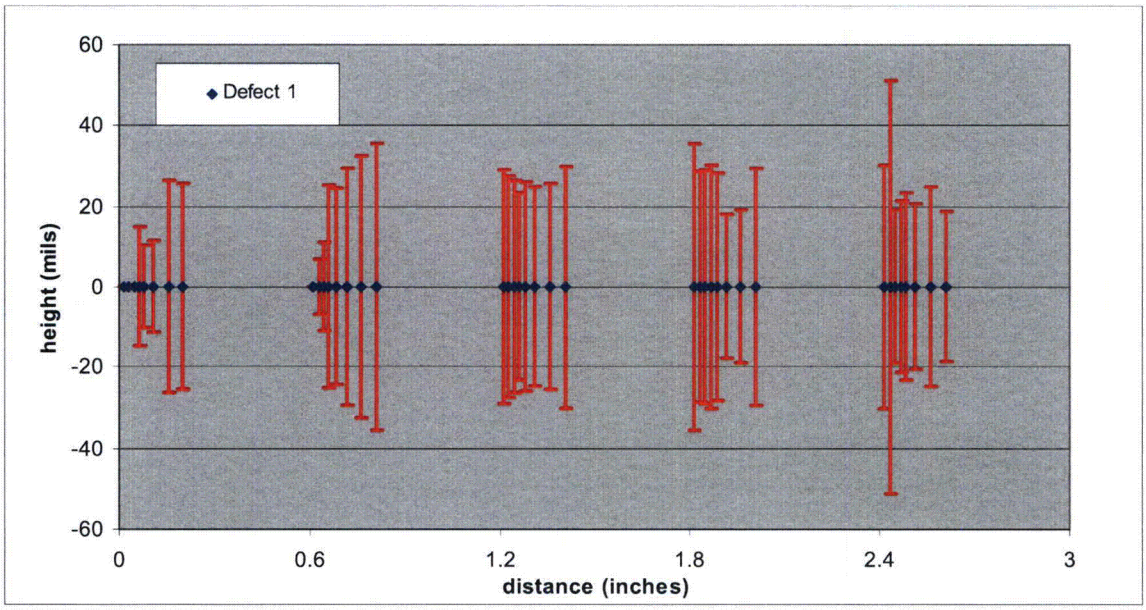

Figure 2-28
Height vs. Circumferential Distance from Defect Initiation.

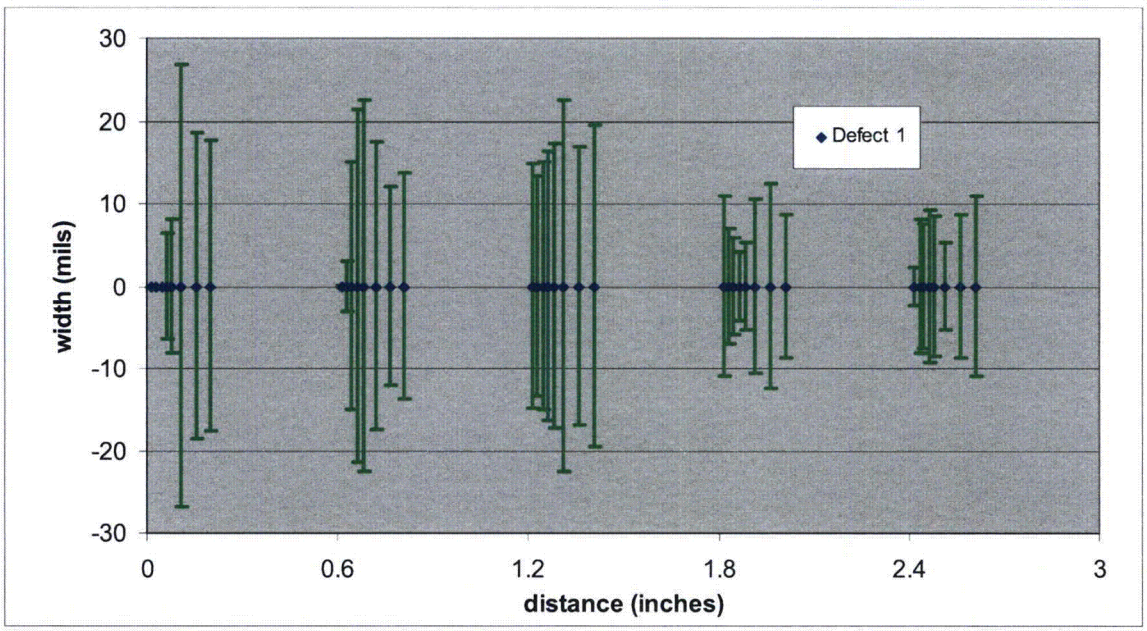

Figure 2-29
Width vs. Circumferential Distance from Defect Initiation.

Note: 1 in = 25.4 mm

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Figure 2-30
Photomicrograph Showing the Cross Section of the Dissimilar Weld Location of the PWOL at the Weld Repair

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Figure 2-31
Photomicrograph Showing Hardness Trace on the Cross Section of the Dissimilar Weld at toe of 182 butter and CS base material (Scan 1 and 2)

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Figure 2-32
Photomicrograph Showing the Cross Section of the Dissimilar Weld at location 3 and 4 (Scan 3 and Scan 4) (CS interface with 182 butter on surface of weld groove (top) and CS interface with 52 overlay (bottom)

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Figure 2-33
Scan 1 Hardness Profile

Content deleted – EPRI/MRP Proprietary Information

Figure 2-34
Scan 2 Hardness Profile

Content deleted – EPRI/MRP Proprietary Information

Figure 2-35
Scan 3 Hardness Profile

Content deleted – EPRI/MRP Proprietary Information

Figure 2-36
Scan 4 Hardness Profile

3
CONCLUSIONS

- Residual Stresses predicted by the Finite Element Analysis (FEA) are consistent with those measured by the XRD residual stress measurements.

- The results discussed above clearly demonstrate FEA is a useful tool for designing preventive weld overlays in various size piping.

- Using the welding techniques to deposit the overlay, satisfactory levels of Cr for PWSCC resistance are present to meet the criteria in Code Case N-740 for accepting the first layer in the design of the overlay.

- Alloy 52 and 52MS are difficult materials to weld. Extreme care must be taken such as using test samples for demonstrations or mockups for field applications to verify the adequacy of the welding procedures and techniques.

- Current PDI qualified UT procedures have been demonstrated as adequate for identifying and sizing fabrication flaws. The UT examinations performed indicate current PDI qualified UT procedures may be effective for finding stress corrosion cracking (SCC) for configurations like the mockup. However additional work on simulated SCC samples is needed.

- Metallography and hardness testing results have shown that acceptable tempering of the heat affected zones was achieved by the ambient temperature temper bead welding.

4
RECOMMENDATIONS

- Additional work in verifying the adequacy of current PDI qualified UT procedures for identifying sizing SCC for configurations similar to mockup should be done.

- Procedures and protocols should be developed to provide guidance on mockups to verify the adequacy of welding procedures and techniques prior to their implementation in actual field activities for repair and mitigation using overlays.

- A program for developing techniques for and evaluation of Plasma Arc Welding application of weld overlays could be beneficial to the industry.

5
REFERENCES

James Pineault, Proto Stress Analyses Report, January 2006.

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