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Light Water Reactor Sustainability Program

Complete Report on the Development of Welding Parameters for Irradiated Materials

November 2017

U.S. Department of Energy

Office of Nuclear Energy

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Complete Report on the Development of Welding Parameters for Irradiated Materials

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November 2017

**Prepared for the
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ABSTRACT

The advanced welding facility at the Radiochemical Engineering Development Center of Oak Ridge National Laboratory, which was conceived to enable research and development of weld repair techniques for nuclear power plant life extension, is now operational. The development of the facility and its advanced welding capabilities, along with the model materials for initial welding trials, were funded jointly by the U.S. Department of Energy, Office of Nuclear Energy, Light Water Reactor Sustainability Program, the Electric Power Research Institute, Long Term Operations Program and the Welding and Repair Technology Center, with additional support from Oak Ridge National Laboratory. Welding of irradiated materials was initiated on November 17, 2017, which marked a significant step in the development of the facility and the beginning of extensive welding research and development campaigns on irradiated materials that will eventually produce validated techniques and guidelines for weld repair activities carried out to extend the operational lifetimes of nuclear power plants beyond 60 years. This report summarizes the final steps that were required to complete weld process development, initial irradiated materials welding activities, near-term plans for irradiated materials welding, and plans for post-weld analyses that will be carried out to assess the ability of the advanced welding processes to make repairs on irradiated materials.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the program management of Keith Leonard and Jeremy Busby, the facilities and operations contributions of Allen Smith, Kathryn Kinney, Scott White, Chad Crawford, Mark Delph, Clay Morris, and numerous technical personnel at the Radiochemical Engineering Development Center and Building 3025E at Oak Ridge National Laboratory, along with the contributions of Alan Frederick and Doug Kyle.

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Complete Report on the Development of Welding Parameters for Irradiated Materials

1. INTRODUCTION

The advanced welding facility at the Radiochemical Engineering Development Center (REDC) of Oak Ridge National Laboratory (ORNL), which was conceived to enable research and development of weld repair techniques for nuclear power plant life extension, is now operational. The development of the facility and its advanced welding capabilities, along with the model materials for initial welding trials, were funded jointly by the U.S. Department of Energy, Office of Nuclear Energy, Light Water Reactor Sustainability Program, the Electric Power Research Institute, Long Term Operations Program, and the Welding and Repair Technology Center, with additional support from Oak Ridge National Laboratory. The first welds on irradiated materials were recently completed, which marked a significant step in the development of the facility and the beginning of extensive welding research and development campaigns on irradiated materials that will eventually produce validated techniques and guidelines for weld repair activities carried out to extend the operational lifetimes of nuclear power plants beyond 60 years.

This report outlines recent welding activities in the facility and summarizes the development of weld procedures and material handling requirements for the program. Included within are details on:

- Initial welding trials on irradiated materials
- Near-term plans for welding irradiated materials
- Weld procedure development and validation of system performance
- Irradiated material transfers
- Pre- and post- weld analysis activities

Both the Laser Beam Welding (LBW) system and the Friction Stir Welding (FSW) system were used in the initial weld trials on irradiated materials. Given the success of the trials, which is documented within, additional welding trials will be carried out in the near-term. Details of near-term projections are discussed. Prior weld procedure development and validation of system performance is discussed on multiple fronts, including the laser calibration that followed the laser system installation and the upgrade of the FSW control software that allows for dynamic changes in tool plunge depth during welding. Requirements for irradiated material transfers between buildings at ORNL, which significantly impacts program efficiency and cost, are outlined, and pre-weld preparation and post- weld characterization activities on irradiated coupons, which are critical to achieving and validating successful welding outcomes, are discussed as well.

2. WELDING OF IRRADIATED MATERIALS

Welding of irradiated materials in the advanced welding facility at REDC of ORNL was first accomplished on November 17, 2017. Prior to welding, irradiated coupons 304B-1, 304C-6, and 304D-1, which contained controlled levels of Boron at 5, 10, and 20 ppm levels (the Boron concentrations in this report are in weight ppm, represented simply by ppm), respectively, prior to irradiation, were transferred from Building 3025E to Building 7930 at ORNL. Material transfer details are highlighted in Section 3.1 of this report. The LBW system was selected for use first, on irradiated coupon 304D-1, which, following irradiation, is expected to contain a level of Helium (approximately 20 appm He by calculation; the Helium concentrations in this report are in atomic ppm, represented by appm) that is so elevated that successful weld repairs on this material would mark a significant step forward in the development of repair techniques for irradiated materials. Helium concentrations will be confirmed through further testing; planned post-weld evaluation activities are summarized in Section 3.1.1 of this report. Initial LBW trials on coupon 304D-1 tested multiple heat input levels and compared conventional laser welding with Auxiliary Beam Stress-Improved (ABSI) laser welding, which can proactively manage the stress state of the material in an attempt to prevent Helium induced cracking. Each laser weld was comprised of three layers of multiple passes, with layer 1 containing 10 passes, layer 2 containing 7 passes, and layer 3 containing 4 passes, for a total of 21 passes per weld. This multilayer, multi-pass method simulates a crack repair configuration which could be either a weld patch overlay or the backfilling of a groove created when a component is ground to remove the existence of a crack. Four welds were made on irradiated coupon 304D-1 (two welds per side), and this same layout will likely be used for additional LBW trials in the near-term. This layout of laser welds for irradiated coupons is shown in Figure 1. Spot welding with the LBW system is also used to create orientation marks that enable weld IDs to be tracked as welded coupons are transferred to other ORNL facilities for destructive testing. Table 1 displays the specific LBW parameters that were utilized for irradiated coupon 304D-1.

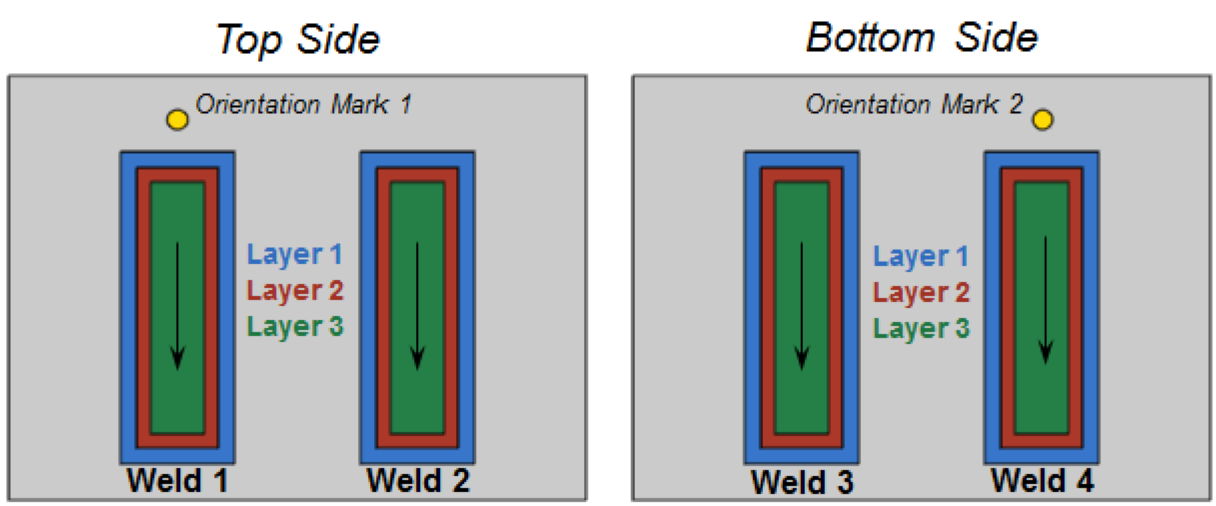


Figure 1. Weld Layout for LBW of Irradiated Coupons; Arrows Indicate the Welding Direction.

Table 1. LBW Parameters for Irradiated Coupon 304D-1.

	Weld 1	**Weld 2**	**Weld 3**	**Weld 4**
Welding Type	CV: conventional, ABSI, FW: filler wire (TURBALOY 308L)			
	CV, FW	ABSI, FW	CV, FW	ABSI, FW
Layer 1, No. of Passes: 10				
Pass Length (inch)	1.375	1.375	1.375	1.375
Weld Laser Power (Watts)	1000	1000	1000	1000
Travel Speed (inch/sec)	0.45	0.45	0.083	0.083
Wire Feed Speed (inch/min)	60	60	15 - 17	17 - 20
Scan Laser Program Name	N/A	No. 51	N/A	No. 51
Scan Laser Power (%)	0	100	0	18.4
Scan Beam Spot Size (mm)	N/A	7.5	N/A	7.5
Layer 2, No. of Passes: 7				
Pass Length (inch)	1.250	1.250	1.250	1.250
Weld Laser Power (Watts)	1000	1000	1000	1000
Travel Speed (inch/sec)	0.45	0.45	0.083	0.083
Wire Feed Speed (inch/min)	60	60	17	20
Scan Laser Program Name	N/A	No. 51	N/A	No. 51
Scan Laser Power (%)	0	100	0	18.4
Scan Beam Spot Size (mm)	N/A	7.5	N/A	7.5
Layer 3, No. of Passes: 4				
Pass Length (inch)	1.125	1.125	1.125	1.125
Weld Laser Power (Watts)	1000	1000	1000	1000
Travel Speed (inch/sec)	0.45	0.45	0.083	0.083
Wire Feed Speed (inch/min)	60	60	17	20
Scan Laser Program Name	N/A	No. 51	N/A	No. 51
Scan Laser Power (%)	0	100	0	18.4
Scan Beam Spot Size (mm)	N/A	7.5	N/A	7.5

Weld no. 1 and no. 2 were created with identical parameters, with the exception that weld no. 1 was made with conventional LBW technology and weld no. 2 utilized ABSI technology. Parameters for weld no. 3 and no. 4 were adjusted to have a higher heat input level when compared to weld no. 1 and no. 2, but the experimental methodology was repeated in that weld no. 3 and no. 4 have similar parameters (identical but for slight adjustments to wire feed speed that were made during welding to ensure process stability; these slight adjustments are not expected to significantly impact weld heat input) except that weld no. 3 was made with conventional LBW technology, and weld no. 4 utilized ABSI technology.

An image of the first pass of layer 1 of laser weld no. 1 on irradiated coupon 304D-1 is shown in Figure 2, as viewed through the primary camera on the laser system. An overview camera is available as well, which provides a wider view of the laser workpoint, including the coupon vise, gas cup, and wire feeder. Figure 3 shows synchronized images from the primary camera and the overview camera of the completion of pass 4 on layer 2 of weld no. 1 on irradiated coupon 304D-1.

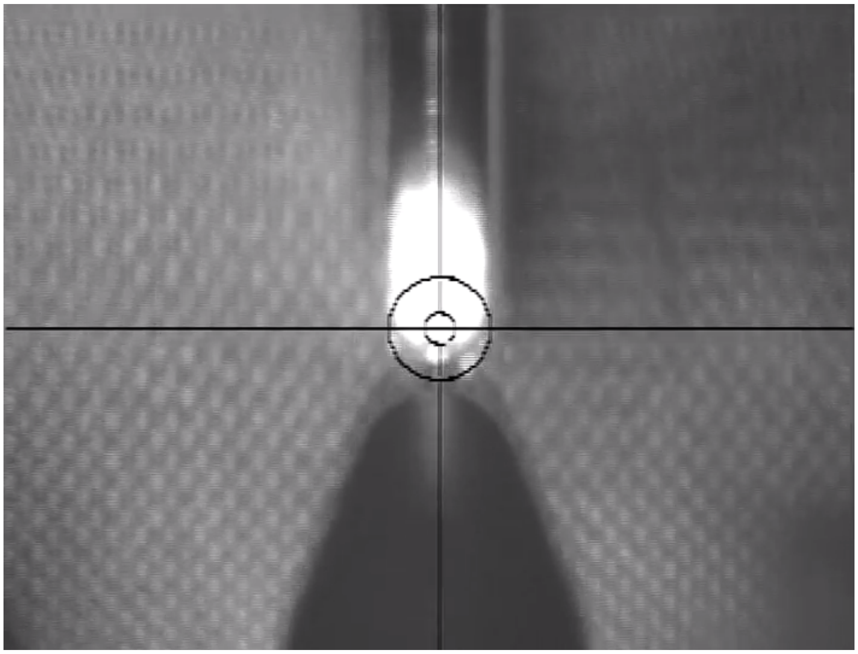


Figure 2. The First Laser Weld Pass to be Completed on Irradiated Material (Pass 1, Layer 1, Weld 1 on Coupon 304D-1) in the Advanced Welding Facility at REDC of ORNL.

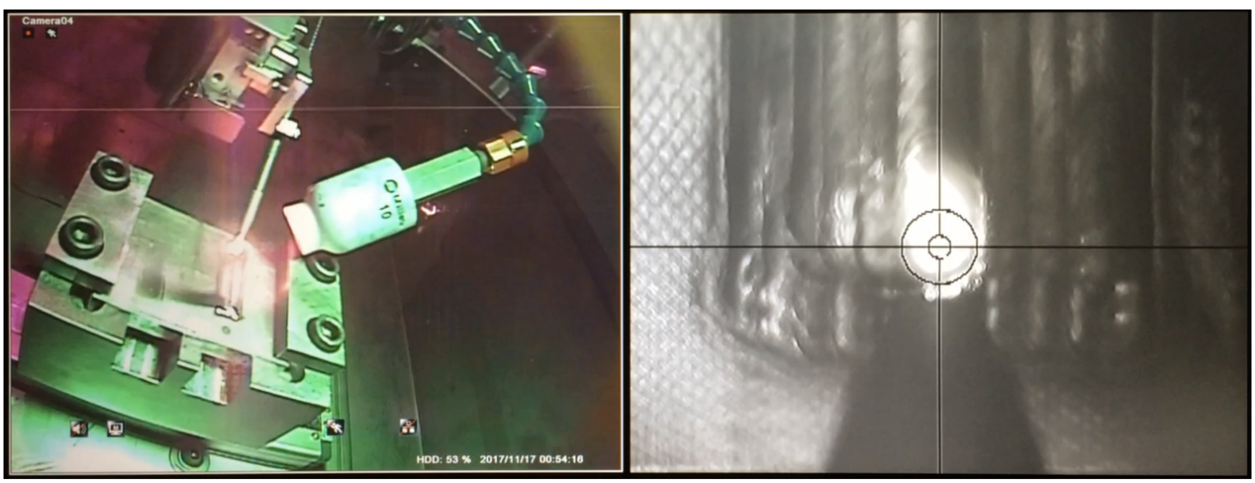


Figure 3. Completion of Pass 4 of Layer 2 of Weld 1 on Irradiated Coupon 304D-1; Overview Camera (Left) and Primary Camera (Right).

Laser welding continued until four welds had been completed on irradiated coupon 304D-1, which means that 84 total passes were made on the sample. Figure 4 displays an image of the completed tri-layer weld structure at the starting point of weld no. 2 on irradiated coupon 304D-1. No obvious cracking or porosity was observed in remote visual inspection that was conducted immediately following welding.

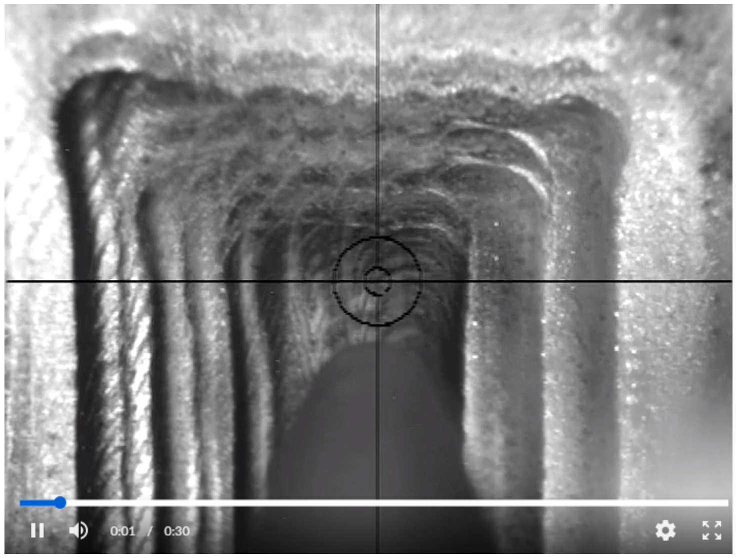


Figure 4. Starting Point of Weld 2 (Completed) on Irradiated Coupon 304D-1.

Figure 5 displays an overview of completed weld no. 1 and weld no. 2 on irradiated coupon 304D-1, as viewed through a spotting scope from the control room. The spot weld orientation mark, used to aid in tracking weld IDs, is visible as a dark, round spot adjacent to weld no. 1.

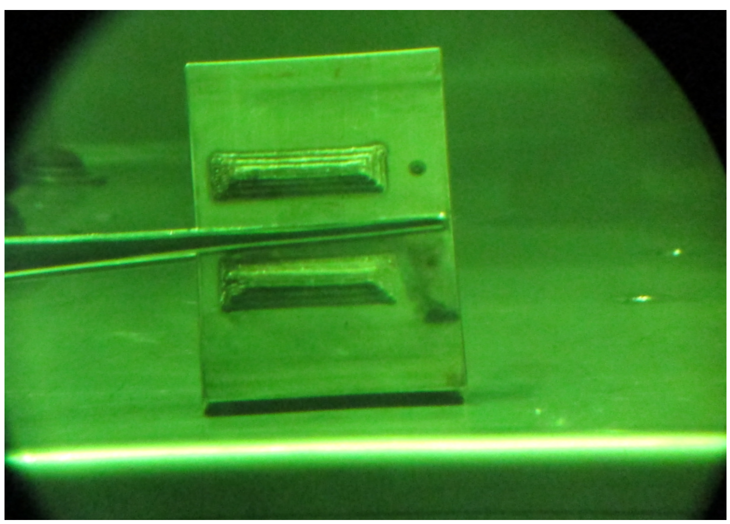


Figure 5. Completed Laser Welds 1 and 2 on Irradiated Coupon 304D-1; Welds 3 and 4 were Completed on the Other Side of the Coupon (Not Visible).

Following the LBW trials on irradiated coupon 304D-1, friction stir welding was performed on irradiated coupon 304C-6. The anticipated Helium content of coupon 304C-6 is approximately 10 appm He. A corner notch had been made in the coupon for sample removal for pre-weld analysis. This notch was orientated at the end of the weld. Conventional FSW involves only a single weld pass per coupon, and parameters for this weld pass are shown in Table 2. Additionally, unirradiated run-on and run-off tabs, of the same alloy (SS 304), were placed on the ends of the irradiated coupon to serve as locations for the tool plunge and retraction. This technique increases the overall weld length and increases the amount of welded, irradiated material this is available for post-weld analysis.

Table 2. FSW Parameters for Irradiated Coupon 304C-6.

Parameter	*Value*	*Units*
Starting Position	4.500 (x), 0.000 (y), 2.747 (z)	inch
Tool Rotation Rate	+400 (counter clockwise)	rev/min
Tool Tilt Angle	0	degrees
Welding Speed	0.033	inch/sec
Weld Path Z Travel	0.342	inch
Plunge Speed	0.004	inch/sec
Weld Length	4.0	inch

Figure 6 shows the weld in progress along with an overview of the completed weld, also shown in Figure 7 with the sample removed from the vise. The FSW system performed well, despite the existence of a small surface defect near the end of the weld, primarily on the unirradiated run-off tab. It is believed that this defect was caused by insufficient tool plunge depth at that location, an issue that can likely be corrected in subsequent weld trials. Interference from the pre-weld notch is possible but indeterminate. No obvious cracking or other flaws were observed.

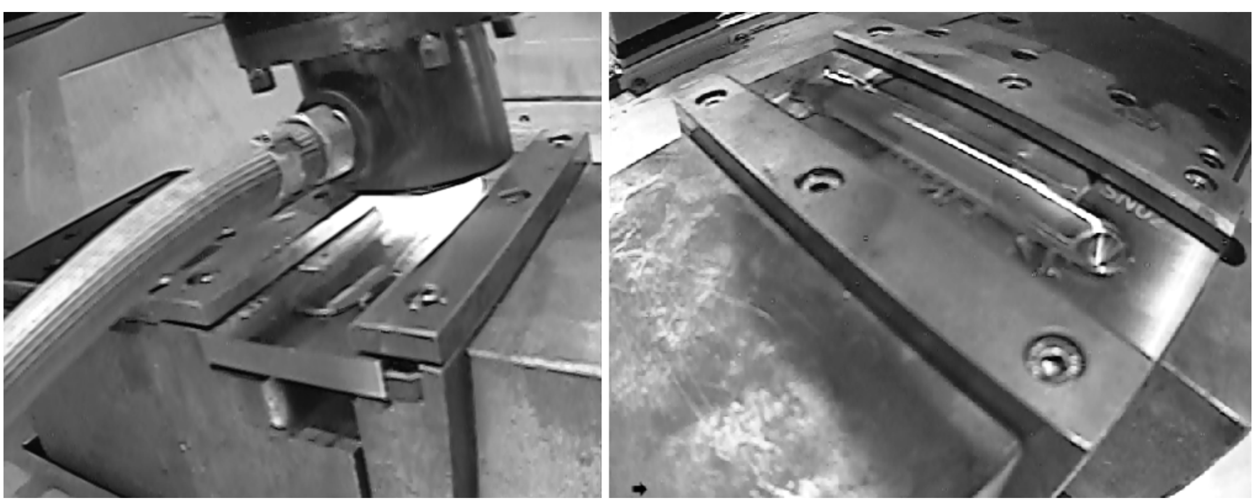


Figure 6. FSW on Irradiated Coupon 304C-6: In-Process (Left); Overview of Completed Weld (Right).

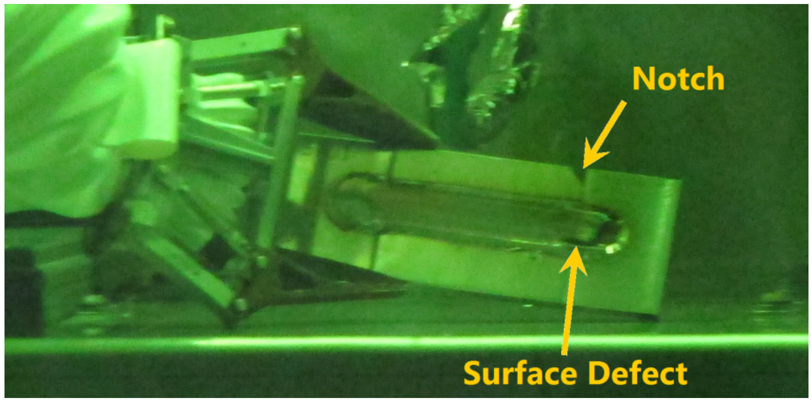


Figure 7. Completed Friction Stir Weld on Irradiated Coupon 304C-6 with Surface Defect and Pre-Weld Corner Notch Visible Near the End of the Weld.

2.1 Near-Term Plans with Irradiated Materials

Welding of irradiated materials will continue in the near term in order to complete welding on the first three irradiated coupons that were introduced to the welding hot cell facility, which have anticipated Helium concentration levels of 5, 10, and 20 appm He based on initial Boron concentrations prior to irradiation. It is anticipated that FSW will be utilized on the third coupon (304B-1) in order to attempt parameter adjustments to produce a defect-free weld. Once complete, the coupons will be transferred from Building 7930 to Building 3025E on the ORNL campus for post-weld examination and cutting of metallographic cross-sections. Section 3.1 in this report highlights the material transfers that are required for this program, and Section 3.1.1 covers the post-weld analyses that are initially planned in order to qualify the performance of the welding processes on irradiated material. Post-weld analysis will guide the decision making process in terms of modifications to welding parameters for improving welding outcomes, particularly if defects are observed in the initial weld trials. For laser welding, this will likely mean further utilization of the Auxiliary Beam Stress-Improved laser welding capabilities for management of the stress-state of the material during welding. Additional friction stir welding of irradiated coupons will follow as well, at initial He concentration levels that are higher and lower than the levels tested so far. After conventional FSW is tested and characterized, the FSW variant known as Friction Stir Cladding (FSC) will be tested on irradiated materials as well (in the long term). FSC can be used to bond a thin layer of unirradiated material to the surface of an irradiated substrate and is a promising technology for repair of degraded materials.

2.2 Prior Weld Procedure Development and Validation of System Performance on Unirradiated Materials

Weld procedures for laser welding and friction stir welding irradiated stainless steels and nickel-base alloys have been developed over the course of a years-long effort. Significant resources have been devoted to developing weld processes and tailoring them to the specific application of nuclear repair welding. System and component level design, construction, and installation followed that yielded a unique facility for enabling direct testing of the weld processes on irradiated material. Recently, and prior to welding irradiated materials, final adjustments were made to the laser and friction stir welding subsystems that included validation of system performance on unirradiated surrogate materials. As system validation was being carried out, formal procedural documents were finalized that would support and guide personnel operating the welding equipment in Building 7930 Cell C. The approved procedures for laser welding and friction stir welding are shown in Appendices A and B, respectively, and are supplemented by detailed equipment operation manuals.

2.2.1 Laser Calibration and Welding on Unirradiated Materials

The Laser Welding System used within the ORNL hot cell cubicle incorporates the simultaneous use of two lasers when performing welding operations. As its name implies, the weld laser (powered via the YLS-1500 power supply) is used solely for performing the weld, and has a maximum output power of 1500 Watts. The scan laser (powered via the YLS-2000 power supply), which is rapidly scanned to create prescribed patterns, is used to perform in-situ post-heating operations on the back side of the weld pool (the temperature of post-heating is pattern dependent, but it is below the melting temperature and does not affect the size of the weld pool). This scan laser has a maximum output power of 2000 Watts. The calibration procedures for both laser systems were performed professionally by the laser manufacturer (IPG) to ensure the beam quality prior to the welding experiments. The actual output power levels were adjusted to match the set points. The resultant output powers as a function of set point for both laser systems are listed in Table 3. The beam profiles were also measured as shown in Figure 8.

Table 3. Actual Output Laser Power vs. Set Points for YLS-1500 (Left) and YLS-2000 (Right).

Displayed Power at 10%	10
Measured Power at10%	24
Displayed Power at 20%	240
Measured Power at20%	230
Displayed Power at 30%	410
Measured Power at30%	388
Displayed Power at 40%	580
Measured Power at40%	545
Displayed Power at 50%	740
Measured Power at50%	695
Displayed Power at 60%	920
Measured Power at60%	854
Displayed Power at 70%	1080
Measured Power at70%	1006
Displayed Power at 80%	1240
Measured Power at80%	1159
Displayed Power at 90%	1420
Measured Power at90%	1314
Displayed Power at 100%	1570
Measured Power at 100%	1468

Displayed Power at 10%	10
Measured Power at10%	23
Displayed Power at 20%	300
Measured Power at20%	290
Displayed Power at 30%	530
Measured Power at30%	506
Displayed Power at 40%	760
Measured Power at40%	716
Displayed Power at 50%	990
Measured Power at50%	932
Displayed Power at 60%	1220
Measured Power at60%	1142
Displayed Power at 70%	1440
Measured Power at70%	1358
Displayed Power at 80%	1670
Measured Power at80%	1563
Displayed Power at 90%	1890
Measured Power at90%	1776
Displayed Power at 100%	2100
Measured Power at 100%	1980

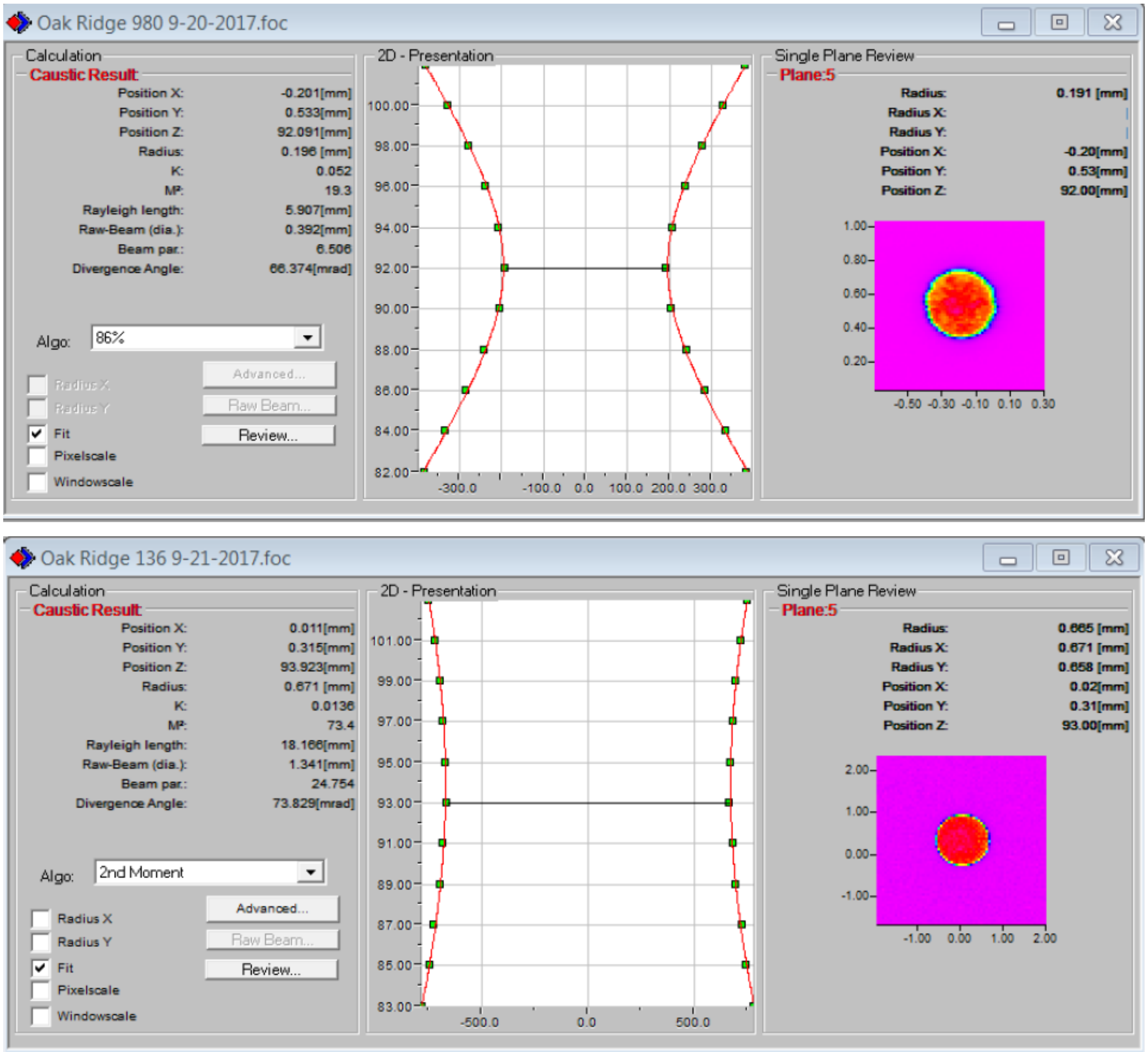


Figure 8. Measured Beam Profiles for both Welding (YLS-1500, Top) and Scanning Lasers (YLS-2000, Bottom); Profiles Represent the Focus of the Stationary (No Splitting or Scanning) Beam; Vertical Axis is Along the Beam Direction; Horizontal Axis is Along the Transverse Direction; Profiles Represent the Convergence and Divergence of the Beam Near the Focal Point.

Laser welding system tests and initial welding on unirradiated (cold), surrogate 304 stainless steel followed the laser system calibration. These activities represented a significant step in the development of the hot cell welding facility. The laser welding system tests included testing of the following components and capabilities:

- Connections between the laser and the controller
- Interlock safety switches and E-stops
- The camera on the laser head

- Laser focus and scanning patterns

Initial cold weld testing trials were carried out that included the following actions:

- Mounting/unmounting weld coupons on the vise by manipulators
- Tightening/untightening the bolts by manipulators
- Adjusting wire feeder position through the camera
- Welding on cold 304 stainless steel plates without the scanning laser beam

Figure 9 displays the laser vise into which weld coupons must be mounted and unmounted and the four bolts which must be tightened and untightened using manipulators, in addition to the wire feeder and the gas cup. Figure 9 also displays an image captured during the initial welding trials.

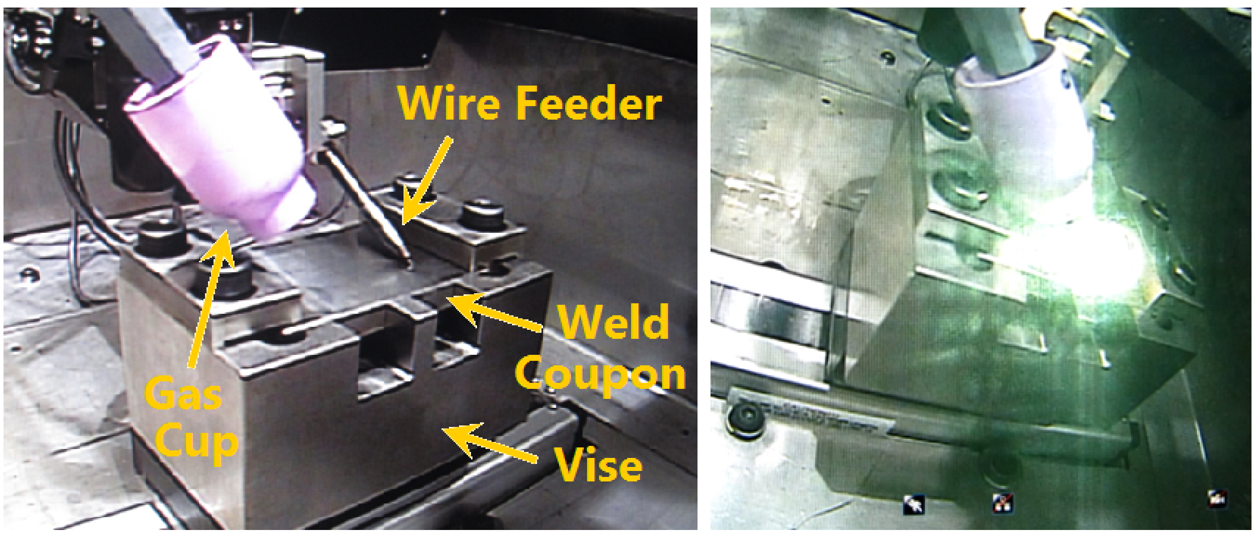


Figure 9. Laser Work-Point: Visible are the Vise with Cold Weld Coupon Inserted, Wire Feeder, and Shield Gas Cup (Left), Laser Weld Testing (Right).

Following the initial laser welding trials, which gave confidence that the full system functionality had been achieved post-installation and calibration, further welding was carried out to simulate the complete welding of a coupon, which included four multi-layer welds (two on each side of the coupon) as well as spot weld orientation marks that will allow weld IDs to be tracked as the coupon is moved to other facilities for post-weld analyses. Use of the scan laser was included in these tests as well. The system performed very well, and the completed weld coupon is shown in Figure 10. Each weld is comprised of three layers, and each layer is composed of multiple passes, with ten passes in the first layer, seven passes in the second layer, and four passes in the third layer, for a total of 21 passes per weld. Primary laser beam power, scan laser power, welding speed, and wire feed speed were varied to simulate the multiple test conditions that are being used on irradiated materials.

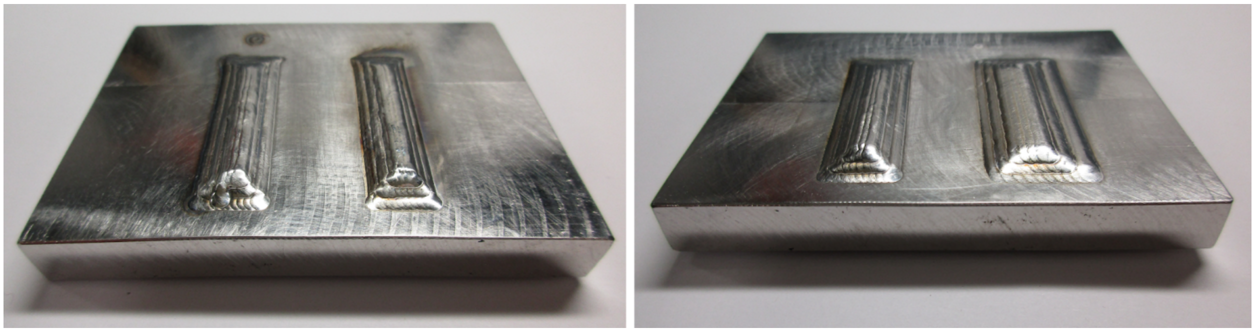


Figure 10. Unirradiated 304 Stainless Steel Laser Welded Coupon: Welds 1 and 2 on the Top (Left), Welds 3 and 4 on the Bottom (Right).

2.2.2 Friction Stir Welding Control Software Upgrade

Start-up testing of the FSW system in the cubicle and completion of the transition from a force-based control system to a position-based control system were documented in refs [1] and [2]. One of the aspects of system operation with the potential for improvement that was highlighted in prior documentation was the control of tool plunge depth during welding. It was desired to have capabilities for dynamic changes in tool plunge depth during welding, either through a planned path technique or through manual adjustments made by the operator. Tool plunge depth is critically important in FSW and can impact weld penetration, defect formation, tool wear, heat generation, and resulting weld properties. In general, inadequate control capabilities can lead to problems when inconsistent workpiece dimensions, thermal expansion, robot deflection due to high process forces, or complex geometries are encountered. The software upgrade for enabling dynamic changes in tool plunge depth during welding was completed in August 2017. Weld testing followed that confirmed the functionality of the system. Weld parameters for test welds 020, 021, and 022 on unirradiated material (304 SS) are shown in Table 4.

Table 4. FSW Parameters for Test Welds Following Software Upgrade.

Parameter	*Value*	*Units*
Starting Position	4.500 (x), 0.000 (y), 2.750 (z)	inch
Tool Rotation Rate	+400 (counter clockwise)	rev/min
Tool Tilt Angle	0	degrees
Welding Speed	0.033	inch/sec
Weld Path Z Travel	0.339	inch
Plunge Speed	0.005	inch/sec
Weld Length	4.0	inch

Welds 020 and 021 were completed with the same, fixed tool plunge depth throughout the welding process to confirm the continued functionality of prior capabilities. On weld 022, the XZ Table, which was added to the software as part of the upgrade, was utilized to increase plunge depth during welding. The XZ Table allows for changes in tool plunge depth at prescribed values of position in the X-axis (along the weld length). Plunge depth was increased by 0.002 inch when the tool reached the 3.000 inch point along the weld length, and by another 0.003 inch, for a total of 0.005 inch, at the 3.500 inch point along the weld length. A screenshot of the XZ Table inputs for accomplishing this planned-path is shown in Figure 11.

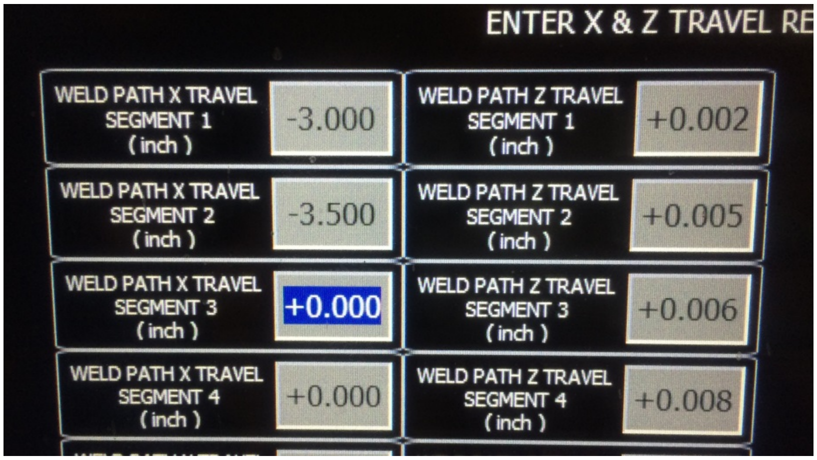


Figure 11. XZ Table for Enabling a Planned-Path of Tool Plunge Depths

The [+0.000] input as a Weld Path X Travel Segment stops the program's use of the XZ Table so that no further changes will be made to plunge depth during the present weld. The welder operated as intended for Weld 022, and the system response was verified via the output data of the welder. This includes the axis positions, which are derived from motor encoder feedback signals, and the motor current signals, indicative of machine movement and load. Figure 12 shows the Weld 022 response data.

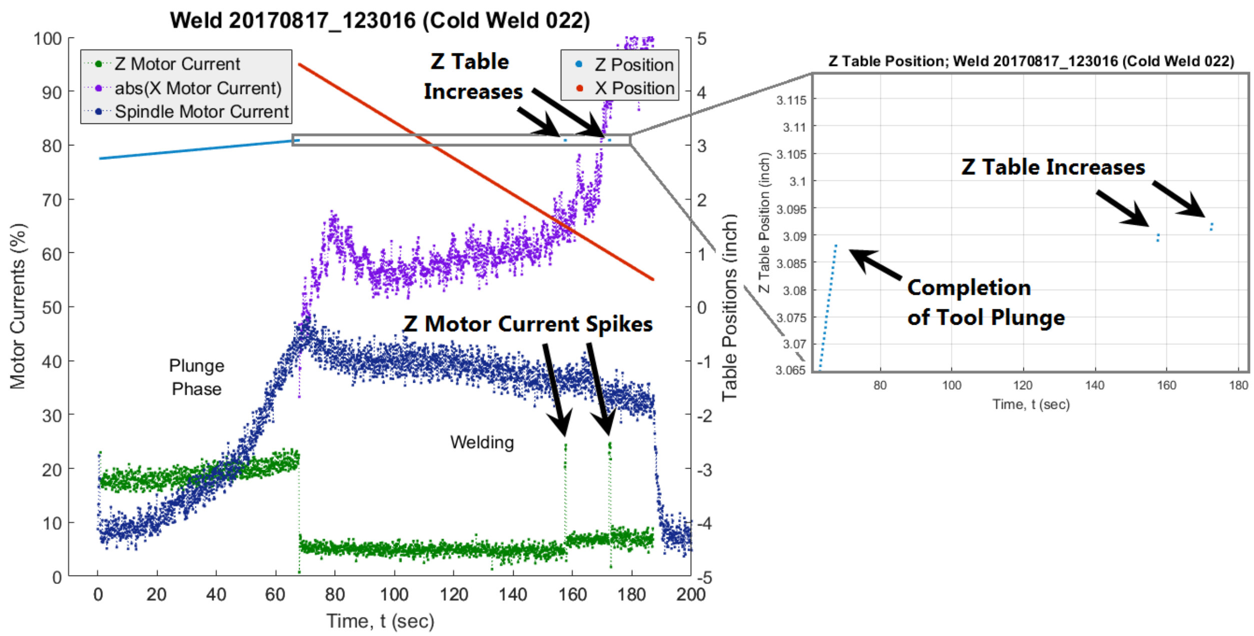


Figure 12. Weld 022 Response Data.

The Z table increases and Z motor current spikes visible in Figure 12 confirmed that the welder was performing the pre-programmed changes to tool plunge depth. The capability for manual changes to tool plunge depth during welding was also verified. Given the success of the software upgrade, the FSW system is well-positioned for the beginning of welding on irradiated materials.

3. MATERIALS

Model materials for initial research and development efforts were produced by doping special heats of 304L and 316L stainless steel with controlled levels of boron and subsequently irradiating the samples in the High Flux Isotope Reactor (HFIR) at ORNL. Helium is produced from boron and nickel (in a two-step reaction) due to neutron capture and decay, yielding test samples with controlled levels of helium, enabling the simulation of reactor structural internal components that have been in-service for decades. Initial anticipated helium concentrations within the first round of irradiated samples range from approximately 1 - 33 appm helium. An additional irradiation campaign has also included Ni-182 alloy, and a future campaign will yield helium concentrations at even higher levels. Post irradiation (pre-weld) examination of weld coupons has included transmission electron microscopy and atom probe tomography, and some of the initial materials characterization results are summarized in ref [3].

3.1 Irradiated Material Transfers and Pre- and Post-Weld Activities

Significant consideration has been given to irradiated material transfers for this program. Material transfer requirements will greatly impact overall efficiency and cost for the program. Following irradiation in HFIR, weld coupons are transferred between multiple buildings on the ORNL campus for post-irradiation examination, welding, and post-weld evaluation activities. A simplified flowchart of these transfers is shown in Figure 13.

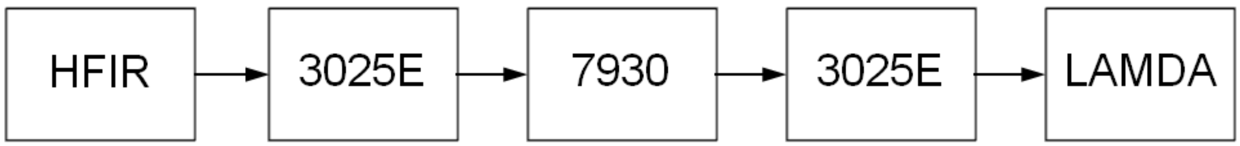


Figure 13. Weld Coupon Transfers between Facilities at ORNL

Weld coupons are irradiated in HFIR for three cycles and then are temporarily kept in storage racks in the HFIR pool to allow the decay of short half-life isotopes produced during irradiation prior to transfer out of the reactor facility. Coupons are transferred to Building 3025E for post-irradiation examination and for unloading of the wet cask used for transportation. Figure 14 shows one of the first irradiated coupons to arrive at Building 3025E for post-irradiation examination on a remote monitor for an in-cell camera system.

Figure 14. Weld Coupon Undergoing Post-Irradiation Examination at ORNL Building 3025E. Coupon Dimensions are 3 inch x 2.2 inch x 0.35 inch.

Coupon transfer to Building 3025E prior to welding, rather than directly to Building 7930, is primarily necessitated due to restrictions on Building 7930 receiving wet casks from the HFIR pool, but transfer to Building 3025E has also provided the opportunity for pre-weld surface preparation and cleaning and the cutting of small slices from coupons and subsequent transfer of slices to the Low-Activation Materials Development and Analysis (LAMDA) laboratory in Building 4508 for pre-weld characterization. Custom coupon transfer baskets were designed and fabricated for the weld repair program to enable efficient transfer of coupons from the HFIR pool to Building 3025E. Figure 15 displays the 3D rendering of the transfer basket design as well as the completed assembly. The basket allows for organized loading, flexibility with respect to coupon orientation, and the transfer of the entire contents of an irradiation holder (15 coupons) at one time. Fabrication of the baskets is complete.

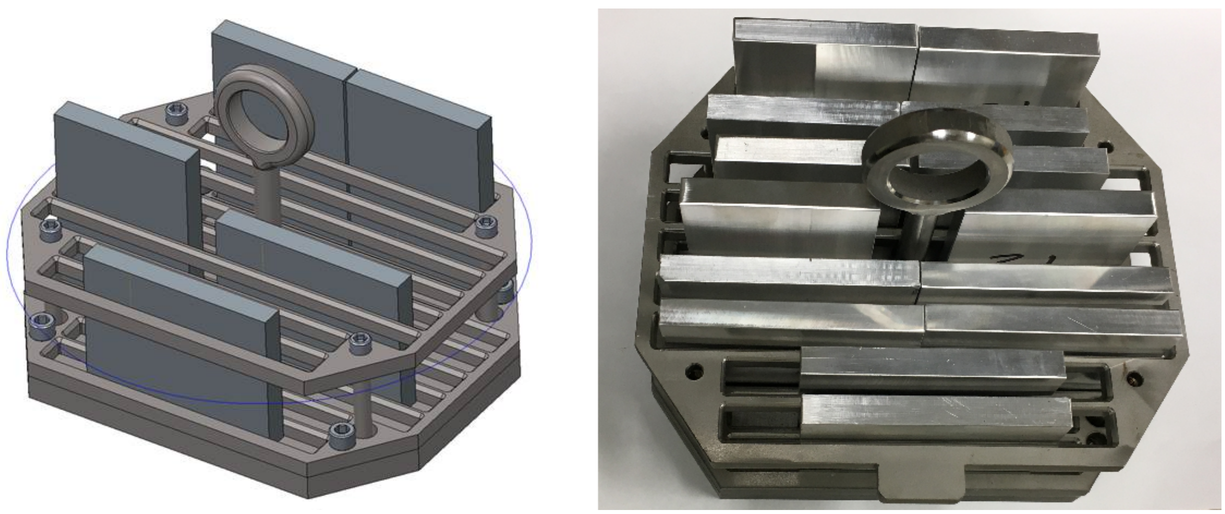


Figure 15. Weld Coupon Transfer Basket: Concept (Left) and Completed with Dummy Coupons (Right).

All actions taken on weld coupons, such as pre-weld cutting of slices or sanding with silicon-carbide paper and cleaning with alcohol at Building 3025E, are documented on coupon travelers that move from building to building with the coupons. Four coupons have had slices cut from a corner for pre-weld characterization (304C-6, 304E-4, 316C-6, 316E-3), and the first three coupons that were transferred to Building 7930 for welding (304B-1, 304C-6, 304D-1) were prepped for welding by sanding and cleaning on September 20, 2017. Figure 16 shows the operator view of coupons during preparation work at Building 3025E and the pre- and post- sanding and cleaning surface appearance of coupon 304B-1, as viewed through a scope. The preparation activity removes a majority of any scale or oxidation present on the coupon surface and re-exposes the machining marks.

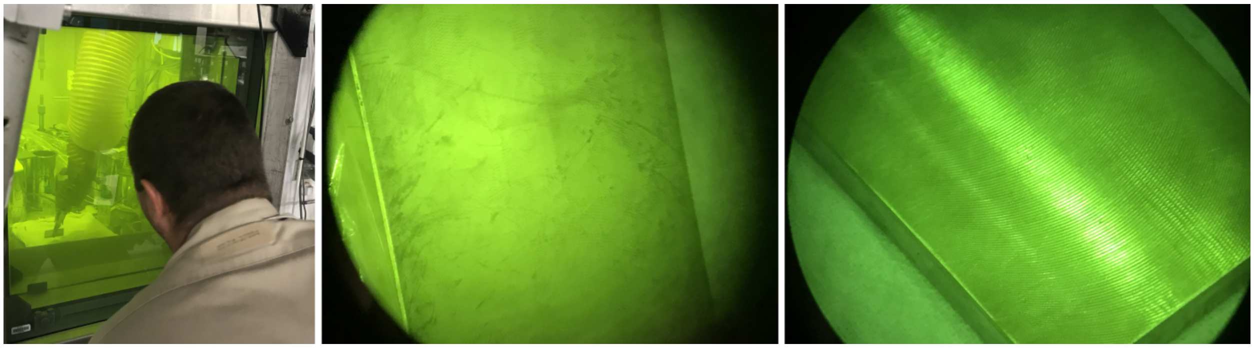


Figure 16. Pre-Weld Coupon Prep at Building 3025E (From Left to Right): Operator View of Coupon, Coupon 304B-1 Prior to Sanding and Cleaning, Coupon 304B-1 after Sanding and Cleaning.

After pre-weld coupon prep at Building 3025E, coupons are shipped to Building 7930 at the HFIR complex for welding, as they are needed. These transfers will typically be batch shipments of three coupons, which is the physical capacity of the shielded storage that is integrated in the work table in Cell C, adjacent to the welding cubicle. Transfers between cells of Building 7930 and transfers into and out of the welding cubicle in Cell C are handled by operations personnel using remote material handling equipment, include a PaR robotic transfer system and master-slave manipulators. These transfers were successfully demonstrated in a 'dry run' prior to introducing irradiated materials in the facility with an empty transfer cask and unirradiated surrogate coupons. After a welding campaign is completed at Building 7930, which can include limited visual inspection of welds using the cubicle or work table camera systems, welded coupons are shipped back to Building 3025E for further inspection and sectioning to produce metallographic specimens for analysis in LAMDA. Metallographic specimens from welded coupons are transferred to LAMDA in Building 4508 once it is verified that the specimens conform to the radiological limits (dose rate below 100 mR/hr/ft) required by the facility.

3.1.1 Post-Weld Evaluation Activities in LAMDA

Weld characterization activities in LAMDA may include, but not be limited to, further trimming or sectioning of specimens if necessary, sample mounting, grinding, polishing, optical microscopy to examine weld structure and identify cracking or other defects, focused ion beam extraction of foils or atom probe tomography needles, transmission electron microscopy, thermal desorption spectroscopy of base material to measure helium concentration, electron backscatter diffraction analysis, tensile bar machining and testing, and microhardness evaluation. Together these analyses will yield a comprehensive picture of the post-irradiation material properties, the impact of subsequent welding on microstructure and mechanical properties, and an assessment of the ability of the advanced welding processes to make crack-free repairs on highly irradiated, helium containing materials.

4. SUMMARY

The first welds on irradiated materials were recently completed in the advanced welding facility at REDC of ORNL. Irradiated samples with Boron concentrations of 10 and 20 ppm prior to irradiation were welded with the friction stir and laser welding subsystems, respectively. Immediate post-weld visual inspection did not reveal any obvious surface defects that would be related to Helium induced cracking, the primary technical challenge being addressed. Further welding of irradiated materials will continue in the near-term, after which irradiated welds will be transferred to other facilities at ORNL for extensive, destructive post-weld analyses. Results will guide decisions related to weld parameter modifications for further irradiated materials welding. This recent effort marks a significant step forward in the mission to develop and validate advanced welding technologies for repair of irradiated reactor components and to transfer those technologies to industry.

REFERENCES

[1] Z. Feng, W. Tang, R.G. Miller, B.T. Gibson, et al., Report on the installation of the integrated welding hot cell at Oak Ridge National Laboratory building 7930, U.S. Department of Energy, Office of Nuclear Energy, Light Water Reactor Sustainability Program, Milestone Report, ORNL/TM-2017/255, June 2016.

[2] W. Tang, B.T. Gibson, Z. Feng, S.R. Clark, et al., Report detailing friction stir welding process development for the hot cell welding system, U.S. Department of Energy, Office of Nuclear Energy, Light Water Reactor Sustainability Program, Milestone Report, ORNL/TM-2017/256, Sept 2016.

[3] Z. Feng, R.G. Miller, N. Cetiner, X. Hu, et al., Report Summarizing the Status of Second Round Irradiation Experiments and Assessment of Materials Available for Testing Advanced Welding Techniques, U.S. Department of Energy, Office of Nuclear Energy, Light Water Reactor Sustainability Program, Milestone Report, July 2017.

Appendix A

Approved Laser Welding Procedure

(Accompanying Operations Manual not Shown)

STANDARD OPERATING PROCEDURE

Title: Advanced Laser Welding Procedures in Hot Cell Welding Cubicle

Prepared by:	Jian Chen Jian Chen, Staff Member Materials Processing and Joining Group	Date	9/15/17
Approved by:	J. Allen Haynes Allen Haynes, Group Leader Materials Processing and Joining	Date	9/15/17
QA Approval:	MCVance Mark C. Vance, Quality Representative Performance Analysis and Quality	Date	9/15/17
DSO Approval:	Tracy Strader Tracy W. Strader, Research Support Group Leader Materials Science and Technology Division	Date	9/25/2017
Building 7930 Approvals:	Allen Smith Allen W. Smith, REDC Facility Manager Non-Reactor Nuclear Facilities Division	Date	9/26/2017
	C. Scott White C. Scott White, 7930 Hot Cell Operations Supervisor Non-reactor Nuclear Facilities Division	Date	9/27/2017

1 Purpose

Develop advanced laser welding techniques and methods to repair highly irradiated materials for existing nuclear power plant operational lifetime extension beyond 60 years.

2 Scope

The activities described in this procedure are to be conducted in the welding cubicle located in

Building 7930. Current planned activities will be conducted using the steps provided in the attached document entitled *ORNL Cubicle Laser Welding Systems Operations Manual.*

3 Environmental, Safety and Health (ES&H) Concerns

- Irradiated materials are involved.
- Laser beam is used.
- Laser-induced melting will result in high temperatures.

Note: Identification and mitigation of risks associated with the described activities are under the purview of subject matter experts affiliated with the Non-reactor Nuclear Facilities Division (NNFD) responsible for work control activities in Building 7930. All activities shall comply with mandated requirements invoked for the facility.

Note: Operation of breakers and electrical disconnect devices must be in compliance with the SBMS Procedure, Operate Circuit Breakers, Disconnect Switches and Motor Starters Rated up to 600V Controls:

- Complete Operating Circuit Breakers, Disconnect Switches and Motor Starters (Rated Up to 600V) Training and Practical.
- PPE Hazard / Risk Category 0 includes long sleeve non-melting or untreated natural fiber shirt, long non-melting or untreated natural fiber pants, safety glasses or safety goggles, hearing protection (ear plugs), and heavy-duty leather gloves. All undergarments must also be made of non-melting or untreated natural fiber.

Note: Non-melting or untreated natural fiber includes untreated cotton, wool, rayon, silk, or blends of only these materials. ORNL "Khakis" or "Blues" are acceptable

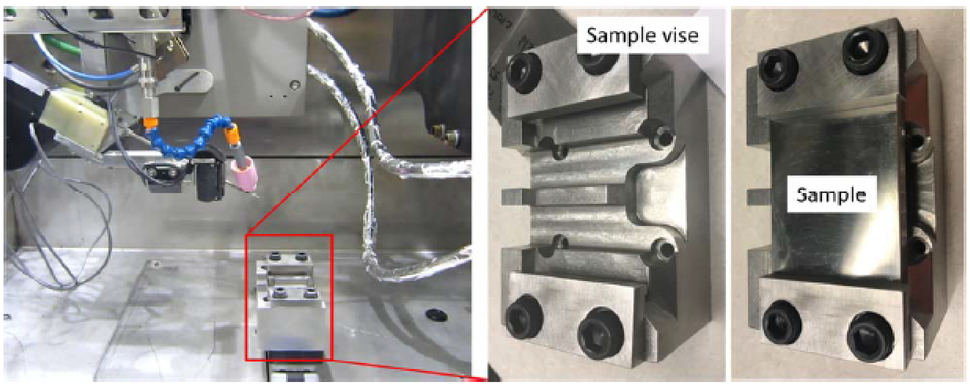
4 Responsibilities

Project personnel from the Materials Science and Technology Division are responsible for oversight of the welding operations described in this procedure. Personnel from NNFD are responsible for ensuring compliance with imposed operational, environmental, safety, health, radiological control and other mandates necessary to comply with facility baseline requirements.

5 Procedural Steps – **Advanced laser welding in hot cell**

Procedural steps for this activity will be found in the attached document entitled *ORNL Cubicle Laser Welding Systems Operations Manual.*

Note: The sample vise will be permanently installed/mounted on the translation stage before welding irradiated materials.



Note: Any deviation from the depicted design of the sample vise and its use – including alternatives for sample fixturing and mounting – shall be documented on the associated traveler required for each weld.

Sample installation procedure:

1. Untighten the four bolts on the sample vise as shown in the figure above.
2. Slide the sample into the vise from right to left.
3. Tighten the four bolts on the sample vise.

Sample removal:

1. Untighten the four bolts on the sample vise.
2. Remove the sample out of the vise from left to right.

6 Quality Assurance

The activities described in this procedure are planned, conducted, and documented in accordance with Document #QAP-ORNL-NR&D-01, Revision 0 entitled *Quality Assurance Plan for Nuclear Research and Development Conducted at the Oak Ridge National Laboratory*.

7 Records

A welding traveler form shall be completed for the welding of each set of coupons.

STANDARD OPERATING PROCEDURE

Review Record

- Required once every 5 years as a minimum
- Signatures indicate adequacy of this document for activity

1st Re-Review

MP&J Group Leader	Date
MST Division Safety Officer	Date

2nd Re-Review

MP&J Group Leader	Date
MST Division Safety Officer	Date

Appendix B

Approved Friction Stir Welding Procedure

(Accompanying Operations Manual not Shown)

STANDARD OPERATING PROCEDURE

Title: Friction Stir Welding Procedures and Maintenance in Hot Cell Welding Cubicle

Prepared by: Wei Tang — Date 9/7/17
Wei Tang, Staff Member
Materials Processing and Joining Group

Approved by: J Allen Haynes — Date 9/8/17
Allen Haynes, Group Leader
Materials Processing and Joining

QA Approval: MCVance — Date 9/7/17
Mark C. Vance, Quality Representative
Performance Analysis and Quality

DSO Approval: Tracy Strader — Date 9/7/17
Tracy W. Strader, Research Support Group Leader
Materials Science and Technology Division

REDC Approvals: Allen Smith — Date 9/11/17
Allen W. Smith, REDC Facility Manager
Non-reactor Nuclear Facilities Division

C. Scott White — Date 9/13/17
C. Scott White, 7930 Hot Cell Operations Supervisor
Non-reactor Nuclear Facilities Division

1 Purpose

Develop friction stir welding and friction stir cladding to repair highly irradiated materials for existing nuclear power plant operational lifetime extension beyond 60 years.

2 Scope

The activities described in this procedure are to be conducted in the welding cubicle located in Building 7930 and includes the following activities.

- Setup for friction stir welding
- Friction stir welding of irradiated metals
- Friction stir cladding of irradiated metals.
- Friction stir welder maintenance.

3 Environmental, Safety and Health (ES&H) Concerns

- Irradiated materials are involved.
- High temperature in welded materials and welding tools.

Note: Identification and mitigation of risks associated with the described activities are under the purview of subject matter experts affiliated with the Non-reactor Nuclear Facilities Division (NNFD) responsible for work control activities in Building 7930. All activities shall comply with mandated requirements invoked for the facility.

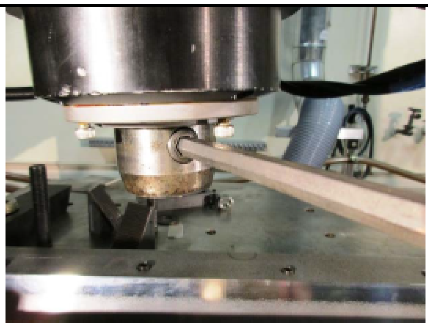
4 Responsibilities

Project personnel from the Materials Science and Technology Division are responsible for oversight of the welding techniques and operations described in this procedure. Personnel from NNFD are responsible for ensuring compliance with imposed operational, environmental, safety, health, radiological control and other mandates necessary to comply with facility baseline requirements.

5 Procedural Steps - **Friction stir welding in hot cell**

5.1 Install the FSW tool on the tool holder

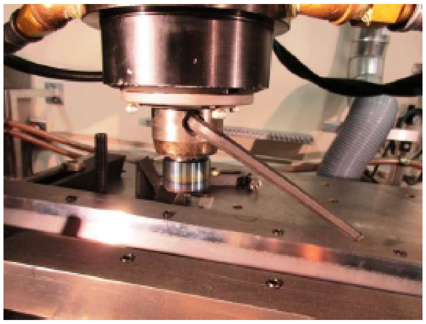
1. Move the welding table down to a proper location so that there is enough vertical space to install the FSW tool on the tool holder.
2. Turn off the controller power.
3. Lockout/Tagout the electrical power switch.
4. Place a thick damping layer on the vise or table at the location underneath the FSW tool.
5. Turn the spindle to a location that the setscrew can be seen and easily accessed.
6. Use a 5/16” hex wrench to release the setscrew on the tool holder so that the tool can be inserted in the holder.



7. Place the tool shank into the tool holder and make sure that the flat on the tool shank faces to the setscrew.

8. Push the tool all the way into the tool holder until it stops.

9. Tighten the setscrew.



10. Check the FSW tool position.
11. Remove the thick damping layer.
12. Release the Lockout/Tagout.

5.2 Clamp FSW coupon with the vise

1. Open the vise jaw wide enough to accept the friction stir welding (FSW) tabs and coupon.
2. Check the vise and jaw for any remaining material from previous work such as chips and particles.
3. Take the first tab, check and record the tab number.
4. Place the first tab into the vise jaw clamp and move it against to the stop along the FSW traveling direction.
5. Take the coupon, check and record coupon number.
6. Place the coupon into the vise jaw clamp and move it against to the first tab.
7. Take the second tab, check and record the tab number.
8. Place the second tab into the vise jaw clamp and move it against to the coupon.
9. Check tabs and coupon positions without tightening the vise.
10. Tighten the vise by turning the handle clockwise. Enough torque needs to be reached to clamp the coupons and tabs firmly.
11. Check tabs and coupon after tightening the vise.

5.3 Clamp FSC coupon with the vise

1. Open the vise jaw wide enough to accept the friction stir welding (FSW) tabs and coupon.

2. Check the vise and jaw for any remaining material from previous work such as chips and particles.
3. Take the first tab, check and record the tab number.
4. Place the first tab into the vise jaw clamp and move it against to the stop along the FSW traveling direction.
5. Take the coupon, check and record coupon number.
6. Place the coupon into the vise jaw clamp and move it against to the first tab.
7. Take the second tab, check and record the tab number.
8. Place the second tab into the vise jaw clamp and move it against to the coupon.
9. Check tabs and coupon positions without tightening the vise.
10. Move the vise jaw close to the coupon and tabs but without direct contact.
11. Release set screws on top of both vise jaw at the clamping ends.
12. Get the cladding metal sheet, check and record.
13. Slide the cladding metal sheet into the clamping vise on top of the coupon and tabs.
14. Tighten the vise by turning the handle clockwise. Enough torque needs to be applied to clamp the coupons and tabs firmly.
15. Tighten set screws on top of both vise jaw at the clamping ends
16. Check tabs, coupon and cladding sheet.

5.4 FSW process*

1. Turn on FSW controller power.
2. Plug in a USB drive to the controller for recording welding data files.
3. Choose FSW control panel.
4. Input or verify FSW control parameters, including home position, rotational speed, welding speed, plunge in depth, and welding distance.
5. Move the welding table to the home position.
6. Turn on the coolant and Ar cover gas.
7. Run the FSW program.
8. Adjust FSW parameters manually if it is necessary during the FSW process.
9. When the FSW is completed, turn off the Ar cover gas.
10. When work is completed for the day, turn off the coolant and turn off the controller power.
11. Take out the USB drive to download welding data files.

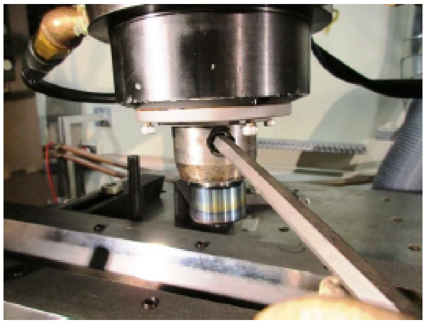
* **Detailed friction stir welder operation steps are provided in "Friction Stir Welder Operating Manual – Appendix A"**

5.5 Release FSW coupon from the vise

1. Release the vise by turning the handle counter clockwise and loosen contact between the moving jaw and the welded coupon.
2. Take the FS welded tabs and coupon out.
3. Check the welded coupon and record.
4. Check if the vise contains loose debris remaining from the FSW. Clean the vise if there is any loose debris remaining from the FSW.
5. Move the vise jaw back to a proper location.

5.6 Remove FSW tool from the tool holder

1. Move the welding table down to a proper location so that there is enough vertical space to take out the FSW tool.
2. Turn off the controller power. Lockout/Tagout the electrical power switch.
3. Place a thick damping layer on the vise or table at the location underneath the FSW tool.
4. Turn the spindle to a location that the setscrew can be seen and easily accessed.



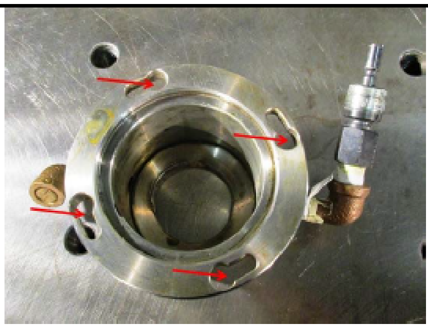
5. Use a 5/16" hex wrench to release the setscrew on the tool holder. (Hold the FSW tool during the process if it is possible)

6. Take the FSW tool out of the tool holder.

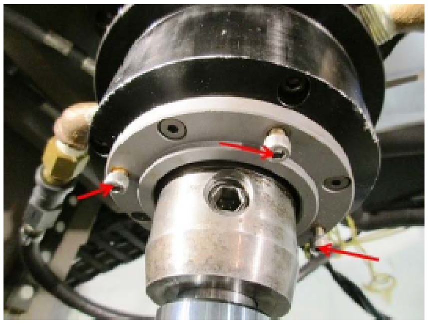
7. Release the Lockout/Tagout.

5.7 Install the cover gas cap on the tool holder

1. The cover gas cap has four slots at the flange.

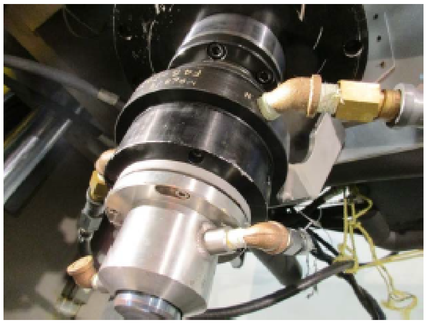


2. There are four screws on the bottom of the tool holder. Release them so that the cover gas cap can be mounted.

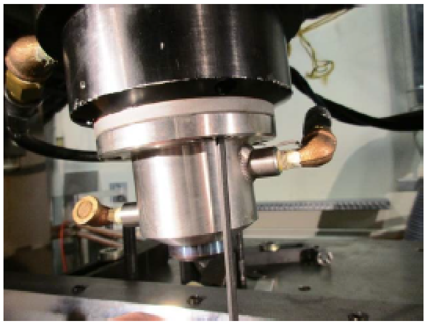


3. Align the cover gas cap slots wider part to the four screws and push the cap up.

4. Rotate the cover gas gap clockwise, as reviewed from the top, so that the cover gas cap can hang on the setscrews.



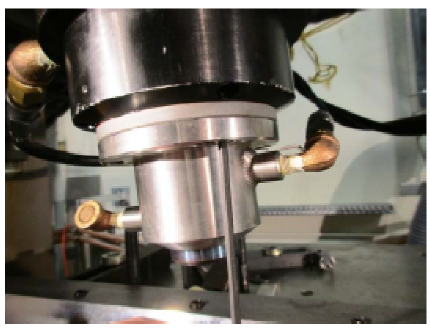
5. Hand tighten the four setscrews (Don't need to be very tight).



6. Connect the cover gas line.

5.8 Uninstall the cover gas cap from the tool holder

1. Turn off the power.
2. Disconnect the cover gas line.
3. Release the four setscrews that hold the cover gas cap.

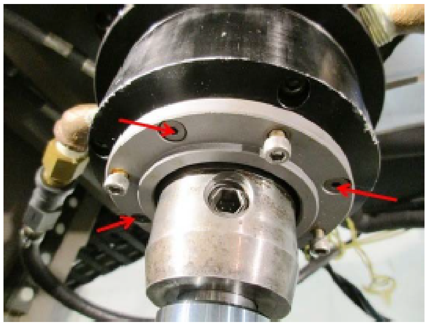


4. Rotate the cover gas cap counter clockwise, viewing from the top, so that the wider part of the slots on the cover gas cap align with the setscrews.

5. Take the cover gas cap out

5.9 Change tool holder seals without removing the tool holder from the machine

1. There are two seals inside the tool holder: Upper seal and lower seal, and they are different sizes.
2. Run the table down so that there is enough space for working.
3. Turn chiller off.
4. Turn power off. Lockout/Tagout the electrical power switch.
5. Place a pan underneath the tool holder to contain any coolant or oil remaining in the tool holder.
6. Take four screws off from the bottom of the tool holder and remove collar.



7. Take the lower seal off.
8. Take four black screws off from the bottom of the black cover on the tool holder and take the black color cover off.

9. Take the upper seal off.
10. Clean metal components, shaft and surfaces.
11. Put the new upper seal on.
12. Place the black cover on and tighten the four black screws.
13. Put the new lower seal on.
14. Place the collar in position and tighten the four screws.
15. Release the Lockout/Tagout.

6 Quality Assurance

The activities described in this procedure are planned, conducted, and documented in accordance with Document #QAP-ORNL-NR&D-01, Revision 0 entitled *Quality Assurance Plan for Nuclear Research and Development Conducted at the Oak Ridge National Laboratory*

7 Records

A welding traveler form shall be completed for the welding of each set of coupons.

Review Record

- Required once every 5 years as a minimum
- Signatures indicate adequacy of this document for activity

1st Re-Review

______________________________	____________
MP&J Group Leader	Date
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MST Division Safety Officer	Date

2nd Re-Review

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MP&J Group Leader	Date
______________________________	____________
MST Division Safety Officer	Date