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Westinghouse Electric Company Technical Paper on Underwater Laser Beam Welding

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Abstract

Recently, stress corrosion cracking (SCC) has been observed in aged components of nuclear power plants located in primary water environments and composed of materials susceptible to PWSCC (Primary Water Stress Corrosion Cracking). Toshiba has developed an Underwater Laser Beam Welding (ULBW) process that applies SCC-resistant weld metal directly onto the surface of the aged components, serving as a method of mitigation and repair. The deposited weld metal will be resistant to PWSCC and will act as a barrier to prevent primary water from contacting the susceptible material, thus rendering the component insusceptible to PWSCC. Westinghouse has joined this development effort, and is working in coalition with Toshiba to develop this process for delivery in the U.S. This paper provides an update on Underwater Laser Beam Welding using filler material Alloys 52/52M.

1.0 Background

The U.S. NRC has requested the industry to address how they plan to comply with the regulatory approach to cladding and inlays, and the applicable ASME Code requirements that govern these mitigation technologies. This document is to provide information regarding the Westinghouse Underwater Laser Beam Welding technology for PWSCC mitigation.

2.0 Components Affected

Reactor Vessel primary nozzle to stainless steel safe-end welds have been made using dissimilar metal (DM) welds with Alloy 82/182 weld metal. These DM welds have been exposed to Primary Reactor Coolant and, therefore, are susceptible to Primary Water Stress Corrosion Cracking (PWSCC). The Underwater Laser Beam Welding (ULBW) process will install a weld cladding, using Alloy 52M filler metal to create a buffer layer to protect the nozzles from the Primary Coolant. The cladding will cover the entire DM weld, and extend over part of the stainless steel safe-end and the stainless steel cladding installed over the low alloy carbon steel nozzle. This process is intended to be installed on both the Hot Leg nozzles and Cold Leg nozzles.

3.0 Principles of Underwater Laser Beam Welding (ULBW)

The Westinghouse underwater laser welding system is a remotely installed and controlled inside-diameter dissimilar metal (DM) weld mitigation process for RV nozzles. This process:

- Deposits high-quality cladding inside an RV nozzle while submerged in water
- Results in reduced ALARA dose over dry weld processes
- Does not require draining of the refueling cavity
- Does not require coffer dams & shielded work platforms

- Requires minimal equipment in containment
- Has a compact configuration; expansive lay-down area in containment is not required

The Westinghouse Underwater Laser Beam Welding (ULBW) system involves the application of weld metal onto a substrate surface where a locally dry area is formed around an optical head as shown in Figure 1. With a level of precision superior to arc-based welding processes, the ULBW system achieves an optimal balance between weld fusion and base metal melting. Submerged application within the reactor pressure vessel has been proven by the Westinghouse and Toshiba Team through several years of research and development. ULBW is designed to maximize safety, minimize risk, and optimize outage schedules.

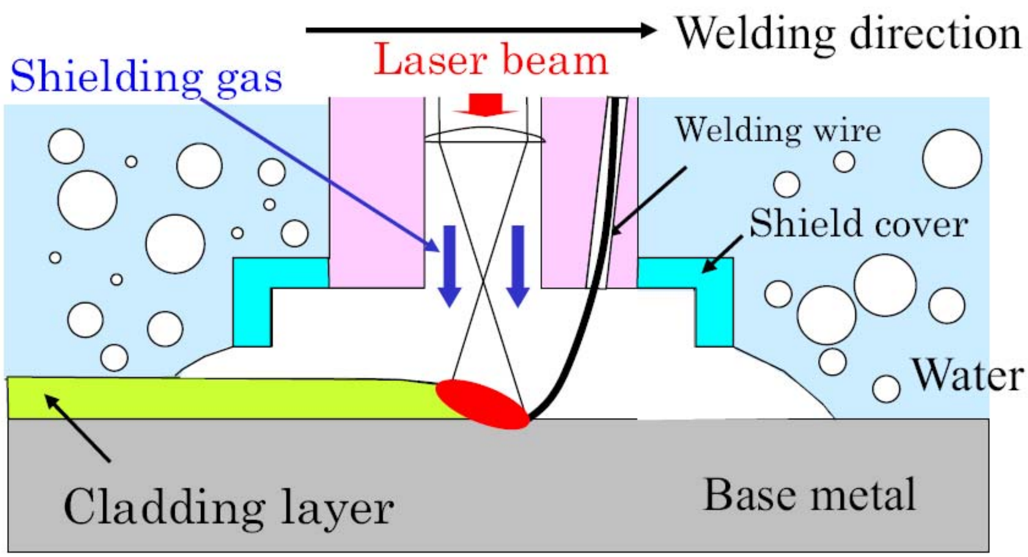

Figure 1: Schematic of Underwater Laser Beam Welding

Laser welding offers high welding speeds, short weld cycles, precise process heat input controls, and minimal distortion. These advantages substantiate the widespread use of laser welding in the medical, automotive, shipbuilding, electronics, aerospace, and steel industries. The Westinghouse ULBW system is powered by an Ytterbium fiber laser coupled with a patented Toshiba laser welding head to apply cladding of Alloy 52M to reactor pressure vessel nozzles.

The Ytterbium fiber laser can precisely operate from 10 to 105% of full power with no change in beam divergence or beam profile. This controlled application enables accurate, precise process welding parameter controls in welding applications. The robust ULBW system is compact and reliable, with diode lifetimes in excess of 50,000 hours.

4.0 General Process Description

The Underwater Laser Beam Welding process is comprised of the following steps:

Ultrasonic and Eddy Current examinations of the Dissimilar Metal Weld will be performed prior to surface preparation and welding, using PDI-qualified techniques. This examination is performed to determine whether any unacceptable flaws are contained in the DMW prior to the installation of the mitigative layer.

The results of the UT examination will determine the next step of the process. If a shallow flaw is detected (depth less than 0.125 inches), an excavation will be performed, and repair welded (where required) using the ULBW process. When the flaw is in close proximity to P3 RPV nozzle material, the repair will be performed using Ambient Temperature Temperbead Welding. Note that rules governing Ambient Temperature Temperbead Welding using the ULBW process are under development. These rules are being developed by the Task Group on ULBW Ambient Temperature Temperbead Welding as part of the ASME Boiler & Pressure Vessel Code Section XI, and a Code Case defining these requirements will be developed in the near future. Rules for ULBW underwater temperbead welding are expected to be similar to those for GTAW ambient temperature temperbead welding, as discussed in Draft Code Case N-XXX (07-1682) Nickel Alloy Reactor Coolant Inlay and Cladding for Mitigation of PWR Full Penetration Circumferential Nickel Alloy Welds in Class 1 Items. If a deeper flaw is detected, the flaw will either be repaired, partially repaired, or left in place and dispositioned using a process similar to the Embedded Flaw repair methodology. The embedded flaw process is documented in WCAP-15987-P, Technical Basis for the Embedded Flaw Process for Repair of Reactor Vessel Head Penetrations, Rev. 2, May, 2003. For flaws that are not completely removed, seal welding in accordance with the Draft Code Case N-XXX (07-1682) will be performed, followed by cladding installation.

Surface preparation prior to cladding consists of base metal preparation to remove surface oxides and contaminants. Metal removal will be minimized, and will consist of grinding/polishing to smooth/clean existing surfaces for welding. No machining is required because the mitigative layer is cladding, and welding will generally follow the existing contours of the nozzle ID surfaces.

Welding of the cladding will be performed using Alloy 52M material. Note that continued Alloy 52M developments will be considered for use, including the recently introduced 52MSS Alloy developed by Special Metals. The final weld cladding dimensions will be approximately 0.118 inches (3mm) thick and 2 inches (51 mm) wide with specific dimensions determined based on actual DMW configuration and Draft Code Case N-XXX 07-1682 requirements. When sulfur/contaminant levels pose a risk of hot cracking in the austenitic nickel weld deposit, prior to installing the cladding, a layer of ER309L will be installed over the stainless steel safe end to prevent hot cracking when welding to the austenitic stainless steel.

4.1 Design: Design of the Weld Cladding will be performed in accordance with Code Case N-XXX (07-1682) being developed.

A development program at Westinghouse addressed several possible cladding designs that are anticipated for actual application. All designs assumed that the weld is applied to the ID of the reactor vessel nozzle without excavation (mitigative cladding design). The impact on the design basis fatigue analysis and on flow were assessed and are not critical issues for typical PWR reactor vessel nozzle dissimilar (DM) weld applications.

A typical outlet nozzle design for a 4-loop plant was considered. Inlet nozzle designs, and nozzles in 2- and 3-loop plants are expected to be enveloped by the outlet nozzle geometry and transients.

4.2 Transients: A generic 4-loop transient set was used with some additional conservatism. The generic fatigue analysis should envelope plant specific transient sets.

4.3 Cladding Design: The weld cladding fatigue crack growth evaluation considered several design thicknesses; 0.070, 0.100, 0.125, and 0.150 inches. These thicknesses are within the range of practical application and requirements being developed in the ASME Code Case.

4.4 Flaws: Two basic kinds of flaws were considered; embedded and surface. Axial and circumferential orientation was considered for each flaw type. Embedded flaws are similar to the axial flaw depicted in Figure 2 (not to scale). The flaws considered should cover the worst cases expected. The embedded flaws were sized based on the inspection sensitivity of current examination methods, about 10% of the DM weld thickness. The surface flaws were postulated to be up to 50% of the clad thickness for a clad thickness of 0.125 inch. The effects of residual weld stresses due to weld repairs performed on the dissimilar metal welds were considered.

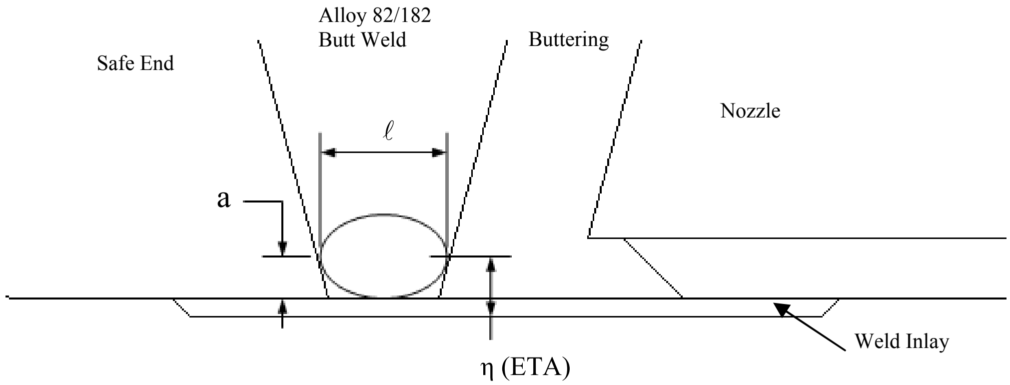

Figure 2: Embedded Axial Flaw Geometry

4.5 Results: The fatigue crack growth calculations demonstrated that a postulated embedded or surface flaw would not grow enough into the cladding to impact the integrity of the cladding as a protective barrier for the DM weld material, based on the design cycles for plant life.

5.0 Welding

Laser beam welding is a process recognized by the ASME Codes as acceptable for use in piping and pressure vessel applications. ASME Section IX specifies detailed laser beam welding essential variables for both procedure qualification and welding operator performance qualification. ULBW is addressed in ASME Section XI Code Case N-516-3, which details specific essential variables for process and performance qualification in the underwater environment. N-516-3 addresses underwater welding for P1, P8, and P43 materials, but does not address ULBW for P3 repair. To address this concern, an ASME Task Group (reporting to the ASME Section XI Working Group on Welding and Special Repair Processes) has been formed to prepare rules for ULBW ambient temperature temperbead welding on P3, P8, and P43 materials and their associated welds. Code Case development will be based on the rules of and the precedents established in Code Case N-638 for GTAW ambient temperature temperbead welding, with additional provisions included to address variables unique to the ULBW process. Process testing and qualification is intended to parallel that proven in the existing GTAW temperbead development and experience.

The ULBW process accomplishes a weld cladding with the Reactor Vessel filled with water. All process steps, including NDE, surface preparation, welding, in-process repair, final surface preparation, and final NDE are performed underwater. Flaws in existing materials will also be addressed underwater, using remote tooling for excavation and using the ULBW process for excavation rewelding. The ULBW welding system includes the welding system, NDE system, excavation/repair (including in-process repair) tooling systems, vision systems, delivery system components, and associated equipment to enable fully remote implementation of the mitigation of all inlet and outlet RPV nozzle DMW locations.

Deposit thickness will comply with the requirements of Draft Code Case N-XXX (07-1682). Current thickness requirements stipulate a minimum of two weld layers, each containing a minimum chromium content of 24%. ULBW testing demonstrates that the first Alloy 52 deposit layer (when deposited on Alloy 600 substrates) achieves a surface chromium content of approximately 23%. The second layer achieves a chromium content of approximately 25%, and the third and subsequent layers achieve chromium contents comparable to those of the original filler material (Approx. 28%). The 25% chromium content achieved for layers 2 and beyond exceeds the 24% minimum generally recognized as the threshold for effective PWSCC resistance. The cladding will, therefore, consist of at least three weld layers, two of which will meet or exceed the 24% chromium requirement. The high deposit purity achievable with ULBW also improves weldability of high-sulfur stainless steel substrates. Testing has demonstrated that ULBW is capable of achieving acceptable Alloy 52 weld quality when welding over high sulfur stainless steel substrates. Quality can be further improved when a sacrificial layer of ER309L is employed.

6.0 Examination

6.1 Baseline Ultrasonic Examinations (As-Found Pre Mitigation)

An As-Found baseline volumetric examination will be performed on a pre-determined boundary which includes as a minimum, the ASME Section XI volume for Category B-F or B-J welds, to a depth from the ID surface of 1/3 thickness minimum. A sufficient amount of material volume (0.5 in.) on each side of the specified volume must also be inspected to conservatively assure the cladding will be properly bounded by examined material. Techniques will be automated ID surface UT, qualified in accordance with ASME Section XI, appendix VIII, Supplement 14. In addition to UT, surface profilometry will be performed using focused immersion type UT probes. The profilometry is used to provide an accurate scaled axial slice of the specified area. Data can be acquired at each axial sweep assuring that a minimum of 360 lines of scaled profilometry data is taken. In cases where a UT indication is detected, the transducer image can be inserted into the profile and the analyst can determine the effect, if any, the surface has on the resulting examination beam and then compensate for it.

6.2 Baseline Eddy Current Examinations (As Found, Pre Mitigation)

Eddy Current examinations will be performed on the ID surface of the Section XI examination volume. Eddy Current data will be acquired in parallel with the Ultrasonic data. An additional amount of ID surface, (0.5 in.) on each side of the volume as a minimum, will be included to conservatively assure that mitigation areas are bounded by examined material. Eddy Current Testing can also be used to verify the material boundaries, to ensure that the susceptible materials are covered completely with the cladding. The Eddy Current examination procedure will be qualified to or designed to conform with the spirit of pending Code Case N-773 "Alternative Qualification Criteria for Eddy Current Examinations of Piping Inside Surfaces," Section XI, Division 1. This Code Case requires that Axial, Circumferential and off-Axis flaws be detected and measured and that procedure demonstration specimens realistically represent all the materials and deposition processes seen in the actual exam item. Eddy Current will be used to detect flaws in areas where UT probe contact might be compromised by rough surface conditions and also to confirm whether or not UT detections extend to the ID surface or are in fact embedded.

6.3 NDE Examinations After the Protective Layer is Applied

After the cladding layer is applied, the Baseline Ultrasonic and Eddy Current examinations will be repeated. In the Ultrasonic examinations, the Code volume will again be examined and particular attention will be paid to the bonded interface between the original surface and the applied layer.

Eddy Current examinations will again be performed to assure the wetted surface of the cladding layer is without cracks. In addition to Angle Beam UT and Eddy Current, additional probes will also be used to inspect for clad bond integrity consistent with Section V, Article 4. The probes will have demonstrated capabilities for detection and measurement of clad dis-bond through the use of samples having a representative range of cladding thickness with expected surface condition variations.

7.0 Approach to ASME Code

ASME Section IX specifies detailed laser beam welding essential variables for both procedure qualification and welding operator performance qualification. ULBW is addressed in ASME Section XI Code Case N-516-3, which details specific essential variables for process and performance qualification in the underwater environment. ULBW is conditionally approved in Regulatory Guide 1.147.

The ULBW requirements contained in N-516-3 are suitable for ULBW, but N-516-3 applies only to P1, P8, and P43 materials. RPV nozzle inlay may, in some circumstances, require weld on or near the P3 RPV nozzle. For these applications, N-516-3 does not provide the necessary requirements. To address this issue, and ASME Task Group on ULBW Ambient Temperature Temperbead welding has been formed. This task group will develop requirements for ULBW temperbead welding. This Code Case will be an essential component of the ULBW development process, and industry/NRC support will be required to help expedite the development and approval process. Development of ULBW Temperbead requirements will continue through 2008/2009, with approval tentatively planned for Fall/Winter 2009. Expedited NRC review will be requested to support the planned field delivery date of Spring 2010.

Design of the cladding to be applied by ULBW and its acceptance examinations will be in accordance with Draft Code Case N-XXX (07-1682).

The preservice and in-service examinations of the cladding will be in accordance with Draft Code Case N-770, Alternative Examination Requirements and Acceptance Standards for Class 1 PWR Piping and Vessel Nozzle Butt Welds Fabricated with UNS N06082 or UNS W86182 Weld Filler Material With or Without Application of Listed Mitigation Activities, Section XI, Division 1.

8.0 Development Schedule

The Underwater Laser Beam Welding technology is currently under development, with a field deployment planned for Spring, 2010. The timeline for field readiness is as follows:

Weld Process Development complete – January, 2009
Delivery Tooling Design complete – January, 2009
NDE Process Development complete – February, 2009
ASME Code Case approval – April, 2009
Prototype Manufacture and Qualification – May, 2009
Integrated Demonstration – July, 2009
First Field Implementation – Spring, 2010