ORNL/SPR-2018/1035

Light Water Reactor Sustainability Program

Complete Report on Development of Weld Repair Technology

M2LW-18OR0406014

September 2018

U.S. Department of Energy

Office of Nuclear Energy

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ABSTRACT

This report summarizes recent post-welding activities on irradiated alloys at the Irradiated Materials Examination and Testing (IMET) and the Low Activation Materials Development and Analysis (LAMDA) facilities at Oak Ridge National Laboratory. Equipment and capabilities were developed 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), and Oak Ridge National Laboratory. The preliminary helium measurements and microstructure characterization revealed successful advanced laser and friction stir welding procedures on high helium content stainless steel. The significant, on-going effort to weld irradiated alloys with high helium concentrations and comprehensively analyze the results will eventually yield validated repair techniques and guidelines for use by the nuclear industry in extending the operational lifetimes of nuclear power plants. The nuclear industry welding workshop was successfully held at ORNL on September 18 – 19, 2018.

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The authors gratefully acknowledge the program management of Keith Leonard, the division and operation management support of Jeremy Busby and Jim Miller, the engineering support of Kurt Smith and Bob Sitterson, hot cell facilities and operations contributions of Mark Delph, Clay Morris, Tony Davis, Rick Bowman, Scott Thurman, Scott White, and Allen Smith, characterization and testing efforts of Joshua Schmidlin, Maxim Gussev, Xunxiang Hu, Linda Hulsey, Patricia Tedder, Travis Dixon, Stephanie Curlin, and Brian Eckhart, along with Doug Kyle from joining team.

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Complete Report on Development of Weld Repair Technology

1. INTRODUCTION

In November and December 2017, the first three irradiated 304L stainless steel (304L SS) welds were produced in the Radiochemical Engineering Development Center (REDC) welding cubicle at Oak Ridge National Laboratory (ORNL) by using advanced laser and friction stir welding. This one-of-a-kind, enclosed, hot cell welding cubicle was developed through a joint effort by the U.S. Department of Energy, Office of Nuclear Energy, Light Water Reactor Sustainability Program and the Electric Power Research Institute (EPRI), Long Term Operations Program (and the Welding and Repair Technology Center), and ORNL. Detailed information of the irradiated material advance welding has been reported in the milestone report M3LW-18OR0406013 "Report on the Progress of Weld Development of Irradiated Materials at the Oak Ridge National Laboratory." Since then, post-weld activities, including microstructure and mechanical properties specimen preparation, welding quality evaluation, helium measurement, microstructure characterization and testing were carried out to support post-weld evaluation and the development of validated weld repair techniques and guidelines for use by the nuclear industry.

This report summarizes recent post welding activities. Included within are details on:

- Equipment modifications and installation to enable post-weld destructive sectioning of coupons in a hot cell at IMET
- Development of detailed procedures and travelers for post-weld destructive sectioning and testing
- Post-weld characterization specimens cutting and preparation in Hot Cell 6 at IMET
- Helium content measurement, irradiated material weld specimen quality evaluation, microstructure characterization and testing at LAMDA
- The progress of the third materials production campaign for irradiation and welding
- Nuclear industry welding workshop

Concurrently, in-cell equipment installation and welded coupons destructive sectioning have been completed at IMET. These cut off specimens have been packed and shipped to LAMDA. Preliminary helium measurements and microstructure characterization are ongoing, the third material production campaign for irradiation and welding is in progress, and the nuclear industry welding workshop was successfully held at ORNL.

2. HOT CELL MODIFICATION AND BAND SAW INSTALLATION

The irradiated material weld specimen cutting was planned to be performed in the Hot Cell 6 of IMET at ORNL. To improve the workability inside the hot cell and to fix issues and prevent potential problems because of long time of usage, the following work was carried out in Hot Cell 6 before setup of the modified band saw for irradiated material weld specimen cutting:

- Removed the broken MTS test frame using rigging support.
- Fabricated and installed new cell table and floor pan.
- Upgraded electrical in cell.
- Replaced lighting fixtures and lights.
- Prepared camera mount, camera, vacuum attachment that connects to current in-cell vacuum, and files to assist the irradiated weld specimen cutting.
- Fabricated and installed shielding rods to accept the new lighting power cord installation of the microscope and camera into the current shield plugs.
- Replaced current milling machine located in Cell 6 with larger and more powerful mill.

After modifications and improvements were completed, the modified band saw for cutting specimen was delivered to Cell 6 and connected to the power cord with a switch installed in the control room. In addition, a slow speed saw was moved into the hot cell for the cutting of small specimens. Other necessary tools such as a paint marker, brushes, cleaning solvent, water, towels, engraved aluminum containers, marked fiber tubes, a stainless steel ruler, tweezers, and pliers were also placed into the hot cell. After the band saw installation, test cutting was performed to ensure every operation was properly controlled and executed by manipulators. The installed band saw with a manipulator arm on the handle is shown in Figure 1.

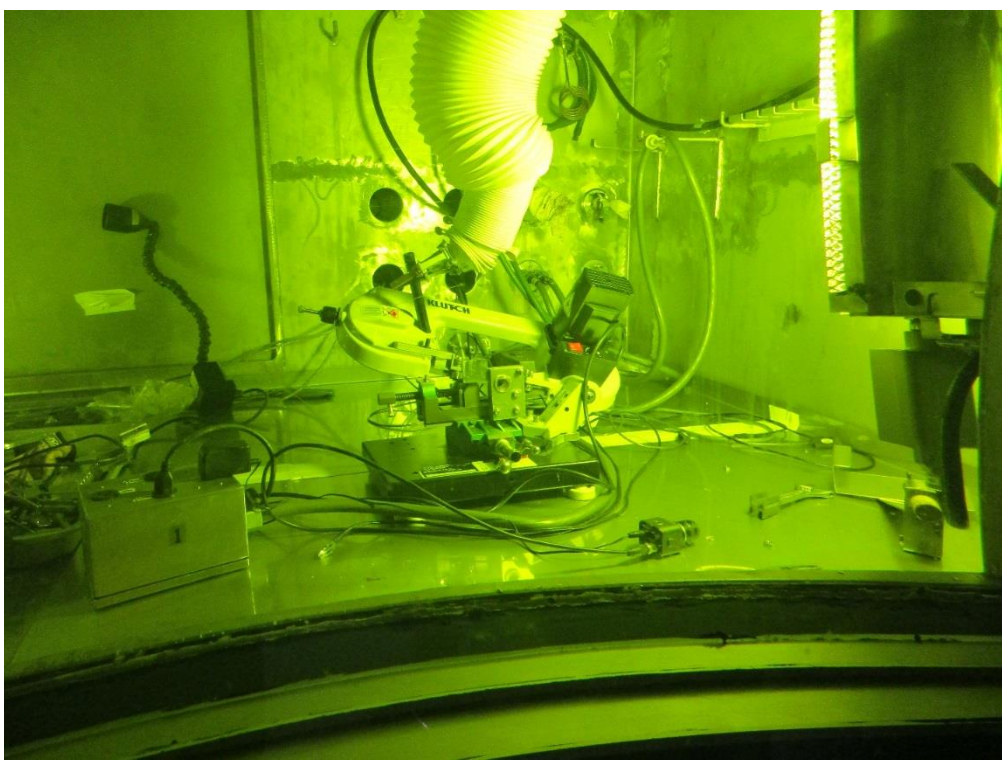


Figure 1 Band saw simulating operation with a manipulator in the Hot Cell 6

3. IRRADIATED MATERIAL WELD SPECIMEN CUTTING IN THE HOT CELL 6

The three welded irradiated coupon, 304D-1 (laser welded coupon with 20 wppm natural boron prior to irradiation), 304C-6 (friction stir welded coupon with 10 wppm natural boron prior to irradiation), and 304B-1 (friction stir welded coupon with 5 wppm natural boron prior to irradiation), were transported into Hot Cell 6 after the band saw and other equipment and tools were installed inside the hot cell. Laser welded specimen cutting followed “Laser Welded Coupon Cutting at Building 3025E” procedure to cut specimens with dimensions of 0.9” X 0.35” X 0.1”, while friction stir welded specimen cutting followed “Friction Stir Weld Specimen Band Saw and Slow Speed Saw Cutting in Hot Cell” procedure to cut specimens with dimensions of 1.2” X 0.35” X 0.1”, for microstructure characterization and mechanical properties testing. Both approved procedures are attached as Appendix A and Appendix B of this report. Moreover, small specimens were cut by slow speed and band saws from coupon base metal sections for helium content measurement. There were 10 microstructure/mechanical property specimens cut from each friction stir welded coupon, and there were 14 microstructure/mechanical property specimens cut from the laser welded coupon. An additional specimen (1” X 0.35” X 0.1”) was cut from the base metal part of each coupon by the band saw for helium measurement after one small specimen (0.1” X 0.1” X 0.35”) was cut from the 304C-6 base metal by the slow speed saw. The cutting process overview from the control room is shown in Figure 2. Note that the monitor on the top left corner of Figure 2 showed the cutting process details through the camera aimed at the clamping vise and the cut specimen.

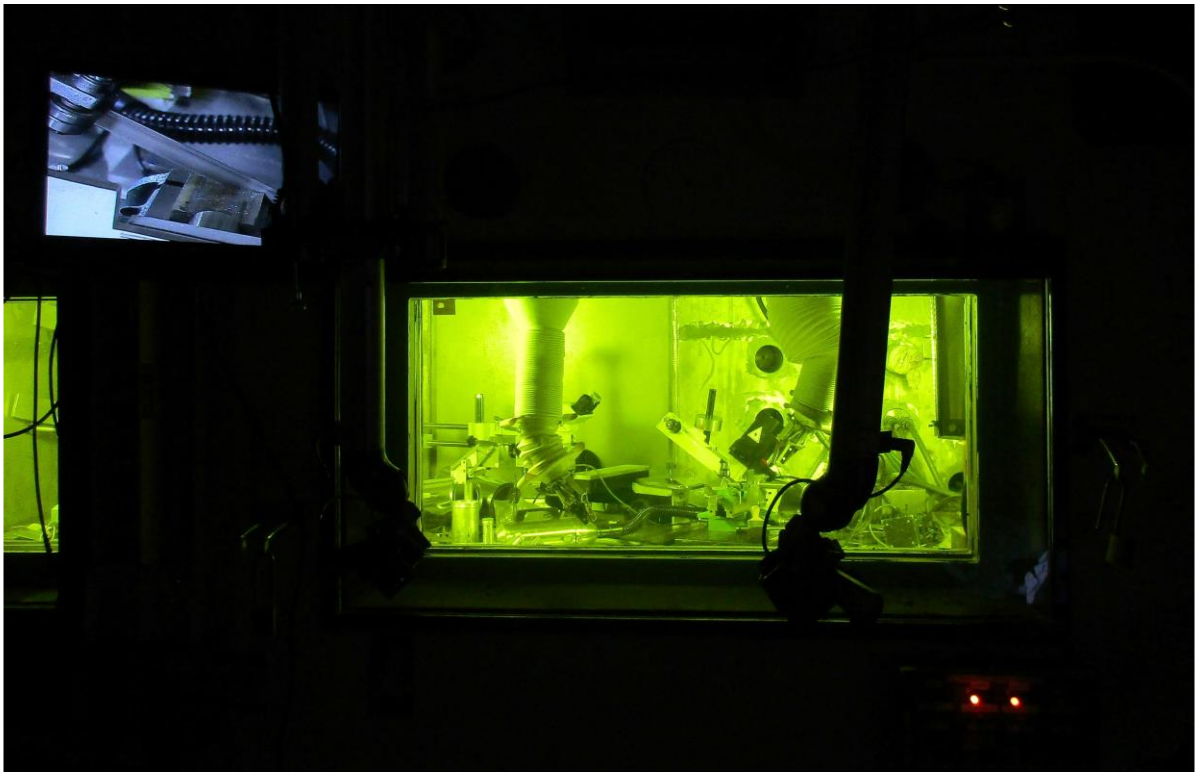


Figure 2 Irradiated material weld specimen cutting overview from the control room

Before each cut, the coupon was marked with a paint marker at proper locations, then they were identified by the operator and a researcher following the cutting procedure. A section from a friction stir weld after the first 5 cuts is shown in Figure 3.

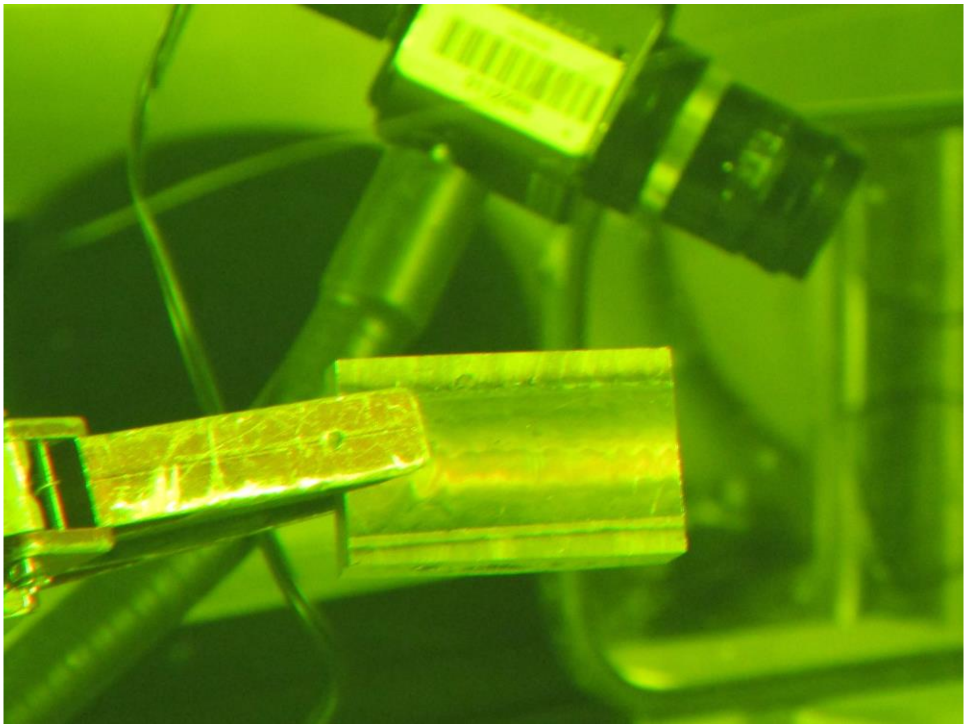


Figure 3 A section of a friction stir weld after the first 5 cuts held by a manipulator for identification

After identification, the coupon was placed in the band saw clamping vise with proper orientation following cutting procedure and against the preset guide pin so that it had proper stick out. Then the coupon was clamped down with a manipulator arm turning the handle. After that, the band saw head was slowly moved down by both manipulators to the position that the saw blade was close to or contacted with the coupon. Through the operator window and the camera monitor, the operator and the researcher double checked the saw blade position relative to the coupon position, and confirmed it with the cutting procedure. When the saw blade position was confirmed, the band saw head was raised up slightly, then the band saw power was turned on from the switch attached to the wall in the control room. After the saw blade speed reached its normal speed, the band saw head was gradually lowered to create contact with the coupon to start cutting. Two weights can be added to the band saw head to speed up the cutting process. A picture taken from the monitor during a friction stir weld specimen cutting is shown in Figure 4.

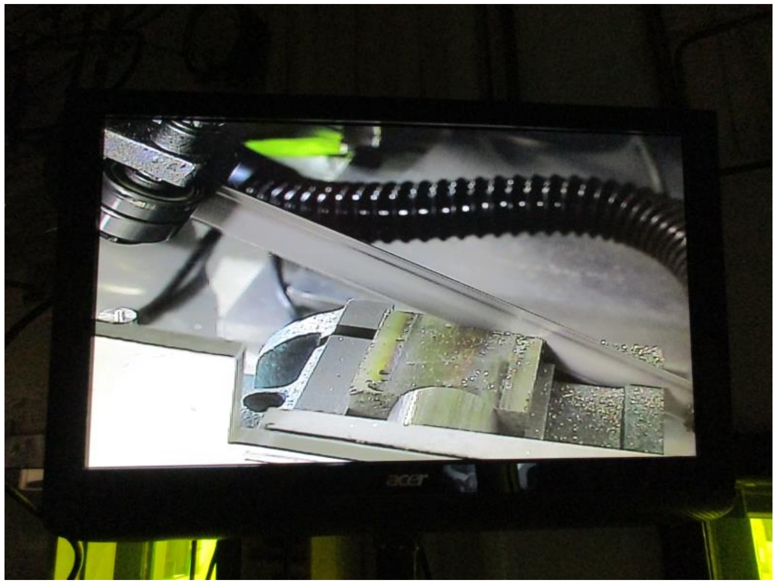


Figure 4 Irradiated material weld specimen cutting monitoring through an in-cell camera

After each specimen cutting was completed, the band saw power was turned off from the control room, the saw head was raised by the manipulator to its rest position. Then the vise clamp was released by using the manipulator, the remaining coupon was removed from the vise for cleaning and marking, and set aside for the next cutting step. The cut off specimen was picked up by the manipulator or a pair of tweezers held by the manipulator. If obvious burrs were observed on the specimen cutting edge, a file would be used for deburring. In this operation, the file was held by one manipulator and the cut off specimen was held by the other manipulator as it is shown in Figure 5.

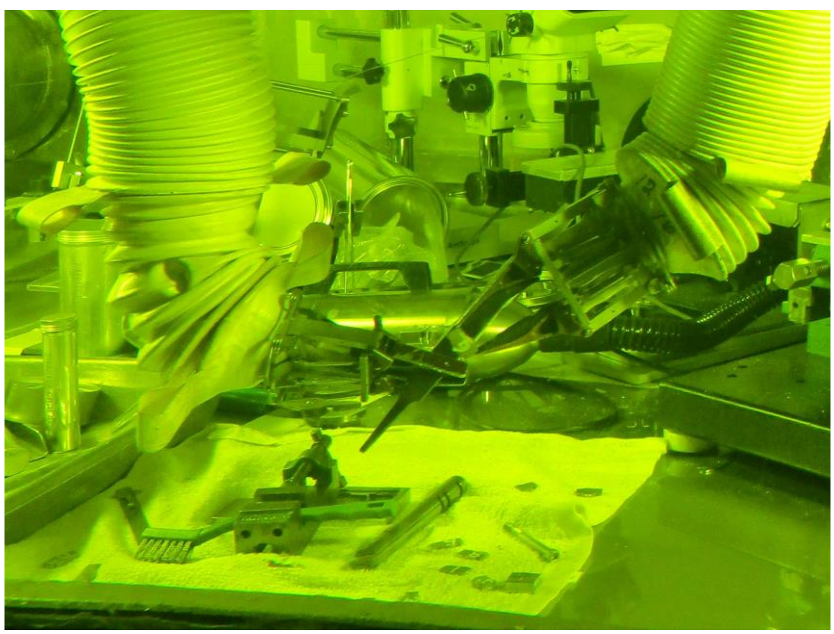


Figure 5 Deburring a laser weld specimen using a file after the cutting

The cut off specimen was placed in a small vise in the hot cell and the specimen ID was written on one side of that specimen using a paint marker. The cut off specimen was laid on the towel until all specimens of that welded coupon were cut off. Some cut off and marked friction stir weld specimens are shown in Figure 6.

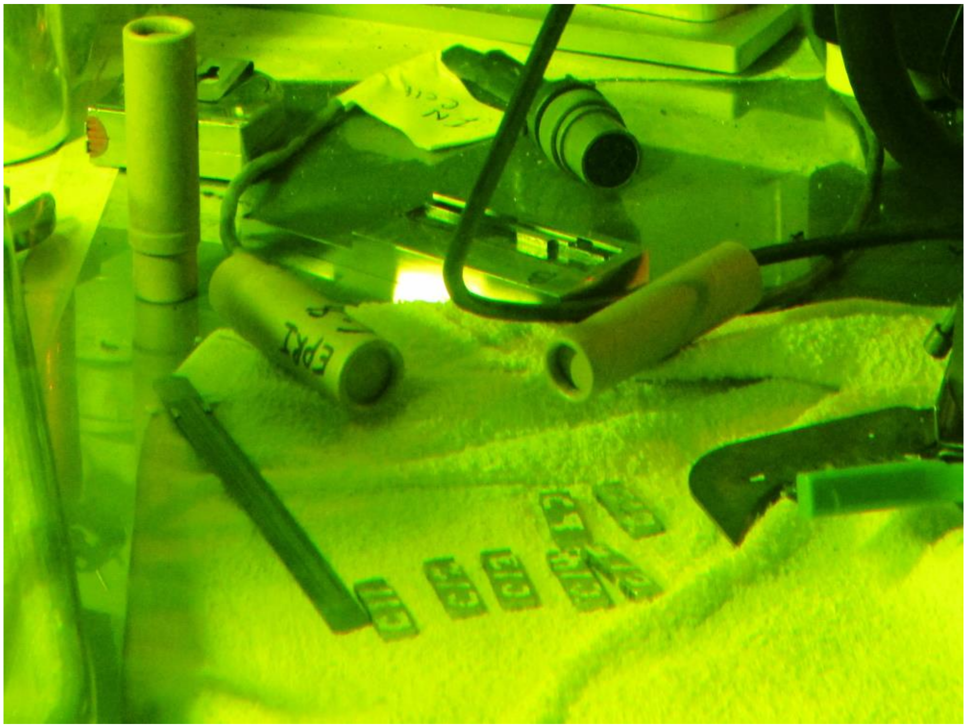


Figure 6 Cut off irradiated material weld specimens

From the initial plan, three small specimens with dimension of 0.1” X 0.1” X 0.35” would be cut from the coupon base metal by a slow speed saw for subsequently helium measurement. Therefore, a slow speed saw was placed in the hot cell and was used for such specimen cutting with water lubricant. The slow speed saw in the hot cell setup is shown in Figure 7. However, during the second small specimen cutting process, the specimen location shifted and caused the jewel saw blade to fail. Considering the time and effort to change the jewel saw blade in a hot cell, the remaining helium measurement specimens switched back to the band saw and the cut off specimen dimensions changed to about 1” X 0.1” X 0.35”. Additional cutting to the final specimen dimensions would be carried out at LAMDA before the helium measurements.

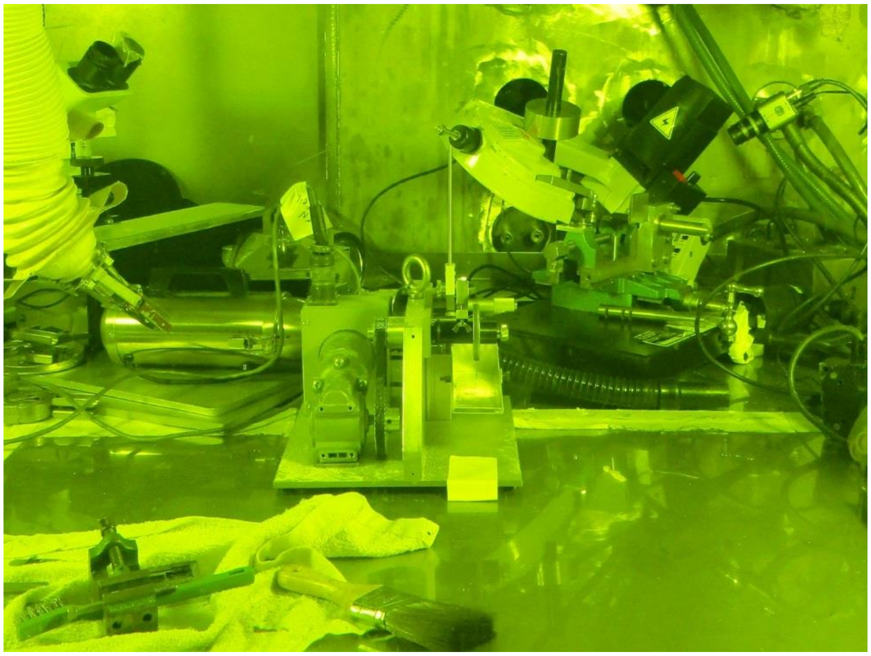


Figure 7 Slow speed saw for helium measurement specimen cutting

After all cutting was complete, specimens and remaining coupon pieces were placed into marked fiber tubes and laser-engraved aluminum cans, respectively. Figure 8 shows a laser weld specimen is sitting on the fiber tube before it was placed in it.

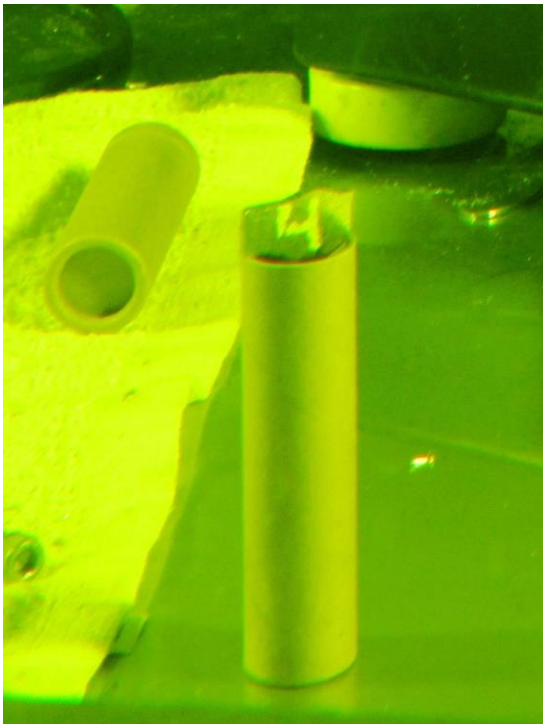


Figure 8 A laser weld specimen sitting on its fiber tube container

All aluminum cans containing welded coupon pieces and a portion of fiber tubes containing specimens were stored in IMET, and 23 fiber tubes containing 24 specimens (the small 0.1” X 0.1” X 0.35” specimen was placed in the same fiber tube of a ~1” X 0.1” X 0.35” specimen and both of them were for helium measurement) would be shipped to LAMDA for helium measurement, microstructure characterization and mechanical properties testing.

4. CUT OFF IRRADIATED MATERIAL WELD SPECIMENS TRANSPORTATION

After all the coupon cuts for this campaign had been made, the specimens were ready to load-out of the hot cell. Before specimens were loaded out of the cell, the hot cell operator (HCO) smeared the cans and tubes to verify the contamination levels were within the radiological work permit (RWP) limits for flashing specimens. Once the smears were counted by the radiological control technician (RCT) and the levels were verified less than 100,000 dpm, the specimens were loaded out, dose rated and packaged for shipment to LAMDA. Anything above 100,000 dpm would have to be placed in new tubes in the cell and the process started over. Subsequent to specimen dose rating, fiber tubes containing cut off specimens were loaded into a lead pig, dose rated and smeared. Finally, the HCO packaged the lead pig into a shipping drum. The RCT again smeared and dose rated final shipping drum and applied RAD tag. The HCO updated RITS and the operations supervisor or designee processed the shipping. When shipping papers were completed and approved and LAMDA screened the activity to receive the drum, the shipping was scheduled.

5. IRRADIATED 304 STAINLESS STEEL HELIUM MEASUREMENT

During service in nuclear environments, helium can be generated in structural alloys as result of reactions between thermal neutrons and boron impurities ^{10}B, and/or through two-step process with nickel present as alloy additions ^{58}Ni, and their reactions are shown in the following equations,

$$^{10}B + n \rightarrow \ ^{7}Li + \ ^{4}He \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$^{58}Ni + n \rightarrow \ ^{59}Ni + \ \gamma \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$^{59}Ni + n \rightarrow \ ^{56}Fe + \ ^{4}He \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

The helium ^{10}B transmuted from reaction with boron occurs early in the component’s life-cycle. While helium generation from nickel ^{58}Ni is non-linear due to the required production of ^{59}Ni, resulting in a slow helium generation rate at the earlier stage of the components life, and higher helium generation rates through the component’s life.

In a previous milestone report, natural boron doped 304L stainless steel coupons with 1 wppm, 5 wppm, 10 wppm, 20 wppm and 30 wppm, respectively, were produced through vacuum arc re-melting (VAR), extrusion, heat treatment, cold rolling and machining. Optical emission spectroscopy (OES) was used to analyze major chemical elements and glow discharge mass spectroscopy (GDMS) was adopted to detect minor chemical elements of specimens from each heat of materials and results confirmed the designed chemical composition. Then they were sent to high flux isotope reactor (HFIR) of ORNL to receive enough irradiation through calculation so that ^{10}B in coupons would transmuted to helium completely.

In this reporting period, helium in coupon 304D-1, 304C-6 and 304B-1 were measured by thermal desorption spectroscopy (TDS) and laser ablation mass spectroscopy (LAMS) under conditions of 1000 °C temperature and vaporization, respectively. During the TDS test, temperature was linearly ramped to 1000 °C at a 28 °C/min ramp rate and was maintained at 1000 °C for 5 minutes. The measured results and curves are shown in Figure 9. The peak helium desorption flux occurred at the highest temperature 1000 °C and measured helium values are 0.06 atom part-per million (appm), 0.031 appm and 0.019 appm for specimen D-15 (Coupon 304D-1), C-16 (Coupon 304C-6) and T-16 (Coupon 304B-1), respectively. The results indicate that most helium in those coupons are in helium bubble form and stable, and most of them remained in the material even with 1000 °C for 5 minutes.

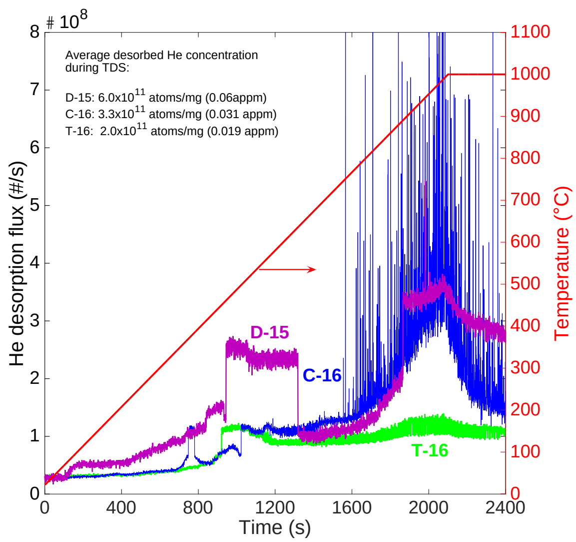


Figure 9 Helium desorption flux and content of three irradiated material specimens measured by TDS

The LAMS adopted a laser with 6.1 micro-J power, 532 nm wavelength and 4 – 5 ns pulse width to ablate the specimen locally. For each specimen, ten positions away from specimen edges were chosen for testing, and ten ablations and measurements were carried out at each position. The LAMS instrument is shown in Figure 10, and the helium desorption spectrum and the crater shape after ablations are shown in Figure 11. With the laser measurement, the crater dimensions after the ablation are about 3.2 µm in depth and 90 µm in diameter. The final converted helium content in the three specimens/coupons as well as the boron content prior to irradiation are shown in Table 1. From Table 1, the helium concentration in specimen 304D-1, 304C-6 and 304B-1 are 19.9 appm, 26 appm, and 8.48 appm, respectively. Measured helium values are close or higher than calculated values for specimens 304D-1 and 304B-1. The measured helium level in 304C-6 was significantly higher than expected and may require additional measurements on samples from other coupons of material heat 304C in the future when available.

Figure 10 LAMS instrument

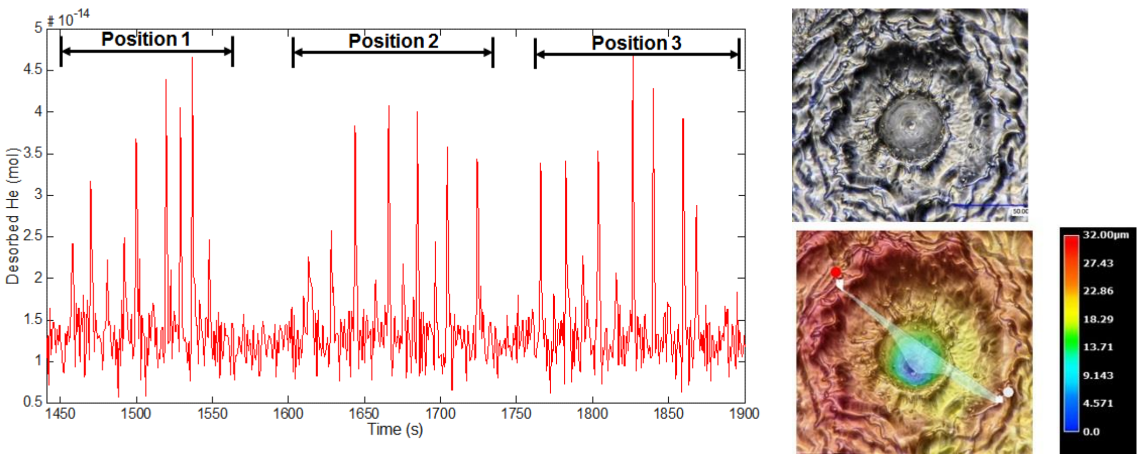


Figure 11 Helium desorption spectrum (left) and specimen crater (right) in LAMS

Table 1 Irradiated coupon helium content measured by LAMS

Sample/ Coupon	**Doped natural B, wppm**	**Calculated He, appm**	**LAMS**		
			Desorbed He, mol	Atoms for each ablation, mol	He concentration, appm
D-15/ 304D-1	20	20	2.4×10^{-14}		**19.9**
C-16/ 304C-6	10	10	3.2×10^{-14}	1.23×10^{-9}	**26**
T-16/ 304B-1	5	5	1.03×10^{-14}		**8.48**

6. IRRADIATED MATERIAL WELD PRELIMINARY MICROSTRUCTURE CHARACTERIZATION

After irradiated material weld specimens arrived LAMDA, they were cleaned, barcoded and recorded into LAMDA system. One weld specimen from each welded coupon was chosen for the initial characterization, and the following four weld specimens were chosen and processed (two laser welding specimens contain four laser welds and two friction stir welding specimens contain two welds):

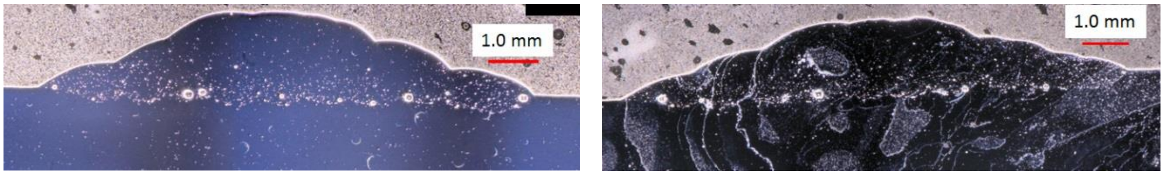
1. Specimen 304D-1-4 (304 SS laser weld L1 (27 IPM welding speed without scanning laser) and L4 (5 IPM welding speed with scanning laser), and material contains 19.9 appm helium)
2. Specimen 304D-1-11(304 SS laser weld L2 (27 IPM welding speed with scanning laser) and L3 (5 IPM welding speed without scanning laser), and material contains 19.9 appm helium)
3. Specimen 304C-6-15 (304 SS friction stir weld C15, and material contains 26 appm helium)
4. Specimen 304B-1-15 (304 SS friction stir weld B15, and material contains 8.48 appm helium)

Specimens were mounted with Epoxy, ground with 600 grits silicon carbide papers, polished with 6 µm, 3 µm, and 1 µm diamond discs, and finished with 0.03 µm colloidal silica. After the completion of the metallographic preparation, the polished specimens were observed and characterized by optical and scanning electron microscopy.

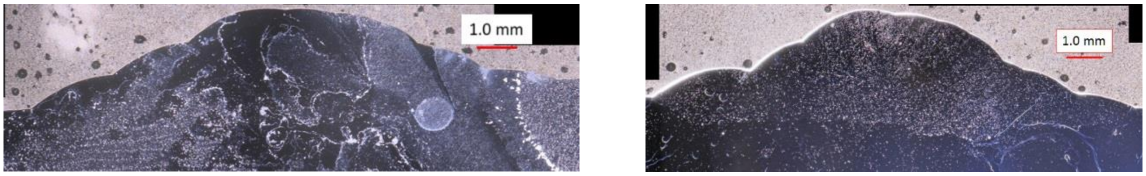
Optical Microscope Characterization of Advanced Laser Welds

Goals of optical microscope observation include weld quality check, possible welding defect detection and weld shape characterization at macro level.

Cross sections of all four laser welds are shown in Figure 12 applied to coupon 304D-1 containing 19.9 appm helium as reported above. As can be seen on these cross sections, there were polishing residues on specimen surfaces. As high radiation dose specimens, and each of their dose rate exceeded 100 mrem/hr/30 cm, the first polishing results were reasonably good for initial observation and analysis.



(a) Fast speed weld L1 without scanning laser (b) Fast speed weld L2 with scanning laser



(c) Slow speed weld L3 with scanning laser (d) Slow speed weld L4 without scanning laser

Figure 12 Irradiated 304 SS laser weld cross sections

As it is seen in Figure 12, no macro level welding defects such as cracks and porosity are seen in any of these welds, even though the measured helium content in this coupon (304D-1) is 19.9 appm. A publication in 1990s showed significant heat affected zone (HAZ) cracking were observed after a conventional welding technique was applied on an irradiated coupon containing 8.3 appm of helium.

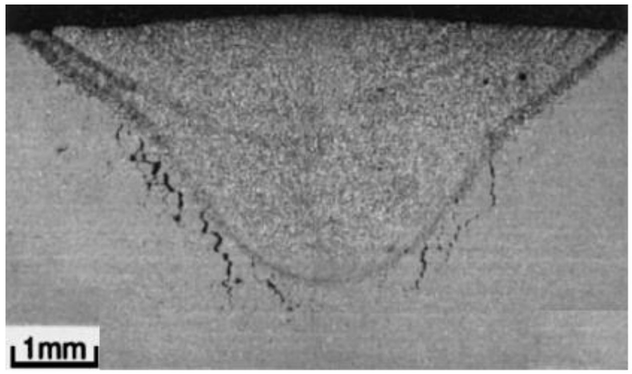
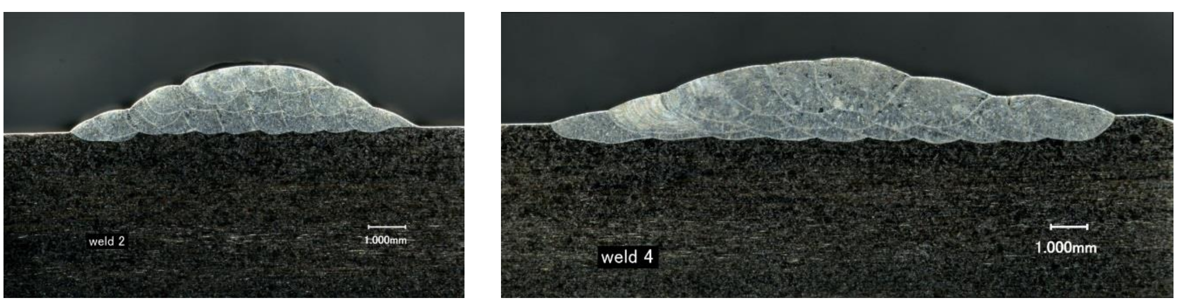


Figure 13 Helium induced HAZ cracks in the stainless steel weld containing 8.3 appm He

(Kyoichi Asano, et al. Journal of Nuclear Materials, 264, 1 – 9 (1999))

It is also seen from Figure 12 that the welding speed had major effect on weld shape, penetration and weld clad thickness as expected. Similar shapes were observed on nonirradiated 304 SS laser welds. The nonirradiated material weld cross sections after etching are shown in Figure 14. The maximum weld penetration of the higher speed weld is about 1.8 mm and that of a slower speed weld is approximately 3.1 mm.

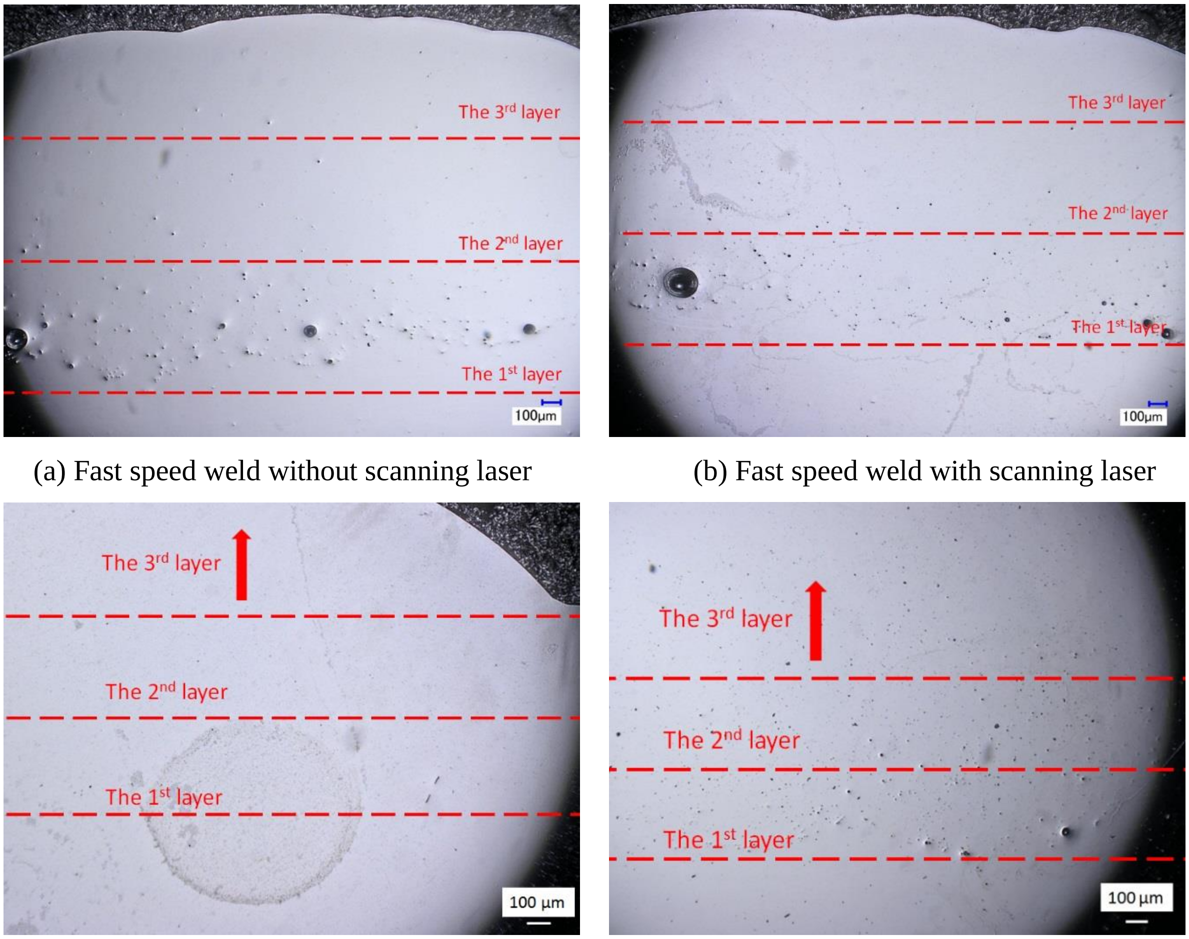


(a) Fast speed weld cross section (b) Slow speed weld cross section

Figure 14 Un-irradiated material laser weld cross sections made with fast and slow welding speeds

Under a relatively higher magnification (~ 100X) observation, micro voids were found in all four welds. Voids and their distributions in different welds are shown in Figure 15. During the first laser welding clad layer, the weld filler metal is diluted with irradiated base metal containing helium and contains the majority of the micro porosity. The second and third layer do not consume the previous layer and therefore contain a decreasing amount of base metal dilution as additional layers are applied.

Subsequently micro-voids are mostly found in the first layer welds with fewer in the second layer weld and the third layer welds are essentially free of micro-voids.



(a) Fast speed weld without scanning laser (b) Fast speed weld with scanning laser

(c) Slow speed weld with scanning laser (d) Slow speed weld without scanning laser

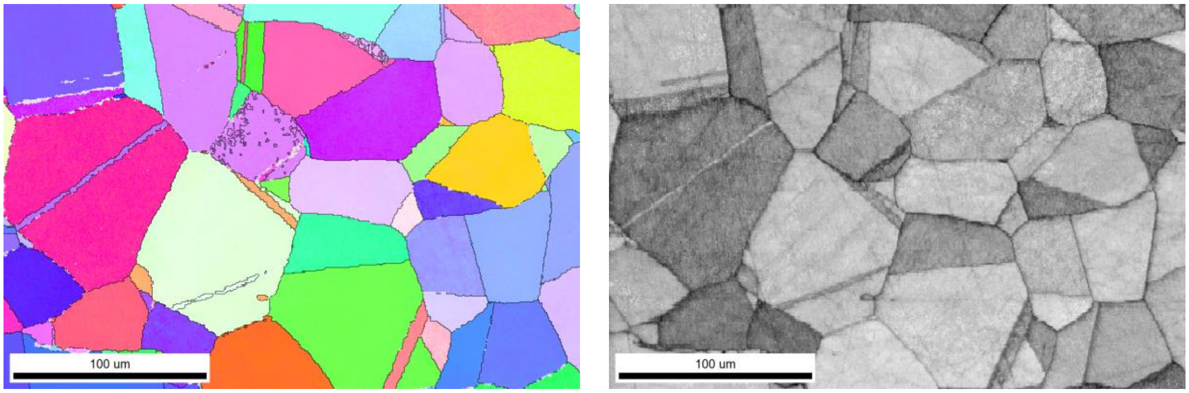
Figure 15 Micro-voids in laser welds

SEM Characterization of a Laser Weld and a Friction Stir Weld

Advanced laser weld

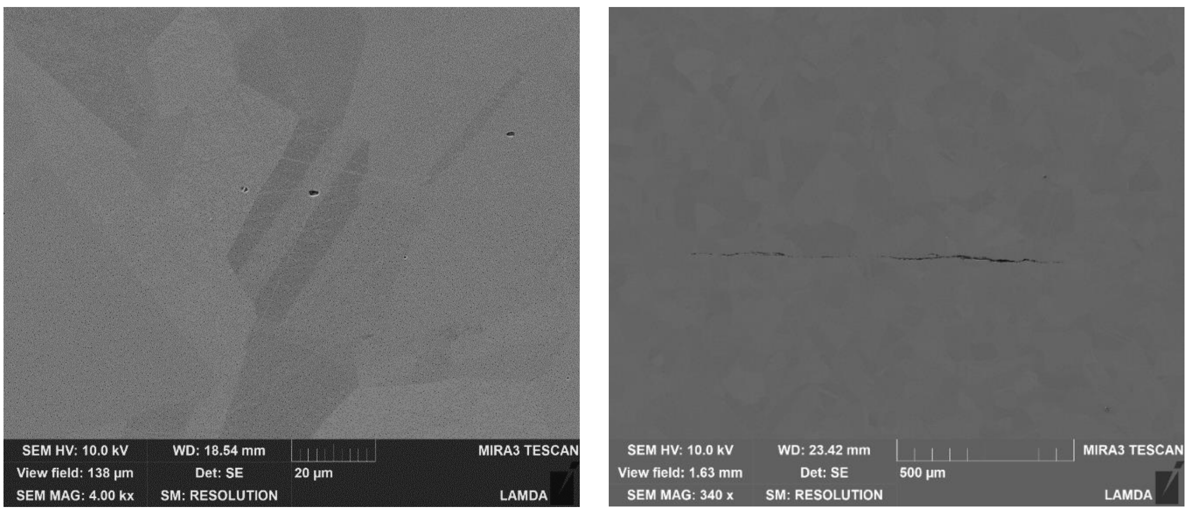
The laser weld and base metal of 304D-1-L4 (5 IPM welding speed weld with scanning laser) were characterized by scanning electron microscopy (SEM).

The base metal microstructure images of specimen 304D-1-L4 showed well-annealed austenite structures with grain size of ~60-80 µm. As expected, multiple annealing twins present in the material without any indications of cold work or deformation. The electron backscatter diffraction (EBSD) inverse pole figure (IPF) and Image Quality (IQ) are shown in Figure 16. There were minor polishing scratches observed in Figure 16(b). Minor inclusions and voids (a few micrometers in size) and one delamination (~ 1 mm long) were found in the base metal and were most likely occurred during the material production processes but overall the base metal microstructure was very clean and representative of commercially produced alloys. See Figure 17 for details.



(a) EBSD inverse pole figure (b) Image quality figure

Figure 16 Irradiated 304D-1 base metal SEM characterization



(a) Minor inclusion and voids (b) Small delamination indication

Figure 17 Minor artifacts in base metal

The cross section of the 304D-1-L4 weld is shown in Figure 18. As with the optical microscopy observation, no macro-level cracks or voids were observed. Therefore, the advanced laser welding on irradiated material was successful and the weld quality is significantly better than that of the irradiated material weld made with a conventional welding technique as shown in Figure 13. The helium level in Figure 18 contained 19.9 appm helium compared to the 8.3 appm helium content in the weld shown in Figure 13.

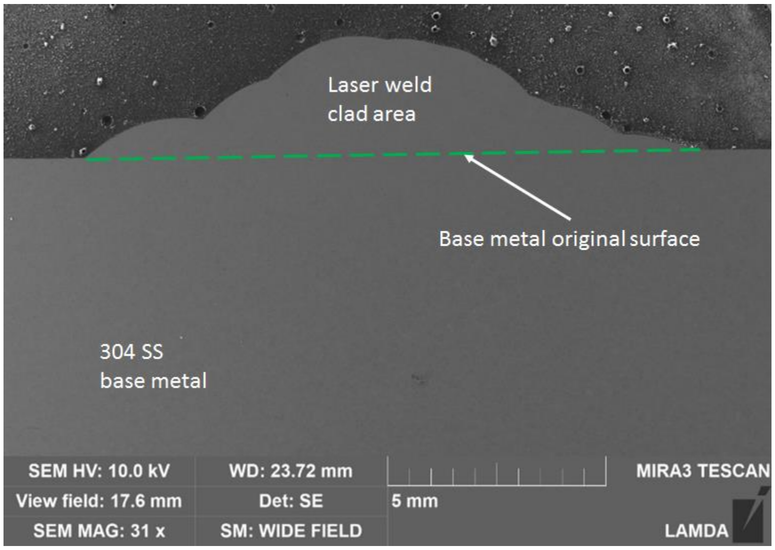
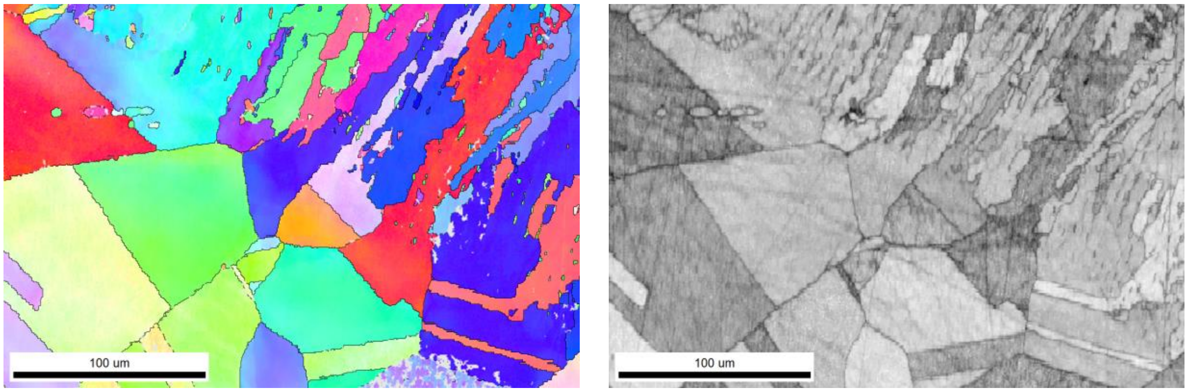


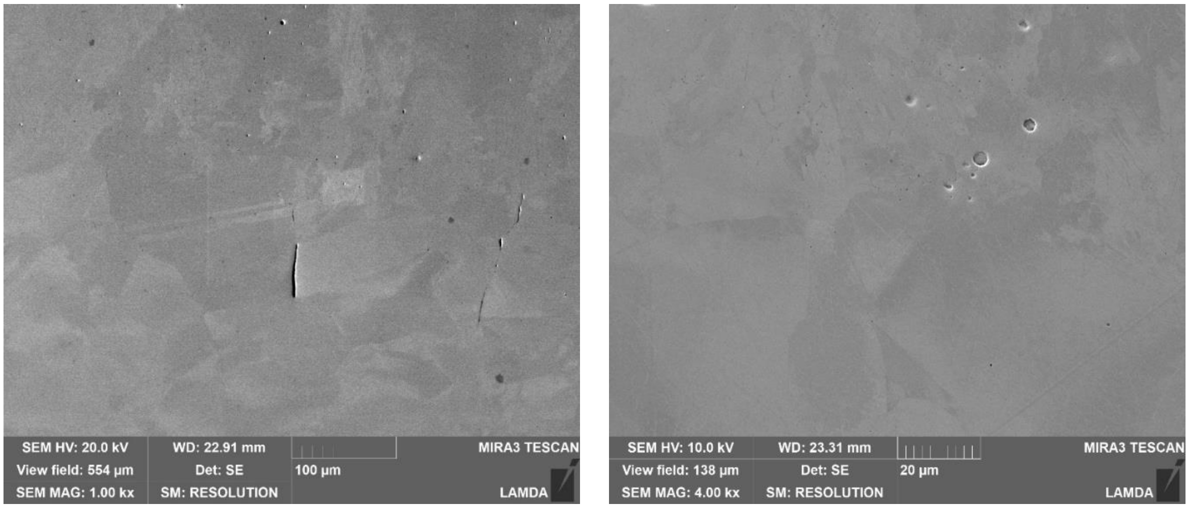
Figure 18 304D-1-L4 cross section under SEM

The 304D-1-L4 weld zone shows a typical fusion weld dendritic microstructure by epitaxial grain growth from the fusion line towards the weld center. Figure 19 shows details of the weld zone, fusion line and HAZ. Compare with conventional fusion weld zone grain structure, the 304D-1-L4 dendritic grains are finer due to the low energy input laser welding. In Figure 19, partial melted grains are also seen along the fusion line, and the HAZ microstructures remain similar to that of the base metal are shown in Figure 16. Moreover, there were two micro-cracks (~ 100 µm in length) observed in HAZ close to the fusion line, and there were also some voids (a few micrometers in size) observed in the weld zone. The micro-level HAZ cracks and weld voids are shown in Figure 20. These HAZ cracks are significantly shorter and fewer than those helium induced cracks shown in Figure 13.



(a) EBSD inverse pole figure (b) Image quality figure

Figure 19 Microstructure on weld zone, fusion line and HAZ



(a) Micro-cracks in HAZ (b) Micro-porosities in weld zone

Figure 20 Micro-level cracks in HAZ and porosities in weld zone

Without accurate quantification, microstructures in HAZ appeared plastic deformed. Large grain reference orientation deviation (GROD) values which indicates local grain bending were observed at triple junction points and in the micro-crack vicinity, points out plastic strain preceded cracking. The GROD scanning results are shown in Figure 21.

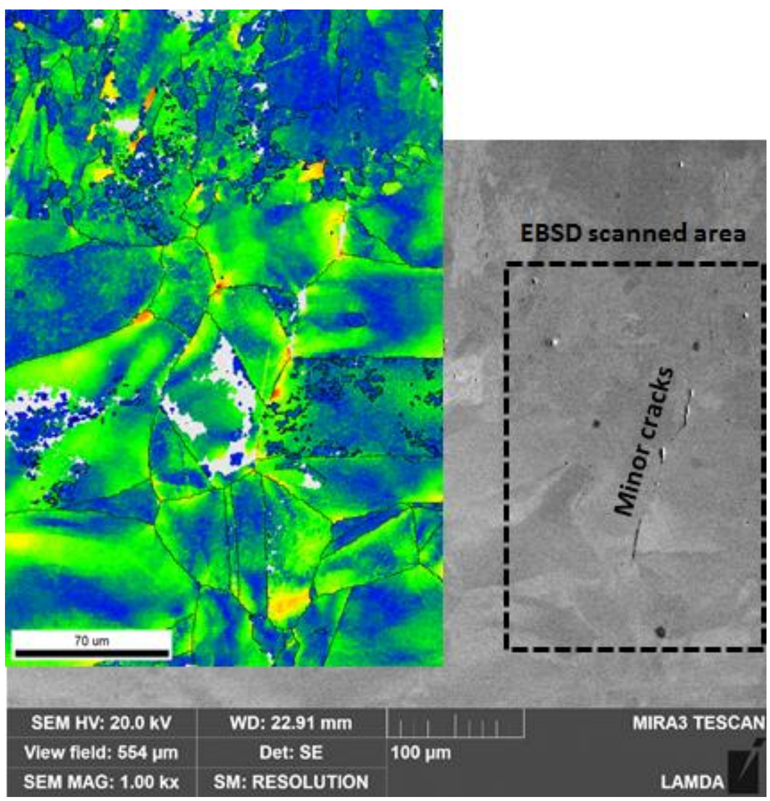


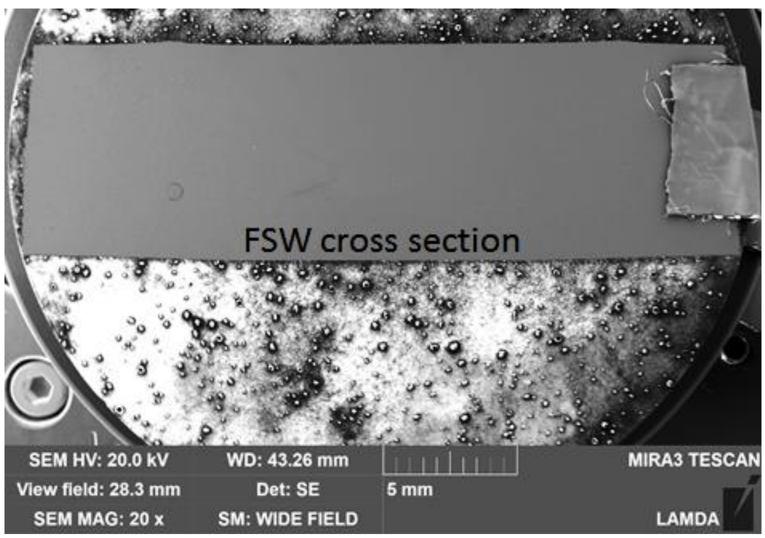
Figure 21 Plastic strain preceded cracking in HAZ

In general, the first trial of advanced laser welding on irradiated 304L SS containing 19.9 appm helium was successful. It produced sound welds with only two micro-cracks in HAZ and some micro-voids in the weld zone.

Friction stir weld

The initial SEM characterization was carried out on the specimen 304C-6-15 containing 26 appm of helium by LAMS measurement as reported above.

The welded specimen cross section image by SEM is shown in Figure 22(a). Since it was not etched, weld boundary under this condition is not visible. Hence, an un-irradiated 304L stainless steel weld cross section specimen after etching is shown in Figure 22(b) for reference, and both welds were welded with the same FSW parameters. From the image showed in Figure 22(a), it is clear that the irradiated material weld is a sound weld without any macro-level cracks and voids in the friction stir weld zone and HAZ.



(a) Irradiated 304L FSW specimen 304C-6-15 SEM image

(b) An un-irradiated FSW specimen scanned image

Figure 22 Irradiated and un-irradiated 304L FSW specimen cross sections

High magnification scanning (Up to 20,000X) was applied on the 304C-6-15 specimen by back-scattered electrons (BSE) and secondary electrons (SE) initially. No cracks or meso-level voids with sizes comparable to the grain size (~100 µm) was observed in weld zone and HAZ. In the weld zone close to the specimen top surface, some black spots, possibly are voids with sizes of 2 – 10 µm, were observed under high magnification. Some of those voids like features were deformed along certain directions, and they are shown in Figure 23. Further microstructure characterization and studies will be carried out on those voids like features.

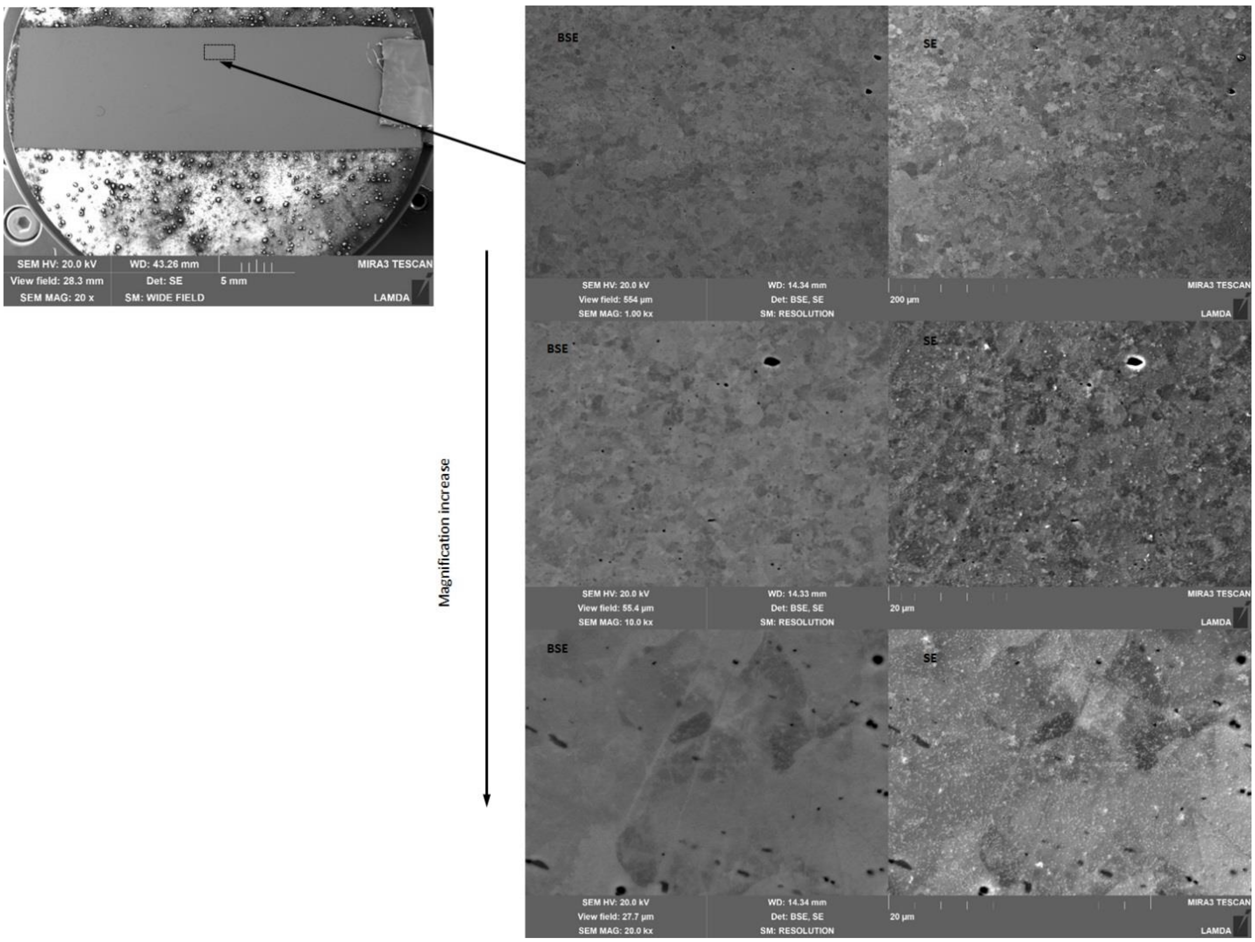


Figure 23 Void like feature in the weld zone close to the specimen top surface

In addition, inverse pole figure (IPF) and image quality (IQ) figure show that this area contains mixed fine and coarse forged grain structures due to the FSW solid phase process and variation in material plastic deformation history. The IPF and IQ images are shown in Figure 24.

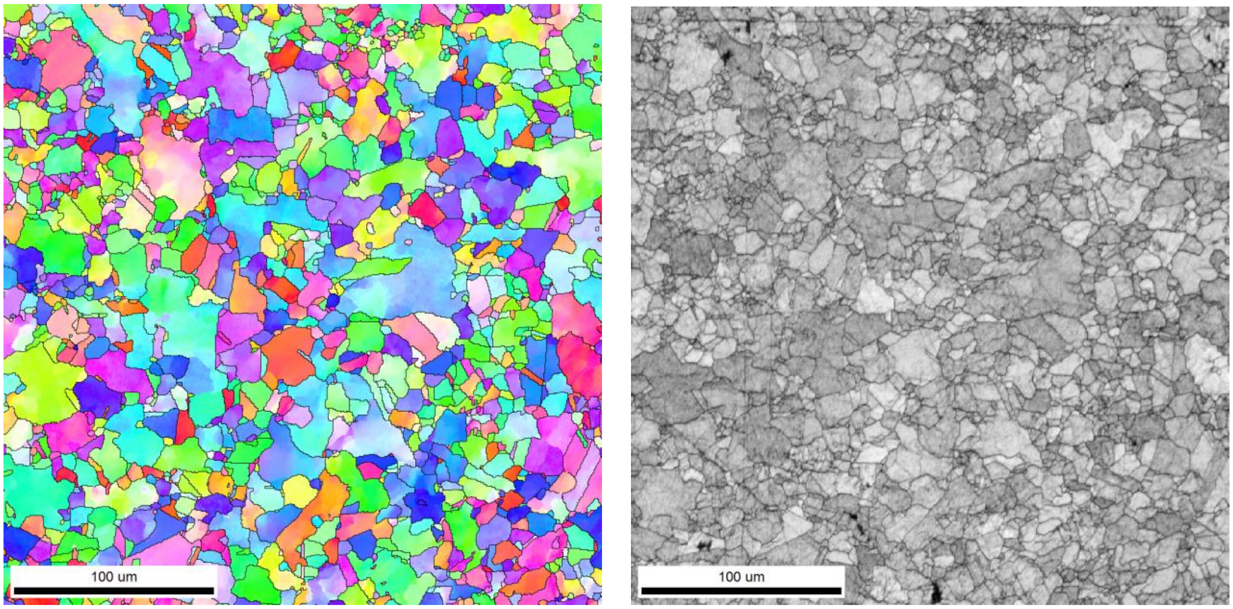


Figure 24 Inverse pol figure (left) and image quality (right) images of the FSW zone close to the specimen surface

As it is shown in Figure 22(b), heavy plastic deformation traces sheared zones are shown inside the friction stir weld due to the FSW thermal-mechanical process. Similar shear zones are observed in the irradiated 304L SS friction stir weld and at the weld boundary, which are shown in Figure 25. Under 20,000X magnification, micro-level (~ 1 to 2 µm) and Nano-level black spots are observed in the sheared zone, and they are not shown in areas without heavy plastic deformation such as the base metal. Some of those black spots appear as a round shape and some of them elongated along the plastic deformation direction. The high magnification pictures of a small area covering the sheared zone and the base metal marked with a black square in Figure 25 are shown in Figure 26, where the left picture is a BSE image and the right picture is a SE image. Further microstructure study and analysis are needed for identification and classification but some of them could be accumulated helium bubbles due to the high plastic deformation in that area. There are also white spots/particles along the sheared zone/base metal boundary, which sizes are also in a couple of micrometers and nanometers, and they will be further characterized in the future.

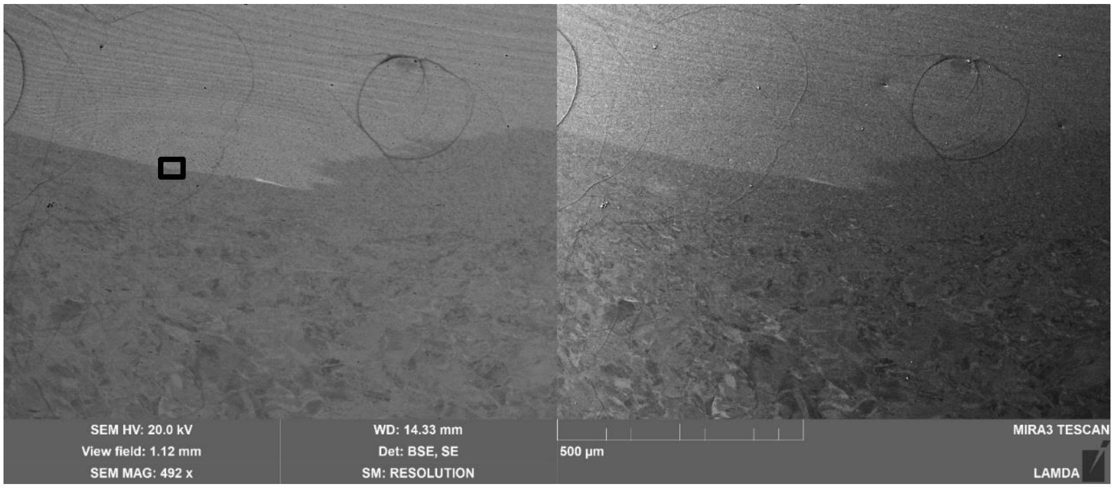


Figure 25 sheared zones in the irradiated 304L SS friction stir weld, BSE (left) and SE (right)

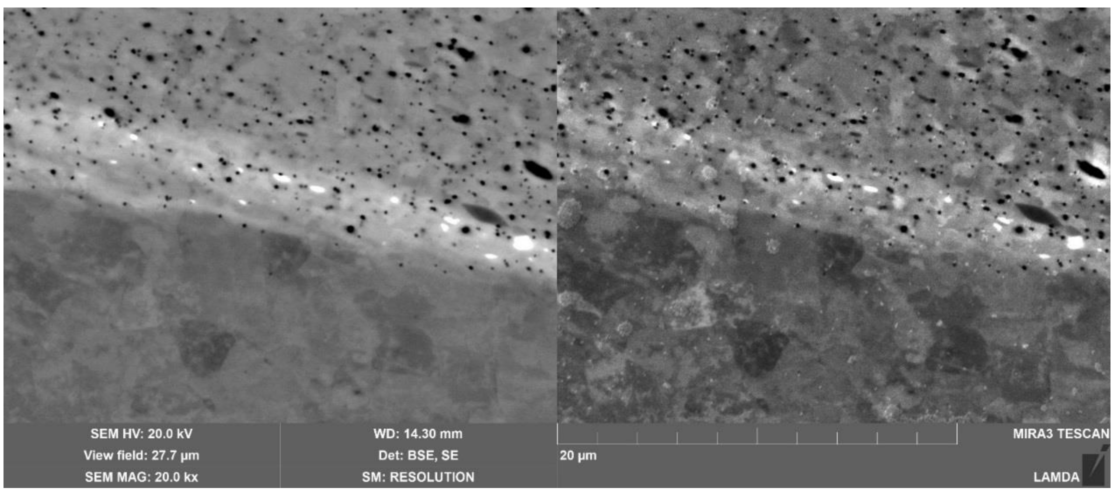


Figure 26 Micro- and Nano- voides and/or inclusions in the FSW shear zone, BSE (left) and SE (right)

The HAZ high magnification characterization showed no macro-, meso-, or micro-level of cracks in the HAZ, and only some 1 – 2 μm void like features were observed in a portion of the area along grain boundaries, roughly 2 – 5% of all scanned HAZ grain boundaries. Interestingly those voids like features were aligned in some certain angles and sometimes they appear to be micro-cracks with the length of 10 – 20 μm. Some of the representable voids at HAZ are shown in Figure 27.

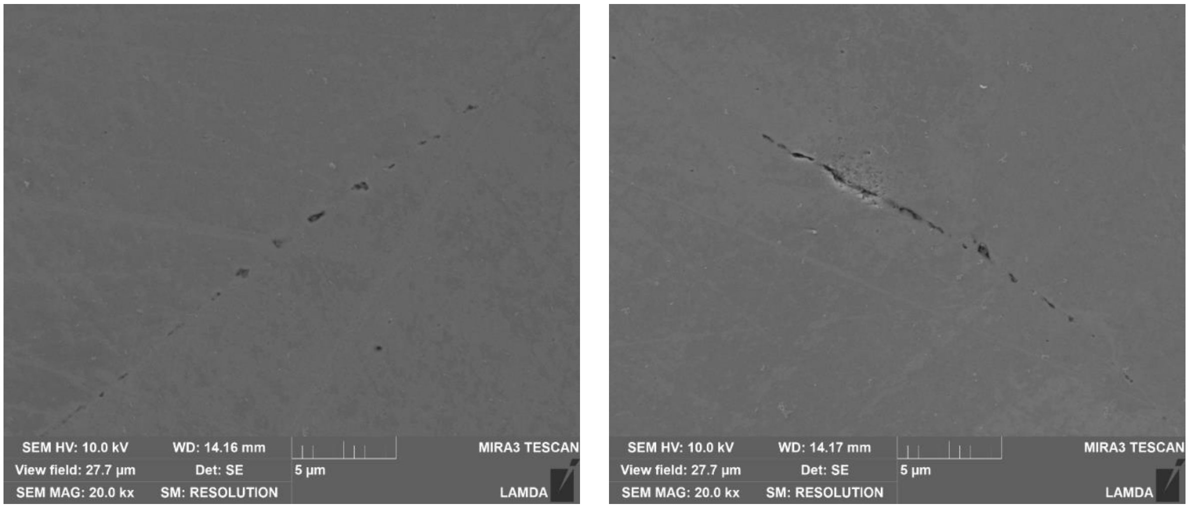
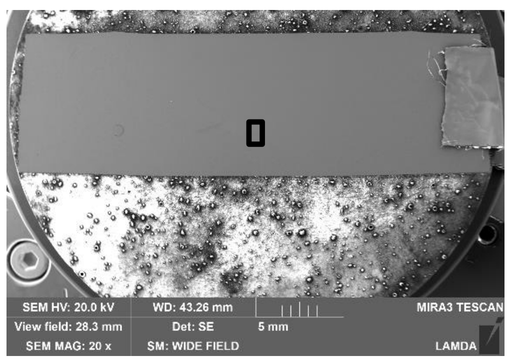


Figure 27 Micro-void like features with about 1 - 2 µm size in a small portion in HAZ

A microstructure morphology from weld zone, thermal-mechanical affected zone (TMAZ) to the HAZ was scanned at the bottom of the weld zone, and the location is shown in Figure 28(a), where an un-irradiated material weld etched cross section is shown in Figure 28(b) to indicate the relative position. IPF, IQ and phase images were constructed together to show the microstructure evolution from the weld zone, TMAZ to the HAZ, see Figure 29 for details.



(a) Irradiated 304L SS FSW cross section microstructure morphology scanning location

(b) An un-irradiated 304L SS FSW cross section image

Figure 28 Irradiated 304L SS FSW specimen microstructure morphology scanning location

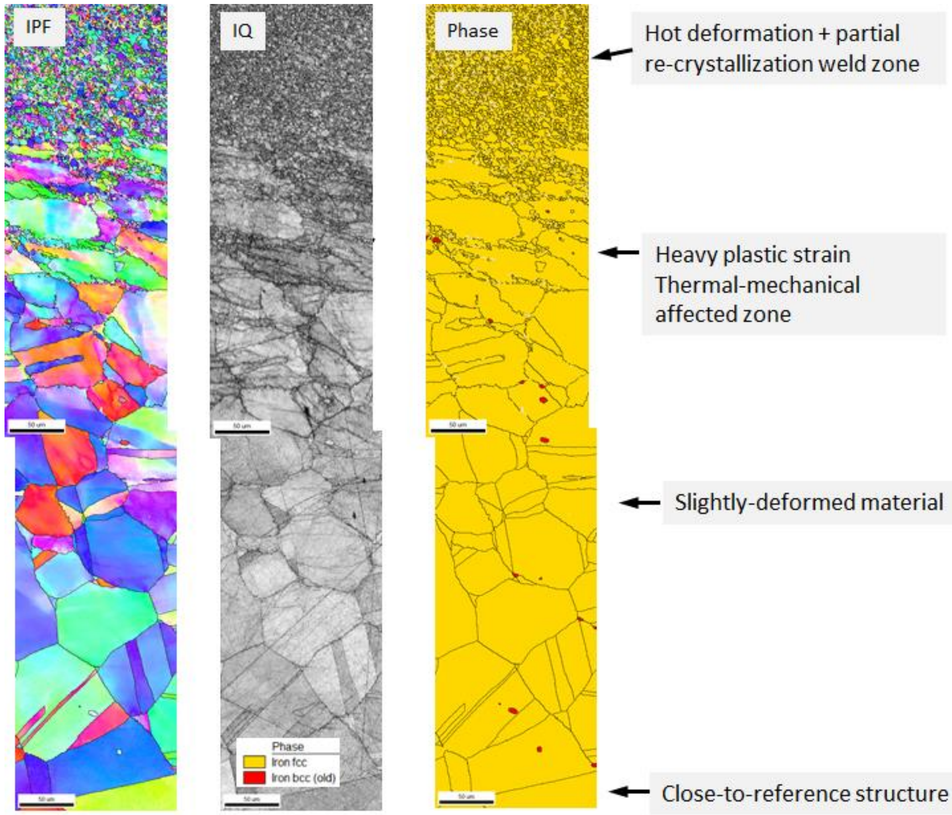


Figure 29 Irradiated 304L FSW specimen microstructure morphology at the weld bottom area

With lower heat input at the weld bottom than that the weld top and middle areas, recrystallized grain sizes at the weld bottom were much finer than those at the weld top and middle sections. Moreover, heavy plastic deformation was observed at the TMAZ and grains in TMAZ were elongated along a certain direction following the weld geometry. The degree of plastic deformation continued to decrease when area under observation moved from the TMAZ towards the HAZ, which matches with the fact that thermal-mechanical effects drop along the same direction. At a location approximately 0.5 mm away from the weld boundary in the HAZ, plastic deformation effect was not evident, and the grain structures were close to base metal microstructures. Furthermore, very small amount of body center cubic (bcc) phase, << 1%, was shown in base metal, HAZ, and TMAZ (Red spots in Phase image of Figure 29) but not in the weld zone. This indicate that a very small amount of residual ferrite from the production process were eliminated after FSW and turned into austinite.

In general, the first trial of FSW on irradiated 304L SS containing 26 appm helium was successful. It produced sound welds with potential no crack observed anywhere in the weld zone, TMAZ and HAZ. Some micro- and nano- sizes voids like features were observed in weld sheared zones and a very small portion of the HAZ grain boundaries contains scattered micro-void like features.

7. MATERIALS FOR ADDITIONAL IRRADIATION

In order to provide material for additional irradiation and eventual welding, three additional heats of 304L and 316L, respectively, with low residual cobalt levels and controlled boron levels began processing in FY 2017 and the status was reported in Milestone Report M3LW-17OR040613. The target boron levels are 10, 30 and 50 wppm for each alloy. Processing was halted after completion of hot extrusion, homogenization and forging. Further processing in FY18 continued as funding became available and has consisted of cold rolling the 19 by 51 mm hot extruded bar into semi-finished bar with an approximate size of 12 X 70 X 100 mm. A minimum of seven rolled bar sections were produced from each heat as shown in Figure 30. After cold rolling, the bars were recrystallized in air for 30 minutes at 1050 C (316L heats) or 1000 C (304L heats) and water quenched. As detailed in the aforementioned milestone report, one heat was lost during vacuum arc re-melt processing (316L + 30 ppm boron). A new electrode will be assembled to replace the lost heat and processed in the same manner.

Characterization will be completed on each heat consisting of grain size determination, ferrite determination, grain structure, sensitization and chemistry. If acceptable results are obtained the bar sections will be made available for machining into coupons for eventual irradiation and welding.

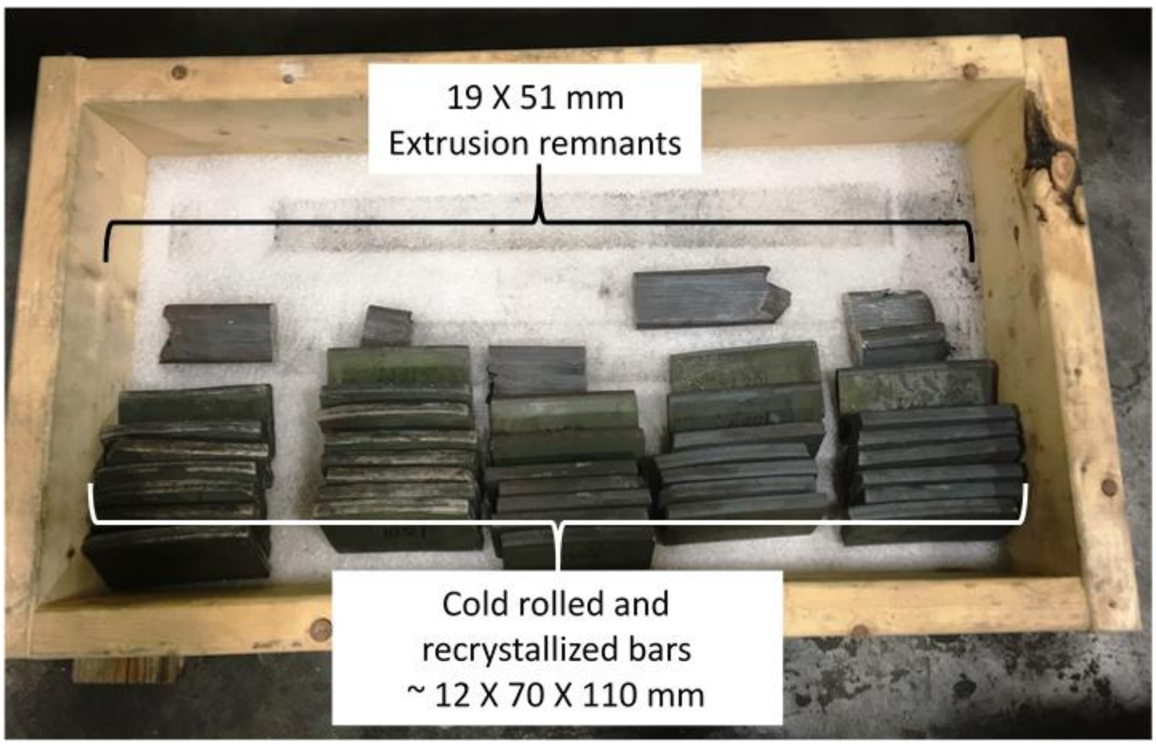


Figure 30 Cold rolled and recrystallized stainless bars

8. NUCLEAR INDUSTRY WELDING WORKSHOP

A nuclear industry welding workshop was held at ORNL on September 18 – 19, 2018. This workshop invited perspectives from industry, utilities and federal sponsors about advanced welding technologies for repair of irradiated materials. The workshop offered ample opportunities for discussion, touring of ORNL facilities, and demonstrations – a-one-of-a-kind, enclosed, hot-cell welding cubicle – of laser welding and friction stir welding to repair irradiated materials. The workshop agenda and participant list are attached in Appendix C.

9. SUMMARY

The preliminary helium measurements and weld microstructure studies of the first campaign of advanced laser welding and friction stir welding on irradiated 304L SS were completed. The measured helium content of the three coupons that had been welded are 19.9 appm, 26 appm, and 8.48 appm, respectively. Both advance laser welding and friction stir welding produced sound welds on irradiated 304L SS containing 19.9 appm and 26 appm helium, respectively. With optical microscopy and SEM observation, there were no macro-level cracks or voids found anywhere in both welds, including weld zones and HAZs. Only micro-level void like features were observed in weld zones and HAZs. In addition, a couple of micro-level cracks were observed in a laser weld HAZ. Further microstructure investigation and mechanical properties testing will be carried out on all welds in the near future. The third material production campaign for additional irradiation and eventual welding is ongoing, and they will be a very good addition to repair welding R&D.

A nuclear industry welding workshop was successfully held at ORNL on September 18 – 19, 2018. More than 20 people from different nuclear industries, universities, institutes, and DOE attended the workshop. Multiple presentations from nuclear industry, EPRI, ORNL and DOE were presented and discussions associated with current R&D, future plans, industrial applications and collaborations were covered at the workshop.

REFERENCES

[1] Z. Feng, R.G. Miller, J. Chen, W. Tang, et al., Complete Report of Progress of Weld Development of Irradiated Materials, U.S. Department of Energy, Office of Nuclear Energy, Light Water Reactor Sustainability Program, Milestone Report, ORNL/SPR-2018/833, April 2018.

[2] Kyoichi Asano, Seiji Nishimura, Yoshiaki Saito, Hiroshi Sakamoto, Yuji Yamada, Takahiko Kato, Tsuneyuki Hashimoto, “Weldability of Neutron Irradiated Austenitic Stainless Steels,” Journal of Nuclear Materials, 264, 1 – 9 (1999).

Appendix A

Laser Welded Coupon Cutting Procedure (Approved)

STANDARD OPERATING PROCEDURE

Title: Laser Welded Coupon Cutting at Building 3025E

Prepared by: Wei Tang Date 04/23/2018
Wei Tang, Staff Member
Materials Processing and Joining Group

Approved by: James A Haynes Date 04/27/18
Allen Haynes, Group Leader
Materials Processing and Joining

QA Approval: MCVance Date 4/23/18
Mark C. Vance, Quality Representative
Performance Analysis and Quality

DSO Approval: Tracy Strader Date 4/24/18
Tracy W. Strader, Research Support Group Leader
Materials Science and Technology Division

3025E Approvals: Mark Delph Date 4/30/18
Mark Matthews Delph, 3025E Hot Cell Operations Supervisor
Non-reactor Nuclear Facilities Division

1 Purpose

Cut specimens from laser welded irradiated coupons using a band saw and a slow speed saw in a hot cell for post weld characterization.

2 Scope

The activities described in this procedure are to be conducted in a hot cell in Building 3025E and includes the following activities.

- Setup weld coupon on the band saw clamping vise and a slow speed saw.
- Cut specimens in different sizes with the band saw and a slow speed saw.

- Use the vacuum which hose is attached to the band saw to collect materials that are removed (waste) during the cutting process. The vacuum has the grounded power supply and is currently used in building 3025E hot cell.
- Apply water during slow speed saw cutting only. Don't apply water or any other lubricant during band saw cutting.
- Mark and store specimens in cans and tubes.

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

- Irradiated materials are involved.
- Cutting fines are produced and cutting fines will go into a waste can following non-reactor nuclear facilities division policy.
- Cleaning wipes will be dried and go into a waste can following non-reactor nuclear facilities division policy.

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 3025E. All activities shall comply with mandated requirements invoked for the facility.

4 Responsibilities

Research personnel from the Materials Science and Technology Division are responsible for oversight of the cutting and operations described in this procedure; a researcher will be present to observe operations. 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 – **Specimen cutting in hot cell**

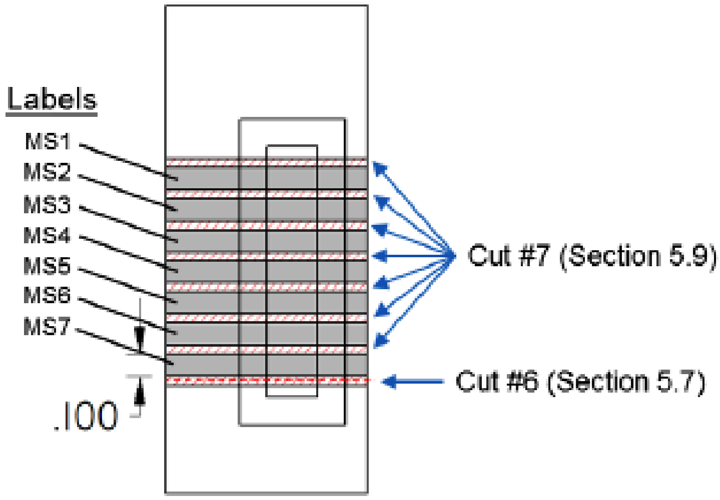
Before coupon cutting, prepare cans for large parts and fiber tubes for small specimens that are cut from the coupons. Mark containers for each part that will be cut prior to introducing the containers to the hot cell. For example: EPRI 304D-1 L1/L4 MS7, for the 7th metallographic specimen cut from coupon 304D-1 that contains welds L1 and L4, or EPRI 304D-1 He, for helium measurement specimens. Excess welded material will be labeled with the coupon ID and L1/L4 or L2/L3 to identify the welds and stored separately. Excess trimmed, un-welded material may be stored in either welded section container.

The complete list of labeled containers required for coupon EPRI 304D-1, as an example, would be anticipated as:

EPRI 304D-1 L1/L4	Can	Excess L1/L4 weld sections (may also include trimmed, un-welded material)
EPRI 304D-1 L2/L3	Can	Excess L2/L3 weld sections (may also include trimmed, un-welded material)
EPRI 304D-1 He	Tube	Helium measurement specimens
EPRI 304D-1 L1/L4 MS7	Tube	Weld L1 and L4 cross-section
EPRI 304D-1 L1/L4 MS6	Tube	Weld L1 and L4 cross-section
EPRI 304D-1 L1/L4 MS5	Tube	Weld L1 and L4 cross-section
EPRI 304D-1 L1/L4 MS4	Tube	Weld L1 and L4 cross-section
EPRI 304D-1 L1/L4 MS3	Tube	Weld L1 and L4 cross-section
EPRI 304D-1 L1/L4 MS2	Tube	Weld L1 and L4 cross-section
EPRI 304D-1 L1/L4 MS1	Tube	Weld L1 and L4 cross-section
EPRI 304D-1 L2/L3 MS7	Tube	Weld L2 and L3 cross-section
EPRI 304D-1 L2/L3 MS6	Tube	Weld L2 and L3 cross-section
EPRI 304D-1 L2/L3 MS5	Tube	Weld L2 and L3 cross-section
EPRI 304D-1 L2/L3 MS4	Tube	Weld L2 and L3 cross-section
EPRI 304D-1 L2/L3 MS3	Tube	Weld L2 and L3 cross-section
EPRI 304D-1 L2/L3 MS2	Tube	Weld L2 and L3 cross-section
EPRI 304D-1 L2/L3 MS1	Tube	Weld L2 and L3 cross-section

Metallographic specimens (MS) will be labeled in reverse order of cutting, with MS7 produced first, MS6 produced next, and so on. A labeling diagram for MS specimens cut from a welded section is shown here:

STANDARD OPERATING PROCEDURE

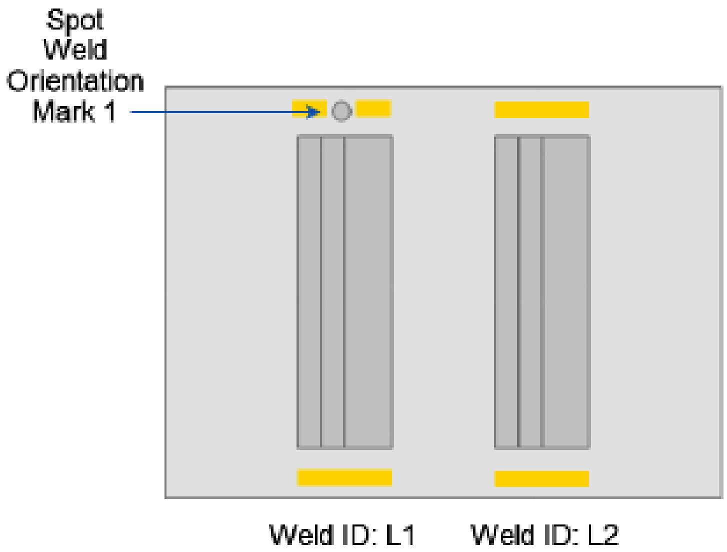


Cutting may proceed if operators are confident that the band saw clamp is properly positioned, relative to the saw blade. If there has been activity that would disturb the positioning since last use of the saw, such as a blade change or movement of the positioning dial on the clamp, the positioning must be reset.

The method of setting the clamp position relative to the saw blade is to indicate the face of the clamp (opposite side from the adjustment dial) against the saw blade, and then turn the dial 0.600 inch, or 6 full rotations, to move the clamp into the proper position such that the saw blade passes through the cut-out in the clamp.

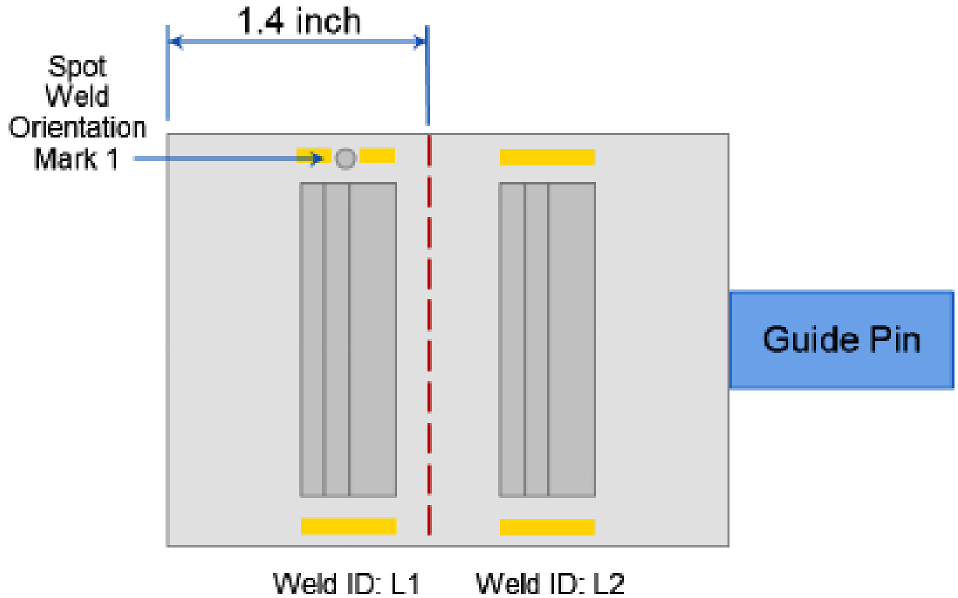
5.1 Verify and Mark Coupon

1. Verify the coupon identity by checking the ID stamped on the short ends.
2. Mark the top side of the coupon with a paint marker as specified in the following figure in yellow. The top side of the coupon is the side on which the spot weld orientation mark can be oriented at top-left, as shown in the figure.



5.2 Cut 1 – Cuts the coupon into two pieces.

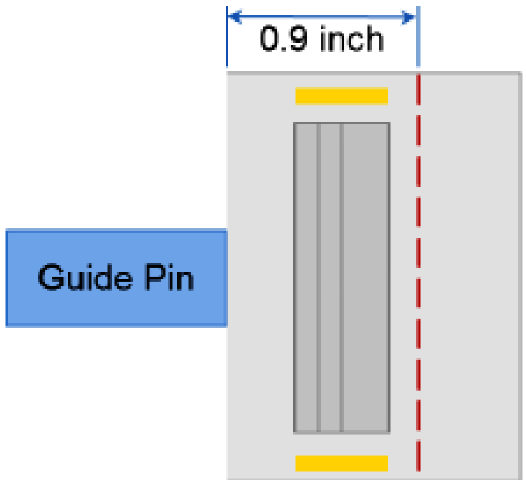
1. Set guide pin **A** to mark **2**.
2. Clamp the laser welded coupon with the edge adjacent to weld L2 firmly in contact with the guide pin such that Cut 1 is located as specified in the following figure. The coupon should be seated in the upper portion of the clamp.
3. Turn on the band saw power and the vacuum power.
4. Unlock and lower the band saw head and start the cut.
5. When the cut is completed, turn off the band saw power, the vacuum power and raise and lock the band saw head.
6. Release the clamp, take out the coupon, deburr the cut edges on both pieces, and clean with alcohol. Coarse silicon carbide papers and/or a file will be used for the deburring for all cut parts in this procedure.



5.3 Cut 2 – Trims excess material from the L2/L3 welded section.

1. Set guide pin B to mark 7.
2. Clamp the laser welded coupon section containing the L2/L3 welds with the cut end firmly in contact with the guide pin such that Cut 2 is located as specified in the following figure. The welded section should be seated in the upper portion of the clamp.
3. Turn on the band saw power and the vacuum power.
4. Unlock and lower the band saw head and start the cut.
5. When the cut is completed, turn off the band saw power, the vacuum power, and raise and lock the band saw head.
6. Release the clamp, take out the coupon section, deburr the cut edges on the welded section, and clean with alcohol.

7. Store cut off piece with excess welded sections when all cutting is complete.

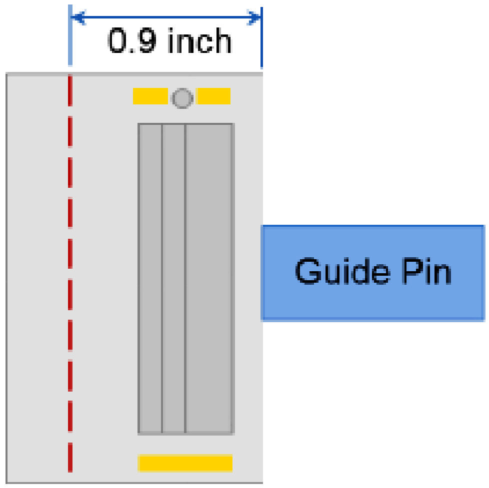


Weld ID: L2

5.4 Cut 3 – Trims excess material from the L1/L4 welded section.

1. Set guide pin B to mark 7.
2. Clamp the laser welded coupon section containing the L1/L4 welds with the cut end firmly in contact with the guide pin such that Cut 3 is located as specified in the following figure. The welded section should be seated in the upper portion of the clamp.
3. Turn on the band saw power and vacuum power.
4. Unlock and lower the band saw head and start the cut.
5. When the cut is completed, turn off the band saw power, vacuum power and raise and lock the band saw head.
6. Release the clamp, take out the coupon section, deburr the cut edges on the welded section, and clean with alcohol.
7. Store cut off piece with excess welded sections when all cutting is complete.

STANDARD OPERATING PROCEDURE

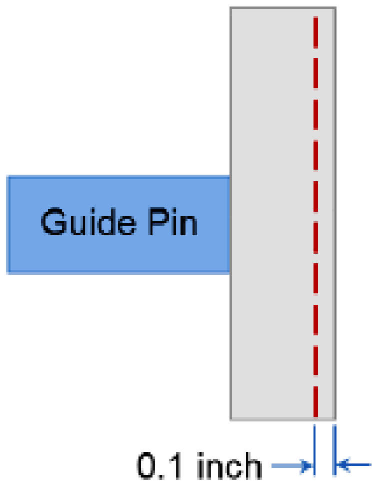


Weld ID: L1

5.5 Cut 4 – Creates a sliver from the larger trimmed excess section.

1. Set guide pin B to mark 9.
2. Clamp the larger of the two excess coupon sections (produced with Cut 2) with the cut end firmly in contact with the guide pin such that Cut 4 is located as specified in the following figure. The section should be seated in the upper portion of the clamp
3. Turn on the band saw power and the vacuum power.
4. Unlock and lower the band saw head and start the cut.
5. When the cut is completed, turn off the band saw power, the vacuum power and raise and lock the band saw head.
6. Release the clamp, take out the coupon section, deburr the cut edges of the sliver, and clean with alcohol.
7. Store the larger section with excess welded sections when all cutting is complete. The sliver that was cut in this step will be used in the next step.

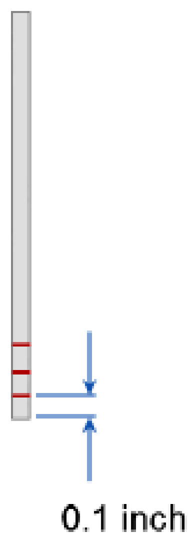
STANDARD OPERATING PROCEDURE



5.6 Cut 5 – Cuts small specimens from sliver. To be repeated three times with a slow speed saw. This step may be delayed until the end, following all band saw cuts, or performed simultaneously with the remaining band saw cuts.

1. Clamp the sliver that was produced with Cut 4 such that a 0.1 inch section will be cut, as specified in the following figure.
2. Turn on the slow speed saw power.
3. Start the cut.
4. When the cut is completed, turn off the slow speed saw power.
5. Release the clamp, take out the sliver section, deburr the cut edges of the (0.1 x 0.1 x 0.35 inch) small specimen, and clean with alcohol.
6. If this is not the third cut of Section 5.6, return to the top of Section 5.6 and repeat.
7. Store the sliver section with excess welded sections when all cutting is complete.

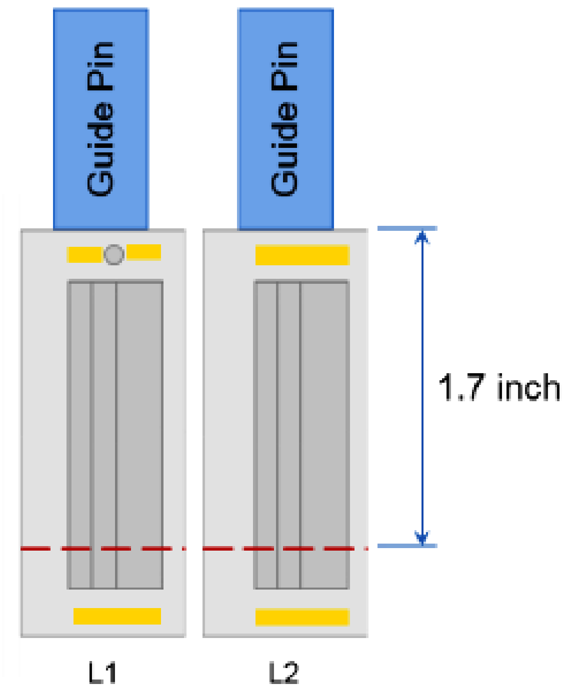
8. Tube the three small specimens together (same container) for shipment to LAMDA with the labeling convention specified at the beginning of Section 5, which is EPRI Alloy-Boron-Serial# He.



5.7 Cut 6 – To be repeated twice. Cut open both welded sections.

1. Set guide pin B to mark **2**.
2. Clamp the welded section with the spot weld mark end firmly in contact with the guide pin such that the cut is located as specified in the following figure. The section should be seated in the lower portion of the clamp.
3. Turn on the band saw power and the vacuum power.
4. Unlock and lower the band saw head and start the cut.
5. When the cut is completed, turn off the band saw power, the vacuum power and raise and lock the band saw head.
6. Release the clamp, take out the welded section, deburr the cut edges on both pieces, and clean with alcohol.
7. If this is not the second cut of Section 5.7, return to the top of Section 5.7 and repeat.

8. Excess welded sections will be stored as specified at the beginning of Section 5.



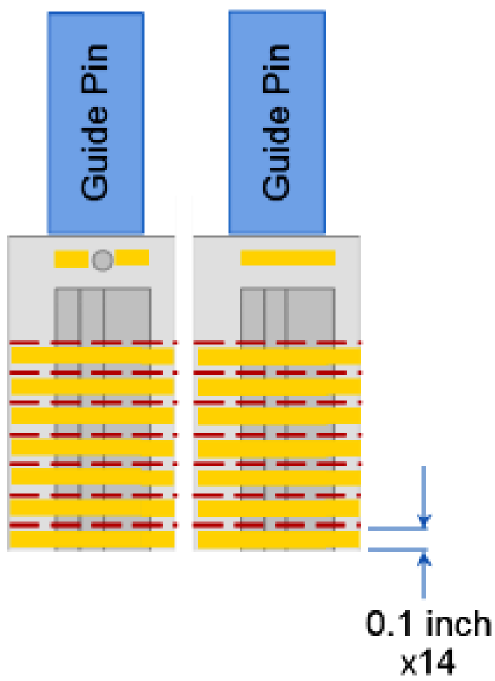
5.8 Apply additional markings.

1. Apply additional marks with a paint marker to the top side of welded sections prior to cutting weld cross-sections as depicted in yellow in the following figure in Section 5.9.

5.9 Cut 7 – To be repeated 14 times. Cut weld cross-sections.

1. Set guide pin B to marks 3, 4, 5, 6, 7, 8, and 9 sequentially, as needed, starting with mark 3.

2. Clamp the welded section with the uncut end firmly in contact with the guide pin such that the cut is located as specified in the following figure. The section should be seated in the lower portion of the clamp.
3. Turn on the band saw power and the vacuum power.
4. Unlock and lower the band saw head and start the cut.
5. When the cut is completed, turn off the band saw power, the vacuum power and raise and lock the band saw head.
6. Release the clamp, take out the welded section, deburr the cut edges on the (0.9 x 0.35 x 0.1 inch) cross-section, and clean with alcohol.
7. Bag or tube the (0.9 x 0.35 x 0.1 inch) cross-section for LAMDA shipment. Label in reverse order of cutting as specified in the beginning of Section 5, i.e. the first cross-section cut from the L1/L4 welded section will be EPRI Alloy-Boron-Serial# L1/L4 MS7, the next cross-section will be MS6, and so forth.
8. If this is not the 14th cut of Section 5.9, return to the top of Section 5.9 and repeat. A total of seven cuts will be made on each of two welded sections.
9. Excess welded sections should be stored and labeled as specified at the beginning of Section 5.



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 cutting 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

Friction Stir Welded Coupon Cutting Procedure (Approved)

STANDARD OPERATING PROCEDURE

Title: Friction Stir Weld Specimen Band Saw and Slow Speed Saw Cutting in Hot Cell

Prepared by: *Wei Tang* Date 04/23/2018
Wei Tang, Staff Member
Materials Processing and Joining Group

Approved by: *James A Haynes* Date 04/27/18
Allen Haynes, Group Leader
Materials Processing and Joining

QA Approval: *MCVance* Date 4/23/18
Mark C. Vance, Quality Representative
Performance Analysis and Quality

DSO Approval: *Tracy Strader* Date 4/24/18
Tracy W. Strader, Research Support Group Leader
Materials Science and Technology Division

Mark Delph Date 4/30/18
Mark Matthews Delph, 3025E Hot Cell Operations Supervisor
Non-reactor Nuclear Facilities Division

STANDARD OPERATING PROCEDURE

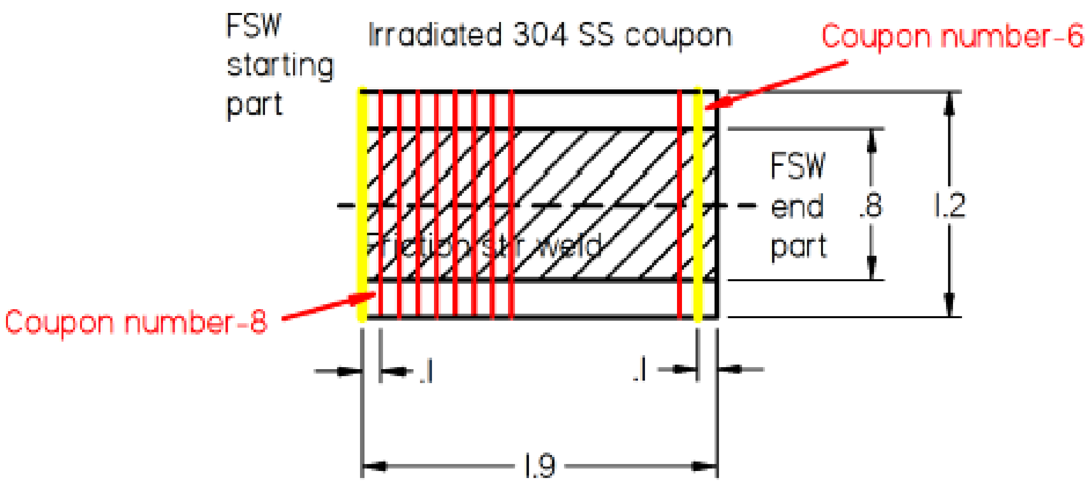
1 Purpose

Cut specimens from irradiated material friction stir welds using a band saw and a slow speed saw in a hot cell for post weld characterization.

2 Scope

The activities described in this procedure are to be conducted in a hot cell in Building 3025E and include the following activities.

- Setup weld coupon on the band saw clamping vise and a slow speed saw clamping fixture.
- Cut specimens in different sizes with the band saw and a slow speed saw.
- Use a vacuum to capture cutting fines/shavings and treat them as waste. The vacuum has the grounded power supply and is currently used in building 3025E hot cell.
- Apply water during slow speed saw cutting only. Don't apply water or any other lubricant during band saw cutting.
- Mark specimens. For each specimen, the mark is always placed on the beginning side of the friction stir weld, as it is shown with yellow color bar in the following schematic.



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

- Irradiated materials are involved.
- Liquid and cutting fines are produced and cutting fines will go into a waste can following non-reactor nuclear facilities division policy.
- Cleaning wipes will be dried and go into a waste can following non-reactor nuclear facilities division policy.

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 3025E. 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 cutting 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.

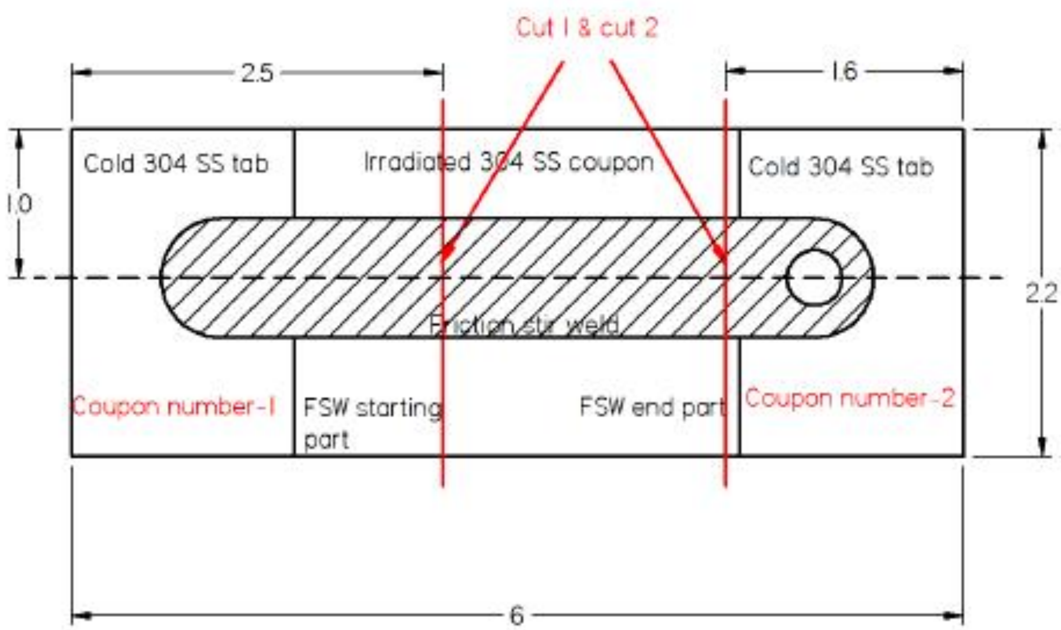
5 Procedural Steps – Specimen cutting in hot cell

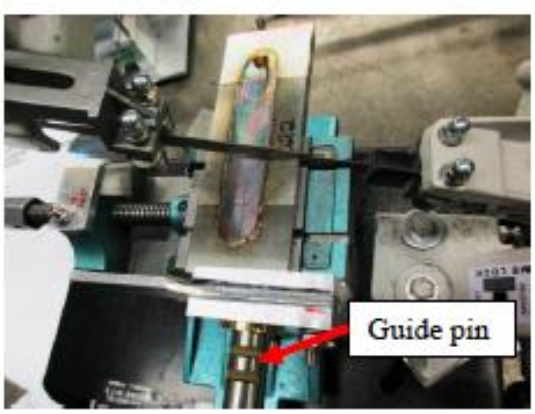
Before the specimen cutting, prepare various aluminum cans for cut off large parts and fiber tubes for cut off small specimens. Following the description in the procedure, mark those aluminum cans and fiber tubes prior to sending them into the hot cell, with Coupon number-x, such as 304C-6-2, where 304C-6 is the Coupon number and -2 is the part from the 2nd cut.

5.1 The 1st cut

1. Set the guide pin A to the mark 1.
2. Clamp the friction stir welded coupon with the run-on tab end firmly in contact with the guide pin shown in the following figure.
3. Unlock the band saw head, and make sure the band saw power and vacuum power are on before the saw blade contacts the coupon.
4. When the cutting is completed, turn off the band saw power, raise and lock the band saw head.

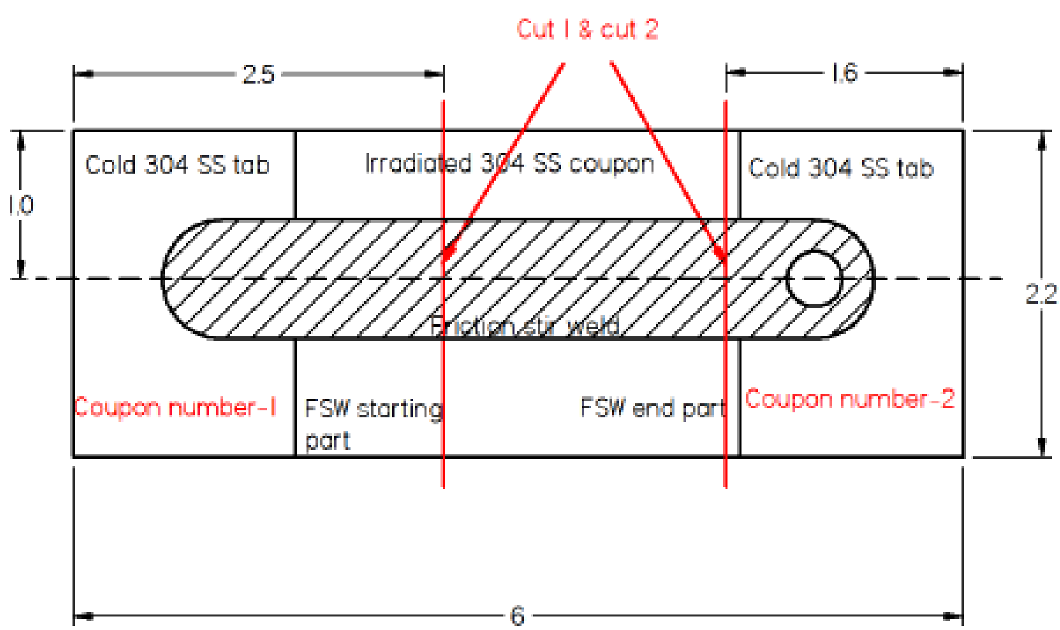
5. Use brush to clean the saw blade and use vacuum to collect loose cutting fines if it is necessary then turn off the vacuum.
6. Release the clamp, take out the clamped coupon, deburr cut edges on both pieces, clean with alcohol and dry, and mark cut sides. Coarse silicon carbide papers and/or a file will be used for the deburring for all cut parts in this procedure.
7. Pack the cut off FSW coupon beginning part (~2.5" X 2.2" X 0.35") into the aluminum can marked as Coupon number-1.
8. The Coupon number-1 will be stored.

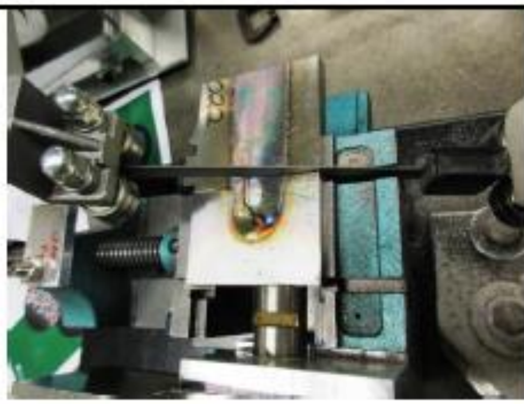




5.2 The 2nd cut

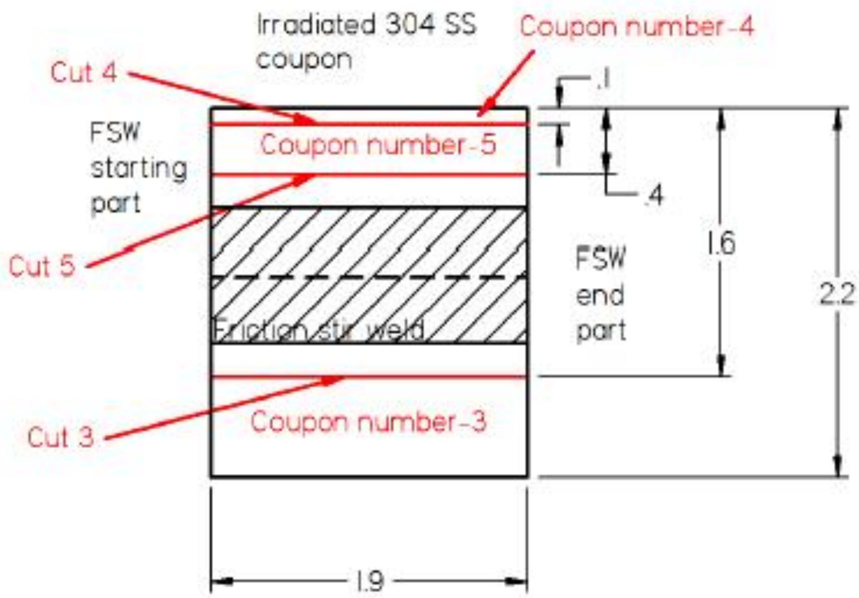
1. Set the guide pin A to the mark 2.
2. Clamp the friction stir welded coupon with the run-off tab end firmly in contact with the guide pin shown in the following figure.
3. Unlock the band saw head, and make sure the band saw power and vacuum power are on before the saw blade contacts the coupon.
4. When the cutting is completed, turn off the band saw power, raise and lock the band saw head.
5. Use brush to clean the saw blade and vacuum to collect loose cutting fines if it is necessary then turn off the vacuum.
6. Release the clamp, take out the clamped coupon, deburr cut edges on both pieces, and clean with alcohol and dry.
7. Pack the cut off FSW coupon end part (~1.6" X 2.2" X 0.35") into the aluminum can marked as coupon number-2.
8. The Coupon number-2 will be stored

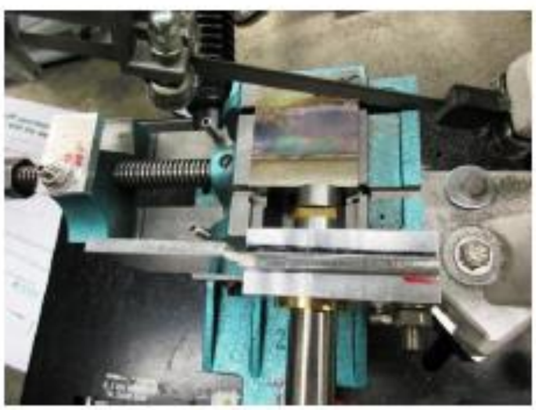




5.3 The 3rd cut

1. Set the guide pin A to the mark 2.
2. Turn the remaining coupon 90 degrees perpendicular with the 1st and 2nd cut orientation, let the arc top (Or bottom of "U") shown on the top of the weld, or weld beginning of the remaining part, or the marked side in step 5.1, point to the band saw motor side. Clamp the friction stir welded coupon with the side firmly in contact with the guide pin shown in the following figure.
3. Unlock the band saw head, and make sure the band saw power and vacuum power are on before the saw blade contacts the coupon.
4. When the cutting is completed, turn off the band saw power, raise and lock the band saw head.
5. Use brush to clean the saw blade and vacuum to collect loose cutting fines if it is necessary then turn off the vacuum.
6. Release the clamp, take out the clamped coupon, deburr cut edges on both pieces, clean with alcohol and dry, and mark cut sides of both pieces.
7. Pack the cut off small part (~1.8" X 0.55" X 0.35") into the aluminum can marked as coupon number-3.
8. The Coupon number-3 will be stored.





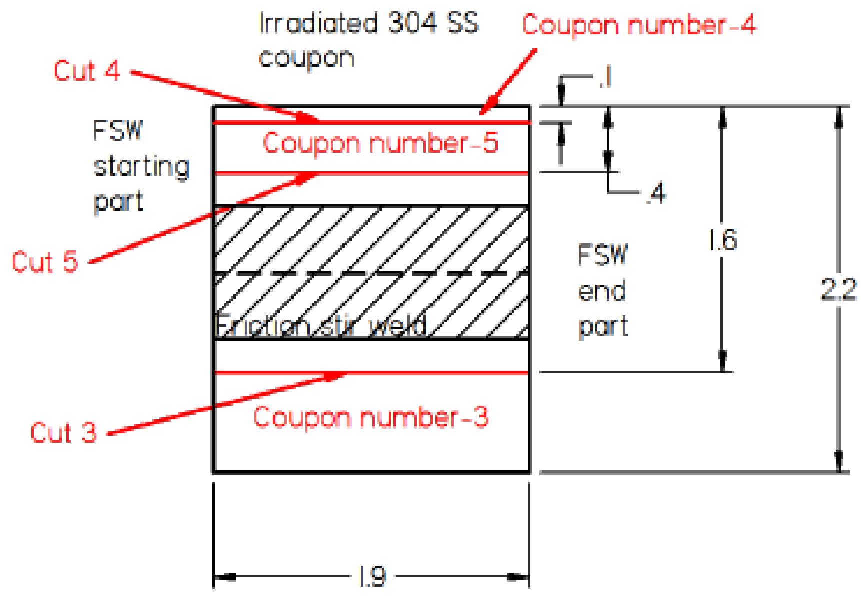
Pack with the Coupon number-3 aluminum can.

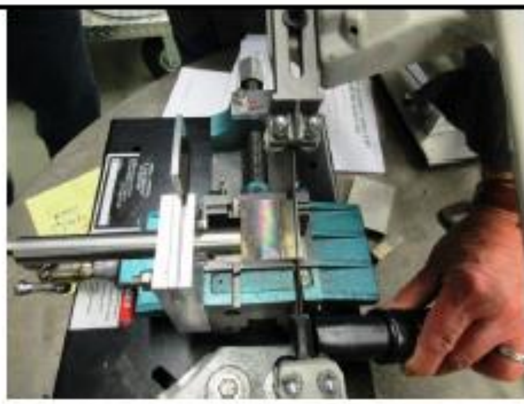
5.4 The 4th cut

1. Set the guide pin A to the mark 4.
2. Turn the remaining coupon 180 degrees from the setup of the 3rd cut orientation, let the arc top (Or bottom of "U") shown on the top of the weld, or weld beginning of the remaining part, or the marked side in step 5.1, point away from the band saw motor side, and the marked cross section in step 5.3 on the longitudinal direction is placed

against the guide pin. Clamp the friction stir welded coupon with the side firmly in contact with the guide pin shown in the following figure.

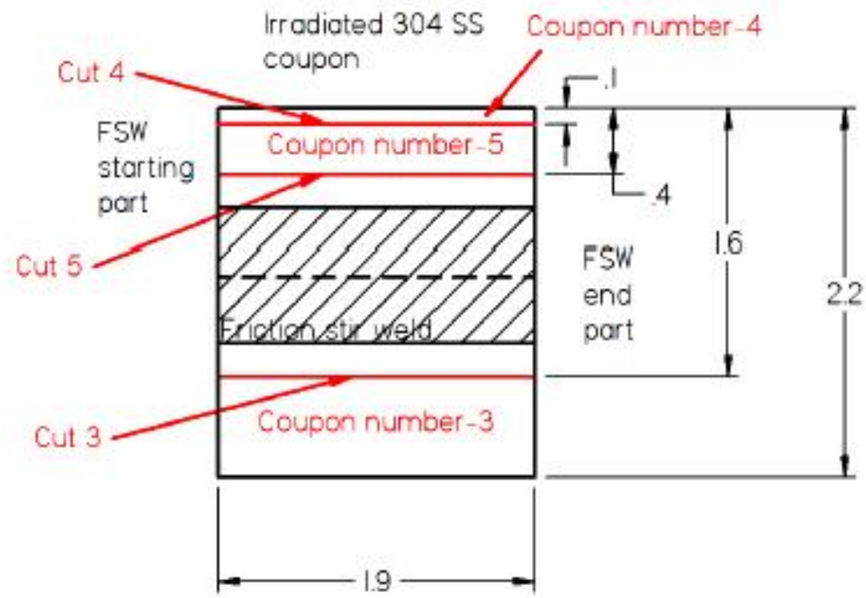
3. Unlock the band saw head, and make sure the band saw power and vacuum power are on before the saw blade contacts the coupon.
4. When the cutting is completed, turn off the band saw power, raise and lock the band saw head.
5. Use brush to clean the saw blade and vacuum to collect loose cutting fines if it is necessary then turn off the vacuum.
6. Release the clamp, take out clamped coupon, deburr cut edges on both pieces, clean with alcohol and dry, and mark cut sides.
7. If later cuts of Coupon number-4 are required a slow speed saw will be used and carried out at Low Activation Materials Development and Analysis (LAMDA), pack the cut off part (~1.8" X 0.35" X 0.1") into the aluminum can marked as coupon number-4.
8. If later cuts of Coupon number-4 using a slow speed saw will be carried out at 3025E, leave it aside for the later slow speed saw cutting.

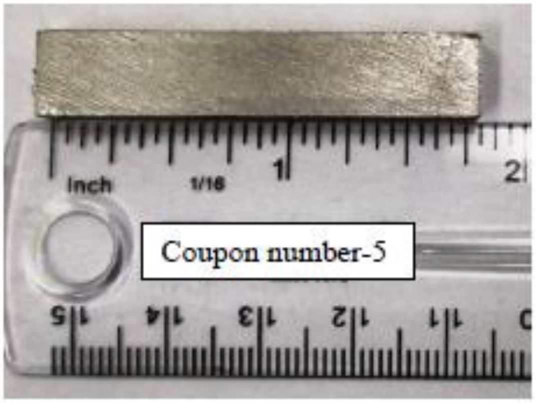




5.5 The 5th Cut

1. Set the guide pin A to the mark 3.
2. Keep remaining coupon the same orientation with the 4th cut, let the arc top (Or bottom of "U") shown on the top of the weld, or weld beginning of the remaining part, or the marked side in step 5.1, point away from the band saw motor side. Clamp the friction stir welded coupon with the side firmly in contact with the guide pin shown in the following figure.
3. Unlock the band saw head, and make sure the band saw power and vacuum power are on before the saw blade contacts the coupon.
4. When the cutting is completed, turn off the band saw power, raise and lock the band saw head.
5. Use brush to clean the saw blade and vacuum to collect loose cutting fines if it is necessary then turn off the vacuum.
6. Release the clamp, take out the clamped coupon, deburr cut edges on both pieces, and clean with alcohol and dry.
7. Pack the cut off part (~1.8" X 0.35" X 0.2") into the aluminum can marked as coupon number-5.
8. The Coupon number-5 will be stored.

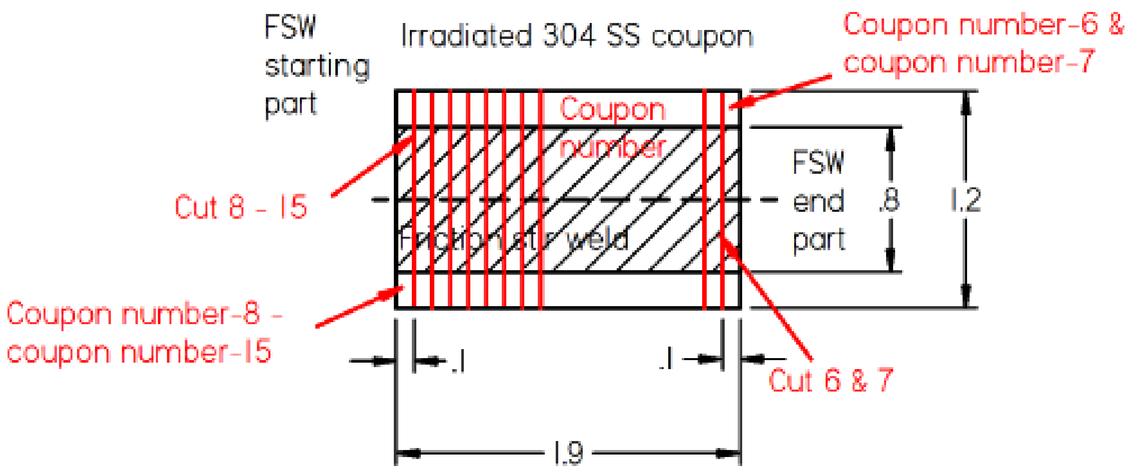


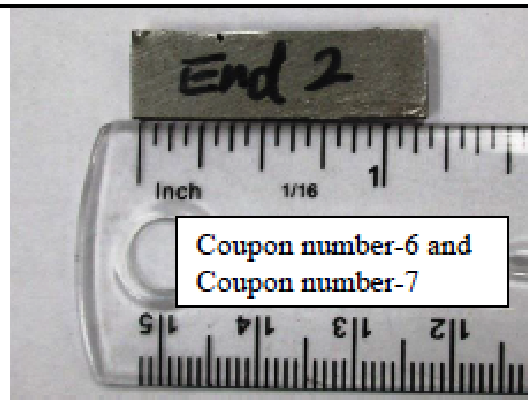


5.6 The 6th and 7th cuts

1. Set the guide pin B to the mark 1.
2. Turn the remaining coupon 90 degrees from the setup of the 5th cut, let the arc top (Or bottom of "U") shown on the top of the weld, or weld beginning of the remaining part, or the marked edge in step 5.1, point to the guide pin. Clamp the friction stir welded coupon with the side firmly in contact with the guide pin.

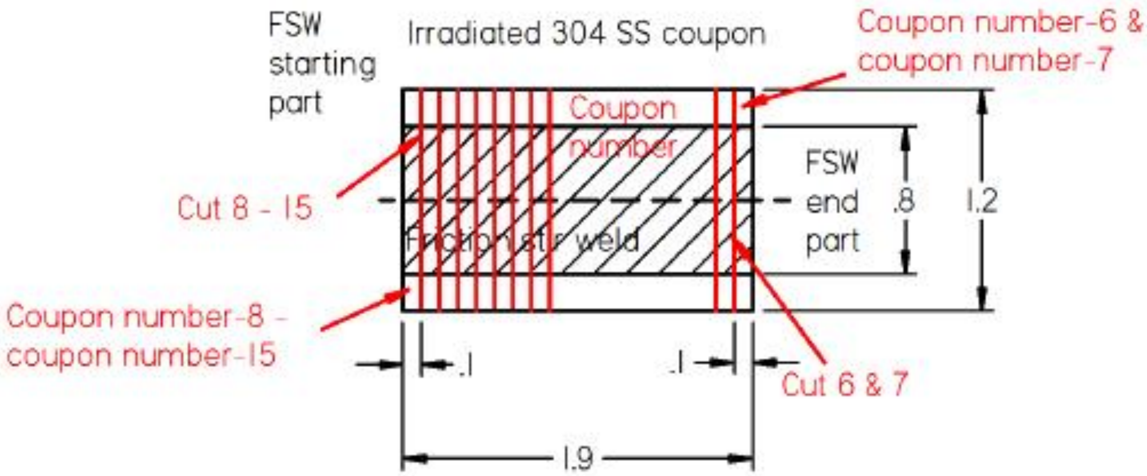
3. Unlock the band saw head, and make sure the band saw power and vacuum power are on before the saw blade contacts the coupon.
4. When the cutting is completed, turn off the band saw power, raise and lock the band saw head.
5. Use brush to clean the saw blade and vacuum to collect loose cutting fines if it is necessary then turn off the vacuum.
6. Release the clamp, take out clamped coupon, deburr cut edges on both pieces, clean with alcohol and dry, and mark the cut surface of the cut off specimen only.
7. Pack the cut off small specimen (~1.2" X 0.35" X 0.1") into the fiber tube marked as coupon number-6.
8. Set the guide pin B to the mark 2.
9. Repeat step 2 to step 6 without changing the weld coupon orientation, cut another specimen off, pack the cut off small part (~1.2" X 0.35" X 0.1") into the fiber tube marked as coupon number-7.
10. Coupon number-6 and Coupon number-7 will be transported to LAMDA.

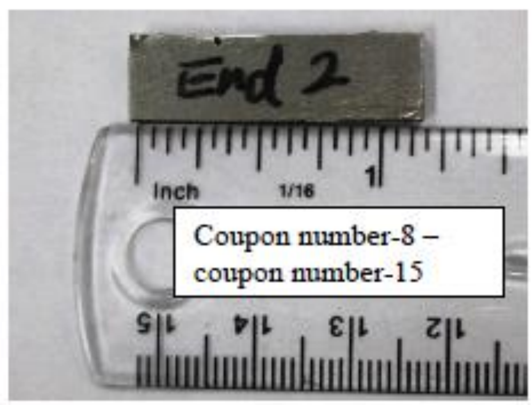




5.7 The 8th – 15th cut

1. Set the guide pin B to the mark 3.
2. Mark the side with arc top (Or bottom of "U") shown on the top of the weld, or the side close to weld beginning of the remaining part, or the side close to the marked side in step 5.1, if it is not marked.
3. Turn the remaining coupon 180 degrees from the setup of the 6th and 7th cuts, let the arc top (Or bottom of "U") shown on the top of the weld, or the side close to the weld beginning of the remaining part, or the marked side in step 5.1, point away the guide pin. Clamp the friction stir welded coupon with the side firmly in contact with the guide pin shown in the following figure.
4. Unlock the band saw head, and make sure the band saw power and vacuum power are on before the saw blade contacts the coupon.
5. When the cutting is completed, raise and lock the band saw head, and turn off the band saw power.
6. Use brush to clean the saw blade and vacuum to collect loose cutting fines if it is necessary then turn off the vacuum.
7. Release the clamp, take out clamped coupon, deburr cut edges on both pieces, and clean with alcohol and dry.
8. Reset the guide pin to the proper mark (Pin B, the mark 4 – the mark 10).
9. Pack the cut off small specimen (~1.2" X 0.35" X 0.1") into the fiber tube marked as coupon number-8.
10. Repeat step 2 to step 8 seven times without change the weld coupon orientation, cut seven more specimens off, pack the cut off small specimens (~1.2" X 0.35" X 0.1") into the fiber tube marked as Coupon number-9 – Coupon number-15.
11. Coupon number-9 – Coupon number-15 will be transported to LAMDA.

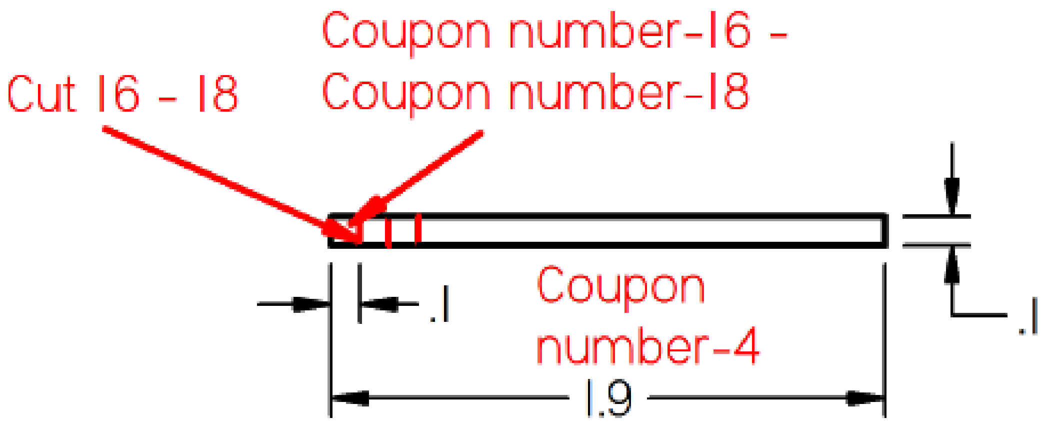




5.8 The 16th – 18th cut

1. Clamp the Coupon number-4 (~1.8" X 0.35" X 0.1") on a slow speed saw with the orientation cutting through the 0.35" X 0.1" cross section.
2. Adjust the Coupon number-4 stick out position to cut a specimen with about 0.1" long.
3. Cut the specimen.
4. Deburr cut edges on both pieces and clean with alcohol.
5. Pack the cut specimen (~0.35" X 0.1" X 0.1") with a fiber tube marked as Coupon number-16.
6. Repeat step 1 to step 5 to cut two more specimens, pack them into fiber tubes marked as Coupon number-17 and Coupon number-18, respectively, and pack the remaining specimen into the aluminum can marked as coupon number-4.

7. Coupon number-16 – Coupon number-18 will be transported to LAMDA. Coupon number-4 will be stored.



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 weld cutting traveler form shall be completed for the cutting of each set of welded 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
MST Division Safety Officer	Date

2nd Re-Review

MP&J Group Leader	Date
MST Division Safety Officer	Date

Appendix C

Nuclear Industry Welding Workshop Agenda and Participant List

OAK RIDGE National Laboratory

AGENDA

MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

Nuclear Industry Welding Meeting / Workshop
Utility, Vendor and Research Communities

Purpose:
To engage utility, industry and laboratories in a discussion of the current needs and capabilities for weld repair in the nuclear industry and to discuss the latest research directed at solutions to current limitations in the repair of highly irradiated materials.

Tuesday, September 18, 2018

Event Contact	Keith Leonard, 8645-576-3687 (office); leonardk@ornl.gov Scarlett Clark, 865-576-1614 (office): clarksr@ornl.gov	
Time	**Event**	**Location**
8:30 – 9:00 am	Visitor's Center check in	Building 5200, ORNL Visitor Center
9:00 – 9:30 am	Welcome / Introduction and purpose of the meeting **Keith Leonard (ORNL)**	Building 5200, Room 214 (Emory)
9:30 – 10:00 am	Presentation **Darren Wood (Framatome)**	
10:00 – 10:20 am	Break	Building 5200, Room 214 (Emory)
10:20 – 10:50 am	Presentation **David Segletes (Structural Integrity Associates, Inc.)**	Building 5200, Room 214 (Emory)
10:50 – 11:20 am	DOE-LWRS, and EPRI-LTO Introduction and research objectives **Keith Leonard (ORNL) and Heather Feldman (EPRI)**	Building 5200, Room 214 (Emory)
11:20am – 1:30pm	Working Lunch – All Discussion – *general discussion of concerns and issues raised from the morning session*	Building 5200, Room 214 (Emory)

LWRS LIGHT WATER REACTOR SUSTAINABILITY

EPRI ELECTRIC POWER RESEARCH INSTITUTE

OAK RIDGE National Laboratory

AGENDA

MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

Event Contact	Keith Leonard, 8645-576-3687 (office); leonardk@ornl.gov Scarlett Clark, 865-576-1614 (office): clarksr@ornl.gov	
Time	**Event**	**Location**
1:30 – 2:00 pm	EPRI: *What challenges can industry expect in extended operations related to repair and weld replacement?* **Wayne Lunceford (EPRI)**	Building 5200, Room 214 (Emory)
2:00 – 2:30 PM	LWRS: *Modeling and developing the basis for advanced weld repair of irradiated materials* **Zhili Feng (ORNL)**	Building 5200, Room 214 (Emory)
2:30 – 2:50 PM	Break	
2:50 – 3:20 PM	EPRI / Westinghouse / Purdue – *Recent findings for the NEUP project on laser welding of irradiated materials* **Jon Tatman (EPRI) and Keyou Mao (Purdue)**	Building 5200, Room 214 (Emory)
3:20 – 3:50 PM	LWRS and EPRI – The Welding Cubicle Discussion / presentation on the welding cubicle, its function, abilities, restrictions, etc. **Jon Tatman and Greg Frederick (EPRI)**	Building 5200, Room 214 (Emory)
3:50 – 4:30 pm	Discussion of the topics presented that day and agenda for Day 2 **All**	Building 5200, Room 214 (Emory)
5:00 pm	Working Dinner – Calhoun's, Oak Ridge Marina **Keith Leonard – Presentation on the Light Water Sustainability Program, Materials Research Pathway**	Calhoun's Oak Ridge

Wednesday, September 19, 2018

Event Contact	Keith Leonard, 8645-576-3687 (office); leonardk@ornl.gov Scarlett Clark, 865-576-1614 (office): clarksr@ornl.gov	
Time	**Event**	**Location**
8:30 – 9:00 am	Gather for Day 2, travel to conference room	Building 5200, Room 214 (Emory)
9:00 – 9:45 am	LWRS – Research Topic 1 Discuss latest results of welding cubicle results on stainless steel **Wei Tang (ORNL)**	Building 5200, Room 214 (Emory)

LWRS LIGHT WATER REACTOR SUSTAINABILITY

EPRI ELECTRIC POWER RESEARCH INSTITUTE

OAK RIDGE National Laboratory

AGENDA

MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

Event Contact	Keith Leonard, 8645-576-3687 (office); leonardk@ornl.gov Scarlett Clark, 865-576-1614 (office): clarksr@ornl.gov	
Time	**Event**	**Location**
9:45 – 10:30 am	LWRS – Research Topic 2 Numerical Modeling and In-Situ Experimental Validation of the Laser Welding Process **Jian Chen (ORNL)**	Building 5200, Room 214 (Emory)
10:30 – 10:50 am	Break	
10:50 – 11:30 am	LWRS and EPRI – future work **Alison Hahn (DOE)**	Building 5200, Room 214 (Emory)
11:30 – 12:45 pm	Working Lunch and Discussions - **All**	Building 5200, Room 214 (Emory)
12:45 – 1:00 pm	Travel to REDC - **All**	In-Transit
1:00 – 2:00 pm	Welding cubicle demonstration and discussion Scott White (ORNL)	Building 7930 (REDC)
2:00 – 2:15 PM	Travel to 3025E Hot Cell	In-Transit
2:15 – 3:00 PM	Tour of 3025E Hot Cell Facility Mark Delph (ORNL)	Building 3025E (IMET)
3:00 – 3:15 PM	Travel to LAMDA and Welding Labs	In-Transit
3:15 – 4:00 PM	Tour LAMDA and Welding Labs Josh Schmidlin (ORNL) and Wei Tang (ORNL)	Building 4508 (LAMDA)
4:00 – 4:30 pm	Return to Visitor's Center and depart ORNL	In-Transit

LWRS LIGHT WATER REACTOR SUSTAINABILITY

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Weld Repair Techniques Industry Workshop Participants			
September 18-19, 2018			
Oak Ridge National Laboratory			
Company	**Name**	**Email**	**Comments**
DEI	Jean Collin	jcollin@domeng.com	
DOE/NE	Alison Hahn	Alison.Hahn@nuclear.energy.gov	**Presenter**
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EPRI	Jon Tatman	jtatman@epri.com	
EPRI	Greg Frederick	gfrederi@epri.com	**Presenter**
EPRI	Ben Sutton	bsutton@epri.com	
EPRI	Heather Feldman	hfeldman@epri.com	
Exelon	Kenn Hunter	kenn.hunter@exeloncorp.com	
Exelon	Jacqui Graham	jacqueline.mansfield@exeloncorp.com	
Framatome	Jeff Enneking	jeffrey.enneking@framatome.com	
Framatome	Darren Wood	Darren.wood@framatome.com	**Presenter**
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NRC	Jeffrey Poehler	Jeffrey.Poehler@nrc.gov	
NRC	Joel Jenkins	Joel.Jenkins@nrc.gov	
NRC	Matthew Hiser	matthew.hiser@nrc.gov	
ORNL	Maxim Gussev	gussevmn@ornl.gov	
ORNL	Keith Leonard	leonardk@ornl.gov	**Presenter**
ORNL	Scarlett Clark	clarksr@ornl.gov	
ORNL	Zhili Feng	fengz@ornl.gov	**Presenter**
ORNL	Wei Tang	tangw@ornl.gov	**Presenter**
ORNL	Jian Chen	chenj2@ornl.gov	**Presenter**
ORNL	Mark Vance	vancemc@ornl.gov	
Purdue	Keyou Mao	kmao@purdue.edu	**Presenter**
Sargent Lundy	Andy Taylor	Andrew.C.Taylor@Sargentlundy.com	
SI	David Segletes	dsegletes@structint.com	**Presenter**
U of TN - Knoxville	Bill Hamel	whamel@utk.edu	
TVA	Keith Dietrich	kadietrich@tva.gov	
Westinghouse	Bruce Newton	newtonb@westinghouse.com	
Westinghouse	Paula Freyer	freyerpd@westinghouse.com	**Teleconference**