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Materials Reliability Program: Recommendations for Testing of Emerging Mitigation Techniques for PWSCC (MRP-119)

Technical Report

Materials Reliability Program: Recommendations for Testing of Emerging Mitigation Techniques for PWSCC (MRP-119)

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PRODUCT DESCRIPTION

The EPRI PWR Materials Reliability Program (MRP), the Mitigation Working Group of the Alloy 600 Issue Task Group (ITG), initiated this effort to evaluate the potential of emerging and available mitigation techniques as remedial measures for primary water stress corrosion cracking (PWSCC). The measures to be identified include the mechanical, nonenvironmental methods that have been developed previously as mitigation measures for intergranular stress corrosion cracking (IGSCC) in boiling water reactors (BWRs). This effort is focused on the stress remedies such as heat sink welding or mechanical stress improvement (MSIP)[1], corrosion-resistant cladding weld overlay, and induction heating stress improvement, as well as on potential emerging technologies that can be applied to existing installed components.

The focus of the program involved the review and selection of potential mechanical technologies (as identified in other tasks under the program). Following this review, the program tasks included making recommendations for testing to qualify the processes so that they can be made available for PWR application in the near future.

Results and Findings

This report includes recommendations for further testing (to be carried out in 2004–2005) to evaluate emerging technologies or to improve the knowledgebase for performance of current technologies. The report identifies existing mechanical mitigation techniques that may be suitable for plant demonstration or use and emerging technologies that can be made available in the near future with appropriate testing and demonstration. Also included are recommendations for testing techniques for each respective process. The processes selected include cavitation peening, weld overlay for stress improvement (WOSI), plasma arc welding (PAW), and low plasticity burnishing (LPB).

Challenges and 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, and Use

The report provides information to aid an owner in evaluating mitigation in lieu of costly repair and replacement of components susceptible 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.

[1] MSIP is a trademark of AEA Technology Engineering Services, Inc.

Approach

The goals of the report were to review new technologies, to define a test program to qualify the process, and to make the process available for PWR applications for mitigating PWSCC. Those goals were met and are represented by the results and other information reported in this document.

Keywords

Cavitation peening
Low plasticity burnishing (LPB)
Mitigation
Plasma arc welding (PAW) and cladding
Primary water stress corrosion cracking (PWSCC)
Weld overlay stress improvement (WOSI)

CONTENTS

1 INTRODUCTION

A number of new technologies have become available recently from both commercial and scientific endeavors that appear promising as mitigation techniques for primary water stress corrosion cracking (PWSCC). The EPRI PWR Materials Reliability Program (MRP), the Mitigation Working Group of the Alloy 600 Issue Task Group (ITG), initiated this effort to evaluate the potential of mitigation techniques as remedial measures to PWSCC. The focus of the program involves the review and selection of potential mechanical technologies as identified in other tasks within the program.

This report represents Task B of the program and includes recommendations for further testing (to be carried out in 2004–2005) to evaluate emerging technologies or to improve the knowledge base for performance of current technologies. The report identifies existing mechanical mitigation techniques that may be suitable for plant demonstration or use, and emerging technologies that can be made available in the near future with appropriate testing and demonstration. Also included are recommendations for testing techniques for each respective process.

2 SELECTION OF EMERGING TECHNOLOGIES SUITABLE FOR MITIGATION OF PWSCC

Several emerging technologies were reviewed to determine which of these techniques were most promising for mitigating PWSCC in Alloy 600 and Alloy 82/182 filler materials. After the candidate technologies were deemed to be technically viable, additional selection factors were considered. These included the need for the technology, suitability for *in situ* implementation, difficulty for field application, potential for meeting field implementation schedules, and relative costs. The most promising technique within a family of similar techniques was identified.

The following four methods have been selected as having the best chance for near-term development, acceptance, and implementation:

- Cavitation peening
- Weld overlay for stress improvement (WOSI)
- Plasma arc welding (PAW)
- Low plasticity burnishing (LPB)

Cavitation peening, plasma arc welding, and low plasticity burnishing were evaluated in Task A of this program. Information on available results from testing may be found in the Task A report [1]. WOSI was evaluated in Task E of this program [2]. The purpose of the WOSI technique is to alter the inside diameter (ID) surface residual stress distribution by constricting the component in a manner comparable to mechanical stress improvement (MSIP)[1]. The residual stress fields in material directly under the overlay and to either end are placed into favorable compression both on the ID surface and for a portion of the wall thickness dimension. Physical implementation of WOSI is closely related to the application of conventional weld overlay that has been used extensively for successful repairs to both boiling water reactors (BWR) and PWR components degraded by stress corrosion cracking (SCC).

2.1 Summary of Method Description and Evaluation

2.1.1 Cavitation Peening

Cavitation peening is a method for inducing residual compressive stresses in the surface layers of metal components to depths reaching 50–60 mils (1.27–1.52 mm) [3, 4]. This procedure enhances fatigue life, improves damage tolerance, and provides resistance to SCC. The process

[1] MSIP is a trademark of AEA Technology Engineering Services, Inc.

entails sweeping ultrahigh-pressure (UHP) water jets over the component surface so that cavitation bubbles form and collapse. A shock wave is formed from each collapsing bubble. The shock wave thus forms, and then deforms, the material directly under the bubble to produce beneficial residual stresses (compressive). Measurements and evaluations have indicated no weight loss of the work piece or changes to the surface finish. A lack of surface heating during cavitation peening means that there can be no detrimental thermal effects.

Compressive residual stress fields can also be produced using laser peening [4, 5]. Laser peening applies a pulsed, high-energy laser beam directly to the surface of the metal being treated. A shock wave is produced when the light energy is rapidly converted to thermal energy as the laser beam strikes a light-absorbing surface [6, 7, 8]. A special coating is used to generate the absorbing surface to facilitate the conversion. The resulting shock wave deforms the material directly under the wave front and produces a compressive residual stress field. The laser application parameters are selected such that heat buildup on the surface is minimized.

Both cavitation peening and laser peening processes were evaluated in Task A [1] of this program, and both were determined to produce similar compressive residual stress fields. The main difference in the two methods is in the cost of the required equipment. Laser peening utilizes a special high-energy pulsing laser source and a system of specially designed mirrors to manage and manipulate the laser beam. Cavitation peening makes use of commercially available UHP water pumps, a custom cavitation peening nozzle, and a robot (or manipulator) to deliver and control the jet nozzle movement over the surface being peened.

Cavitation peening is the approach of choice because of the commercial availability of equipment and the huge differences in costs between the two systems. In addition, cavitation peening equipment should be easier to apply in a radioactive environment. Because cavitation peening will be able to achieve similar depths of residual compressive stresses at a much lower cost than laser peening, it stands to reason that the process will be more cost-effective and should be equally effective. In fact, preliminary projections place the cost of cavitation peening at less than 5% of the cost of laser peening. As noted previously, this innovative approach uses commercially available equipment to produce the UHD water jets that are swept over the surface of the part to generate the beneficial residual compressive stress fields without eroding the base material. In addition, the high-coverage cavitation peening speeds will enable the process to be used in applications requiring large surface areas to be treated.

The fact that the capital equipment costs for cavitation peening are so much less than laser peening also indicates that there should be rapid acceptance of the process by the PWR industry. Another potentially large advantage of the cavitation peening process is a capability to miniaturize the nozzle housing to facilitate application in locations where access is limited. It is anticipated that the technology could be used for *in situ* treatment of welds in power plants. Potential *in situ* applications include:

- Existing J-groove welds at nozzle penetrations of reactor vessel bottom heads and top heads having low head temperatures
- Repairs or replacements of nozzles such as control rod drive mechanisms (CRDMs)
- Accessible ID locations of reactor coolant piping welds

2.1.2 Weld Overlay Stress Improvement (WOSI)

The concept of weld overlay for stress reduction is similar to that of conventional weld overlay and MSIP in the following manner. Weld metal is deposited around a pipe outside diameter (OD) surface. The shrinkage of the cooling weld metal produces weld shrinkage that results in a constriction of the pipe under the weld. The resulting deformation forces the residual stresses under and near the overlay to redistribute on the ID to a favorable state of compression. The resulting residual stress improvement can be calculated using finite element analysis (FEA) techniques or measured on full-scale mockups. The same design considerations for flexibility and existing flaws used for standard weld overlays would apply to the WOSI technique. The process is implemented as follows:

- The design of a weld overlay for stress reduction would specify bead placement, axial length, overlay thickness, and location of the circumferential weld band. The overlay weld is not necessarily placed directly over the existing weldment.
- The WOSI could be placed over an existing weldment to improve the residual stress patterns as well as to provide a corrosion barrier to crack propagation from the ID. A material resistant to PWSCC crack initiation would be used and would be capable of arresting any axial cracks that might have been missed during the in-service inspection.
- The process requires conventional gas tungsten arc (GTAW) machine welding equipment for effective control of welding. The same types of filler materials used for standard weld overlays would be utilized for the WOSI. Delivery and manipulation tooling are also similar.
- The WOSI process may be used on cracked or uncracked pipe locations. The restrictions that exist for either MSIP or induction heating stress improvement (ISHI) should be applied.
- The use of automated remote GTAW allows work in limited access and higher radiation locations. The use of machine equipment also facilitates high-quality welds.
- The WOSI process may be used near pumps or valves where IHSI and MSIP may be less effective because of the requirements for complex coil geometries for IHSI or by physical size constraints for MSIP clamps.
- The WOSI process can be mobilized quickly in order to meet schedules of an existing outage after in-service inspections have detected cracking. Overlays could be designed for flawed welds (depending upon the defect size) or as a preemptive mitigation for welds in the system believed to be susceptible to PWSCC.
- The WOSI process should not be restricted by pipe sizes.

A WOSI applied to a butt-welded nozzle-to-safe-end location would be designed to ensure that any residual tensile stresses would be located only in PWSCC nonsusceptible materials (low-alloy steel nozzle or stainless steel safe end). Other design objectives would define minimum thickness and length to achieve compressive residual stress fields and facilitate ultrasonic testing (UT) examinations. The design thickness would be justified by FEA to produce a compressive stress field in the susceptible material exposed to reactor coolant. The thinner overlay, relatively fine weld-cast structure of the deposit, proper length, and smooth surface finish from machine GTAW and post-weld surface machining would help to minimize UT examination difficulties.

The WOSI process is applicable not only for preemptive mitigation, but also for repair if necessary. If a WOSI is used only for mitigation purposes, it is anticipated that as few as two layers would effectively produce the desired ID compression. The overlay deposit would not necessarily be applied across the weld, nor would it intersect with the low-alloy steel nozzle material. These restrictions would eliminate a need for using temperbead welding procedures and thus would not require separate regulatory approval of the welding process.

If the WOSI is designed to be leak-limiting to mitigate axial cracking in the weldment, the initial two layers normally would not be counted as PWSCC-resistant because the weld deposit would be diluted by the substrate. The design likely would include four layers, including the first two dilution layers. In this case, the initial three layers applied over a P-1 or P-3 material would utilize a temperbead welding approach to eliminate the need for post-weld heat treatment (PWHT). As in the previous case, the initial two layers would not be counted toward the overlay thickness because those two layers would have unacceptable dilution from the carbon or low-alloy steel substrate such that the corrosion resistance of the overlay deposit is degraded.

A number of American Society of Mechanical Engineers (ASME) Code Cases that have been approved by the Nuclear Regulatory Commission (NRC) are available to support temperbead weld repairs. It is anticipated that the ASME Code will shortly (within the next year) issue the additional cases to address temperbead welding approaches for BWR and PWR dissimilar metal and Alloy 600 weldments and components. NRC endorsement of these cases is anticipated shortly thereafter. Currently, this work would require relief for dissimilar metal applications and also from the 100-square-inch (64,516-square-mm.) surface area limitation for ambient temperature temperbead welding over carbon and low-alloy steel piping and nozzles. Recently a pressurizer surge line nozzle-to-safe-end weldment was overlaid to repair a PWSCC axial crack in a PWR. The NRC approved the overlay repair for service.

Some question exists as to whether the NRC would require demonstration work as well as analysis to qualify the process for PWR applications. Although the process is similar to the conventional weld overlay, it is not currently developed for stress improvement nor is it qualified by testing. It is anticipated that both analysis and physical demonstration/qualification would be necessary.

WOSI is a viable process for mitigating unfavorable residual stresses in PWRs using a simpler, less time-consuming amount of welding than is required for a standard weld overlay repair. The WOSI would be designed to minimize interference of the weldment with UT. Inspection of the WOSI used only for stress improvement should be minimal because it is nonstructural and not relied on for any purpose following its application. It is anticipated that this process could be implemented without NRC approval. Cost savings could be realized if multiple welds were mitigated at a single outage. Credit for the stress improvement for the weldment with regard to future in-service inspections would need to be established with the ASME Code and the NRC. The process would require qualification for PWR applications.

2.1.3 Plasma Arc Welding (PAW) and Cladding

Plasma arc is a welding process that achieves coalescence by heating with a constricted arc between an electrode and the work piece (transferred arc) or with the electrode and the constricting nozzle (nontransferred arc) [9, 10]. Transferred arc is of interest for cladding welds and components because of the deposition rates that are possible and the control over dilution. The process was described in detail in the Task A report [1] for this project.

The plasma arc process is capable of deep penetration because of the controllable collimated arc. Arc energies can be produced that are three times greater than those possible with GTAW. In spite of the higher arc energies, plasma arc can be readily controlled with minimum dilution. An arc diameter can be chosen via the nozzle orifice to facilitate selection of weld bead size. Another feature of plasma arc is that the arc standoff distance is less critical than it is with the GTAW process. The relative insensitivity to standoff distance aids in achieving good weld consistency. The weld torch uses a secondary inert purge gas to shield the molten weld pool from oxidation.

Commercially available plasma arc equipment should be compatible with automated delivery systems for GTAW typically used in the nuclear industry. With some modifications to the standard plasma welding nozzle, it may be possible to deposit cladding underwater with minimum porosity. Plasma equipment offers advantages for repair as well as mitigation applications because the deposition of filler materials is significantly higher than with GTAW equipment. This feature alone could shorten the time required for overlay repairs or for applications depositing corrosion-resistant cladding.

2.1.4 Low-Plasticity Burnishing (LPB)

Another method of producing a layer of compressive residual stress of high magnitude and significant depth with minimal surface cold working [11, 12, 13] is LPB. The process is characterized by the use of a single point contact achieved with a smooth free-rolling ball. The ball is supported in a fluid bearing under a pressure that is sufficiently high for the rolling ball to be lifted from the surface of the retaining spherical socket. The burnishing ball develops subsurface Hertzian stresses in the work piece, acting parallel to the plane of the surface. These stresses reach a maximum value beneath the work surface. The stresses can be generated normal to the surface that exceed the yield strength of the work piece when sufficient pressure is applied through the burnishing ball.

The normal force required and the depth at which yielding first occurs depend on the ball diameter and material properties. Upon loading, the material is deformed in tension and, upon unloading, the surface is left in a state of residual compression. Unlike traditional fixed-ball burnishing tools, the ball is in solid mechanical contact with only the surface to be burnished. It rolls freely under pressure so that it cannot cause shearing forces to develop surface cold work. Controlling the path of the tool in a computer numerical controller (CNC) lathe or milling machine allows the tool to traverse any point on the surface only once, minimizing the plastic deformation necessary to develop a compressive layer. The width of the deformed zone has been found to vary from nominally 20–40 mils (0.5–1 mm), depending upon the burnishing force applied normal to the surface. The LPB process produces minimal cold work with a single deformation cycle. LPB can be applied to an arbitrary surface topography. The low plasticity burnishing process is described in detail in the Task A report [1] for this project.

LPB has been demonstrated as a process that can achieve compressive stresses in test samples to depths of about 40 mils (1 mm). The tooling and delivery systems for this process would be relatively simple and inexpensive compared to laser peening. The limits for weld surface roughness and applicability for difficult-to-reach component surfaces would need to be established. Testing would be required to establish performance on samples with varying surface roughness. LPB should be considered for use as a surface stress mitigation method for treating J-groove welds, butt welds, and base metals both in air and under water.

3
QUALIFICATION AND PROCESS DEVELOPMENT

The program task of recommending testing and qualifying each process is explained in this section.

3.1 Cavitation Peening

Cavitation peening is a new technology process identified for future near-term nuclear power plant applications. Available test results cited previously suggest that the process may be a practical method for producing compressive residual stresses near the surfaces of nuclear components that may be vulnerable to PWSCC initiation and propagation. The method is capable of developing these favorable compressive stresses to depths that are sufficient to impart durable corrosion resistance without producing a cold-worked surface layer; however, test data on materials of interest and prototype equipment capable of being used in the field do not exist. A comprehensive program is needed to evaluate and establish the process. Such a program should include the following elements as a minimum:

- A prototype application nozzle and machine controlled manipulation system should be developed that can be fitted to existing delivery hardware to perform work remotely in-reactor, semi-remotely on reactor heads, and semi-remotely inside large-diameter reactor coolant piping. It is anticipated that commercially available components could be procured readily to produce most of the prototype.
- Carbon/low-alloy steel-to-stainless-steel test samples should be prepared to simulate nozzle-to-safe-end welds. The carbon/low-alloy steel ends would be buttered with Alloy 182 filler using the SMAW process. After the weld geometry is machined, the weld would be completed using an Alloy 82 root (GTAW) and the groove would be filled with Alloy 182 using the SMAW process. Pipe material having a suitable diameter and thickness would be used for both the carbon steel and the stainless steel. Each segment length should be at least 6 inches (15.2 cm) to produce a completed sample of approximately 12 inches (30.48 cm)—including the width of the weld and butter deposit thickness. Either Type 304 or Type 316 stainless steel material would be suitable for the safe-end material. The weldments would be fabricated using an open-root butt joint similar to that used for original field pipe welding. It is suggested that approximately 6–10 test coupons would be needed to provide materials for a control specimen and for samples having various peening intensities applied.
- The testing scenario should be developed to examine welds and heat-affected zones (HAZs) that have been peened with at least three different intensity levels. One control sample would be peened at the maximum intensity to provide a sample for metallographic evaluation and microhardness profiling.

- Residual stress measurements should be performed on the test samples using either X-ray diffraction and/or strain gage techniques. Surface material of the samples will be removed incrementally by either chemical milling or electropolishing to measure residual stress as a function of depth through the thickness.
- Welded samples (treated at each intensity level plus an untreated control sample) should be tested to evaluate the overall ID surface residual stress distributions by exposing the nickel base materials to a sodium thiosulfate test solution. Stainless steel materials would be tested using a boiling 42% magnesium chloride test medium. The purpose of these tests is to provide a qualitative measure of freedom from high tensile stress locations based on corrosive environment exposures. It will be possible to reference these results to similar testing performed on residual stress mitigation for BWR IGSCC applications.

3.2 Weld Overlay Stress Improvement (WOSI)

Two overlay stress improvement concepts are suggested for near-term mitigation qualification. These are:

- A WOSI designed only for stress improvement purposes
- A WOSI designed as a mini-overlay (using Alloy 52 filler material to provide both a corrosion barrier and a state of residual compression)

The goal is to provide a repair configuration that mitigates stress and arrests any shallow axial cracks that may be present.

FEA would be used to identify and determine key weld design details that optimize residual stress redistribution on the inside surface of the sample. For the WOSI intended only for stress improvement, the placement location, thickness, and length would be established. For the WOSI intended for stress improvement and leak-limiting purpose (repair of axial cracks), the placement location, length, and thickness of the overlay would also be determined. FEA would be used to predict residual stress distributions along the inner surface and through-wall. Parameters would be developed to facilitate direct comparisons with stress and displacement measurements in welded test samples. The analyses would be done initially and then appropriate benchmarking measurements taken during welding.

The analysis of the WOSI would involve four distinct tasks. Task 1 of the analysis (stress improvement only) would use axisymmetric FEA to determine an initial uncracked condition. Three different lengths of the overlay and three different widths would be introduced and each analysis repeated. The elastic analysis can be used to identify an optimum location for the center of the overlay. The prescribed length can be determined for achieving a desired residual stress distribution. The analysis will produce results similar to MSIP except that the compressed pipe or fitting is never released for elastic spring-back. This suggests that less compressive strain may be needed than is applied for MSIP. The results from this task also would provide insight into the leak-limiting WOSI task (see Task 2) because it will be possible to evaluate residual stress fields directly below the WOSI based on overlay design parameter variations.

Task 2 would evaluate the leak-limiting WOSI by analyzing three different overlay lengths, beginning with the axial length required for a leakage type overlay based on ASME Boiler and Pressure Value (B&PV) Code, Section XI [14] (assuming two layers and an uncracked condition). Additionally, two thicknesses of overlay would be examined that accommodate two additional layers for weld dilution.

Task 3 would analyze a cracked condition using the final parameters selected from Task 1. The depth of crack that can be mitigated would be determined from the results of analysis where the selected parameters were varied.

Task 4 would analyze a cracked condition using final parameters from Task 2. Finding the depth of crack that can be mitigated would be determined from the results of analysis where the selected parameters were varied.

After obtaining the results from the fracture mechanic's analyses, two pipe sizes (6 in. and 14 in., Schedule 120 or 160) would be fabricated from carbon and stainless steel pipes for testing. The samples would be prepared by initially buttering the end of the carbon steel pipe weld preparation with Alloy 182 using the SMAW process, then welding the joint with an Alloy 82 root (GTAW) and filling the groove with Alloy 182 (SMAW). A total of 10 samples would be fabricated—5 from each pipe size. All butt welds would be fabricated by welding the lower one-third of the pipe wall, then conditioning (smoothing) the ID for subsequent strain gaging. The weld would then be completed. Two samples would be used as controls. Two welds of each pipe size for each mitigation concept would be overlaid with the pipes water-filled. Shrinkage measurements of all overlay welding would be performed by measuring diametral displacement (constriction) at four equally-spaced azimuths around the inner circumference (0–180, 45–225, 90–270, and 135–315) for four equally-spaced axial locations under the overlay (both ends and two intermediate locations). Overlaid samples would be examined ultrasonically to determine adequacy of the overlay bonding.

One-half of the weld overlaid samples and a control sample would be used to evaluate residual stress distributions by strain gage measurements. The other one-half of the welded samples would be used to evaluate overall ID surface residual stress distributions using a sodium thiosulfate or an alternative aggressive solution selected to provide a qualitative measure of high tensile stress.

3.3 Plasma Arc Welding (PAW) and Cladding

The cladding/welding method selected for near-term development is plasma arc because of its potential for high deposition rates and underwater *in situ* application. This method would be used to clad the environmentally exposed surface to produce a PWSCC-resistant layer by welding a PWSCC-resistant nickel alloy cladding. Cladding technology is currently available for the GTAW process and has been used for repairing J-groove welds in reactor heads. It is believed that this same automated technology can be adapted readily to the plasma arc transfer processes. In addition, it is suggested that plasma arc equipment can be adapted to existing delivery systems to produce quality weld overlays that repair and mitigate Alloy 82/182 weldments in PWR piping.

Additional work is necessary to determine if the plasma weld nozzle can be adapted to provide suitable shielding so that the process can be utilized for underwater applications. Additionally, it is suggested that a mockup demonstration would be required to show that the technology is suitable for welding cladding *in situ* with an appropriate delivery system.

Samples should be produced with this system to demonstrate that cladding can be produced free from unacceptable porosity that is completely bonded to the substrate. Mechanical tests (guided bend tests) and metallography should be performed to demonstrate bonding and soundness of the cladding. A simulated J-groove mockup should be prepared and subsequently clad underwater. It is suggested that two cladding filler materials be used—pure nickel and Alloy 52. Because the cladding is designed for corrosion resistance, cladding strength is not of concern. A pure nickel deposit may be easier to apply and still provide excellent corrosion resistance. The nominal 30% chromium in the Alloy 52 nickel-based filler also needs to be examined for applications where strength is a significant variable and where chromium oxide is needed for corrosion resistance.

Samples would be prepared using optimized parameters for weld overlay repairs with commercial welding equipment and existing delivery systems. The evaluation should include deposition on carbon steel piping samples that are filled with water to establish a minimum dilution first layer using welding parameters known to produce adequate tempering of the base metal interface. It can be shown that constant penetration weld layers are known to optimize temperbead welding. Subsequent layers, perhaps as few as one, should be applied to complete the tempering. It is expected that a technique can be established that would minimize the number of layers that must be disregarded because of dilution concerns. The samples would be evaluated by metallography, microhardness testing, and by scanning electron microscope (SEM) or microprobe to determine the Cr gradient in the dilution layer(s). After the process parameters have been optimized, two weldments (82/182) of dissimilar metal pipes (carbon-to-stainless steel) should be overlaid and the resulting residual stress pattern measured and compared to overlays produced by the GTAW process.

3.4 Low Plasticity Burnishing (LPB)

Low plasticity burnishing is a new technology process identified for near-term future work. Test results indicate that the process is capable of producing compressive stresses to depths similar to those produced by laser peening (about 40–60 mils [1.02–1.52 mm]). However, neither test data nor prototype equipment are available for applying low plasticity burnishing in nuclear plant environments. A program is needed to evaluate the process for this purpose and should include the following:

- Development of a prototype LPB system that can be used with an existing delivery system to perform work remotely in reactors, on reactor heads, and internal to large-diameter reactor coolant piping. Special attention should be addressed to mounting mechanisms and for rigidity of the tooling required to achieve proper control of the process.
- Preparation of carbon/low-alloy steel-to-stainless steel test samples with 82/182 welds from pipe material would be required for testing. The pipe curvature would assist in evaluating the capability of the equipment system to produce the required burnishing tool manipulation while maintaining perpendicularity with the surface. The weldments should be fabricated using an open-root butt joint similar to that used for original field pipe welding. It is estimated that approximately 6–10 mockup test coupons would be needed to provide sufficient test material for examining different burnishing application parameters.
- Both welds and HAZs would be burnished at three different intensity levels. An additional sample should be burnished at a maximum intensity to provide a control sample for metallographic examination and hardness profiling. Welds having different surface finishes should be included in the test matrix to determine the effect of initial surface finish on the final residual stress distribution.
- Residual stress measurements should be completed for the test samples using either X-ray diffraction and/or strain gage methods. Strain gages are preferred because the sampling volume is greater. Surfaces of the samples would be removed incrementally by either milling (chemical or mechanical) or electropolishing to measure residual stress as a function of depth through the thickness.
- Welded samples that are treated and untreated should be exposed to aggressive environmental mediums to provide a qualitative measure of any locations having tensile residual stress peaks. Sodium thiosulfate or a suitable alternative should be selected to examine nickel base surfaces and boiling 42% magnesium chloride solutions for stainless steel surfaces.

3.5 Additional Considerations Related to PWSCC Resistance of Nickel Alloys

The qualification program for development of emerging mechanical processes for PWSCC mitigation has been described in this section. There are additional issues that must be addressed. The first issue concerns the weldability of Alloy 52/152 filler materials. A second issue concerns the expected service performance of these high-chromium nickel-based materials in the PWR environment (crack growth behavior).

As part of the 2004–2005 programs, it is proposed that an evaluation be performed on prototypical heats of Alloy 52/152 that were used in the early development of the alloy. The purpose is to determine the characteristics of this filler that were responsible for the good weldability experienced with the early prototype materials. By identifying the characteristics (chemistry and metallurgical structure), it should be possible to better guide the improvements to the commercial heats of the Alloy 52/152 filler materials. Weldability of filler materials is a concern in at least two troublesome areas. These include interlayer oxide entrapment and hot ductility dip cracking. Interlayer oxide entrapment is a known problem with Alloy 52 because of the presence of readily formed heavy surface oxides coupled with the low viscosity of the molten puddle. The tendency for solidification cracking and/or hot ductility dip cracking is typical for nickel base materials. However, Alloy 52/152 is particularly susceptible—at least in the current commercial formulation.

Testing of multiple heats of this material is necessary to determine the characteristics responsible for the good weldability that was experienced in the early prototype materials. Both constrained (stiff groove geometries) and unconstrained (cladding) situations should be examined. It is noted that optimal chemistries are being pursued by INCO Specialty Products and others and that the final chemistry has yet to be defined at this time. It is suggested that detailed planning be conducted in conjunction with input and heavy involvement from filler material suppliers and welding vendors.

There is a pressing need to generate reliable PWSCC crack growth data for Alloys 52/152 to justify the use of this material to mitigate PWSCC. If it can be shown that the chromium content is the dominant characteristic, then the proof is easily justified. If the corrosion resistance is the result of a combination of chemistry variables, then the proof is more complicated and must rely on testing of actual welded coupons. The NRC is requesting such data to evaluate the longevity of repairs or replacements incorporating these weld materials.

Details of the weld qualification program and the crack growth testing program for the Alloy 52/152 weld materials are beyond the scope of this project.

4 CONCLUSIONS

The most promising candidates to mitigate PWSCC in nuclear components identified and reviewed in Task A of this program have been evaluated, and four methods were selected for development and qualification. These are:

- Cavitation peening
- Low plasticity burnishing (LPB)
- Weld overlay stress improvement (WOSI)
- Plasma arc welding (PAW) and cladding

A test program has been suggested for each of the four promising candidates based upon the corrosion parameters addressed by the techniques. The first three methods listed here are stress mitigators and deal with two methods that place near-surface material into favorable compressive residual stress distributions while minimizing any surface cold work. A testing program has been suggested that is based upon showing comparability to similar successful stress remedy applications in the BWR industry. MSIP is a current method that has been used successfully in both BWR and PWR nuclear equipment. The method is reviewed thoroughly in Tasks C and D [15, 16] of this program. The WOSI method provides a promising alternative to MSIP that is achieved using weld overlay technology. The equipment with which to implement WOSI is much smaller than that required for MSIP and should find application in space-limited locations. The conventional weld overlay has already been applied to mitigate PWSCC in a nuclear plant, but was discussed as an alternate method to mitigate and arrest known or suspected crack locations in piping components.

The plasma welding applications are included because the method offers significant advantages with which to reduce the welding time required to produce large-diameter overlays. Plasma welding can be effectively controlled to limit dilution and thus has a potential to eliminate the requirement discount two weld overlay layers because of substrate dilution. In addition, plasma welding has a significant potential for underwater welding applications.

A pressing need to improve the weldability of Alloy 52/152 consumables has been identified. The corrosion resistance of the selected consumable should be established through suitable environmental testing.

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