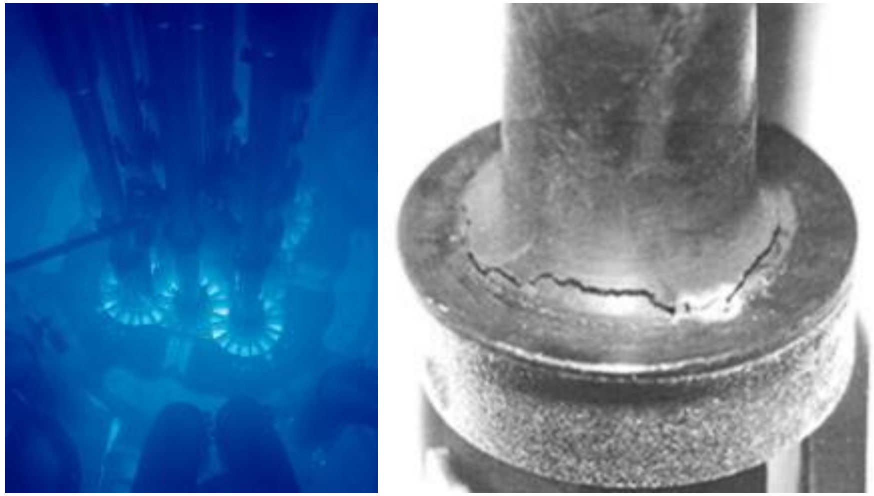
Irradiated Material Advanced Repair Welding

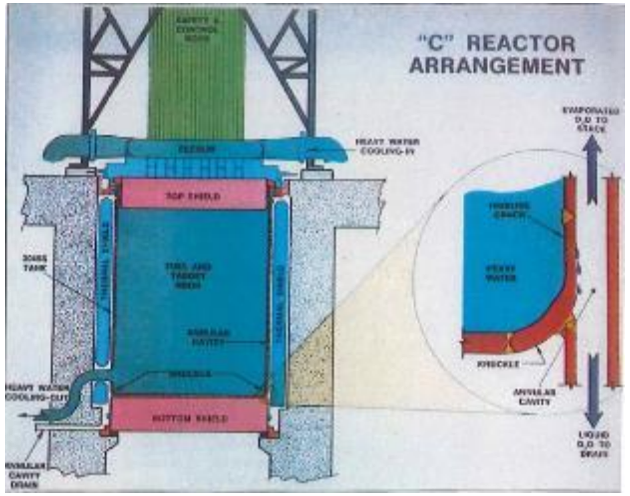
LWRS
LIGHT WATER REACTOR SUSTAINABILITY

Molten Salt Reactor Workshop 2018
October 3, 2018

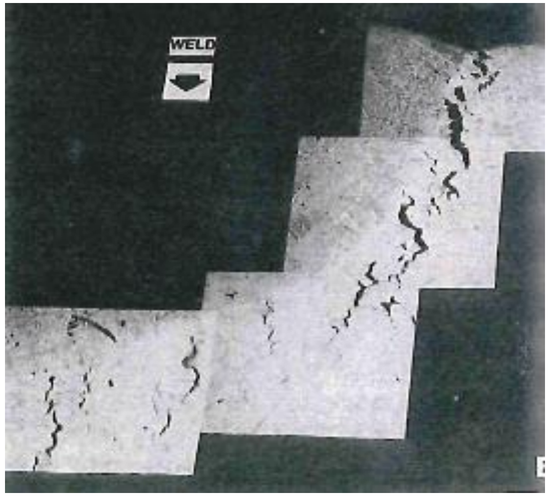
Historical Perspective



Nuclear reactor core component and irradiation induced damage



Location of Savannah River reactor water leakage

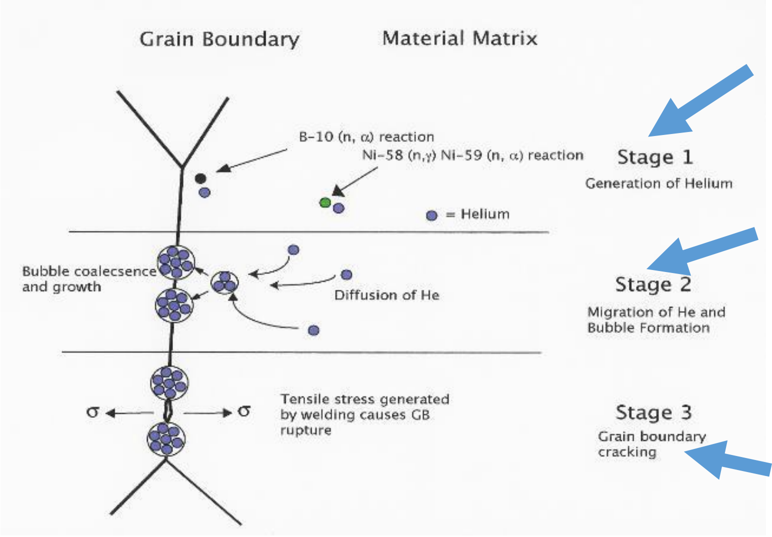


Weld toe cracks after repair welding

W. R. Kanne, Jr., "Remote Reactor Repair: GTA Weld Cracking Caused by Entrapped helium." Welding Journal, 67(8), 33 – 39 (1988)

- Extended operation in nuclear environments can produce changes to metal alloy components, creating damage that needs to be mitigated through either repair or replacement which involves welding.
- The heavy water moderator of a nuclear reactor located at Savannah River Plant, built in the 1950's, was detected with leakage first in 1968 and again in 1984 after the repair of the first time leakage. Welding toe cracking during the second repair led to permanent shut down of the reactor.
- What caused challenges in irradiated material repair welding?

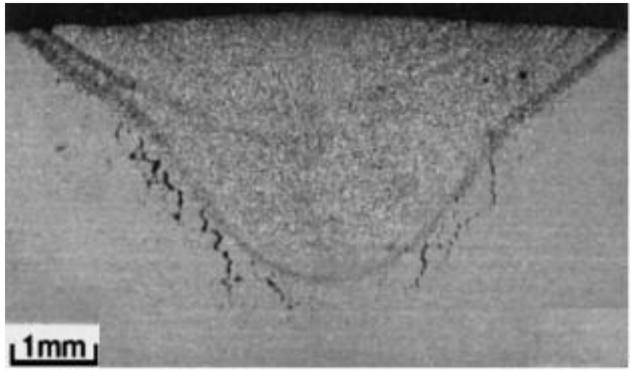
Key Research Issues Being Addressed



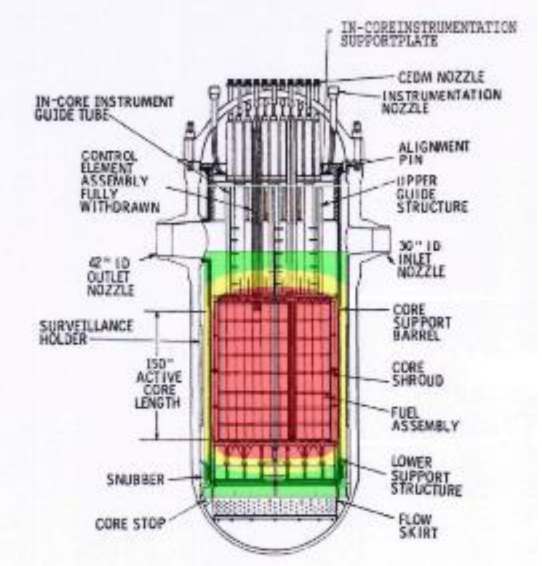
Helium generated in reactor internals throughout the life of the plant, from the boron and nickel transmutations

Diffusion and coalescence of helium occurs at grain boundaries during welding and embrittle the metal

Tensile stress generated during the cooling cycle of the weld exacerbate grain boundary helium bubble growth, resulting in rupturing



Helium-induced cracks in the HAZ after welding stainless steel contains 8.3 appm He.[1]



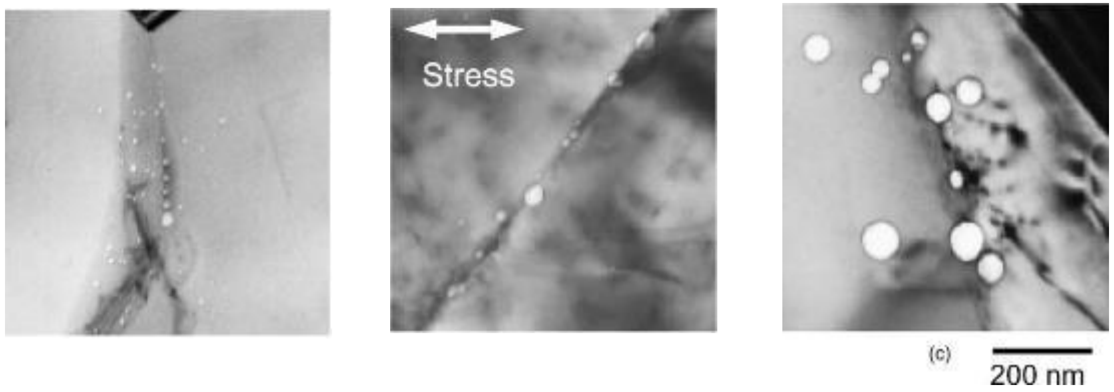
Helium Generation at 60 effective full power year (EFPY).[2]
Red Zone: >10 appm He (not weldable with current welding processes);
Yellow Zone: 0.1 to 10 appm He (weldable with heat input control welding);
Green Zone: <0.1 appm He (No special process control is needed in welding repair).

- Helium is generated in nuclear structural materials from reactions between the thermal neutrons and boron impurity, or through two-step reactions with nickel. Helium levels in the majority part of pressurized water reactors (PWR), with 60 effective full power years, will be more than 10 appm.
- During repair welding, helium will diffuse and coalesce at grain boundaries and embrittle the metal, resulting helium-induced cracking by welding residual stress, with as little as a couple of appm helium concentration in welded metal.
- Key factors affect irradiated material welding quality are high temperature and tension stress.

1. Kyoichi Asano, et al. Journal of Nuclear Materials, 264, 1 – 9 (1999)
2. EPRI, BWR Vessel and Internals Project, Guidelines for Performing Weld Repairs to Irradiated BWR Internals, BWRVIP-97-A, June 23, 2009.

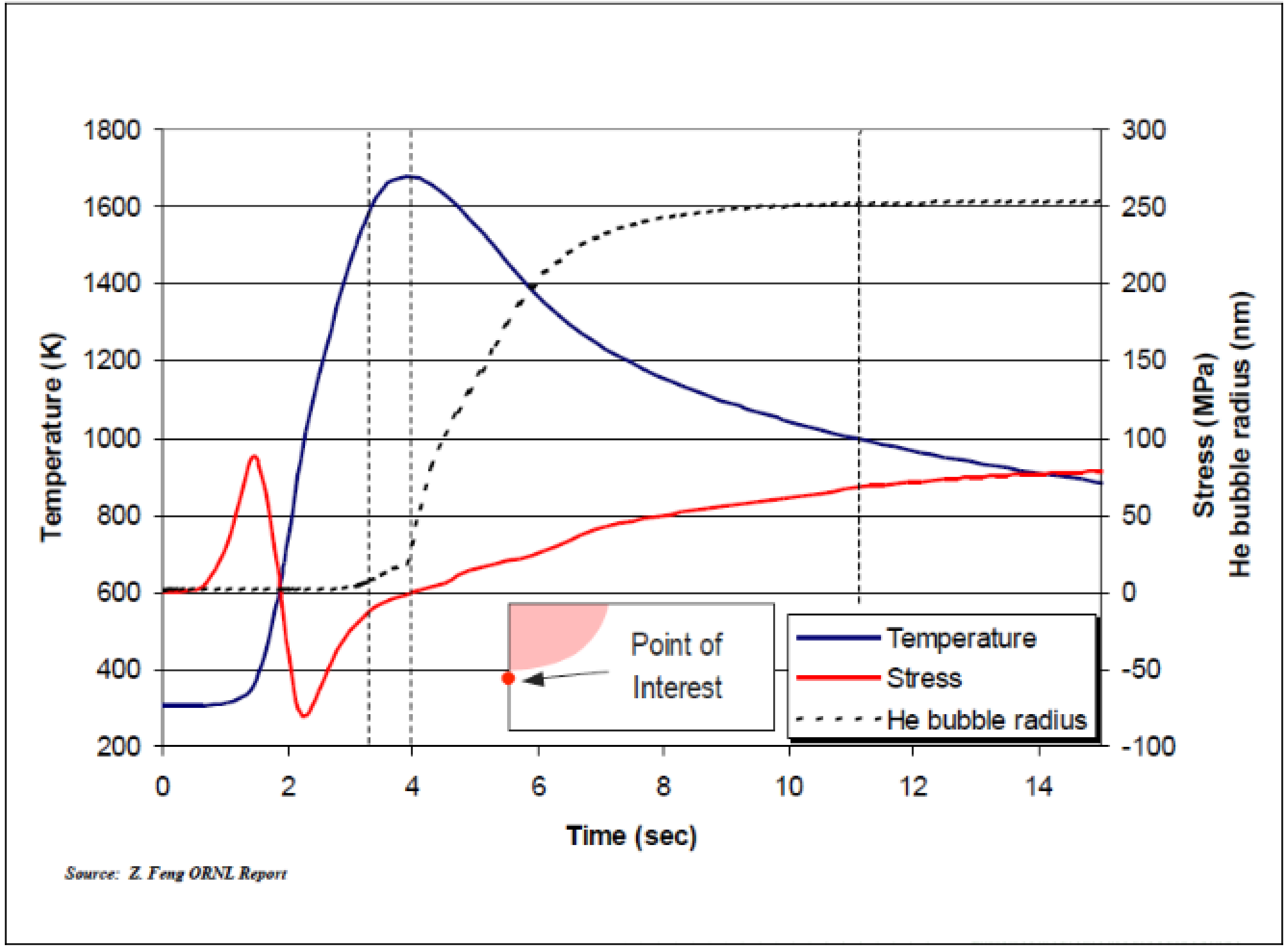
Technology Gap: Control Grain Boundary Helium Bubble Coalescence During Welding

- Key welding factors to control the helium bubble migration and growth at the grain boundary during welding:
  1. Controlling welding heat input and weld thermal cycle (i.e., reduce time above 800°C)
  2. Controlling the tensile stress profile during cooling (during maximum helium bubble growth period)
- Conventional welding processes can not be controlled to a level that reduces or eliminates the He-bubble growth to prevent grain boundary cracking

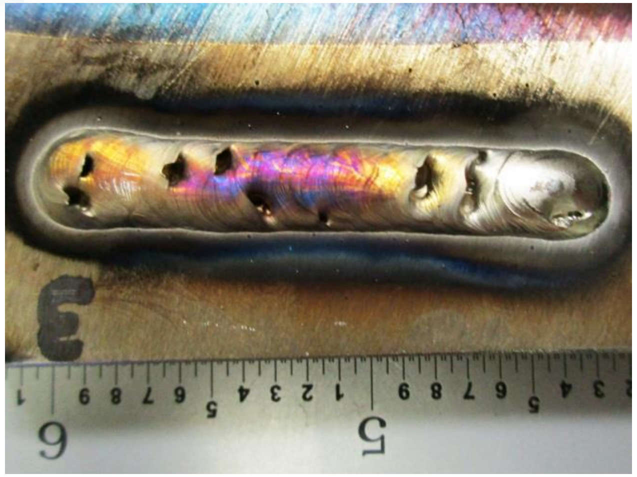


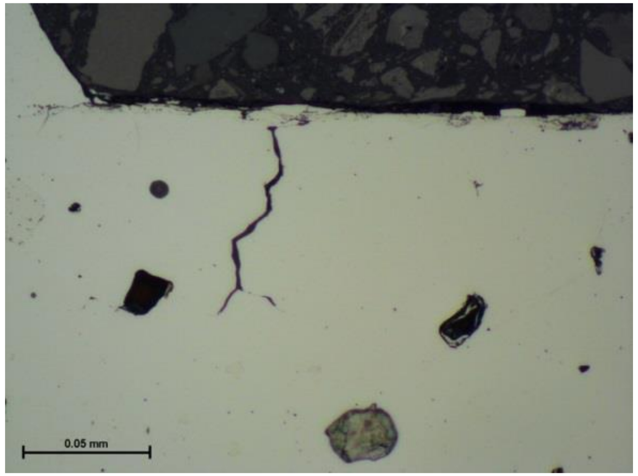
1073 K, 2MPa 1273K, 2 MPa 1273 K, 8 MPa

S. Kawano, F. Kano, C. Kinoshita, A. Hasegawa, K. Abe, Journal of Nuclear Materials, 307–311, 327–330 (2002)



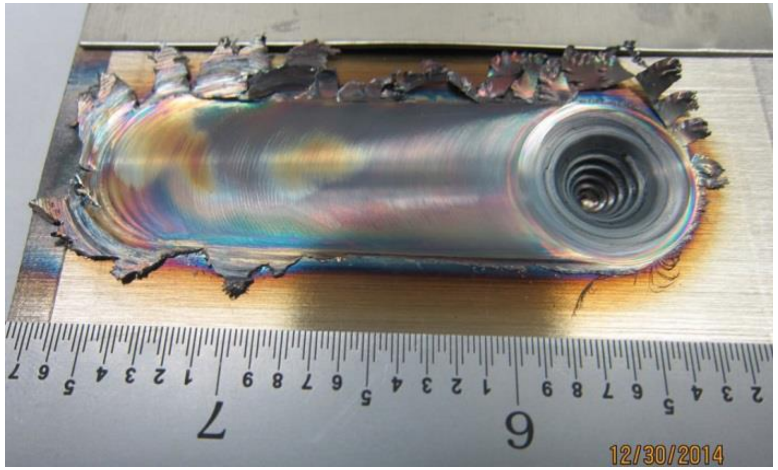
Advanced Welding Technology May Provide Solutions to Repair and Mitigation Concerns

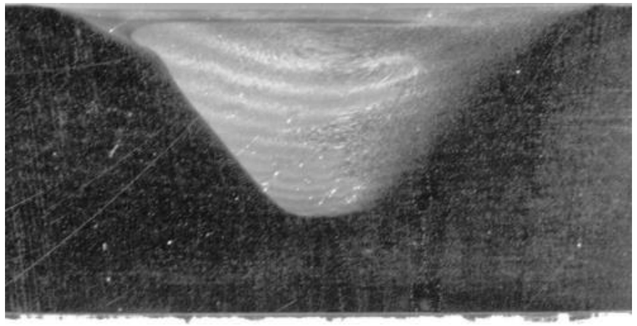


Huge voids and cracks with fusion welding

- Recent work performed on high helium content stainless steel produced by powder metallurgy
- Friction stir welding (FSW) suppressed voids and cracks due to its solid state low welding temperature.

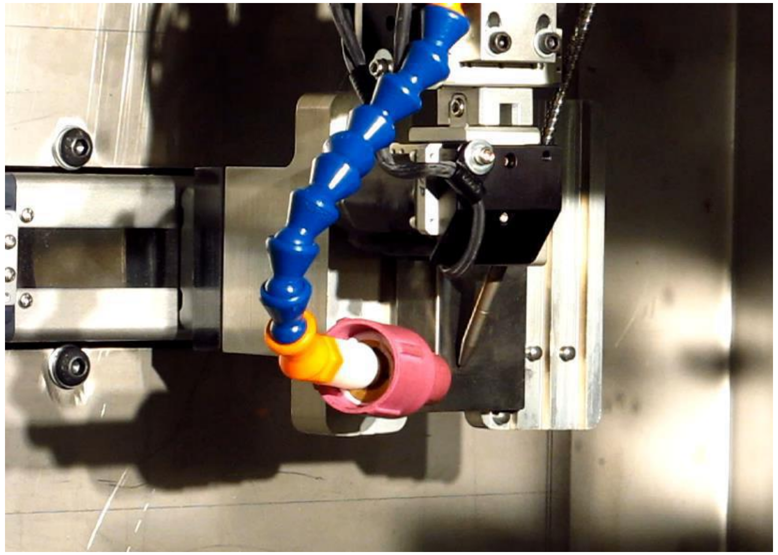


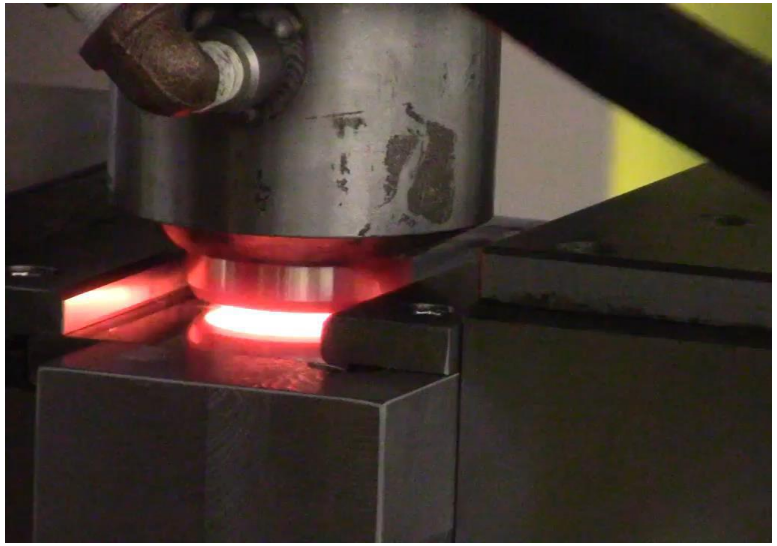


Friction stir welding and cross section

Advanced Welding Processes Development

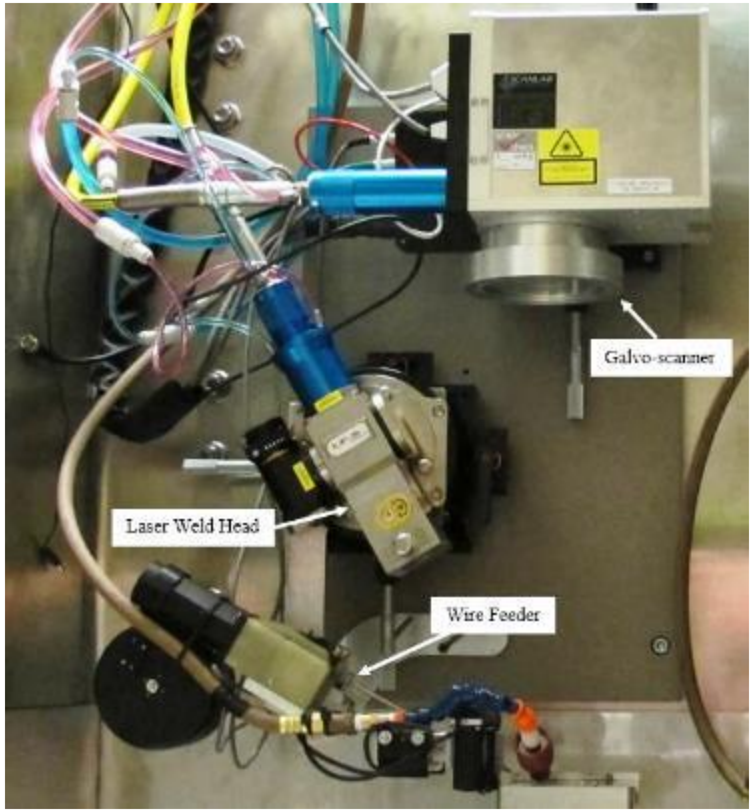
- Overall project objectives:
  1. Obtain comprehensive understanding of the metallurgical effects of welding on irradiated austenitic materials and Nickel alloys
  2. Develop and validate advanced welding processes tailored for repair of irradiated austenitic materials
  3. Provide generic welding specifications and welding thresholds for irradiated austenitic materials
- Welding processes under development
  - Auxiliary beam stress improved (ABSI) laser beam welding
  - Solid state friction stir welding/cladding

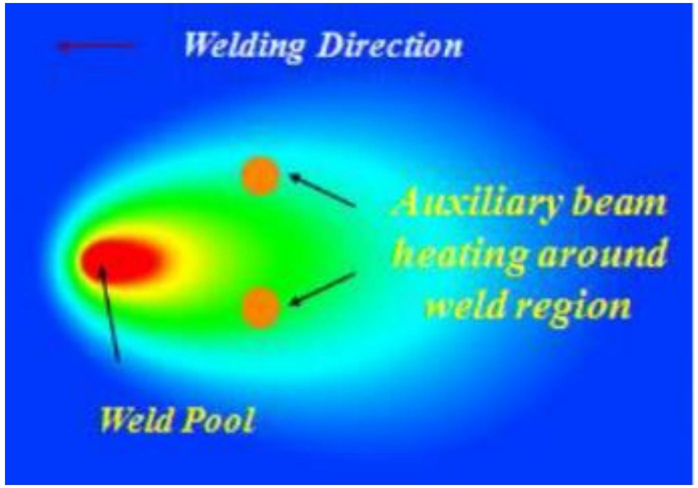


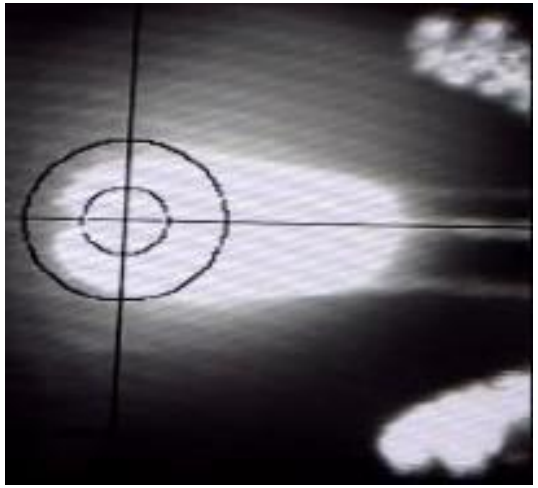


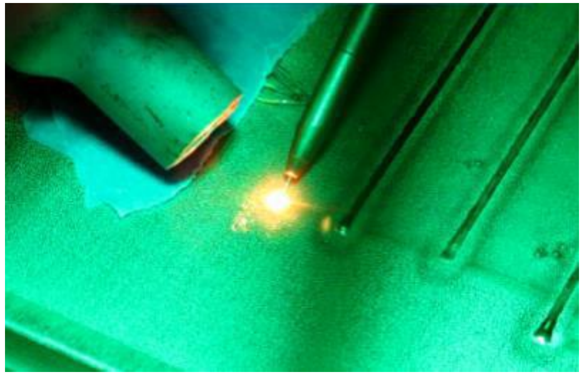
Auxiliary Beam Stress Improved (ABSI) Laser Welding

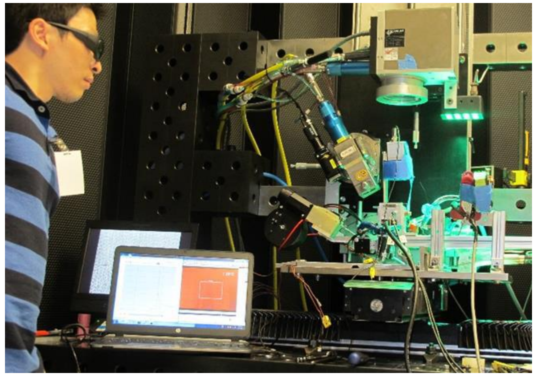
- Two lasers beams, the primary laser and the scanning laser, are used in the ABSI laser welding, while the primary laser is used for welding and the scanning laser is used for auxiliary heating around the weld region.
- The scanning laser beam is used to change the welding residual stress distribution around the welding pool





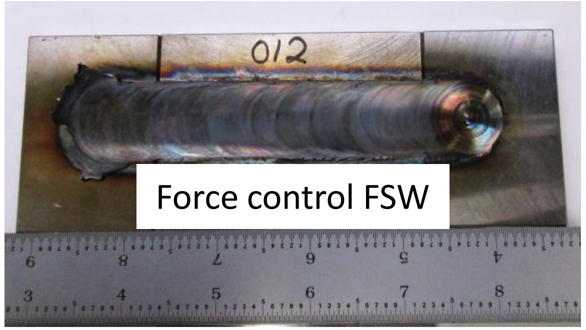


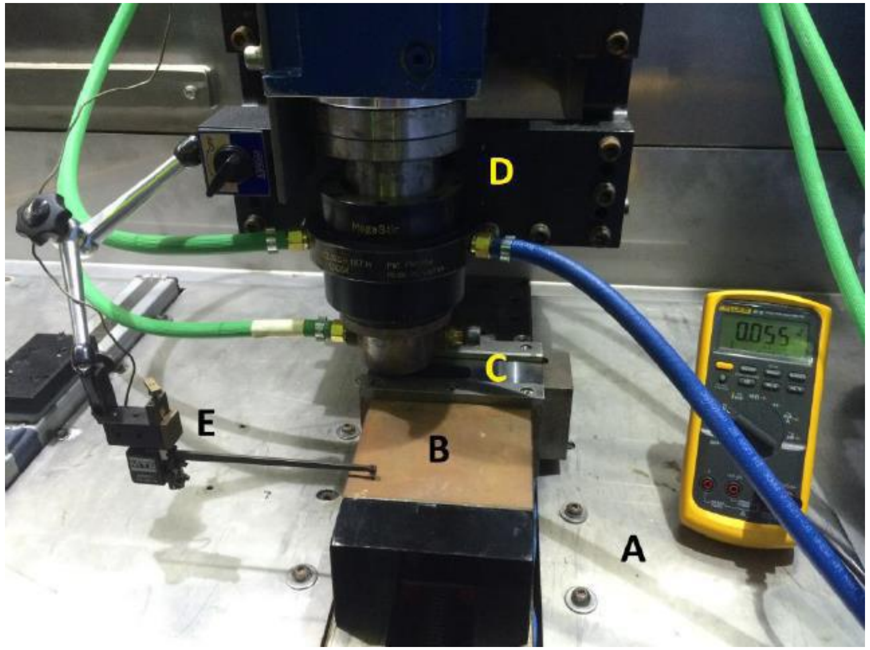




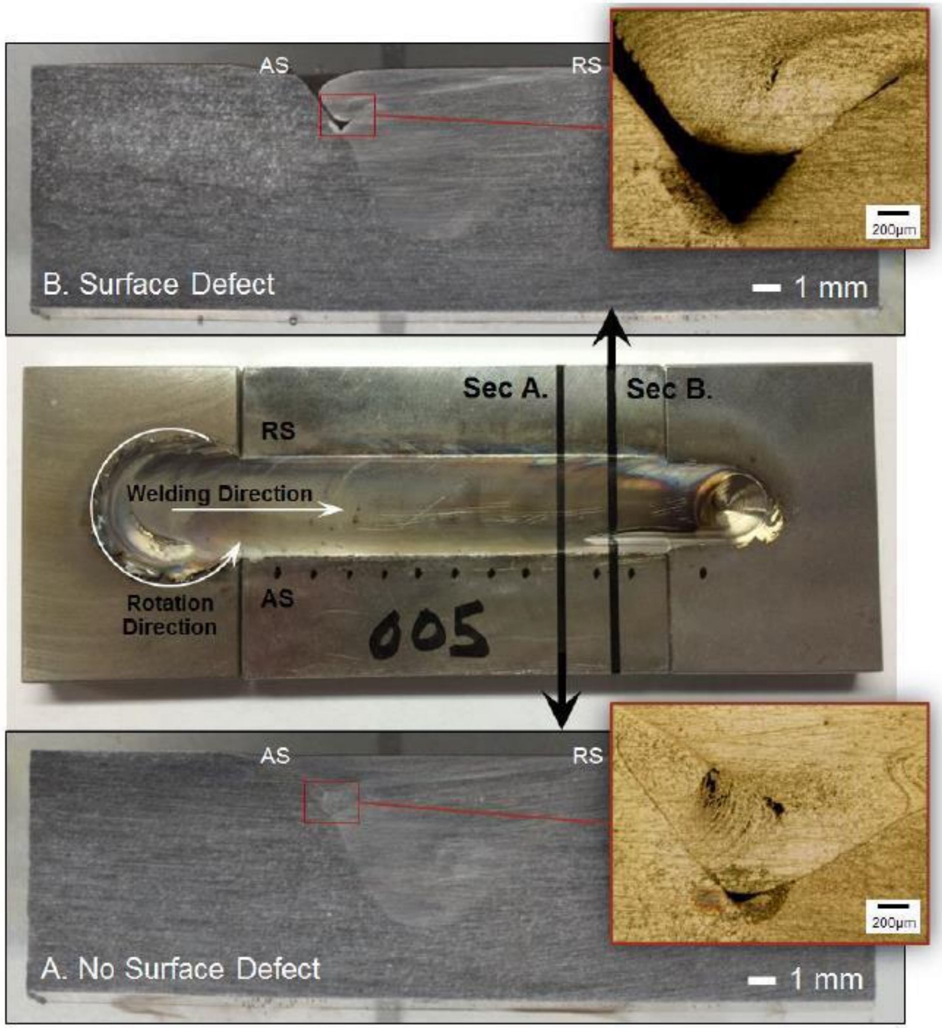
Friction Stir Welding Process Development

- Initial parameter development performed using ***force control*** friction stir welding, whereas the hot cell will rely on ***position control***
- Machine deflection was identified as a contributor to surface defect formation during initial friction stir welding trials inside hot cell on unirradiated materials
- Software updated to incorporate z-axis position control (preprogrammed or manual)



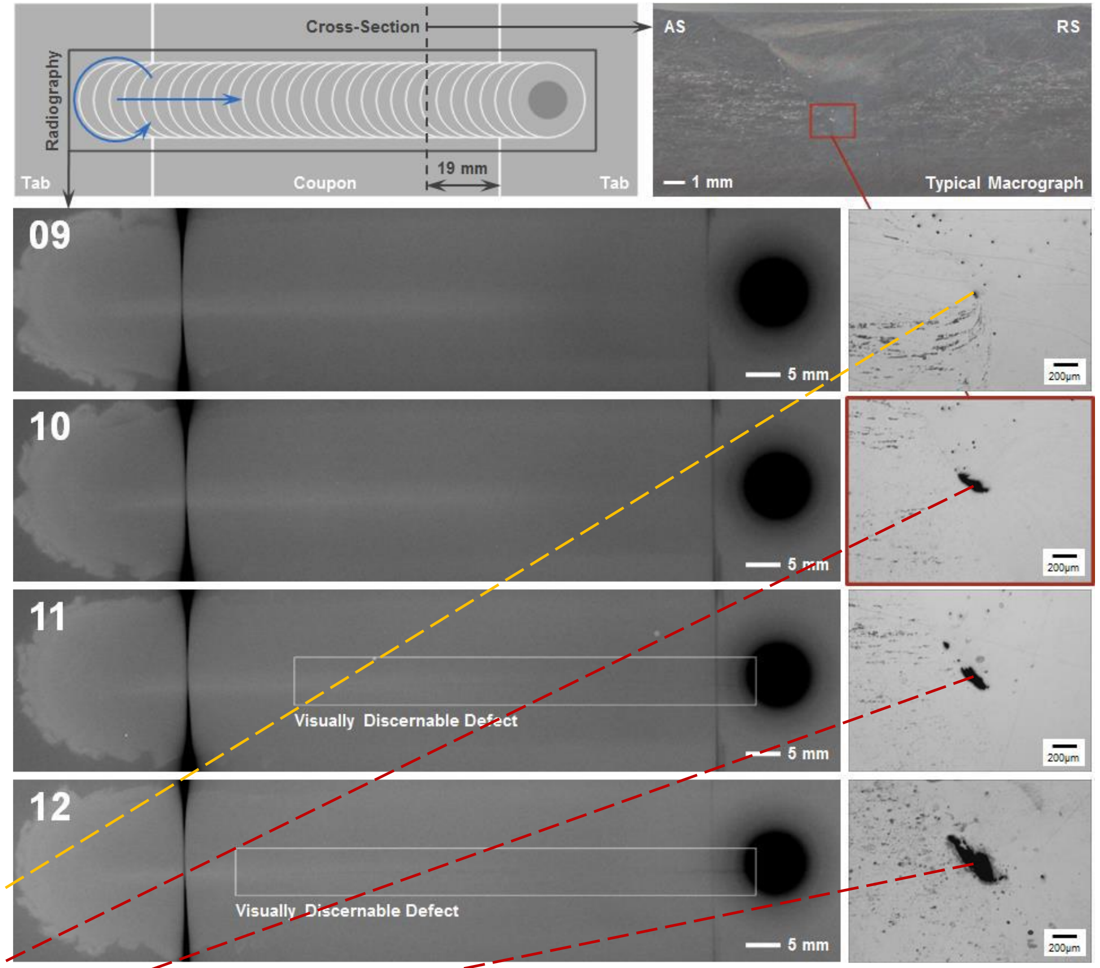


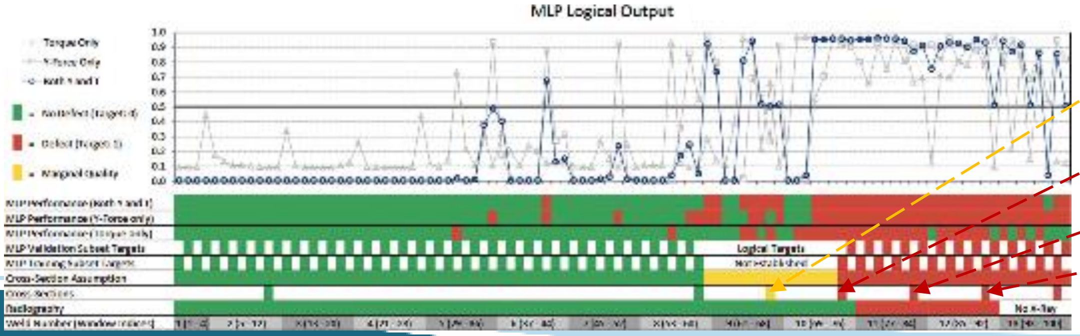
A. Welding Table
B. Clamping Vise
C. Coupon
D. FSW Head
E. Extensometer



Friction Stir Welding Process Development – Tool wear

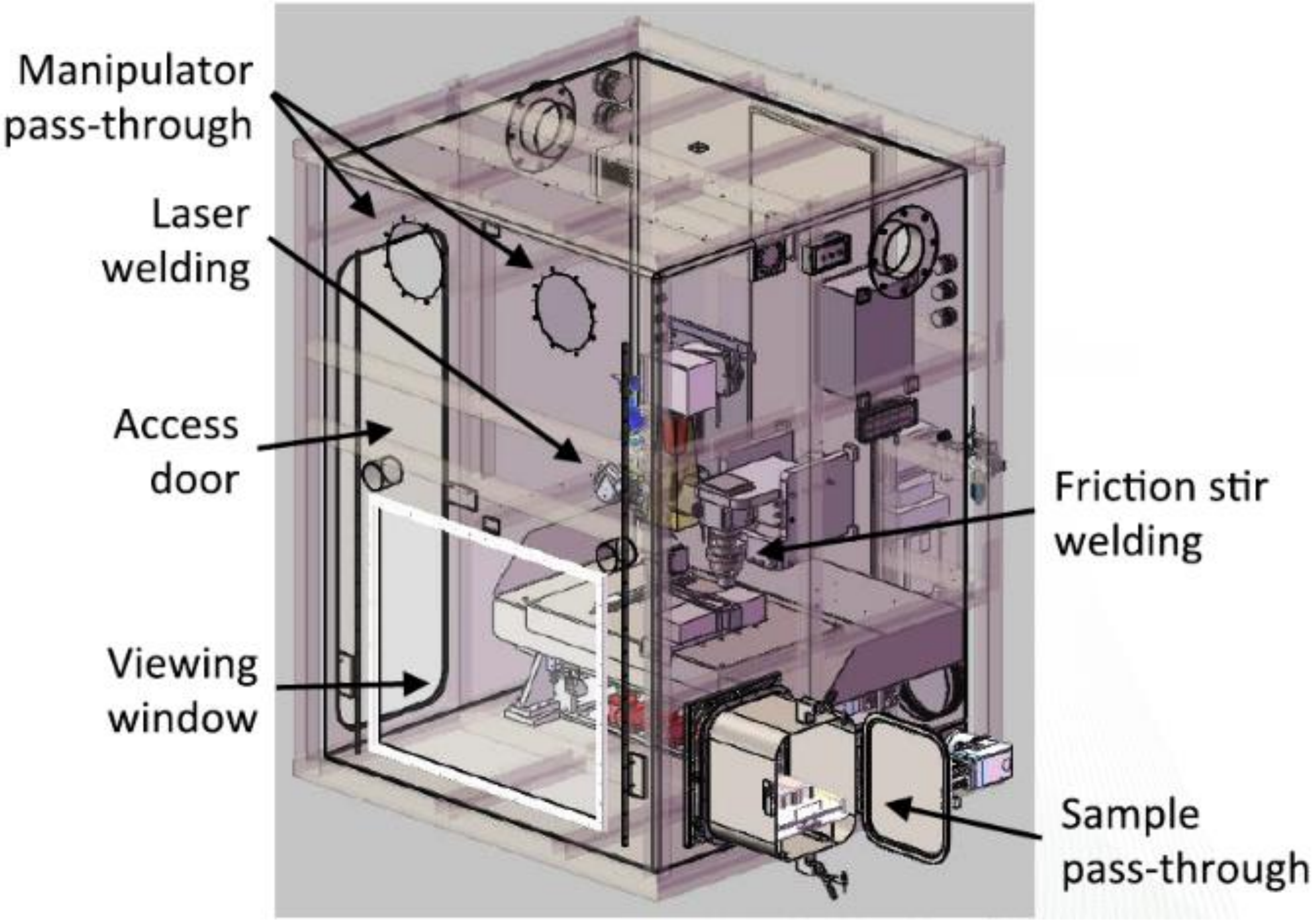
- Friction stir welding trials conducted with optimized process parameters and new tool on unirradiated stainless steel coupons
- Breakdown of the Polycrystalline Cubic Boron Nitride (PCBN) tooling during FSW of stainless steels is a known issue
- Defect formation occurs in the form of a “worm hole” on the advancing side of the rotating tool after 10 weld passes
- Process monitoring involved the examination of the spectral content of weld forces (torque, traversing force, and side force) and the utilization of an artificial neural network (ANN) for identification of the conditions associated with significant tool wear and the formation of volumetric defects
- With the proper combination of inputs, the ANN yielded a 95.2% identification rate of defined defect states in validation





Irradiated Materials Welding Facilities at Oak Ridge National Laboratory (ORNL)

- A welding cubicle (1.711 m X 2.296 m X 1.765 m) was designed, fabricated, and equipped with advanced laser and FSW machines so that any contamination during irradiated material welding will be enclosed inside the sealed cubicle.
- The welding cubicle is located at the Radiochemical Engineering Development Center (REDC), Building 7930, Cell C.
- The primary function of REDC is supporting isotope production and transuranium element product recovery, waste handling and conversion. Therefore, significant adaptations had to be made for the placement of the cubicle.

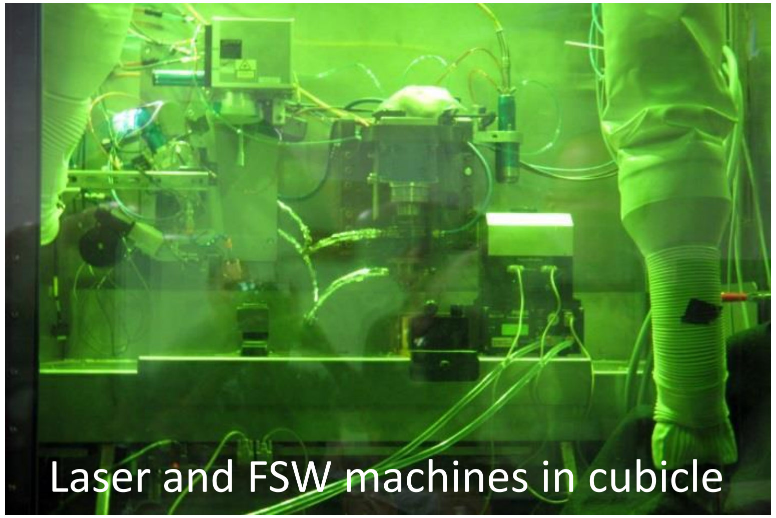


Installation of Cubicle and Testing of Systems

Installation of the cubicle

- Welding cubicle is installed at the Radiochemical Engineering Development Center (REDC), Cell 6.
- Manipulators are used for material transportation and welding preparation
- Cameras are installed in and outside of the cubicle for monitoring
- Material surface preparation at Irradiated Materials Examination and Testing (IMET)

QA testing of the various systems


Laser and FSW machines in cubicle


Irradiated coupon prep.

Test Coupon R&D Process Flow Chart

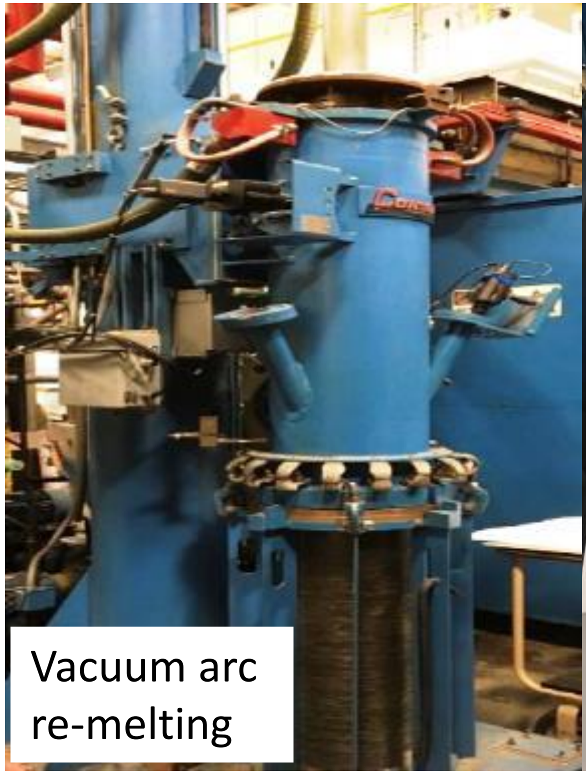
1. Test coupon fabrication at Building 4508
2. Test coupon Irradiation at HFIR
3. Irradiated test coupon storage at IMET Building 3025E
4. Irradiated test coupon preparation at IMET Building 3025E
5. Irradiated test coupon welding at REDC Building 7930
6. Welded irradiated coupon specimen cutting at IMET Building 3025E
7. Irradiated specimen characterization and testing at LAMDA Building 4508

- Test coupons were fabricated, irradiated, stored, prepared, welded, sliced, characterized, and tested using different facilities located in various buildings at ORNL
- Irradiated materials handling, welding and transportation followed ASME DQA-1-2008 Nuclear Quality Assurance (NQA-1) Certification

LWRS LIGHT WATER REACTOR SUSTAINABILITY

Test Coupon Fabrication

- Custom made 304L, 316L, and 182 alloys
- Targeted boron concentrations of 0, 1, 5, 10, 20 and 30 wppm B.
- Low Co impurity levels.
- Processing:
  - Vacuum arc re-melting (VAR) stock material
  - Hot extrusion at 1100 ºC
  - Homogenized at 1100°C for 5 hours in air
  - Hot rolled to 19 mm thick, followed with cold rolling to 12 mm thick.
  - Solution heat treatment (1000°C for 30 minutes for 304L and 1050°C for 30 minutes for 316L followed by water quenching)
  - Machined to: 76 x 56 x 8.9 mm coupons
- PNNL and ORNL modeling to estimate helium concentrations based on alloy composition and neutron spectra
- Thermal desorption spectrometry (TDS) and laser ablation mass spectroscopy (LAMS) at ORNL to determine level of helium after irradiation.


Vacuum arc re-melting

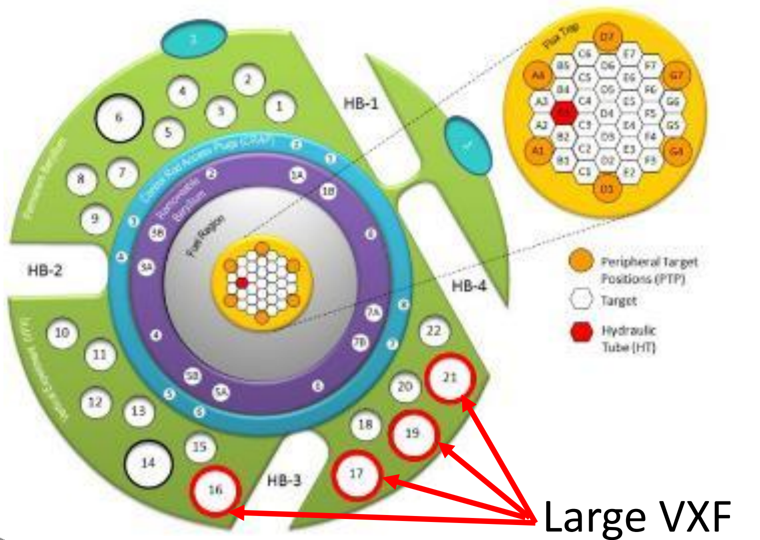

Material rods for VAR

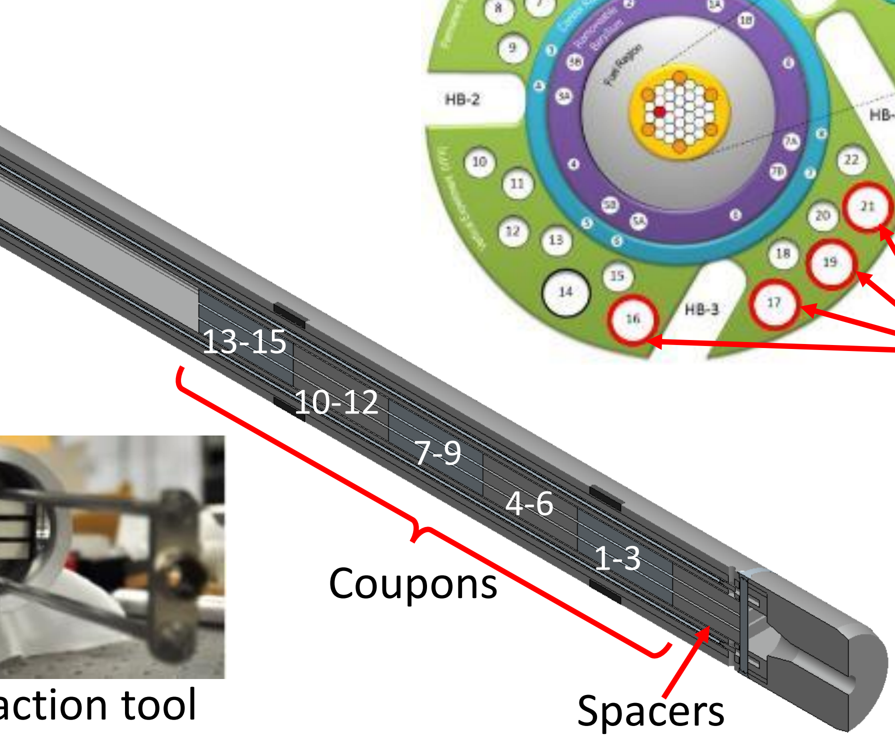

Re-melted Material

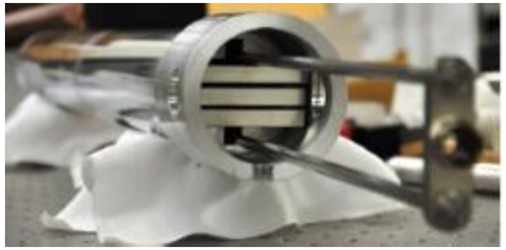

Extruded Material

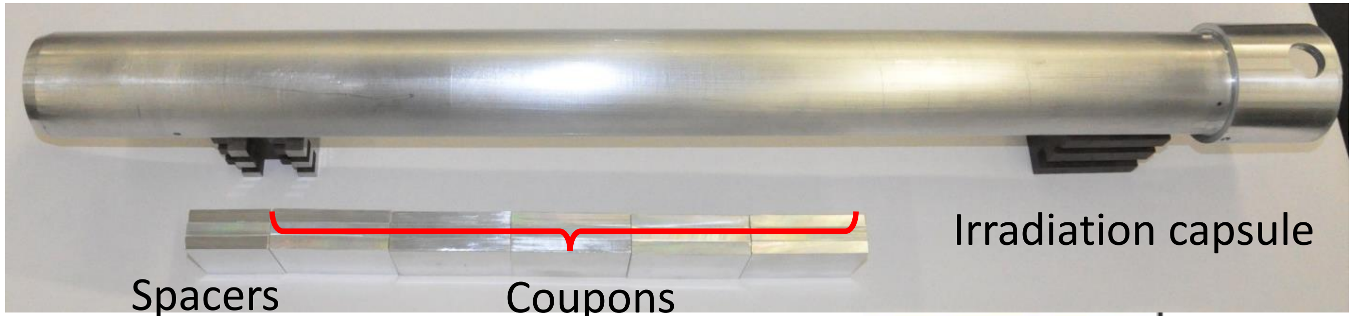
Test Coupon Irradiation

- High Flux Isotope Reactor (HFIR) Large-Vertical Experiment Facility (VXF) positions (VXF-16, VXF-17, VXF-19 and VXF-21):
  - 4.3×10^{14} n/cm^{2}s thermal (E < 0.4 eV)
  - 1.2×10^{13} n/cm^{2}s fast (E > 0.183 MeV)
  - 3 cycle irradiation (1 cycle ~ 24.5 days)
- 15 coupons per irradiation capsule, water cooled
- Flux monitors included during irradiation
- First irradiation campaign (304L and 316L) –*Complete*
- Second irradiation campaign (304L, 316L, and Alloy 182) -*Complete*
- Third irradiation campaign -*Samples being prepared*



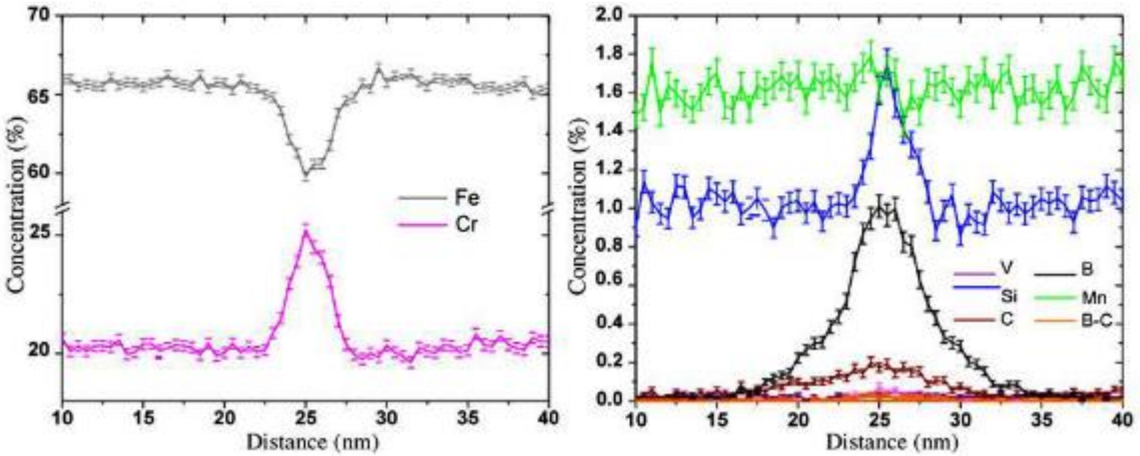



Coupon extraction tool

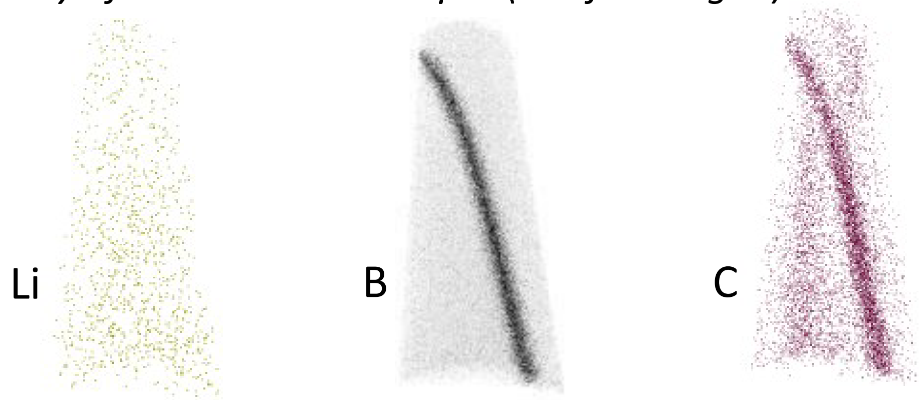


Irradiated Materials Characterization

- Characterization of pre-irradiated, post-irradiated and post-weld materials
- Examinations to take place at ORNL's Low Activation Materials Development and Analysis (LAMDA) Laboratory:
  - Bulk chemistry
  - Solute segregation
  - Microstructure
  - Mechanical behavior
- Current activities:
  - Collaborative effort between EPRI, ORNL, PNNL, and University of Michigan
  - Funded through the DOE –Nuclear Science User Facility (NSUF)
  - Transmission electron microscopy of irradiated samples to observe He distribution
  - Atom probe tomography (ATP) of irradiated samples to observe radiation-induced segregation
  - Thermal desorption spectroscopy (He concentration) of irradiated materials



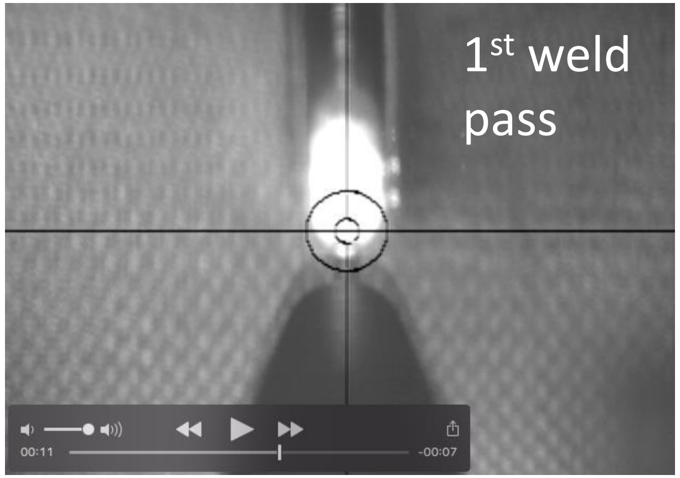
Concentration profile across a high angle grain boundary: courtesy of Emmanuelle Marquis (U. of Michigan)

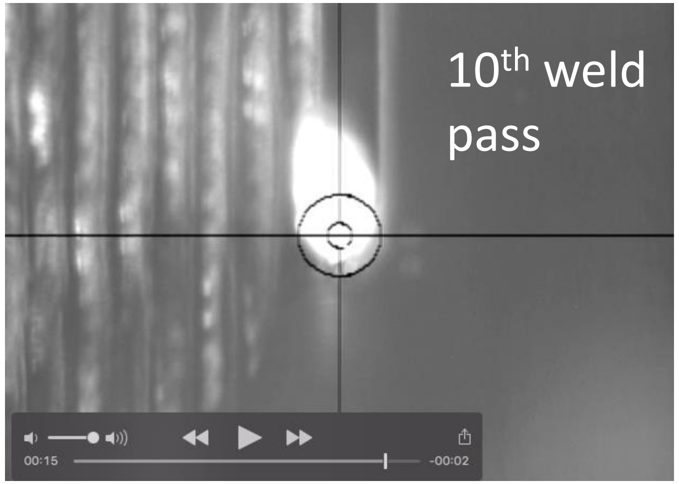


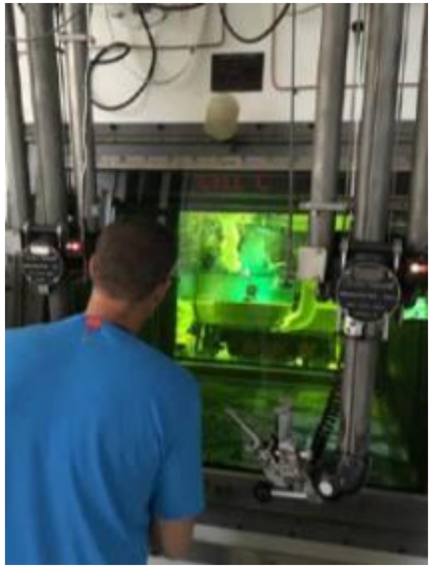
Reconstructed APT datasets from the neutron irradiated 304L (10 ppm B) sample showing distribution of Li, B and C along a high angle grain boundary: courtesy of Emmanuelle Marquis (U. of Michigan)

Start of Welding on Irradiated Materials (November 17, 2017)

- Developing advanced weld technologies capable of addressing challenges associated with highly irradiated materials
- The LWRS Materials Research Pathway Welding team at ORNL partnered with the Electric Power Research Institute to begin weld testing on irradiated materials at the Radiochemical Engineering Development Center at ORNL
- Auxiliary beam stress improved (ABSI) laser welding on irradiated 304L stainless

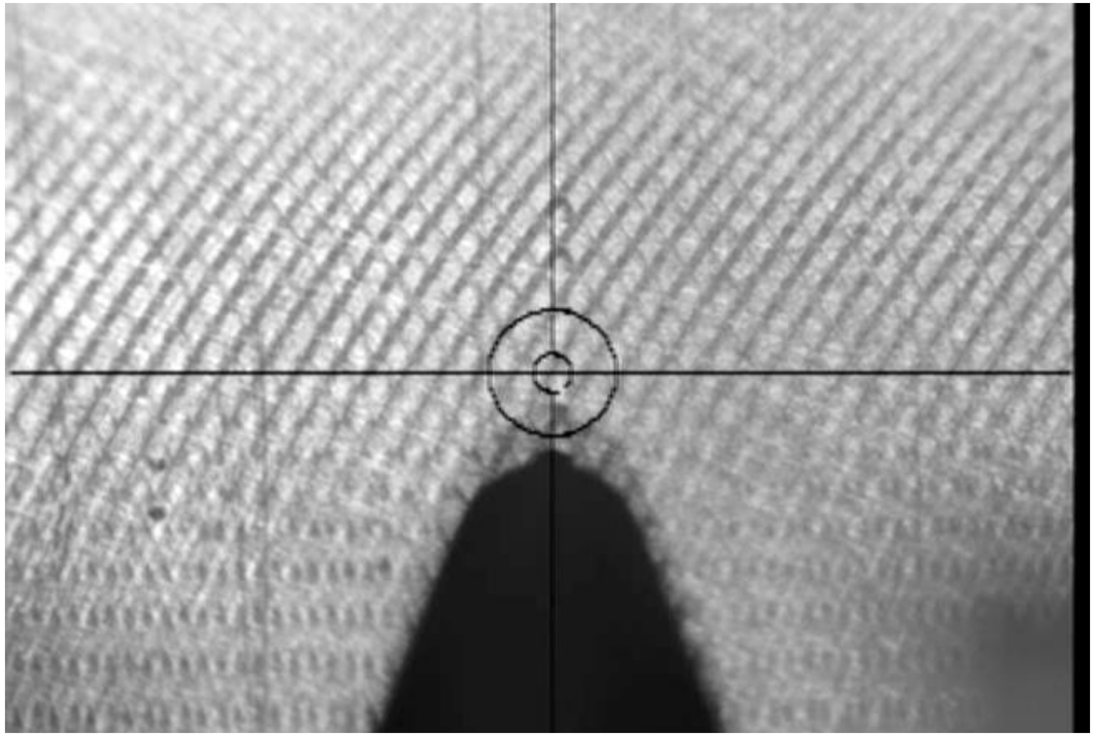






The hot cell welding facility is a strategic asset for researchers and industry stakeholders in the development and testing of advanced weld repair technologies for extending the lives of aging reactors.

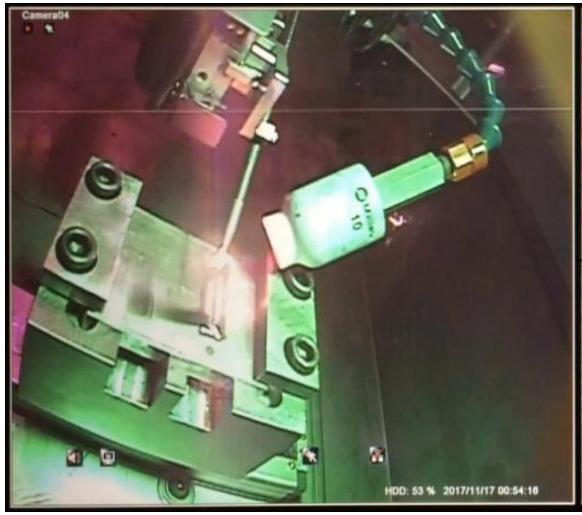
Laser Welding of 304 Stainless Steel

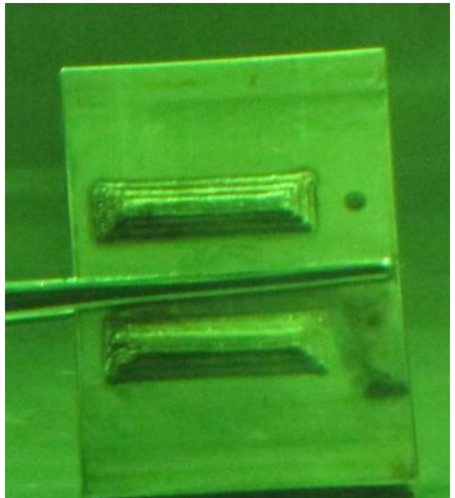


The first laser pass on irradiated 304L (19.9 appm He)

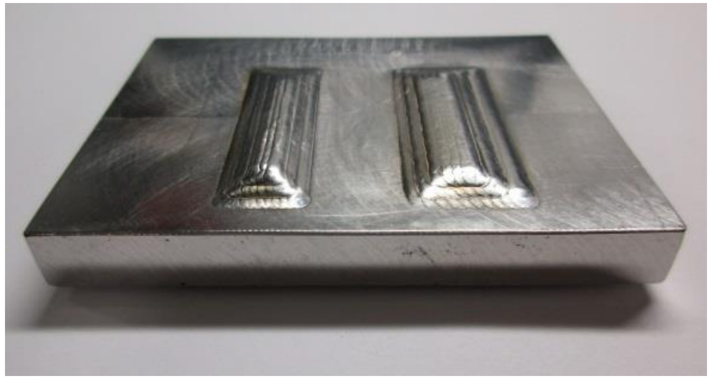
- Four overlay laser welds with high and low heat input (5 IPM and 27 IPM welding speed), w/wo the scanning laser, were made on the 20 wppm B coupon prior to irradiation (19.9 appm measured He)
- No He-induced defects, cracks and/or voids were observed on the surface of the welds and adjacent areas

In cell welding process monitoring





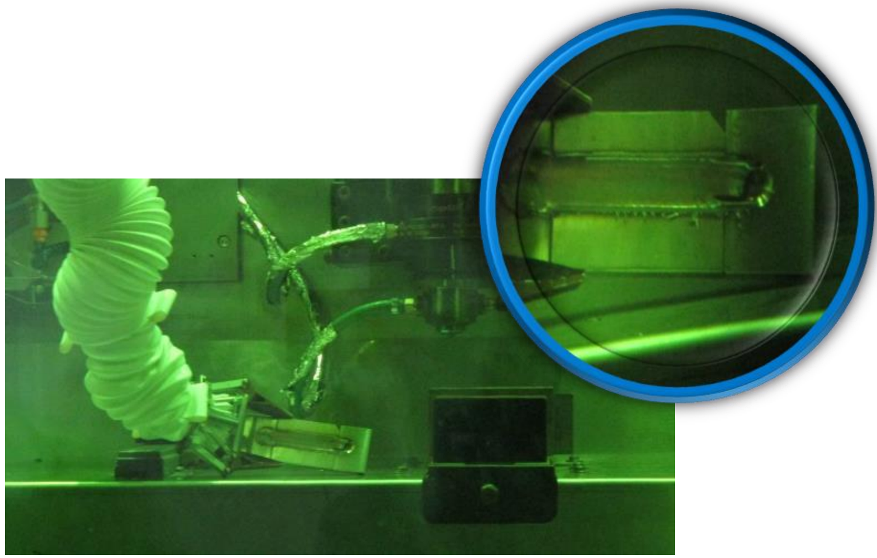
Post weld view



Examples of un-irradiated 304 SS coupon welding

Start of Friction Stir Welding of Irradiated 304 SS (November 27, 2017)

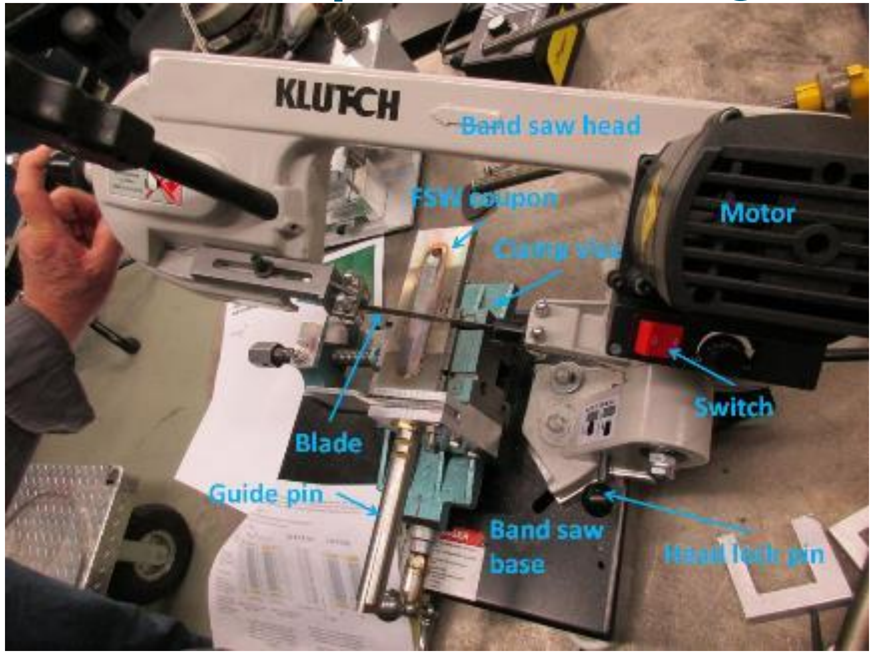
- Developing advanced weld technologies capable of addressing challenges associated with highly irradiated materials
- Weld repair technologies are needed as a critical technology for extending the service life of nuclear power plants
- The LWRS Materials Research Pathway Welding Team at ORNL partnered with the Electric Power Research Institute to begin friction stir weld tests on irradiated materials with 10 wppm B and 5 wppm B prior to irradiation (26 appm and 8.48 appm measured He) at the Radiochemical Engineering Development Center



The hot cell welding facility is a strategic asset for researchers and industry stakeholders in the development and testing of advanced weld repair technologies for extending the lives of aging reactors.

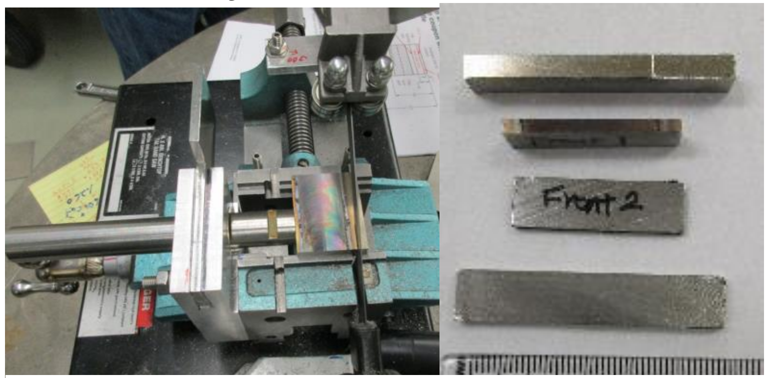
Preparing for Irradiated Welds Specimen Cutting and Characterization

- Irradiated material welds need to be sliced into specimens for further studies, such as metallographic characterization and properties evaluation.
- A band saw has been modified with additional fixtures so that it can perform precise cutting on irradiated welds in hot cell.
- Band saw cutting trial runs on un-irradiated material demonstrated precisely cut specimens with good surface finish.
- The modified band saw has been installed at IMET.
- Specimen cutting procedures have been generated and approved, and specimen storage containers have been prepared and designated with laser engravement.



Modified band saw

Time for a cut

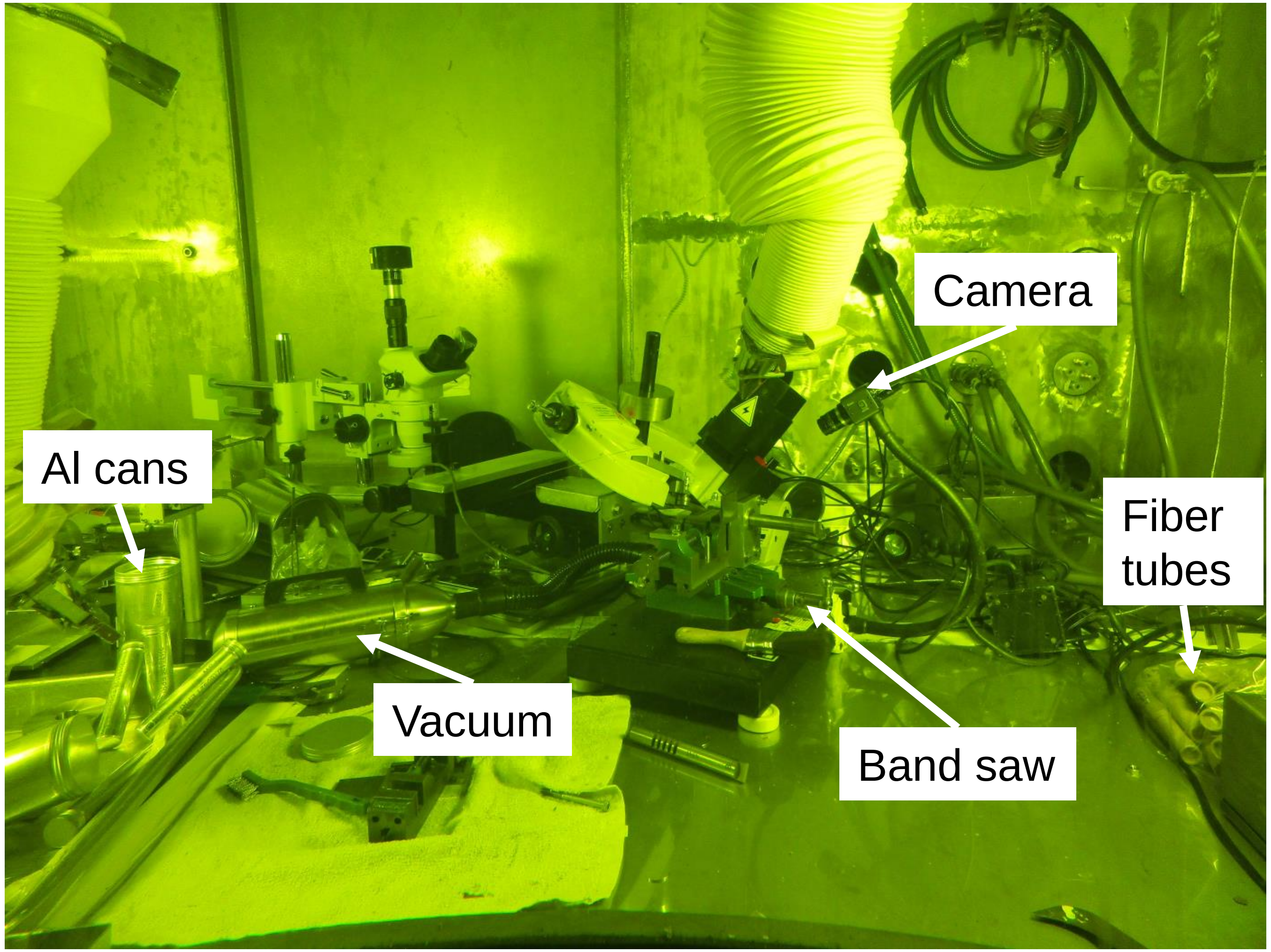


Cutting process and sliced specimens

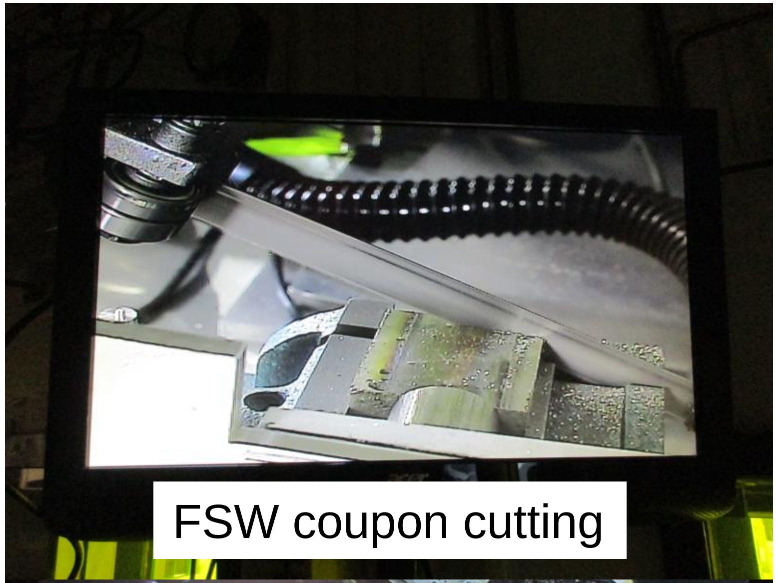
Specimens storage containers

Band Saw and Accessories Inside the Hot Cell

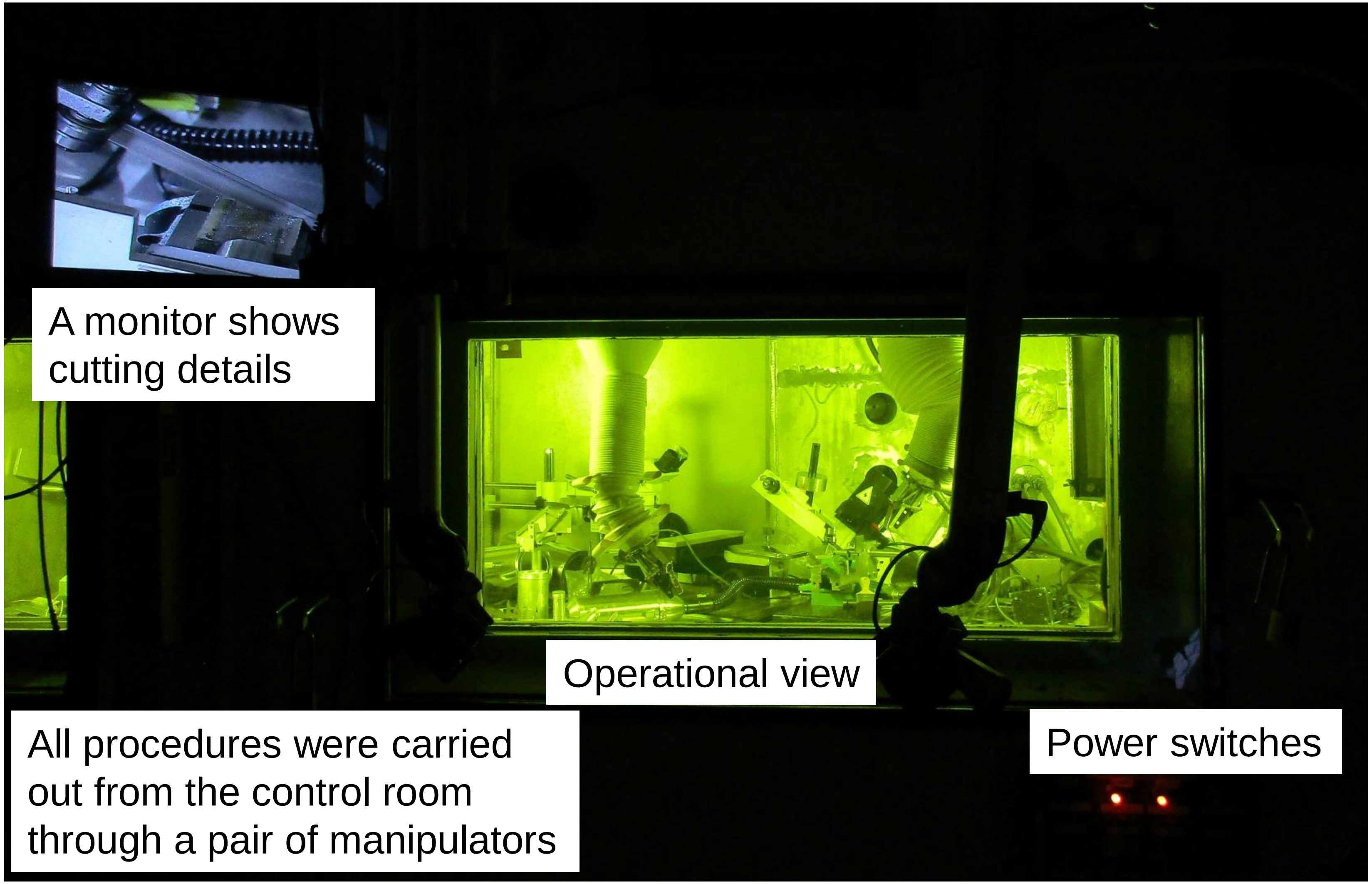
- Modified band saw was setup in hot cell 6 of Irradiated Materials Examination and Testing (IMET) at ORNL.
- An additional digital camera was setup to monitor the cutting process and quality.
- A hot cell qualified vacuum was attached to the modified band saw to collect cutting chips.
- All power switches of the band saw, the camera and the vacuum were installed outside the hot cell and in the control room.
- Aluminum containers were adopted to contain big coupons for long term storage, and fiber tubes were adopted to contain each individual specimens for characterization and testing.
- All other necessary tools such as files, brushes, a paint marker, and a mirror were placed in the hot cell before the irradiated weld coupons were sent in.



Irradiated Material Weld Cutting Operational View


FSW coupon cutting

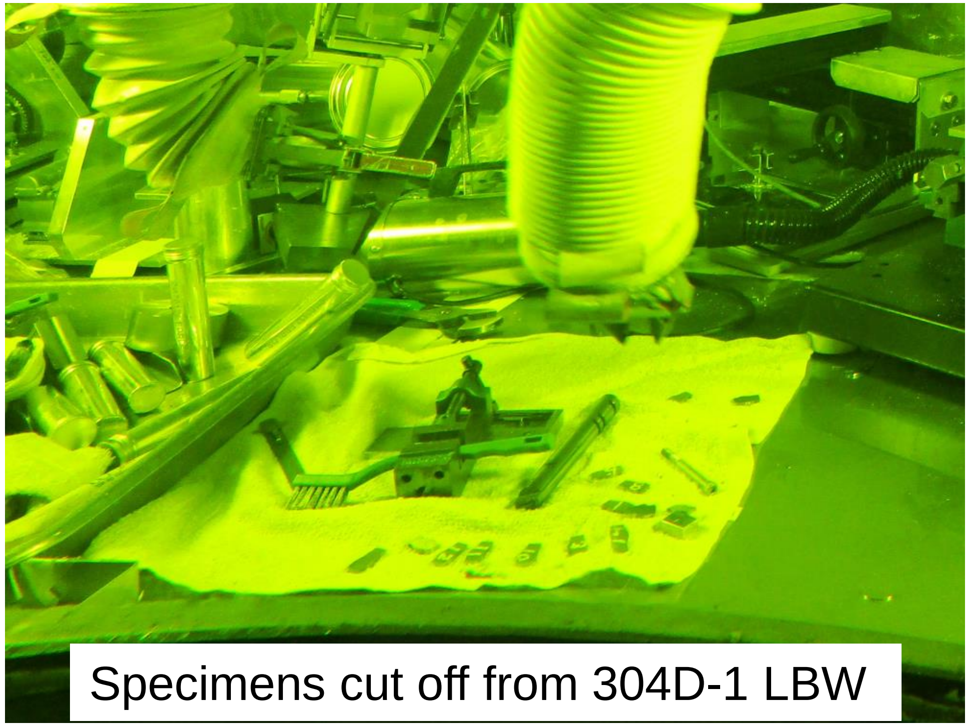
LBW coupon cutting

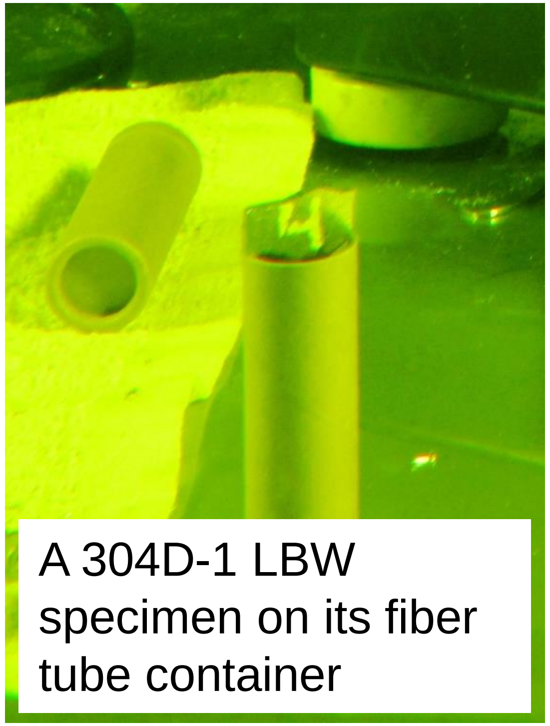


All procedures were carried out from the control room through a pair of manipulators

Cut Off Specimens Layout and Packaging


Specimens cut off from 304C-6 FSW

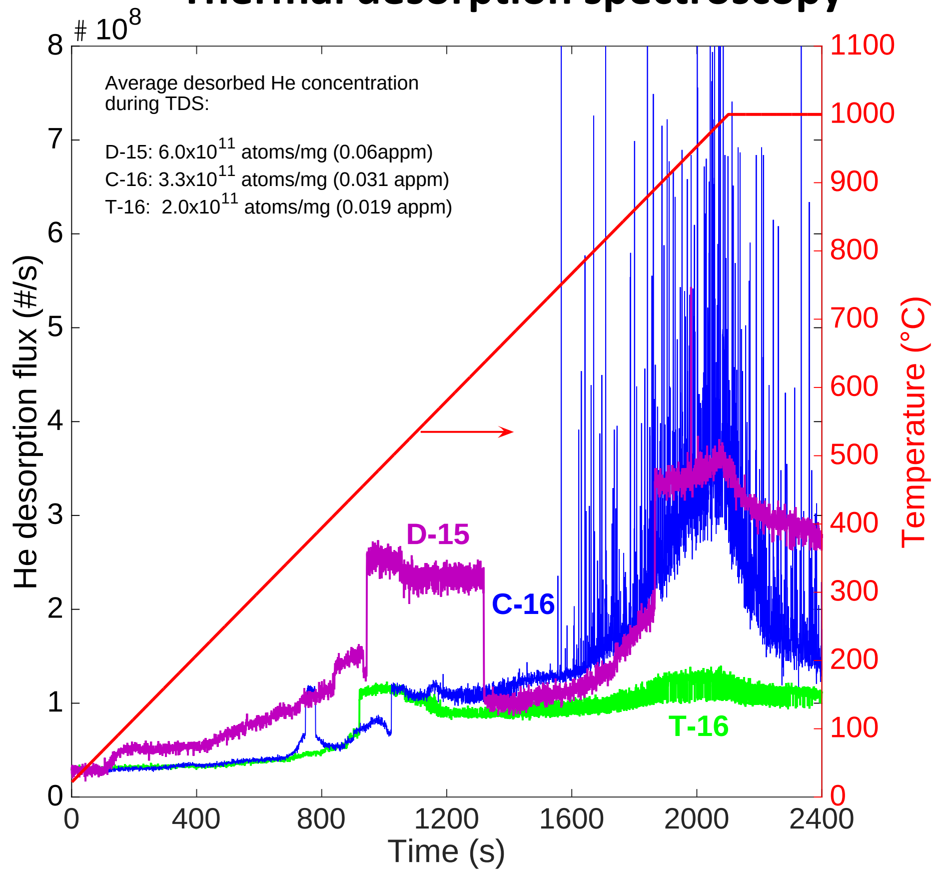

Specimens cut off from 304D-1 LBW


A 304D-1 LBW specimen on its fiber tube container

- For each irradiated material welded coupon, cut off specimens were marked with a paint maker, laid out on a towel inside the hot cell, and placed into corresponding fiber tubes after all specimens were cut off from the welded coupon.
- Remaining parts of irradiated material welded coupons were placed into corresponding aluminum containers for long term storage at IMET.
- Cut off specimens will be sent to Low Activation Materials Development and Analysis (LAMDA) for microstructure characterization, helium measurement, microhardness mapping, mini-tensile specimen machining, and tensile testing.

Helium Determination Preliminary Results of Irradiated 304L Stainless Steel Coupons – Xunxiang Hu, ORNL

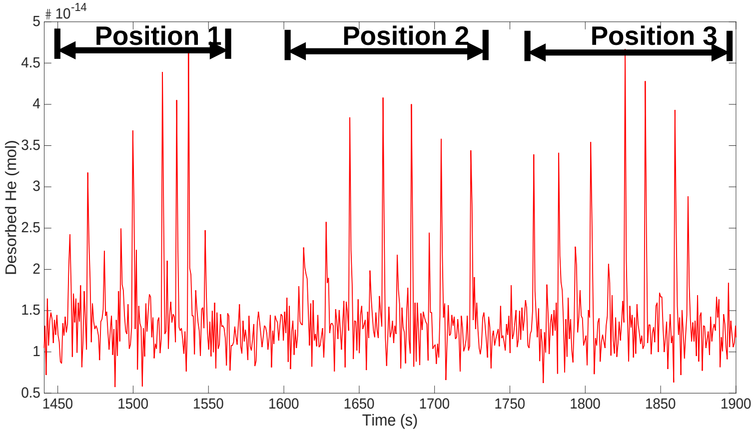
Thermal desorption spectroscopy

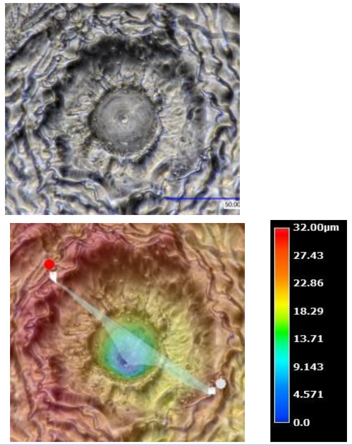


- Temperature ramping rate: 28°C/min
- Major helium desorption occurred at the maximum temperature. He was not completely desorbed until melting.
- Desorbed He during TDS measurements: D-15 > C-16 > T-16.

Laser Ablation Mass Spectroscopy

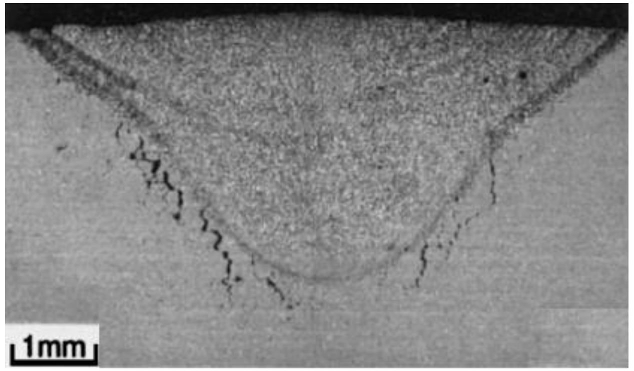
- Laser Energy: 6.1micro-J (10^{-3} J)
- Wavelength: 532nm
- Pulse Width: 4-5 ns
- Ablations: 10 positions and 10 ablations/position
- Crater size: 3.2 μm in depth, 90 μm in diameter
- Quadrupole mass spectrometer
- Uncertainty ±20%



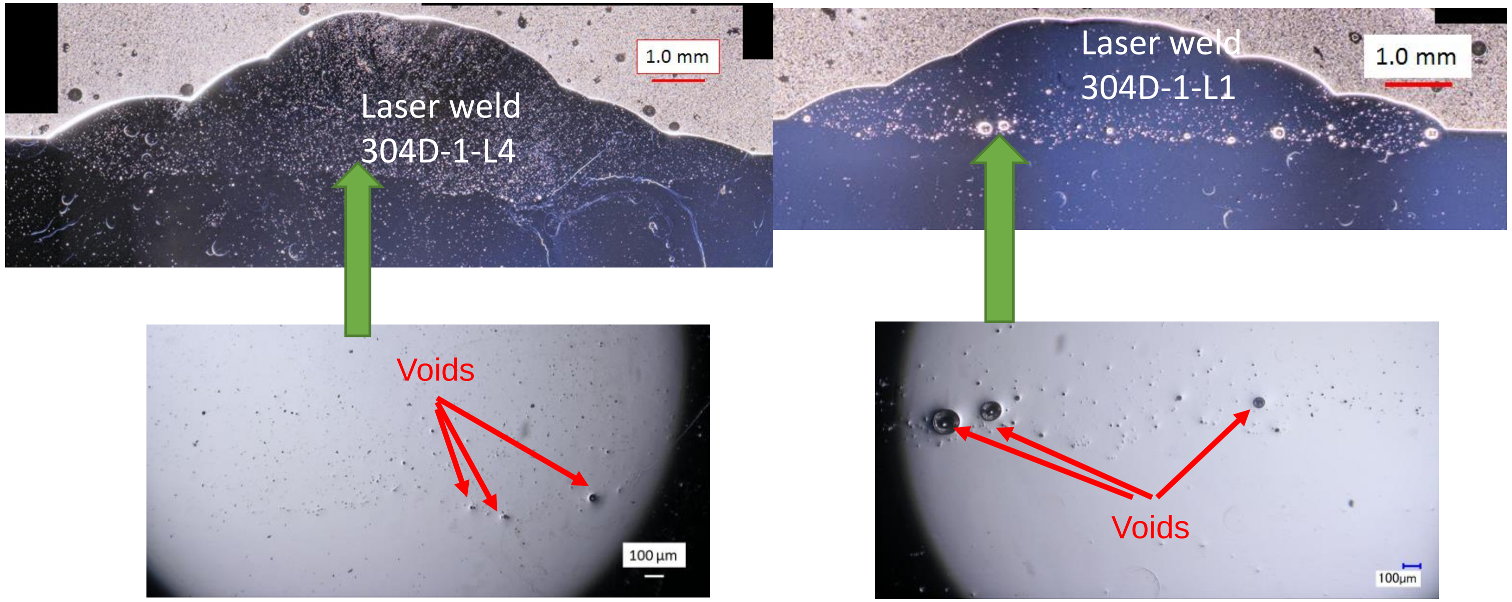


Sample/ Coupon	Doped B, wppm	Calculated He (appm)	LAMS		
			Desorbed He (mol)	Atoms/ablation (mol)	He concentration (appm)
D-15/304D-1	20	20	2.4×10^{-14}	1.23×10^{-9}	**19.9**
C-16/304C-6	10	10	3.2×10^{-14}		**26**
T-16/304B-1	5	5	1.03×10^{-14}		**8.48**

Laser Welds Optical Microscopy Initial Results



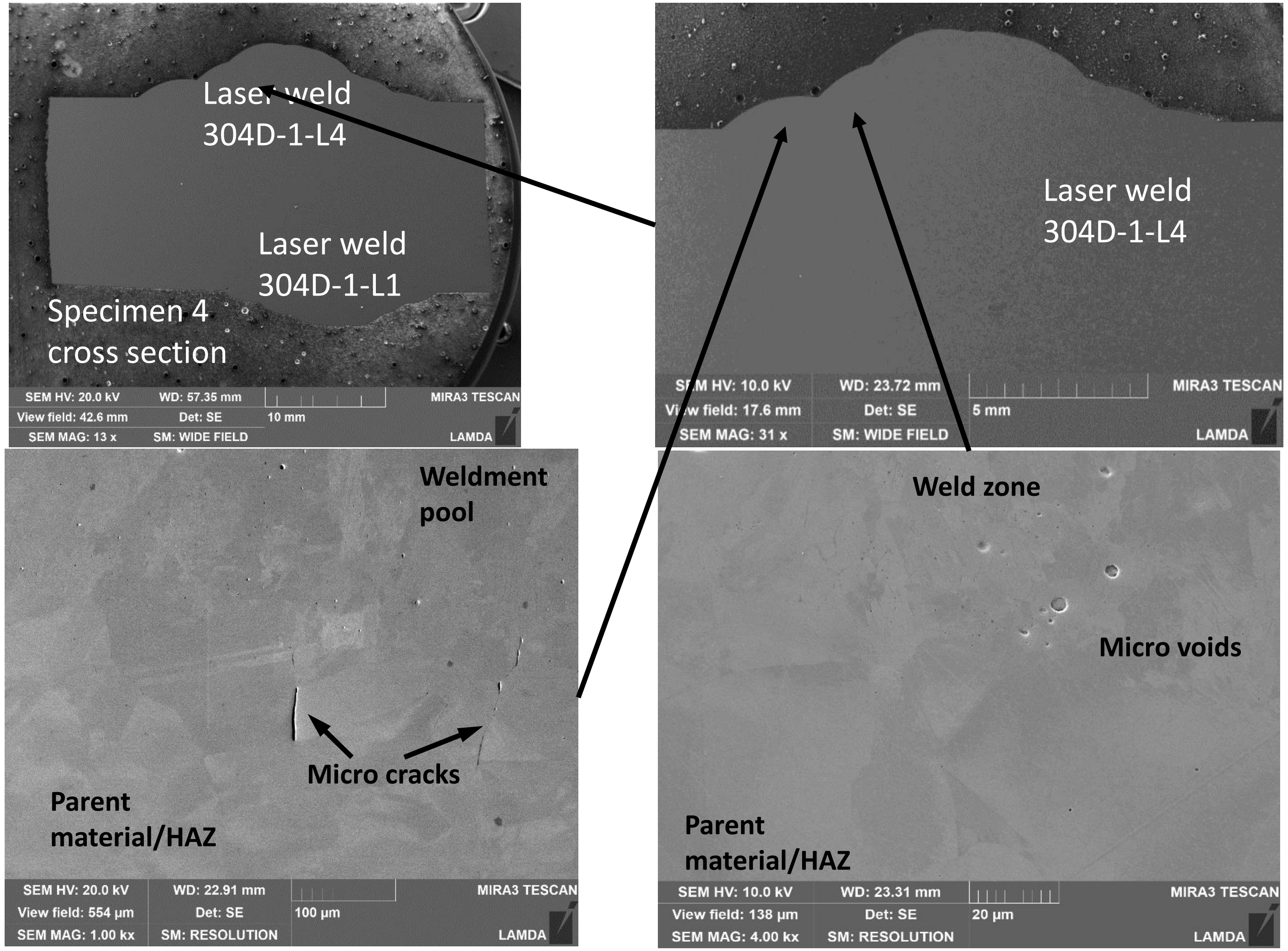
Helium induced cracks in the weld HAZ on stainless steel contains 8.3 appm He (*Kyoichi Asano, et al. Journal of Nuclear Materials, 264, 1 – 9 (1999)*)



- All microstructure specimens cut off from three irradiated 304L stainless steel welds , 304D-1 (19.9 appm He), 304 C-6 (26 appm He) and 304B-1 (8.48 appm He), were prepared at Low Activation Materials Development and Analysis (LAMDA) of ORNL for characterization.
- Specimens analysis and tests include microstructure characterization, helium measurement, microhardness mapping, mini-tensile specimen machining, and tensile testing
- Initial optical microscope observation of all four laser welds, which coupon contained 19.9 appm of He, was completed. Overall, the laser welds were successful with only micro-porosities observed under optical microscope.

Laser Weld SEM Preliminary Results – Maxim Gussev, ORNL

- SEM characterization was carried out and analyzed by Maxim Gussev of ORNL.
- Initial scanning electron microscopy (SEM) characterization on a laser weld (BM contains 19.9 appm He) made with 5 IPM welding speed and stress improvement laser welding technique developed in this project.
- No macro porosity or macro crack was observed in the weld, which is the major concern in repair welding of helium containing irradiated stainless steels.
- Several micro-cracks (~100 μm in length) were observed in HAZ close to the fusion line, despite the 19.9 appm He level is much higher than the those reported by Asano et al.
- A few micro-pores (~2 – 10 μm) were observed in weld zone close to the fusion line.

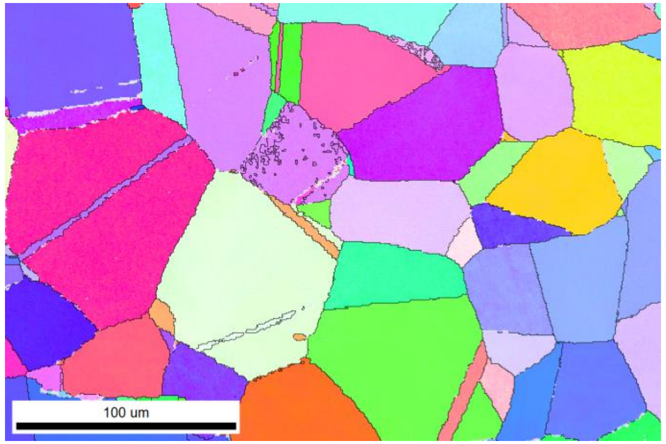


Group of minor cracks observed at the boundary between weldment and HAZ.

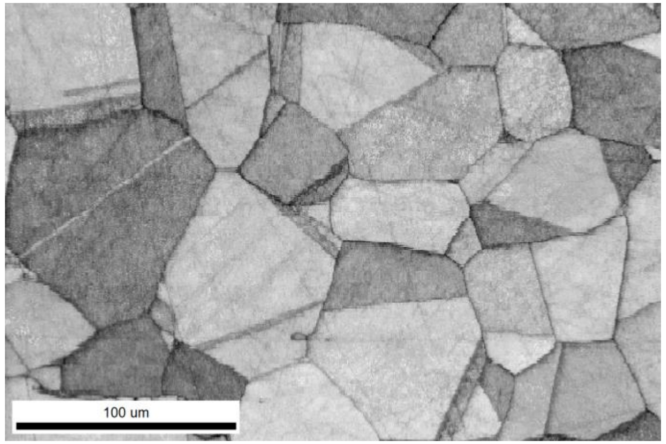
Micro-porosities (~2-10 μm) were observed in the pool near HAZ.

Laser Weld Coupon Grain Structures Of Base Metal, HAZ, Fusion Line and Weld

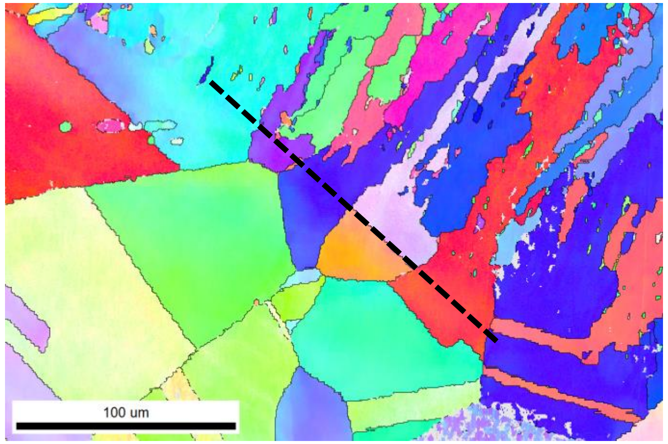
- Irradiated 304L stainless steel base metal containing 19.9 appm He presented well-annealed austenite structure with grain size of ~60-80 μm, and there was no signs of cold work or deformation.
- Weldment boundary/fusion line is clearly visible (dashed line in the IPF map).
- Relatively small dendritic grain structure grew from the fusion line towards the weld center in the weld zone due to low heat input laser welding.



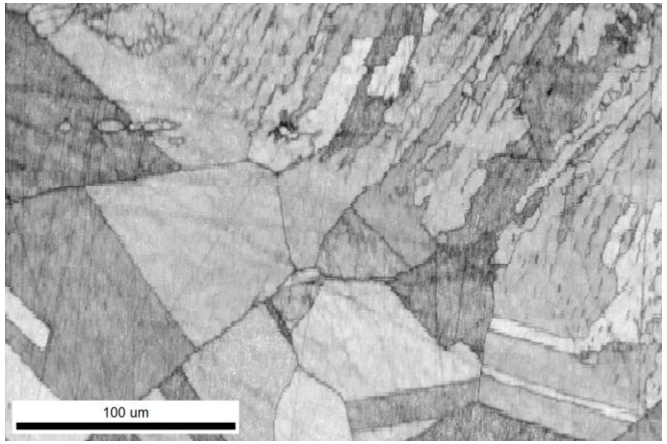
Base metal EBSD inverse pole figure



Base metal image quality grains



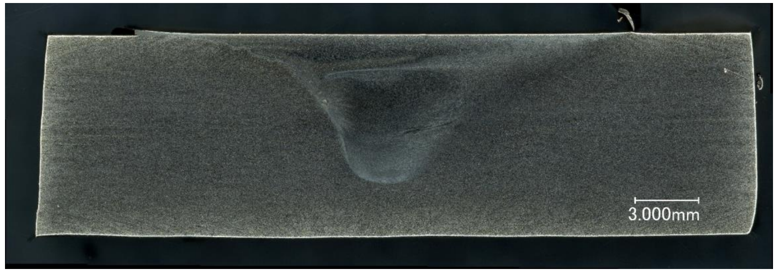
EBSD inverse pole figure around weld fusion line



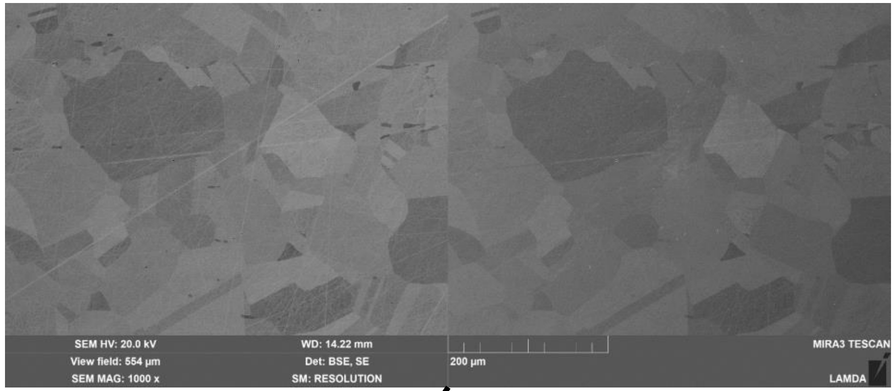
Grain around weld fusion line

Friction Stir Weld General View

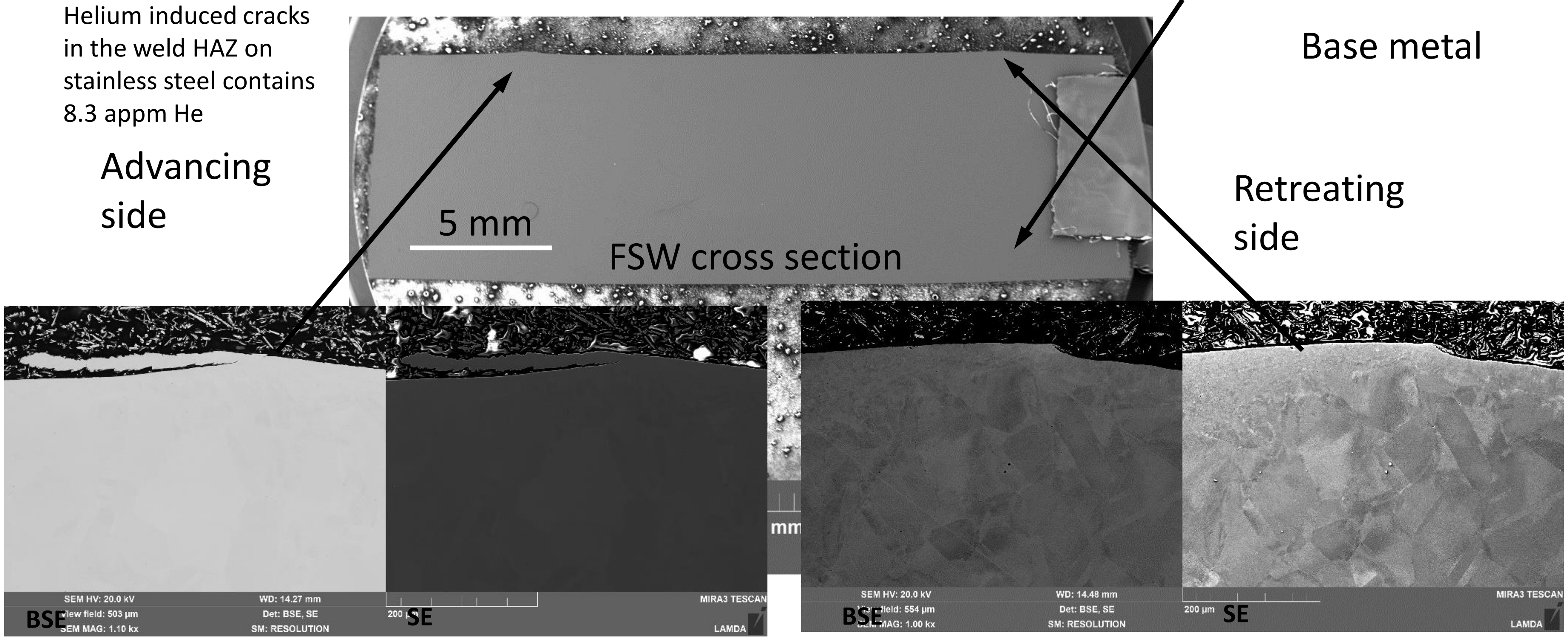
- The friction stir weld coupon 304C-6 contains 26 appm of He by preliminary measurement.
- The friction stir weld is a solid weld and no macroscopic cracks or severe internal damage was observed in weld zone and HAZ.
- SEM revealed annealed structure with well-shaped equiaxial austenitic grains in base metal.



Friction stir weld on un-irradiated 304 SS

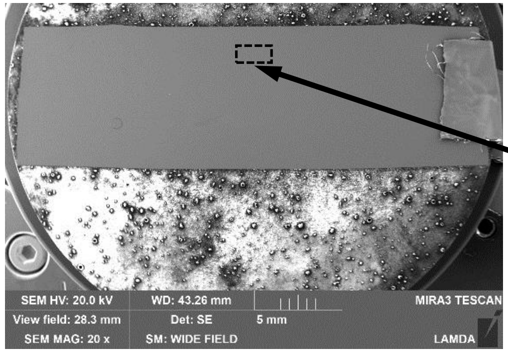


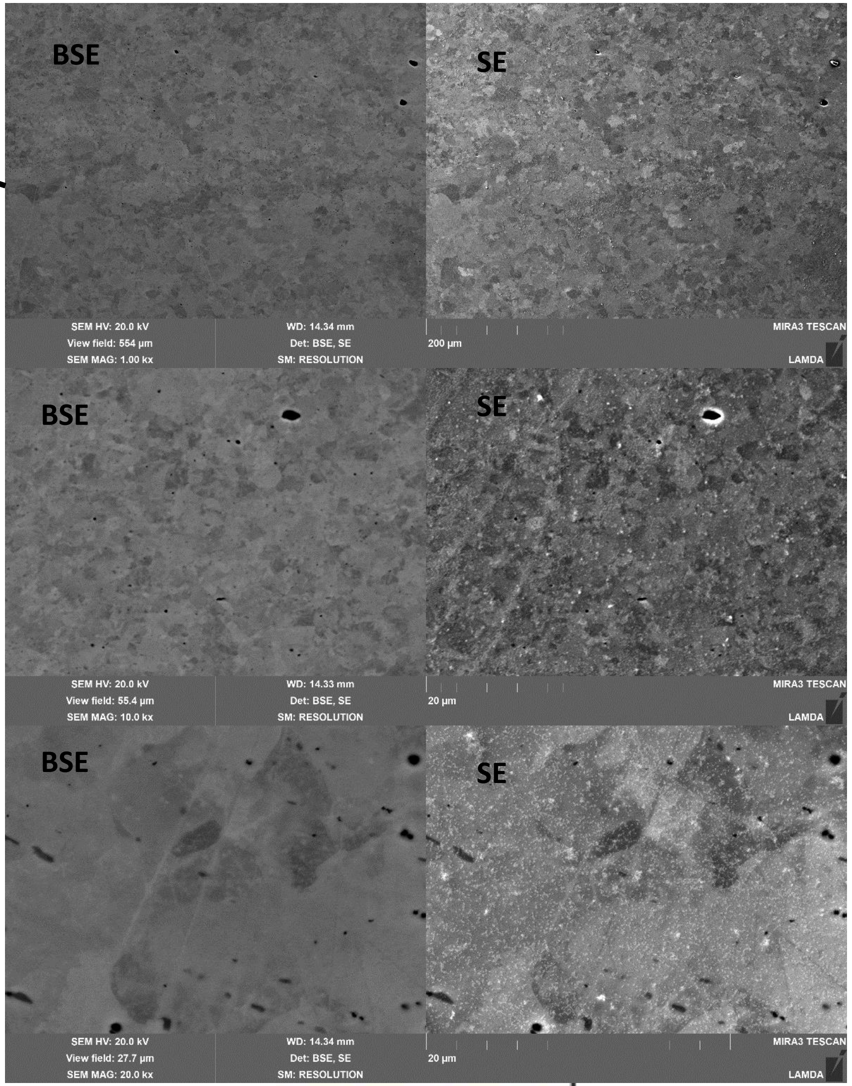
Base metal



Microstructure Close to the Top of the Friction Stir Weld

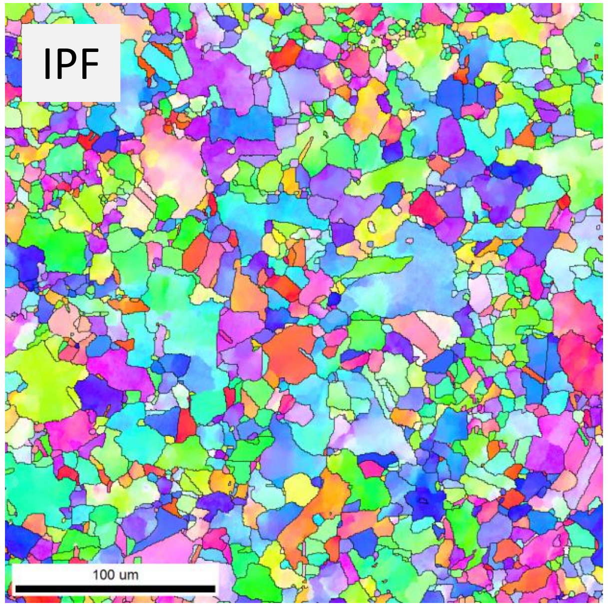
- Microstructure in the middle of the weld close to the surface was characterized by back-scattered electrons (BSE) and secondary electrons (SE).
- No crack was observed.
- Typical mix of relatively fine and coarse grains.
- Small void like features, which sizes are mainly below 5 – 10 µm, are observed at this area, and they are only elongated along some directions, probably due to the plastic deformation during FSW.



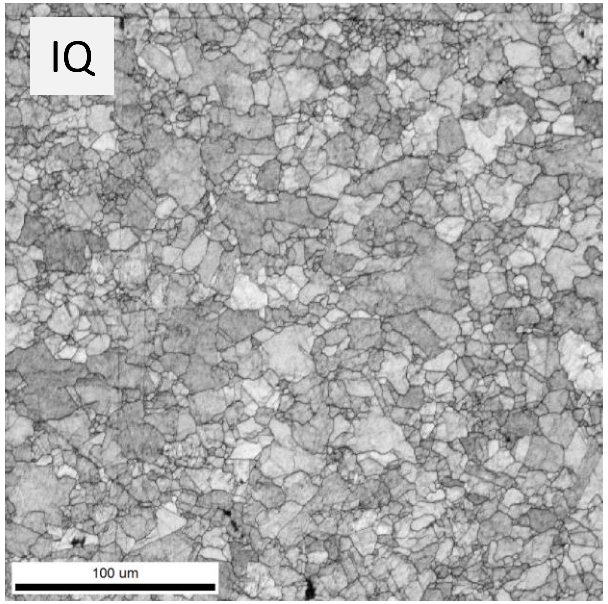


Magnification increase

Mixed grain size at the top of the weld due to different plastic deformation history



Weld EBSD inverse pole figure

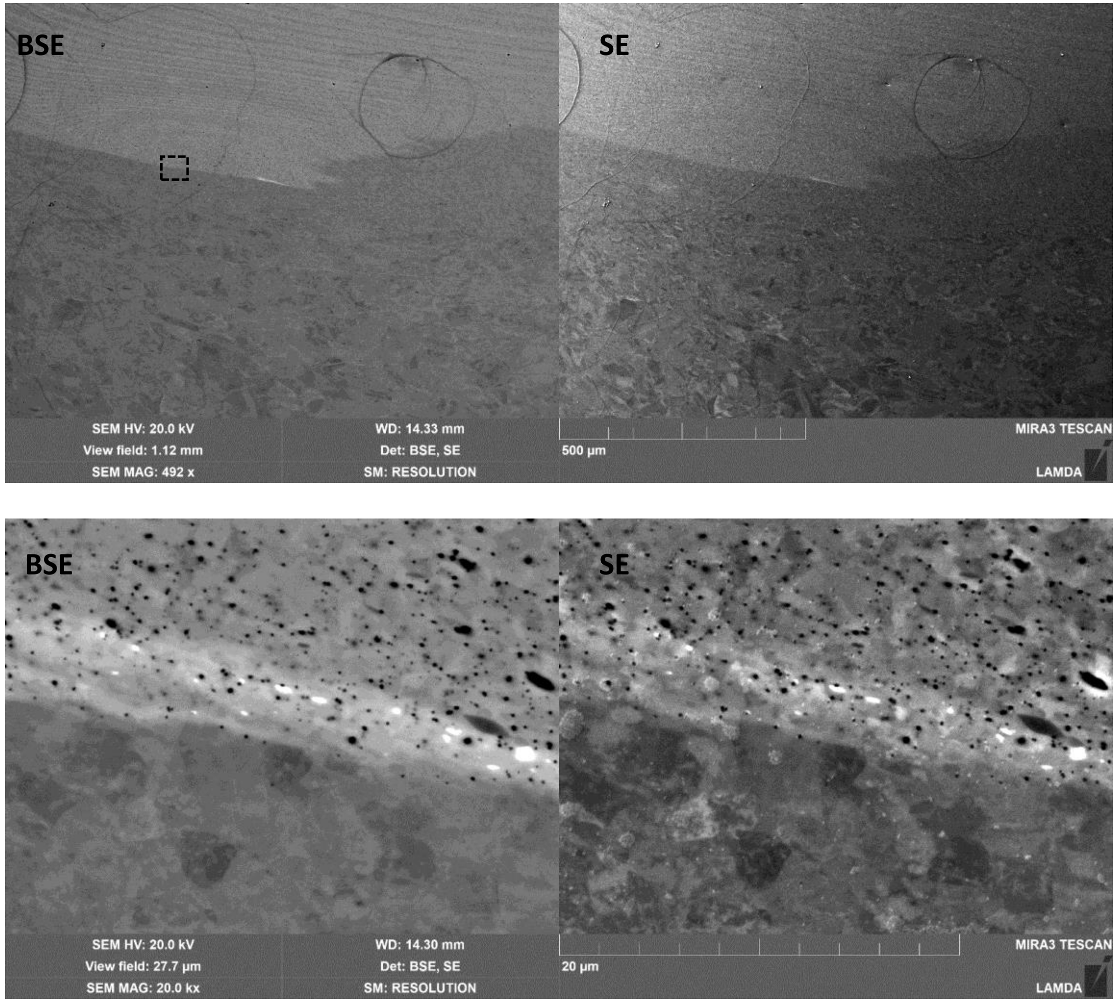


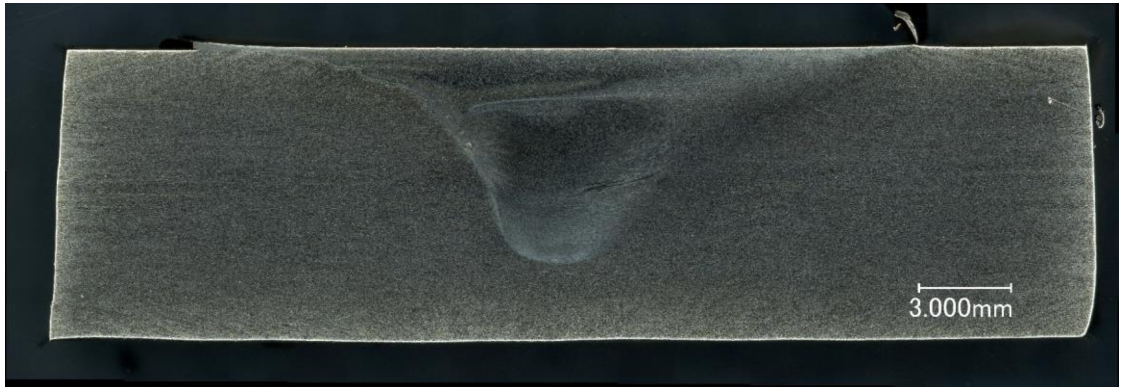
Weld image quality figure

High Shear Zone Microstructure

- Due to the high plastic deformation in FSW, high shear zones are observed with both un-irradiated material and irradiated material FSW.
- At high shear zone interfaces of irradiated material FSW joint, such as weld boundary, lots of black spots, which sizes are mostly in nanometer scale and a couple of micrometer scale, were observed. They could be voids or inclusions. Further study is needed to Identify them.

Irradiated 304L friction stir weld cross section





Un-irradiated 304L friction stir weld cross section

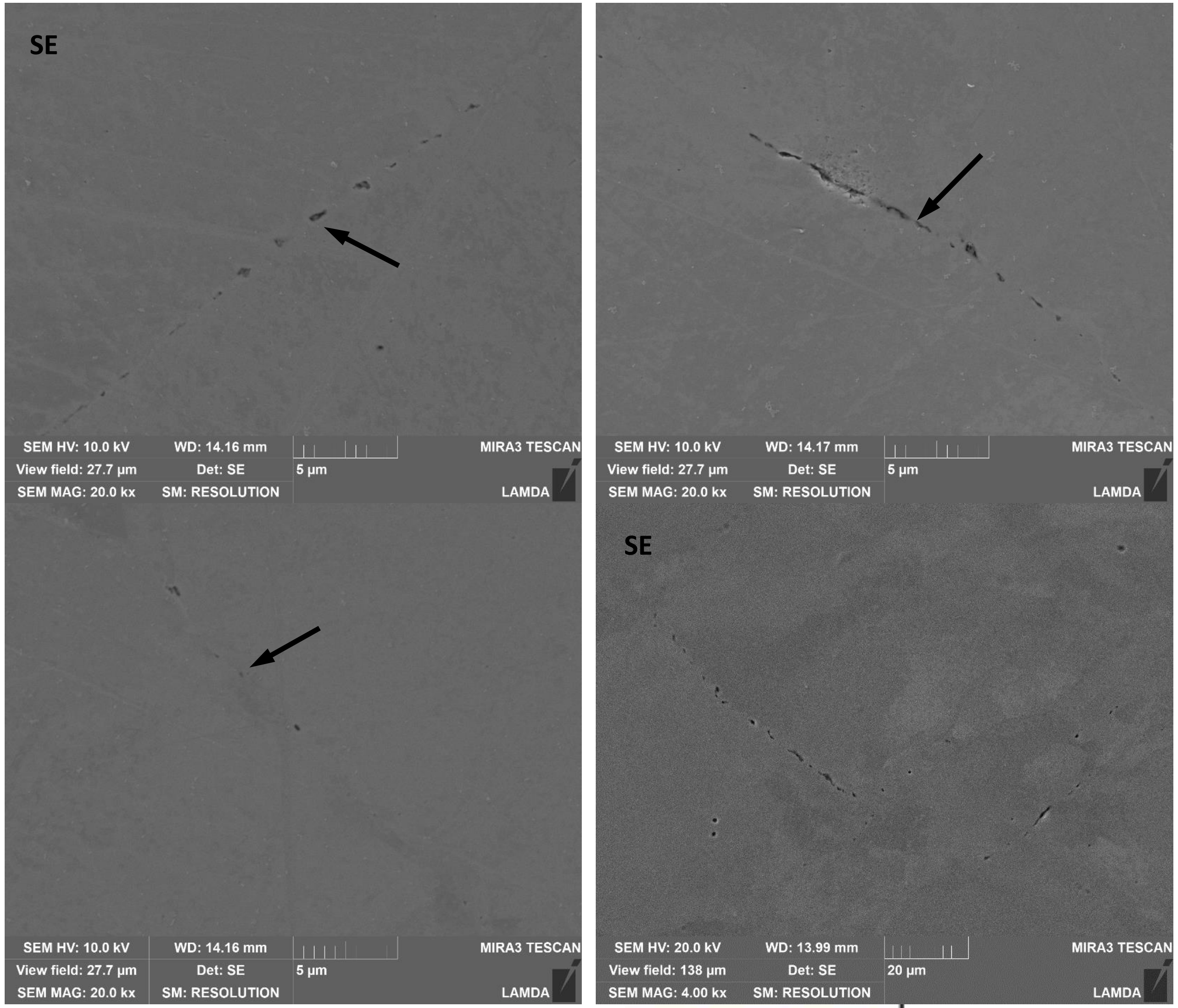
Microstructure Features in HAZ – Preliminary Results

- Specific chains of small voids (~ 1 μm) are observed in the HAZ, within ~1-2 mm from the FSW zone. Sometimes, the void chain looks like small cracks (<10-20 μm in size).

- These void chains very often appear at some angles (~40-45°) and it may be connected to some specific plastic strain mechanism and/or welding tool geometry.

- Only small fraction of grain boundaries is affected by the void chain (roughly, only < 2-5% of all GBs).

- The void density is larger at the advancing side of the weldment; the retreating side has much smaller void density.



Summary

- A welding cubicle has been constructed for use in the development of weld repair technologies for highly irradiated materials
- Laser welding system utilizes an auxiliary beam stress improvement (ABSI) configuration that has been optimized through computational modeling and validated through experimental testing to reduce stresses near the weld zone
- Laser welding and friction stir welding performed on irradiated 304L stainless steel containing 19.9, 26 and 8.5 appm of helium, respectively.
- The advanced laser welding has been successfully applied on 304L SS containing 19.9 appm helium, with only some micrometer level micro-porosities in the weld and a couple of about 100 μm long micro-cracks in the HAZ.
- Friction stir welding has been successfully applied on 304L SS containing 26 appm helium. No crack or micro-crack was observed in HAZ and weld zone, and micrometer level micro-porosities were observed in weld zone and HAZ.

Current Repair Welding R&D Key Personnel

- Oak Ridge National Laboratory (ORNL)
  - Keith J. Leonard, Zhili Feng, Scarlett Clark, Wei Tang, Roger G. Miller, Jian Chen, Brian T. Gibson, Mark Vance
- Electric Power Research Institute (EPRI)
  - Jonathan Tatman, Benjamin Sutton, Gregory Frederick

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  - The engineering support of Kurt Smith and Bob Sitterson.
  - Microstructure characterization and mechanical testing efforts of Joshua Schmidlin, Maxim Gussev, Xunxiang Hu, Linda Hulsey, Patricia Tedder, Travis Dixon and Brian Eckhart from LAMDA.
  - Joining team technicians Alan Frederick and Doug Kyle.
  - People who left or retired
- EPRI
  - Other technical personal at EPRI
  - People who left or retired
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Thank you

Questions?

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