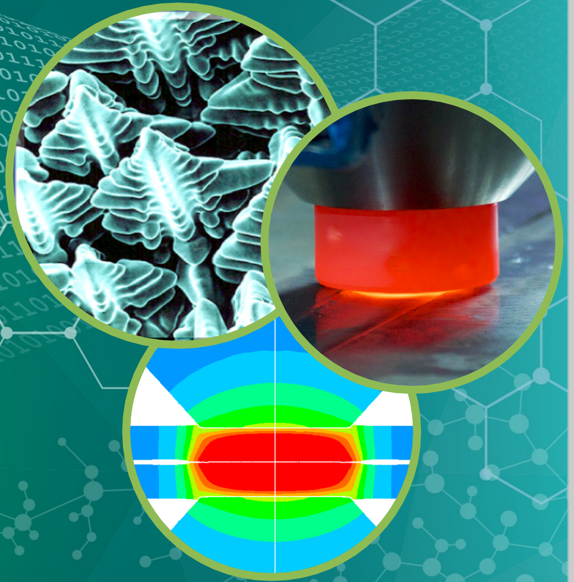
All-position cladding by friction stir additive manufacturing (FSAM)



Zhili Feng (PI), David Frederick, Wei Tang, Xue Wang, David Gandy, and Greg Frederick

Oak Ridge National Laboratory
Electric Power Research Institute

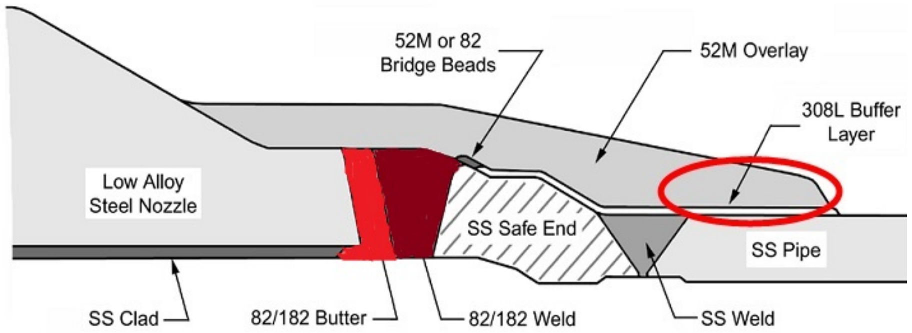
DOE NE AMM Annual Review
December 17-18, 2019
Oak Ridge, TN

Outline

- Background
- Project goal/Objectives
- R&D plan
- Progress and status
- Next Activities
- Summary

Background

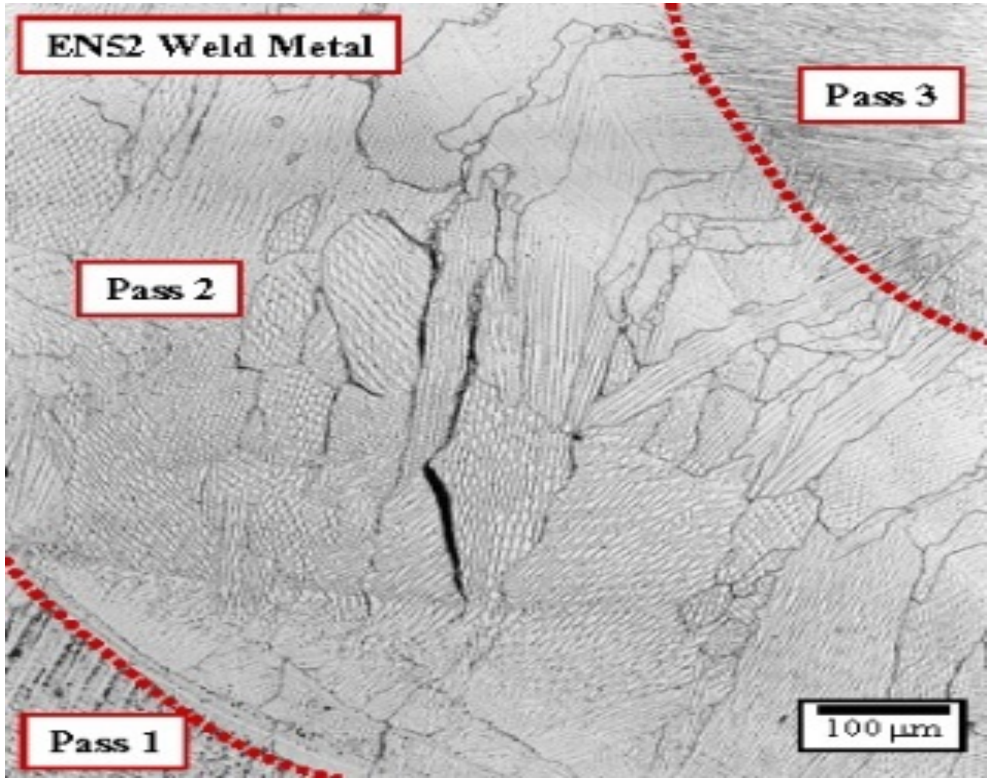
- Cladding and surface modifications are extensively used in fabrication of nuclear reactor systems. It essentially involves adding a layer of different material to component surface.
  - Cladding of reactor vessel internals to improve erosion, corrosion, and wear resistance
  - Build a buffer layer for dissimilar metal weld (hundreds of them)
- Fusion welding based processes, i.e. various arc welding processes, are typically used for cladding of today's reactors.



Limitations of today's cladding process

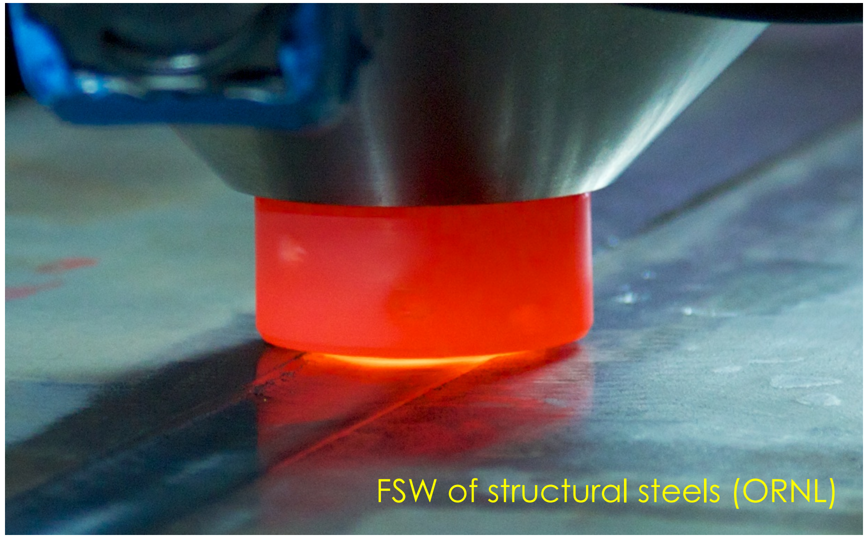
Major barrier in adopting new cladding materials

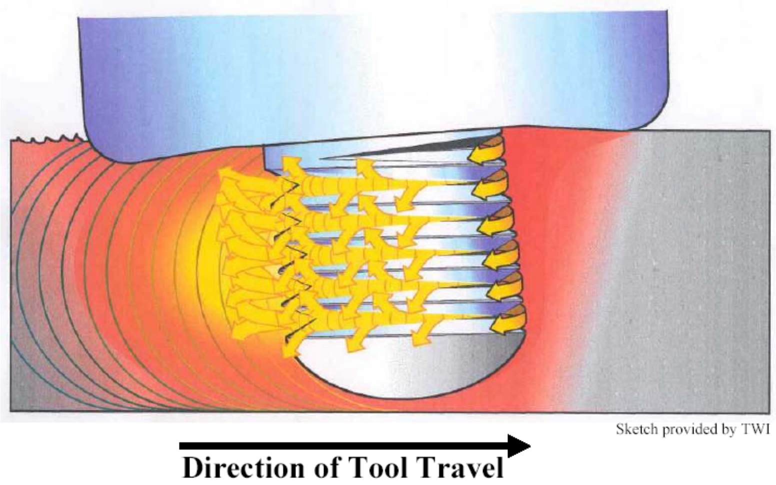
- More SCC resistance alloys (Alloy 52 vs Alloy 82) in the DM weld for piping systems
- Alloy 52 is prone to ductility dip cracking associated with fusion welding processes



Can we develop a solid-state friction stir welding based cladding/additive manufacturing process?

- Friction Stir Welding (FSW) is a novel solid-state joining process. A specially designed tool rotates and traverses along the joint line, creating frictional heating that softens a column of material underneath the tool. The softened material flows around the tool through extensive plastic deformation and is consolidated behind the tool to form a solid-state continuous joint.
- Metallurgically bond/weld materials together without melting and solidification
  - Inherently immune to defects related to fusion based joining processes


FSW of structural steels (ORNL)

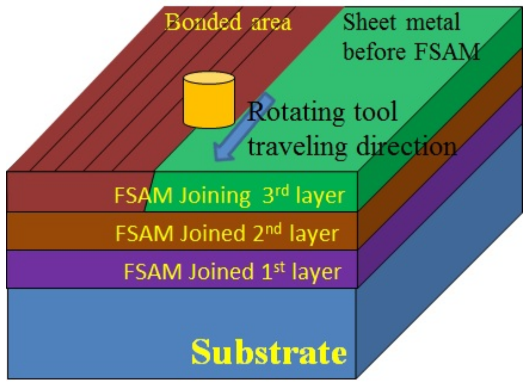


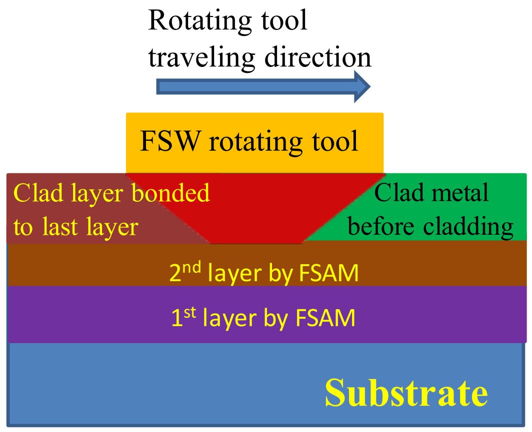
Goals

- To develop and demonstrate a novel solid-state friction stir additive manufacturing (FSAM) process for high productivity surface cladding
  - Improve erosion, corrosion and wear resistance,
  - >20% reduction in cost and improvement in productivity and quality.
- Focus on two targeted applications
  - Cladding of reactor internals
  - Fabrication of the transition layer of dissimilar metal welds
- Support on-site repair in addition to construction of new reactors
  - Cladding of corrosion resistance barrier for MSR
- Demonstrate feasibility of solid-state additive manufacturing of nuclear reactor structural materials with improved properties

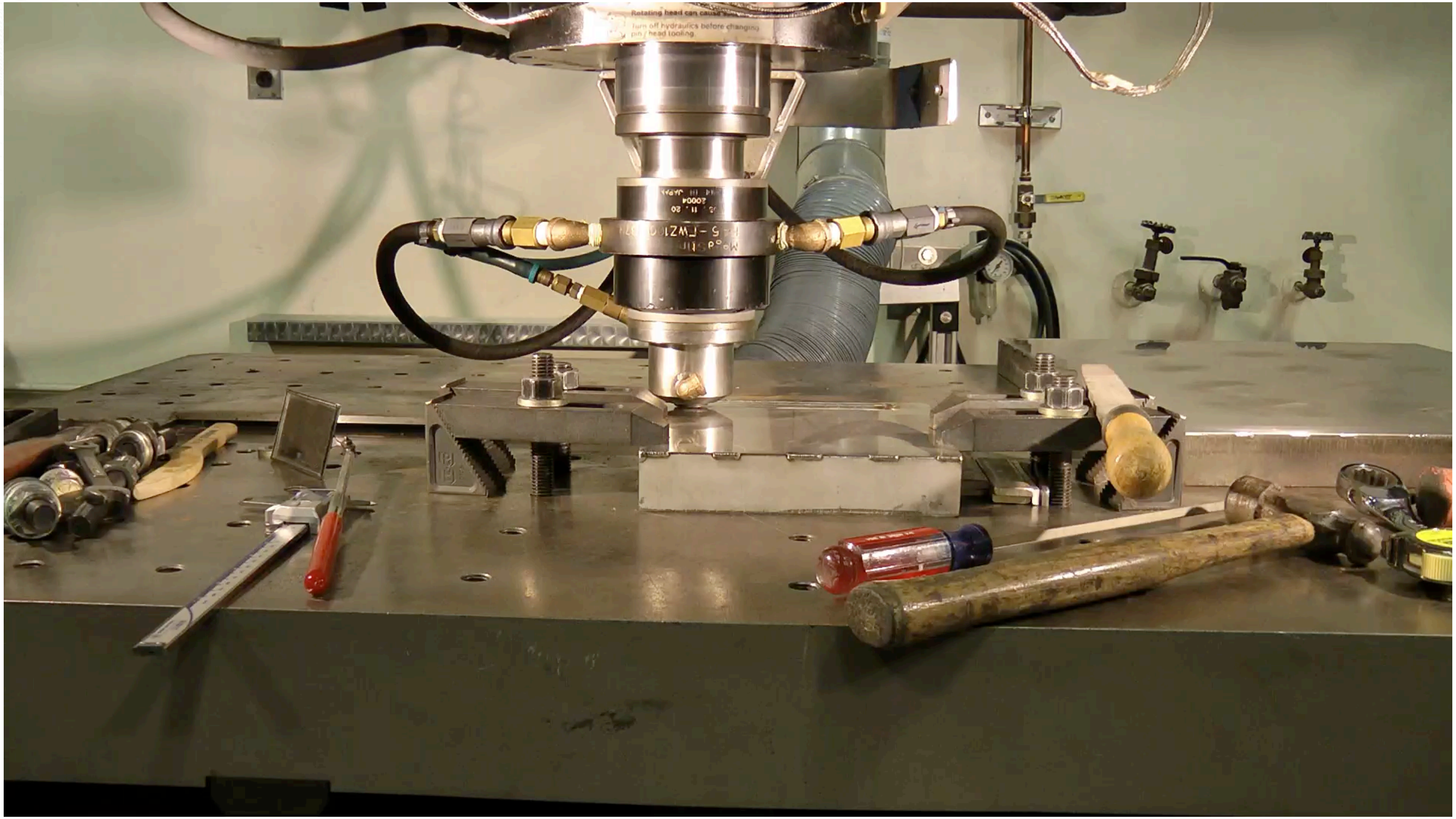
Friction Stir Additive Manufacturing (FSAM)

- FSAM is a novel extension of FSW
- Based on ORNL's multipass, multilayer FSW
- Patent pending process innovations practically eliminate tool failure and tool wear critical to FSAM of high-temperature materials
- The non-consumable tool approach has potential of much higher cladding rate and producing homogeneous microstructure and properties
- Solid-state process also addresses other key shortcomings of fusion welding based cladding process
  - Ease the metallurgical incompatibility constraints in use of new cladding materials
  - Minimize the microstructure and performance degradations of the high performance structural materials
  - Near zero dilution reduces the number of cladding layers for material/cost reduction and increase in productivity





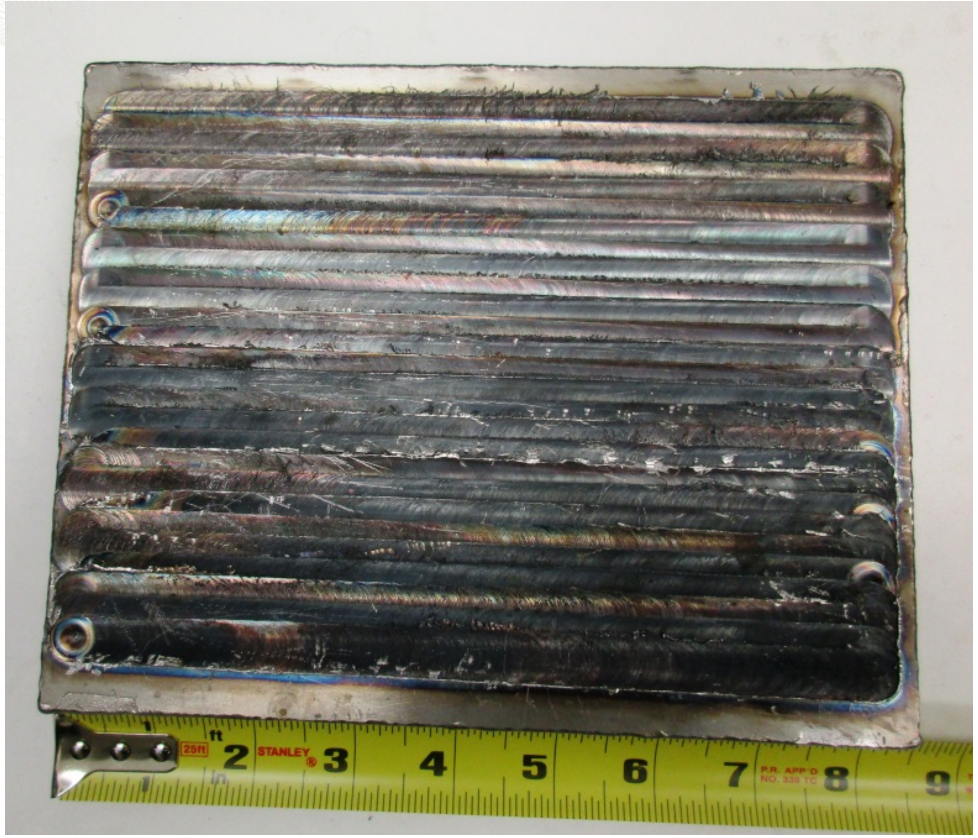
FSAM Process



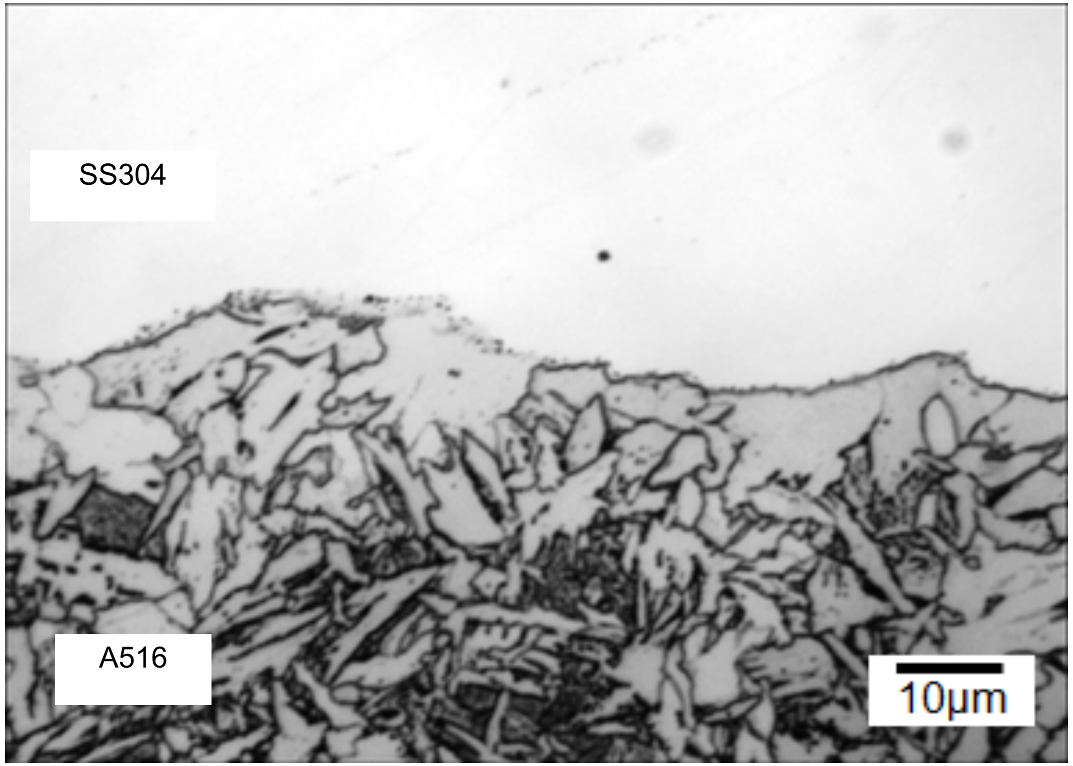
R&D Focuses on

- Can we scale FSAM process up for large area cladding?
  - Process parameter/tool geometry design and improvement
  - Robust tool life
- How can we effectively evaluate the bonding quality of large area cladding?
  - Essential to assist the process development
  - Ultrasonic C-scan non-destructive evaluation to provide macroscopic level quantitative evaluations (~1mm range)
  - Bending test and cross-sectioning to correlate ultrasonic NDE results with bonding quality
- What is the process conditions to form solid-state bonding in FSAM?
  - Temperature measurement at the bonding interface
  - Robust modeling tool to determine the bonding condition to assist FSAM process development and optimization for given applications
- Increasing cladding productivity
- Materials used
  - ASTM A516 pressure vessel structural steel
  - SS304, Alloy 600, Alloy 82/182, Alloy 800 as cladding materials

Single Layer FSAM development



As cladded surface
(surface flush and oxidation, to be addressed)

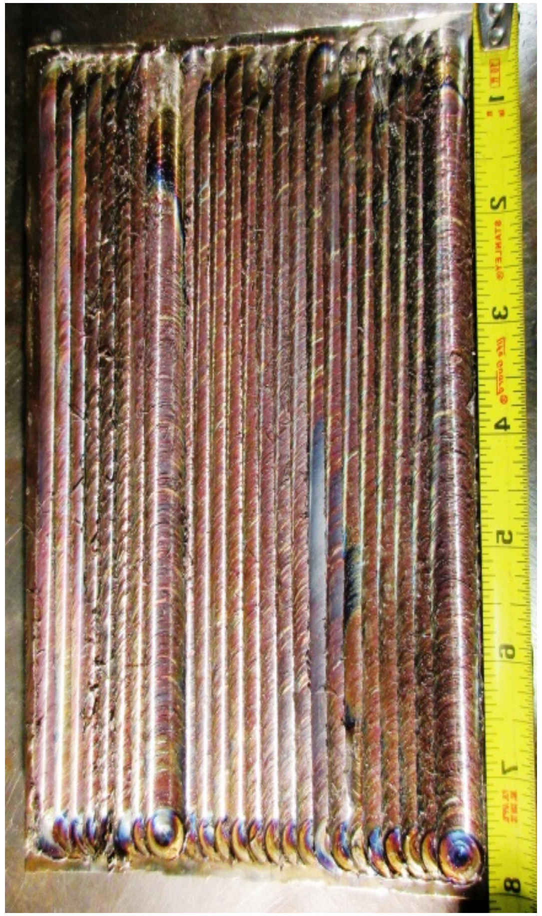


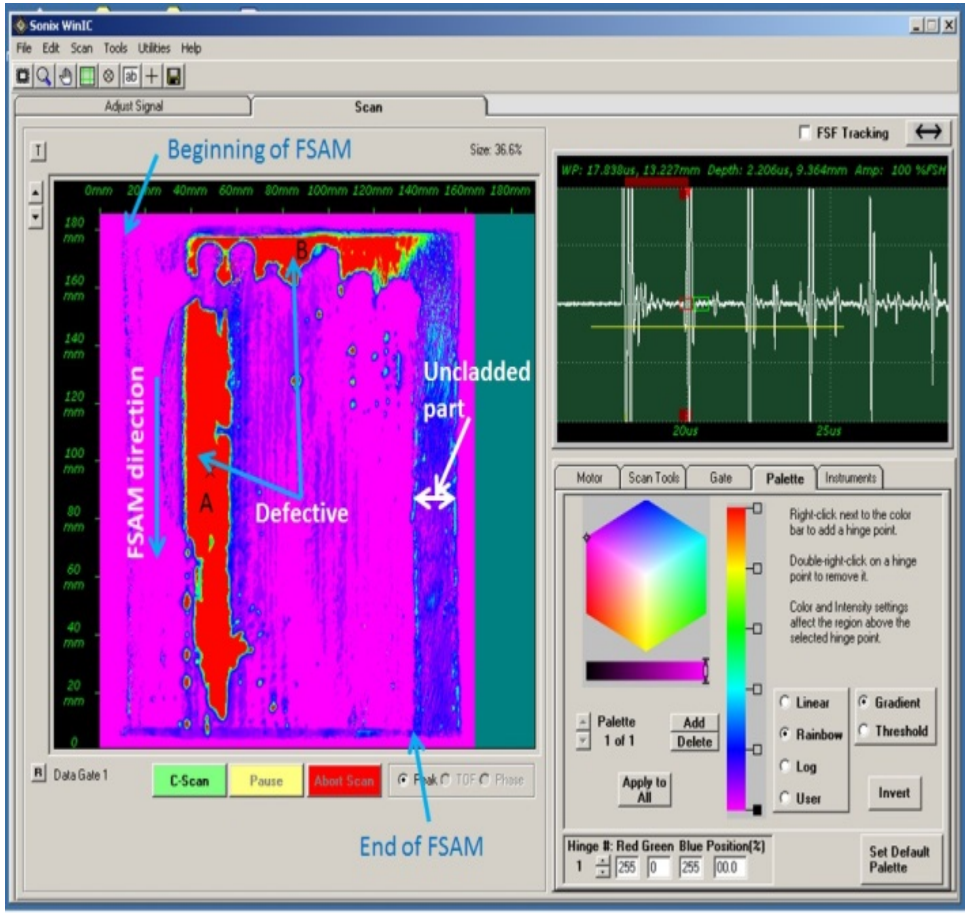
304 SS on structural steel A516

OAK RIDGE
National Laboratory

C-scan Ultrasonic NDE was effective to determine the bonding quality

- Enable us to examine an large area quickly to assist process development

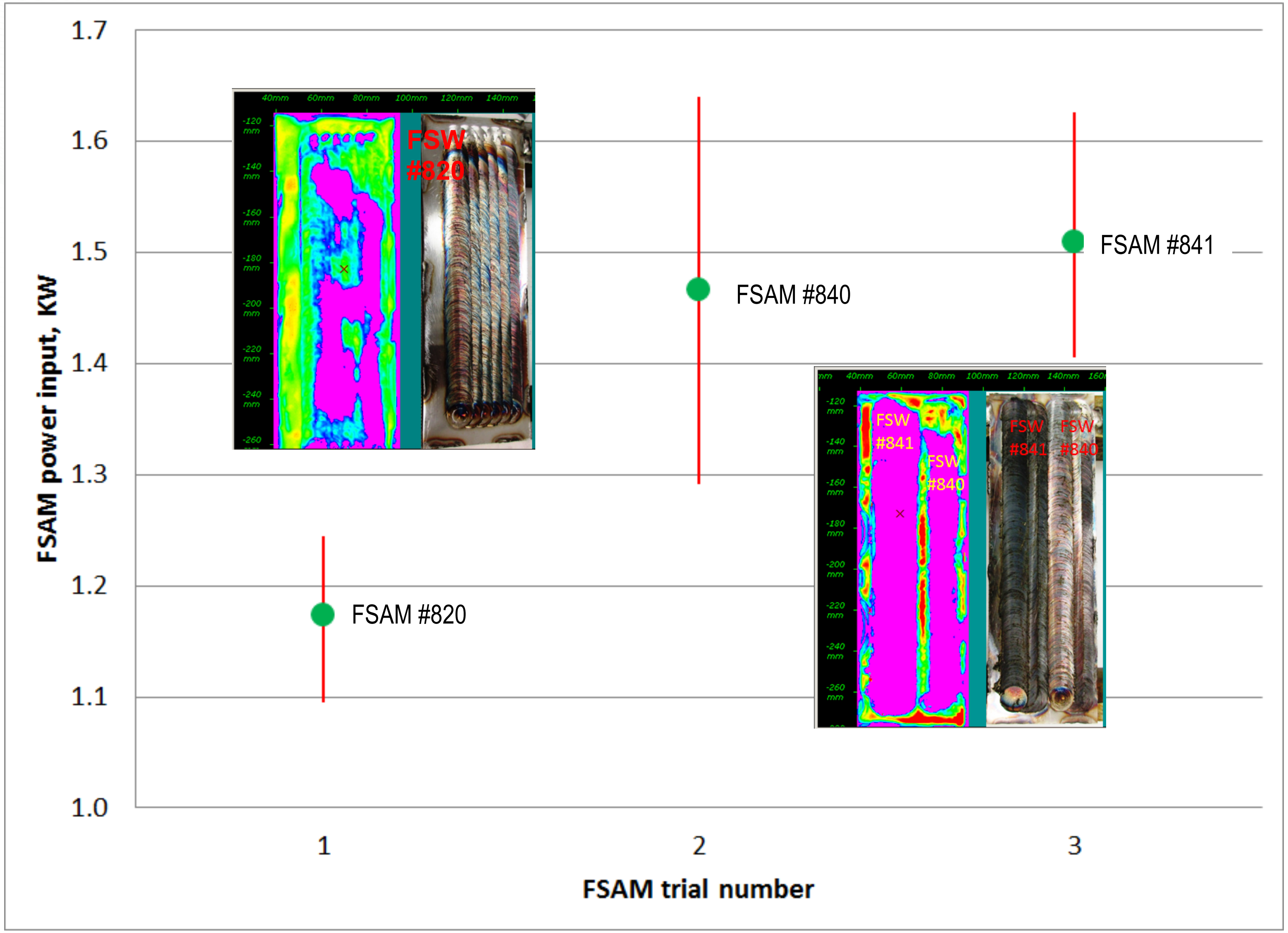




SS304 on A516

OAK RIDGE National Laboratory

Effect of process conditions on bonding

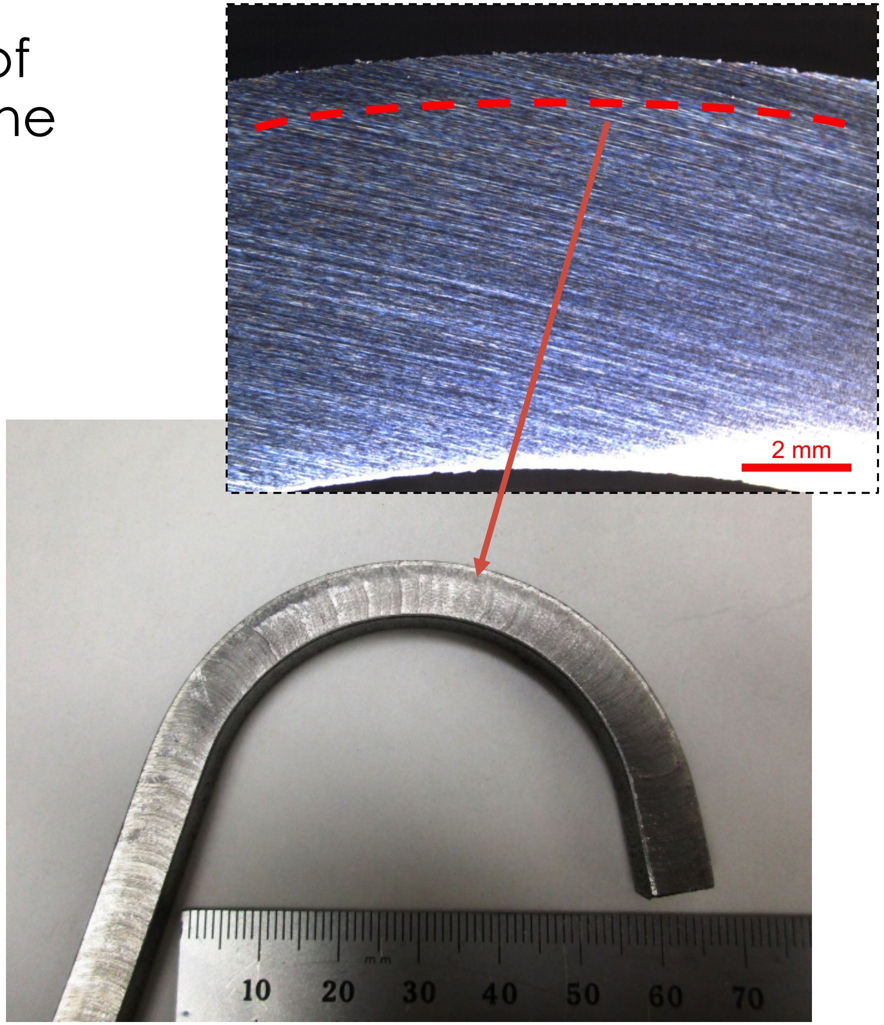


SS304 on A516

Guided side bending test also used to evaluate bonding quality and strength

- The bonding interface is off the neutral plane of bending. This creates relatively large strain at the interface.
- Unbonded regions can revealed after the side bending

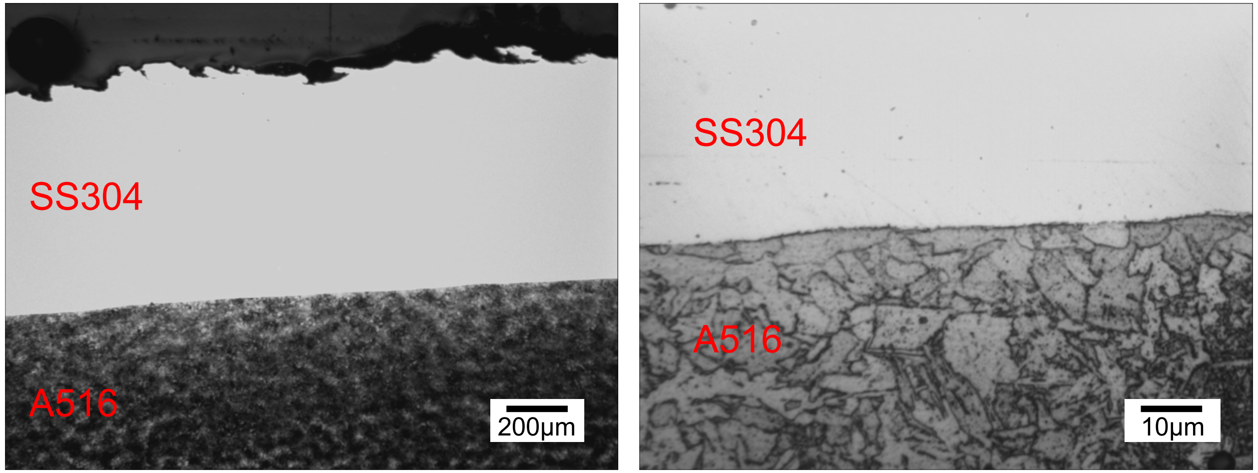
(a) 3" roller (5% elongation)



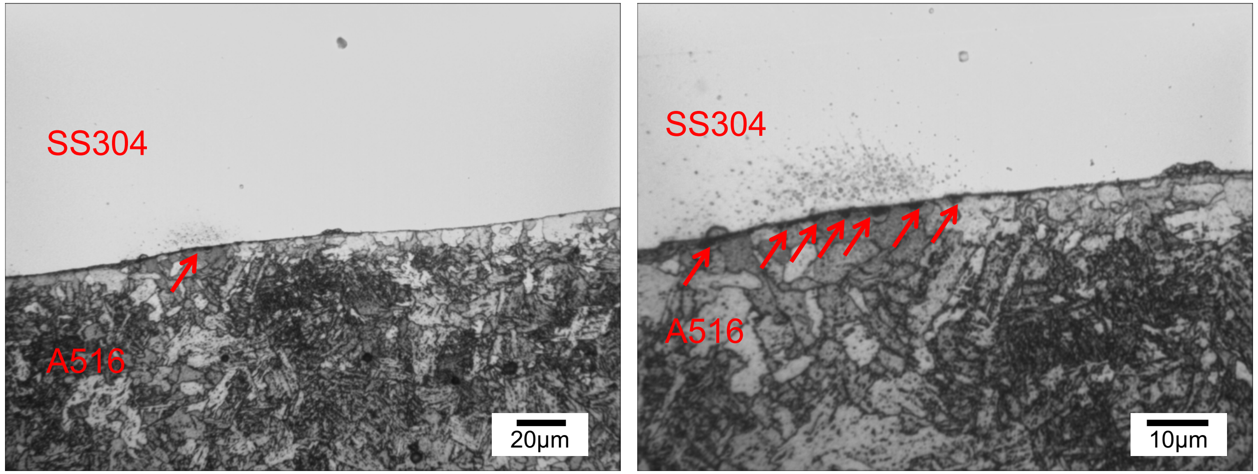
(b) 2" roller (10% elongation)

SS304 on A516

Interface bond quality from side bend test



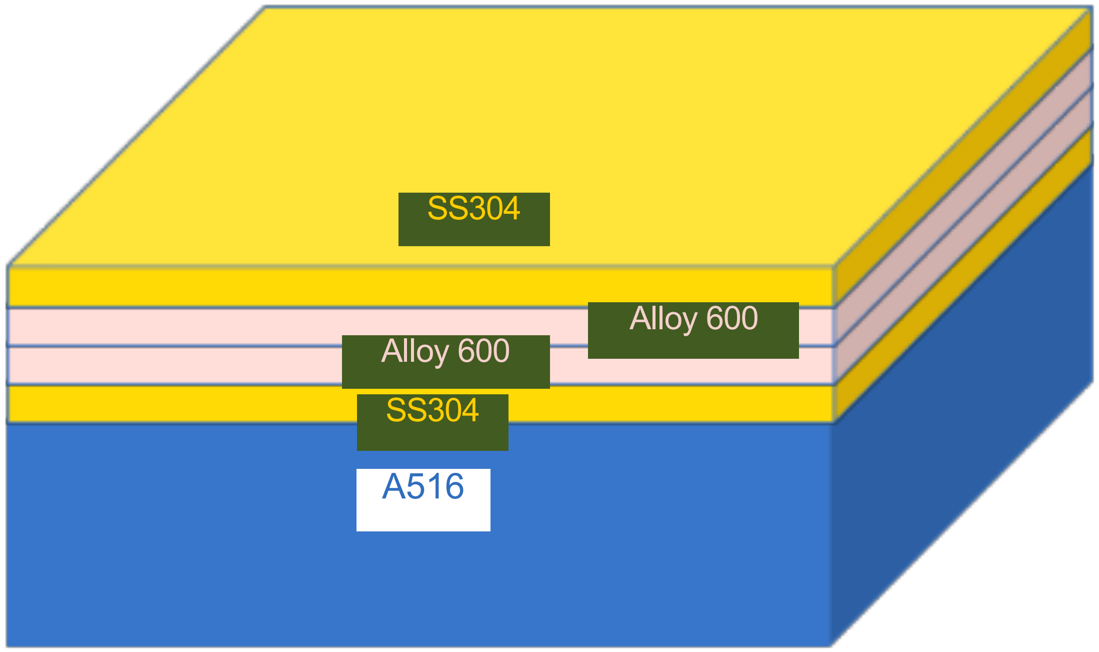
Bonded interface as revealed in the side bend test



Unbonded interface revealed in the side bend test

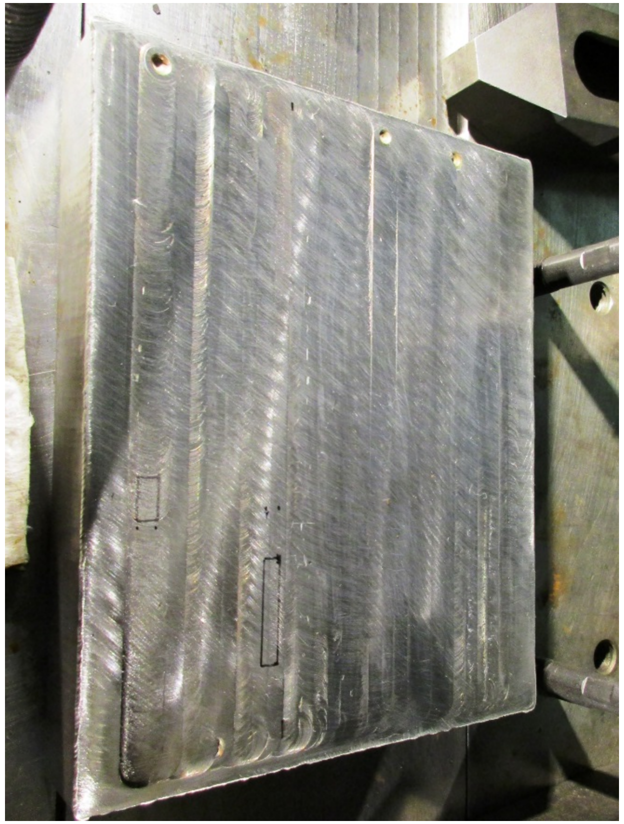
Multi-layer Multi-material FSAM Development

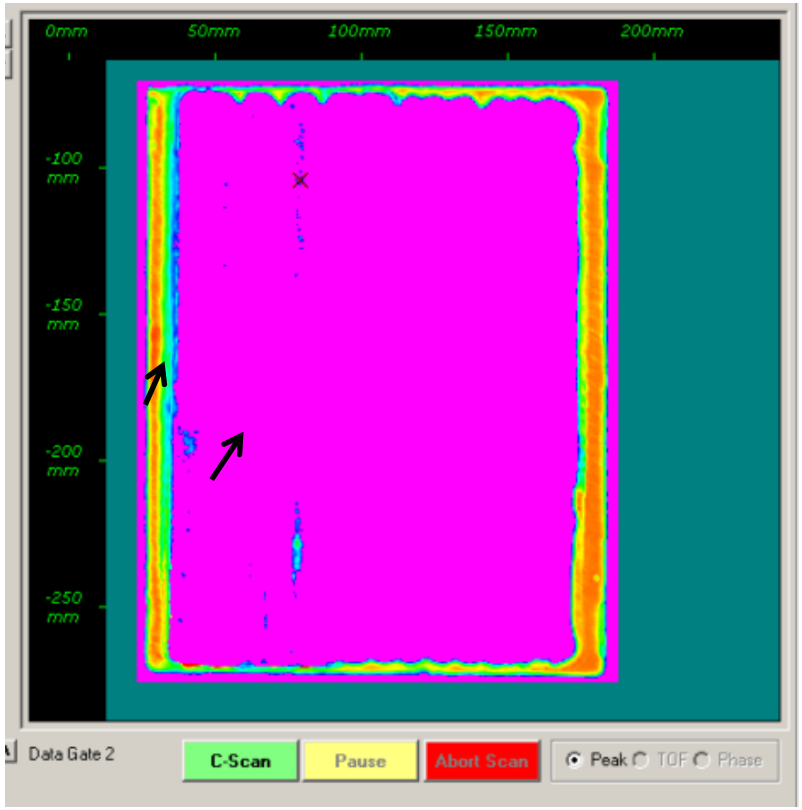
- Materials
  - Substrate: ASTM A516Gr70
  - Layer 1: SS304
  - Layer 2: Alloy 600
  - Layer 3: Alloy 600
  - Layer 4: SS304
- Cladding area: 8x6.5”
- Thickness of each cladding layer: 0.86mm



Multi-layer Multi-material FSAM Development

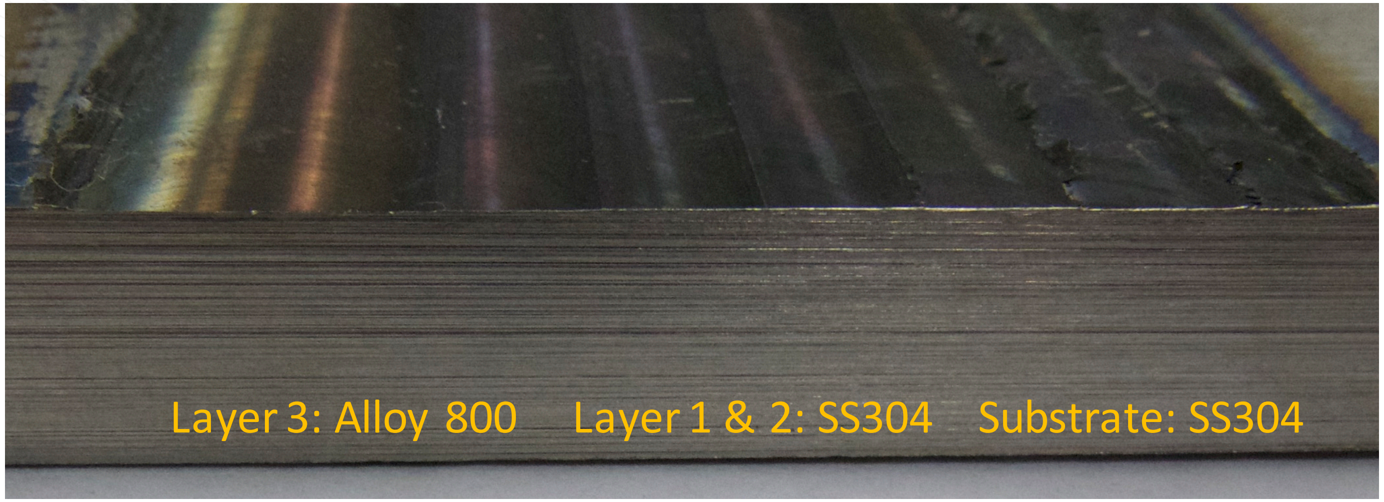
- Bonding was inspected after cladding each layer by C-scan ultrasonic NDE
- Overall good bonding except several locations
- These locations could be "repaired" by FSAM before next layer



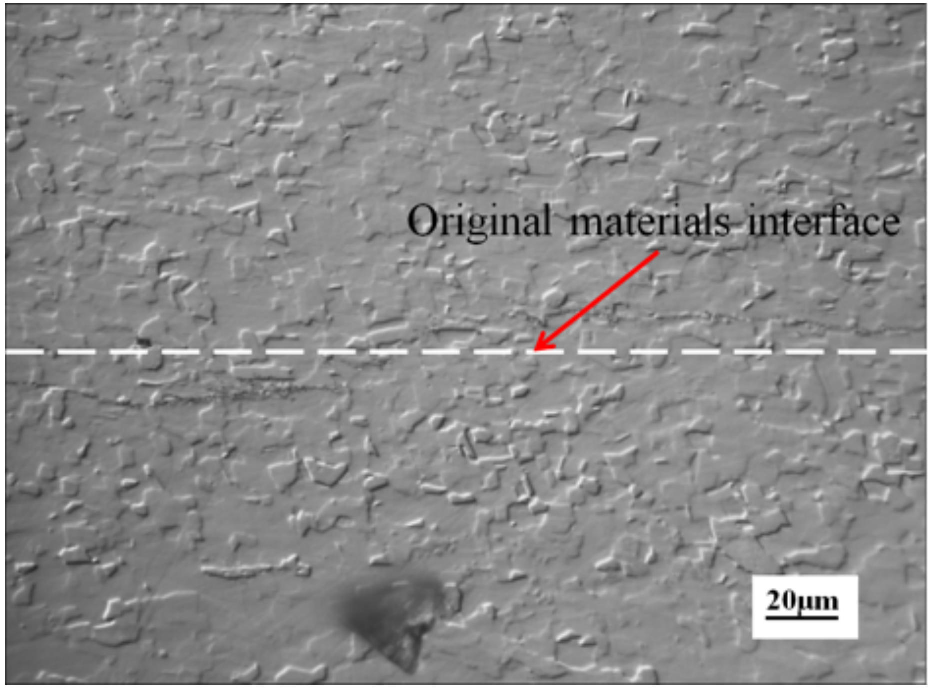


Ultrasonic NDE after clean up by steel wire brush wheel (common practice to clear weld surface)

Multilayer FSAM cladding



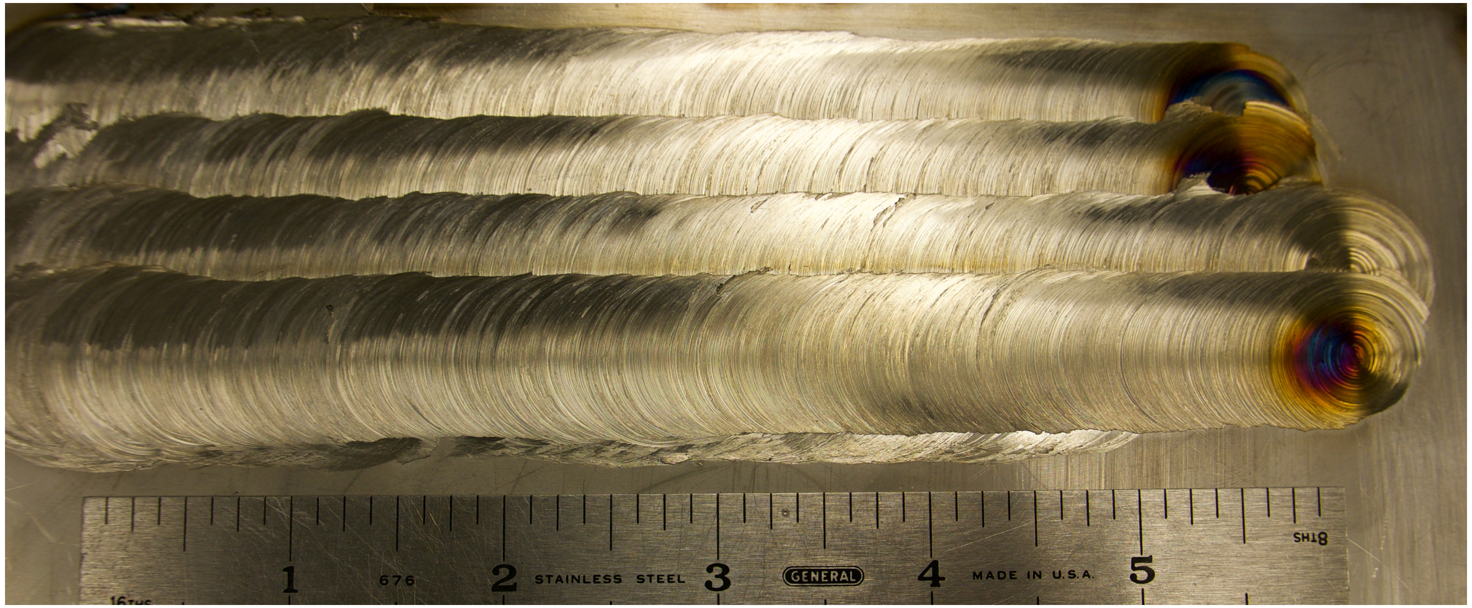
FSAM build of two layers SS304 and one layer alloy 800 on a 304 SS substrate.



Microstructure near the clad bonding interface between two SS304.

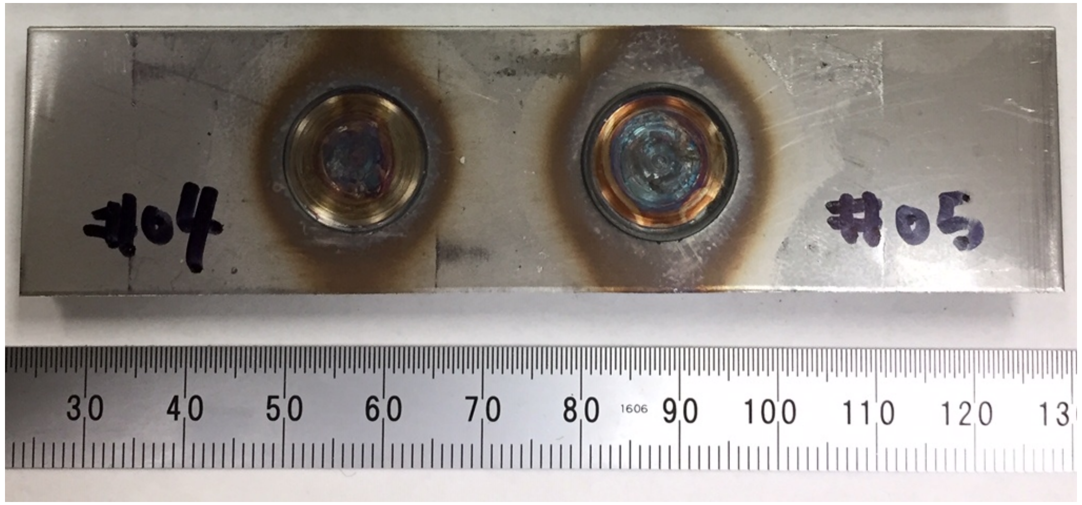
Increasing Cladding Rate/Productivity

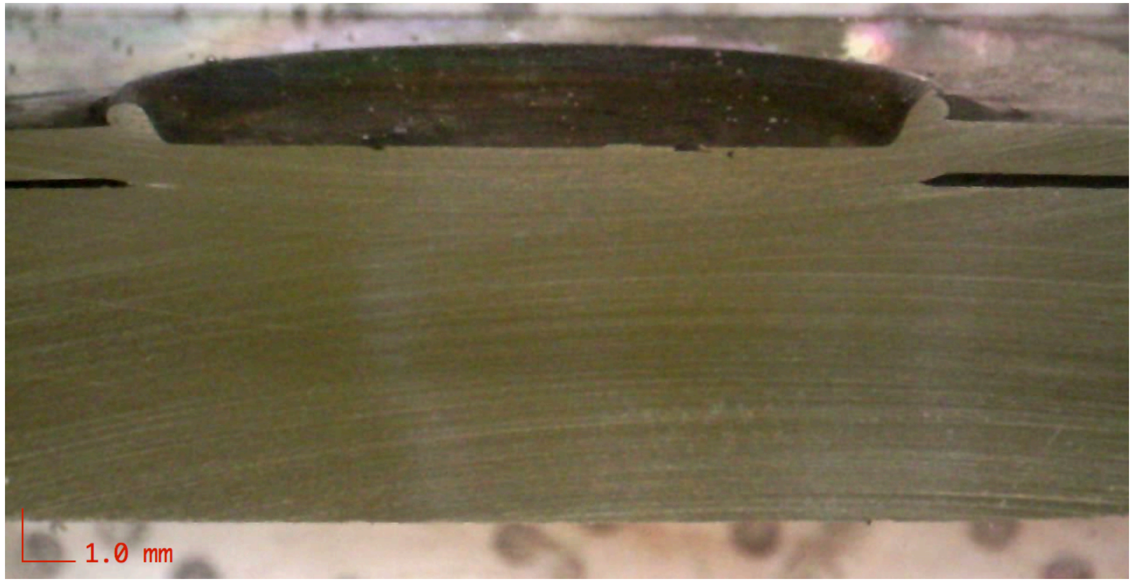
- Use larger tools, higher travel speed, thicker cladding layers
- System modifications
  - Increased torque/process load requirement
  - Solved surface oxidation problem with an argon gas shielding system
- So far, increased tool diameter from 0.5" to 1.0"
  - Larger tool planned, up to 2" diameter
  - On industry partner's system



Tool Wear and Life

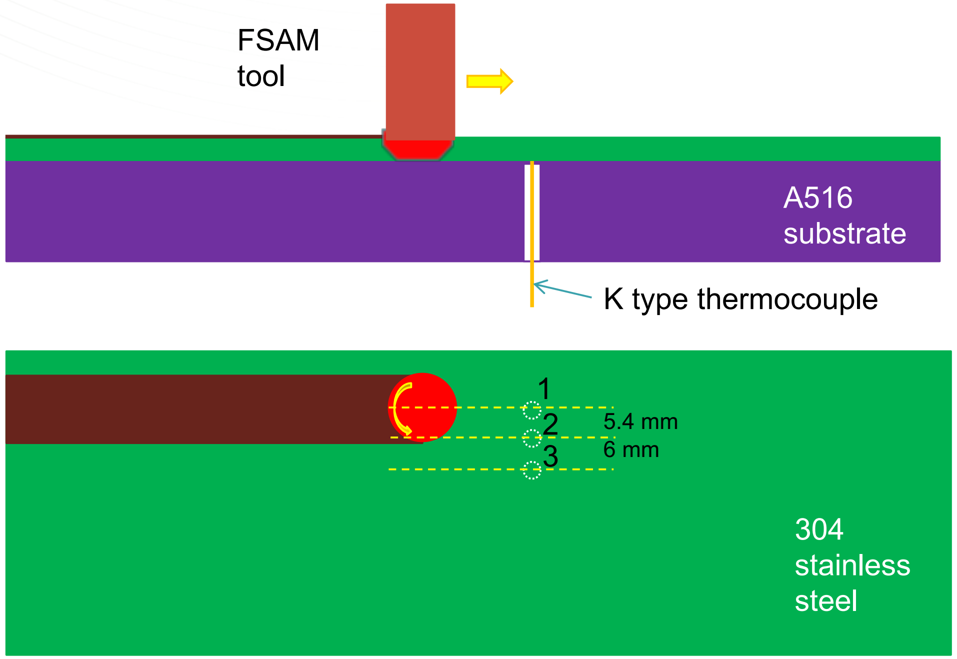
- Our innovative tool design and FSAM process approach have resulted in excellent tool wear performance
  - Only two W based tools were used in all the experimental trials and they are still performing well now.
  - Opens possibility to consider other "low cost" tool materials
  - Possibility for add "features" to tool surface
- Identified several ceramic based tool materials
  - Cost less than 10% of W based tools
  - Initial experimental trials were promising

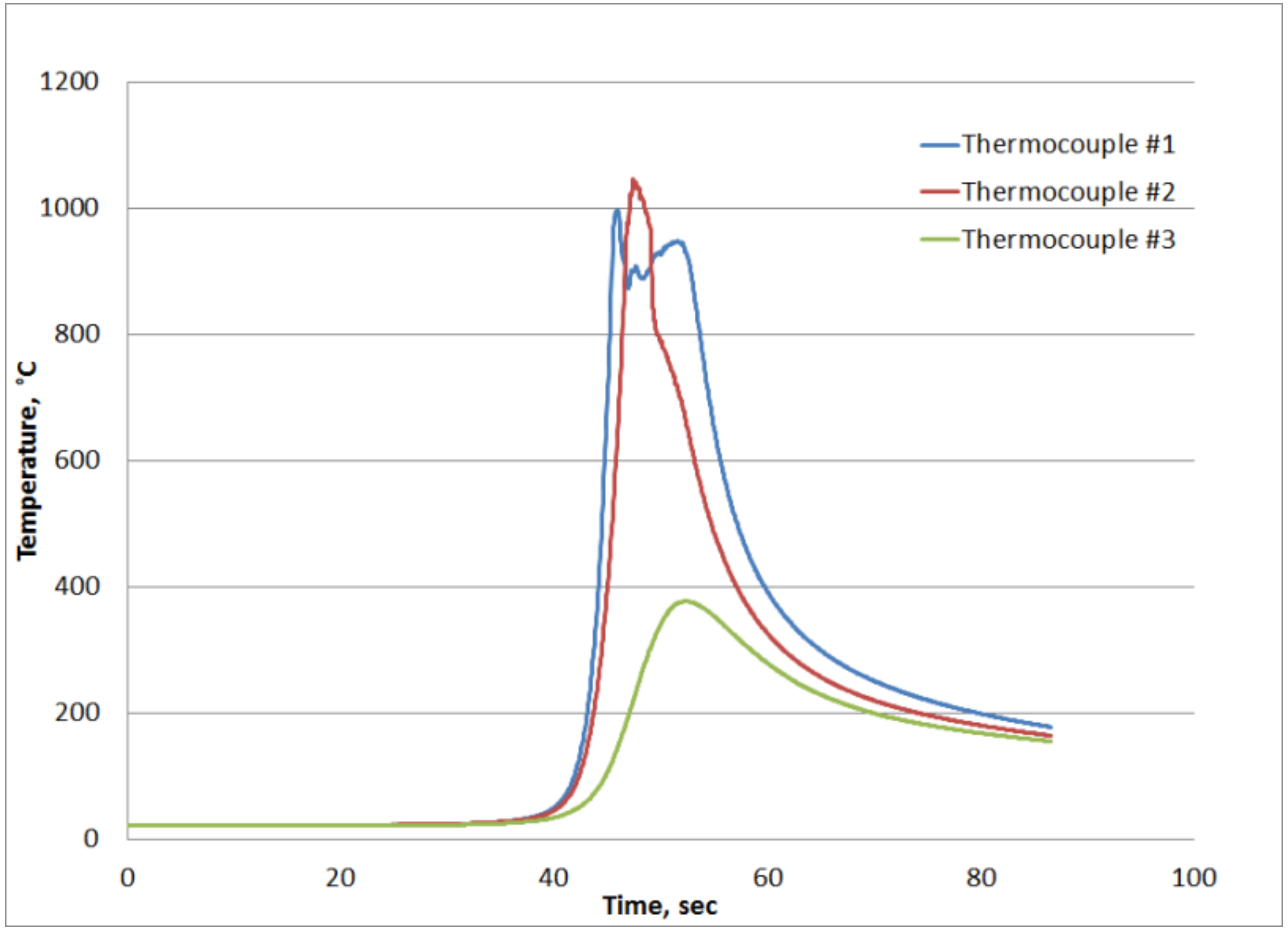




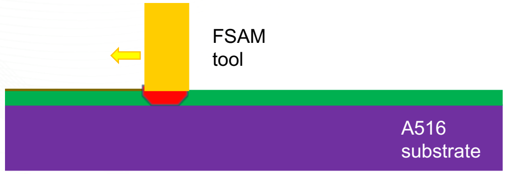
Understanding the process conditions to form Solid-state bonding

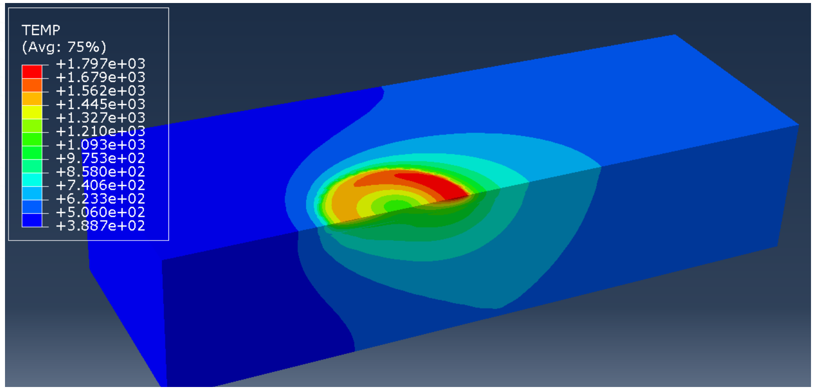
- Temperature measurement at the bonding interface
- Solid state metallurgical bonding forms in the range of 900 - 1100C

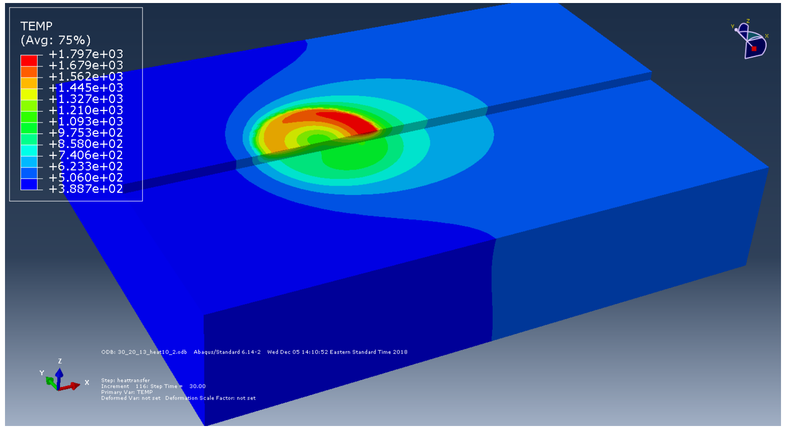


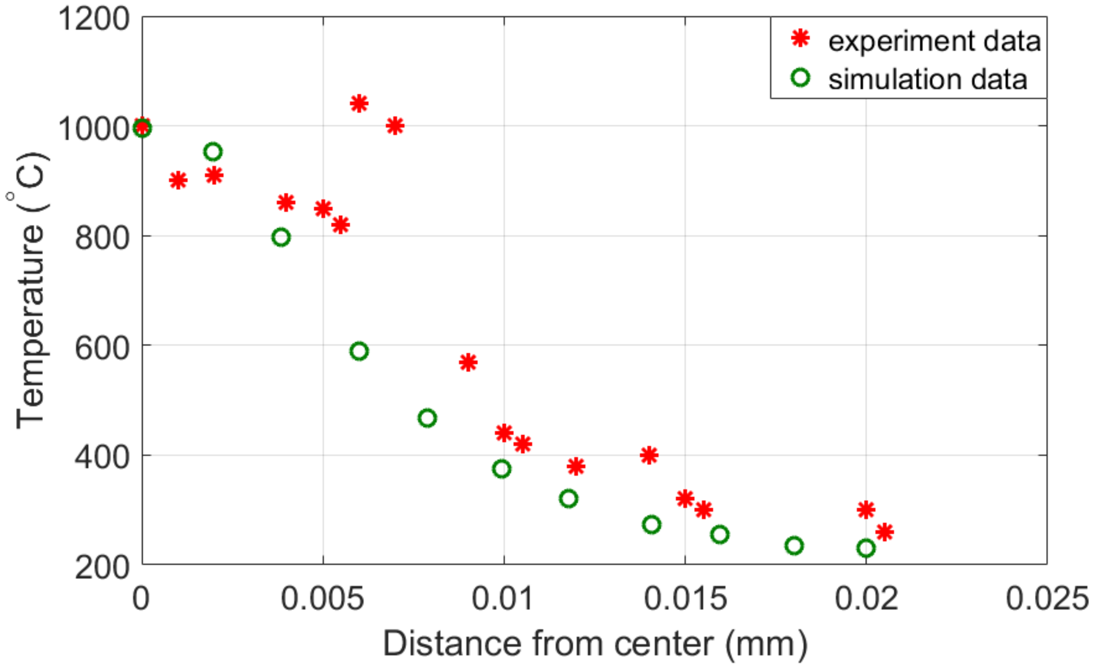


Development of a robust modeling tool for FSAM process development





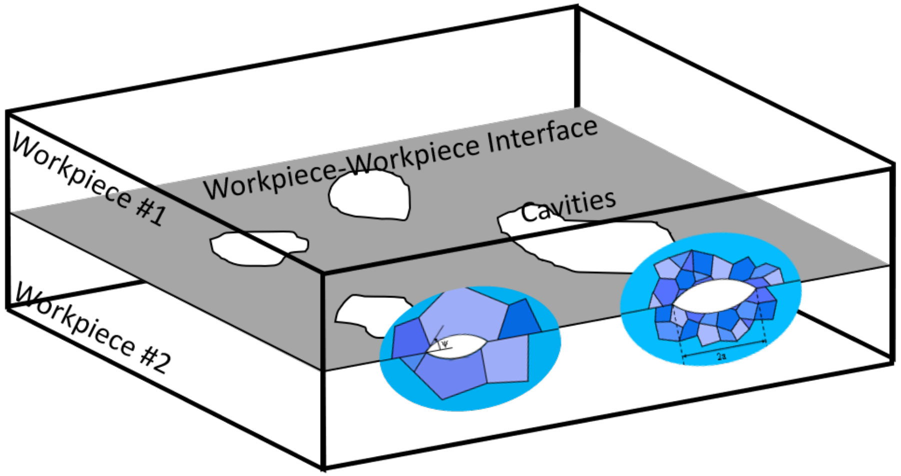




Oak Ridge National Laboratory

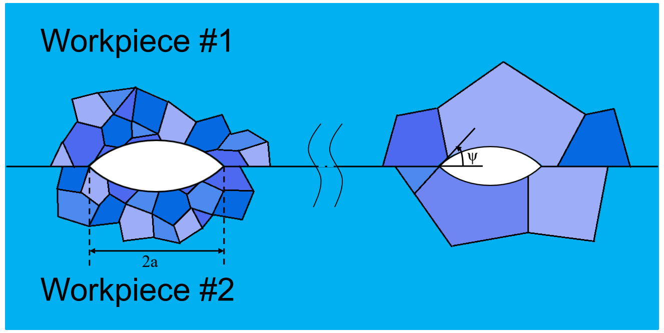
Extend the modeling tool to predict bonding in FSAM

- Treated bonding as creep-dominant "cavity closure" approach to predict the solid-state interface diffusion based bonding from essential FSW/FSAM variables (temperature, stress, strain rates, and time)
- Connect the FSAM process conditions (rpm, travel speed, tool geometry, cladding layer thickness etc) to the above essential process variables



$$\frac{df_h}{dt} = \frac{f_h}{a^3 \ln\left(1/f_h\right)} 2D\sigma_n = \frac{2f_h}{\ln\left(1/f_h\right)} \dot{\varepsilon}_e^c \left(\frac{\sigma_n}{\sigma_e}\right)\left(\frac{L}{a}\right)^3$$

Cocks and Ashby (Prog. Mater. Sci., 1982)



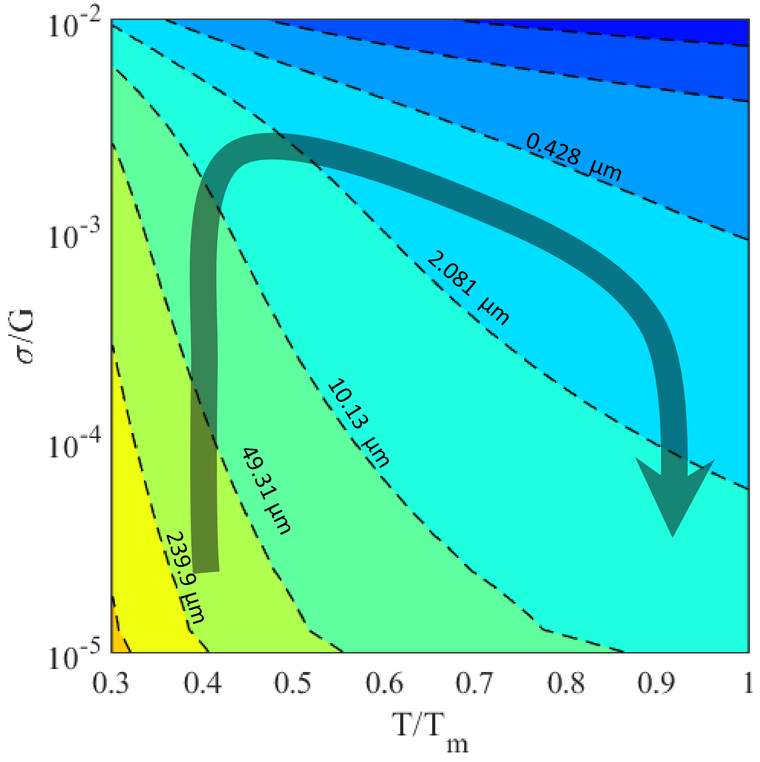
Oak Ridge National Laboratory

FSAM Process Stress-Temperature Trajectory Map

- Bonding is the result of both grain boundary diffusion and creep deformation of surrounding materials.
- L_{NR} could be used to evaluate the competition between these two mechanisms.
- The stress-temperature trajectory during FSAM for locations underneath the tool are in regimes with very low L_{NR}, thus indicating the dominance of creep-controlled cavity closure. The evolution rate of the interfacial bonding depends primarily on the creep strain rate int the surrounding workpieces abutting at the interface

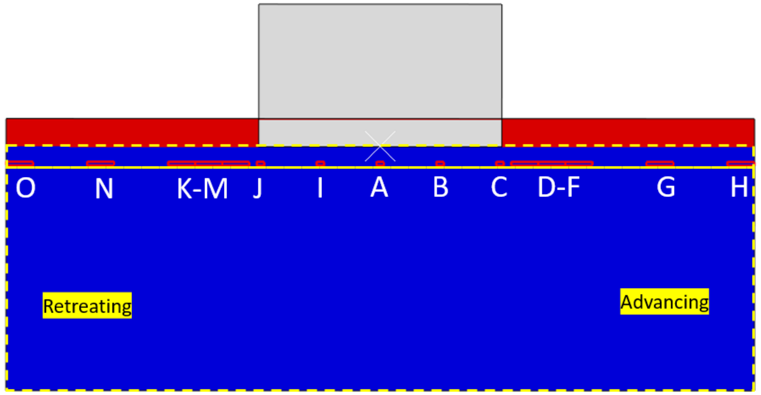
$$L_{NR} = \left[D \frac{\sigma_e}{\dot{\varepsilon}_e}\right]^{1/3} \qquad D = \frac{D_{0b}\delta_b\Omega}{kT} exp\left(-\frac{Q_b}{RT}\right)$$

Needleman and Rice (Acta Metall., 1980)



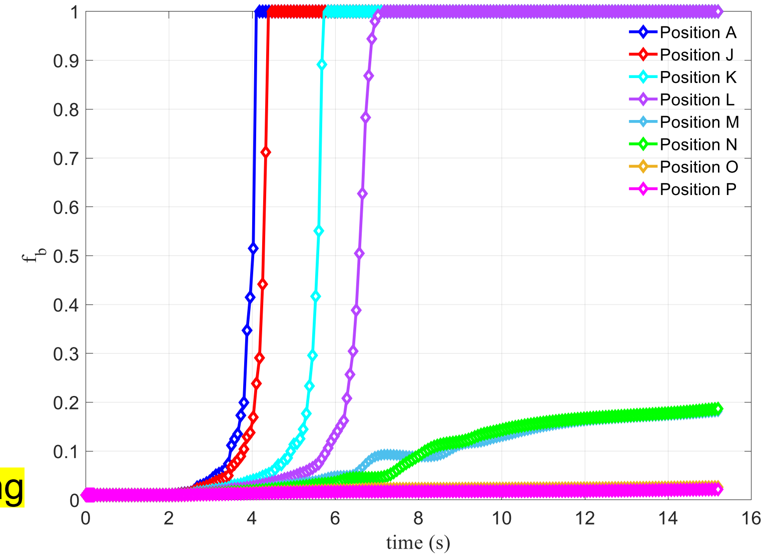
L_{NR} map for stainless steel 304

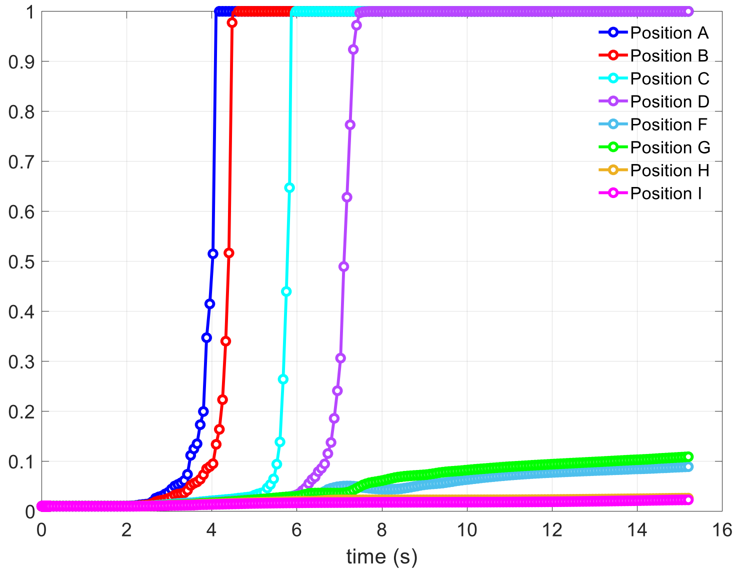
Predicted Bonding region during FSAM



Full bonding

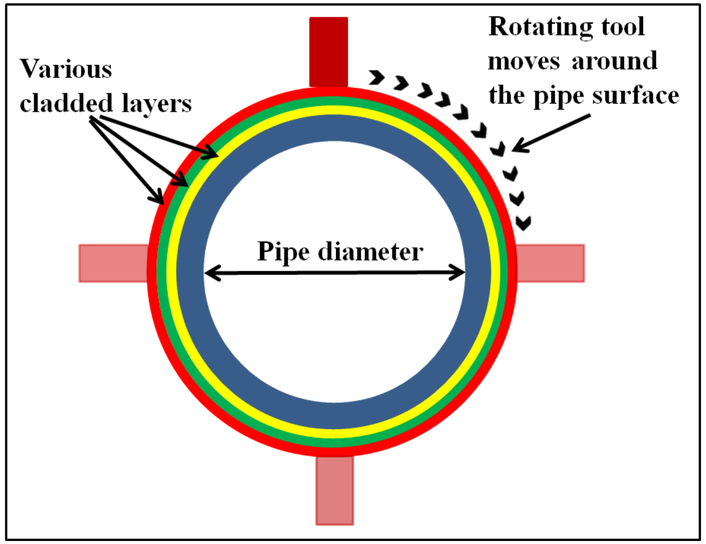
No bonding



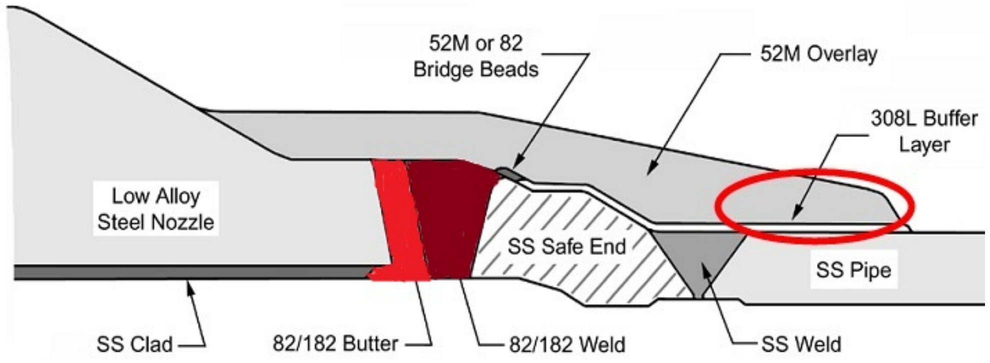


Planned Activity: Feasibility demonstration

- All-position cladding
  - Surface cladding on steel pipe
  - Buttering layer of DM weld



To simulate

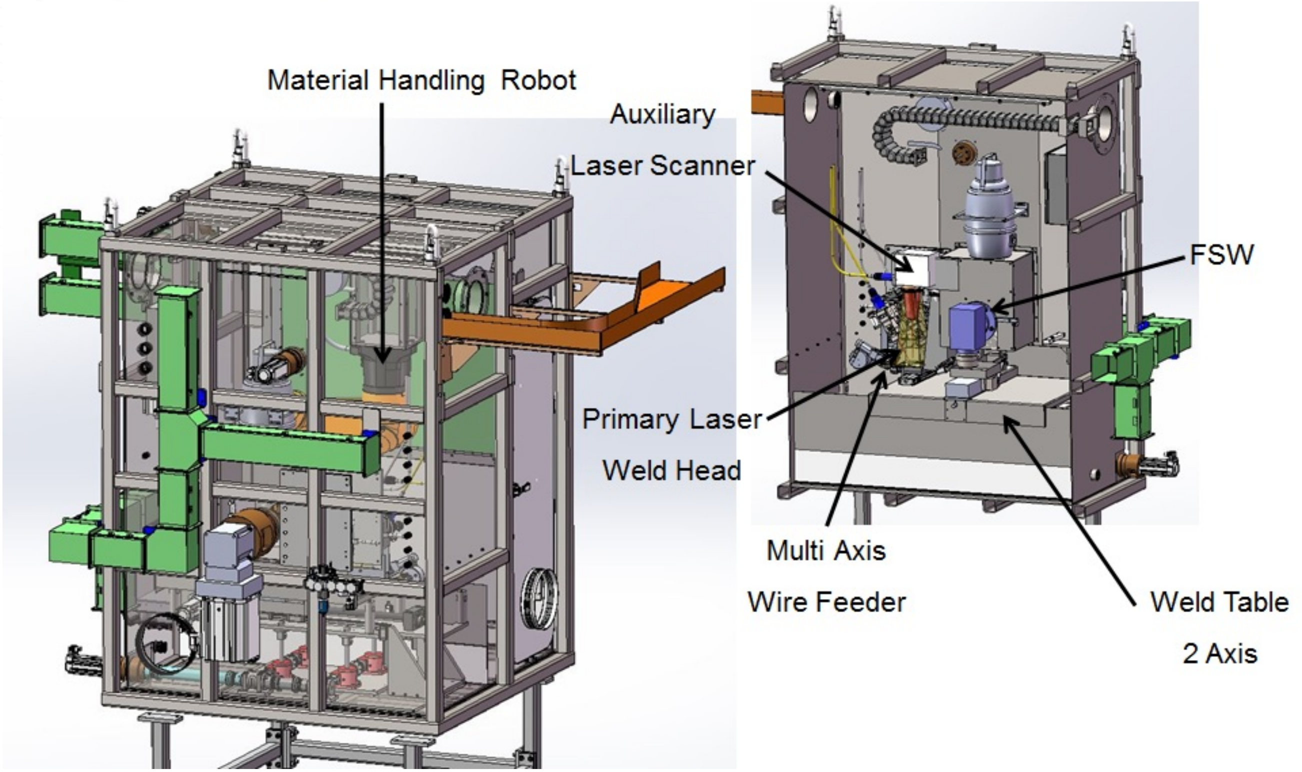


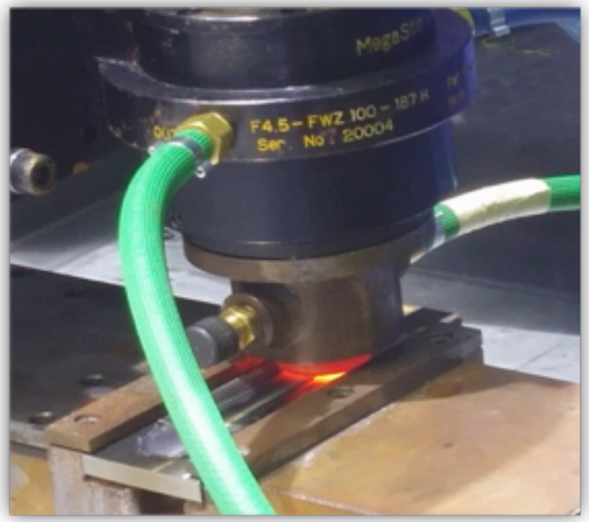
Technology Demonstration

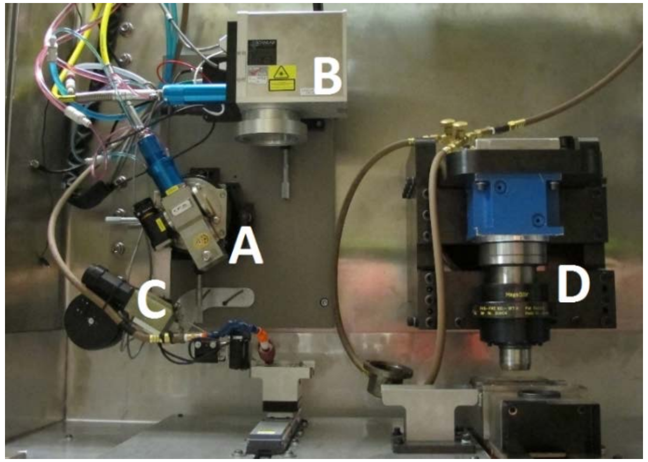
- Effectively utilize an existing FSW pipeline system from previous past FSW R&D (ORNL, ExxonMobil, MegaStir)
- System modification for FSAM underway
  - Clamping system
  - Control system

Support DOE NE:
Development of Advanced Welding Technology to Repair Nuclear Reactor Internals (Joint DOE/NE LWRSP and EPRI LTO Programs)

- Solve tool wear and eliminate boron contamination from FSW tools







Key Milestones

- Year 1
  - FSAM cladding of stainless steel and nickel-base alloy onto low alloy structural steel with multi-pass, multilayer on small sized coupons. Completed
  - FSAM cladding temperature measurement. Completed
  - Feasibility demo of FSAM cladding with larger cladding area. Completed (rescoped to 12x12" clad area due to system modification and process optimization for productivity)
- Year 2
  - Microstructure characterization of lab scale coupons. Completed
  - Develop NDT techniques for FSAM clad inspection. Completed
  - FSAM cladded coupons mechanical properties testing. Completed
  - High temperature creep tests of cladded coupons. Postponed to year 3
- Year 3
  - Complete FSAM cladding parameters optimization. Completed
  - Complete NDE on FSAM coupons. Completed
  - Complete refine processing parameters assisted with numerical modeling. On-going
  - Produce FSAM cladding on prototype mockup nuclear reactor components. On-going

Summary

- Demonstrated feasibility for solid-state diffusion bonding of dissimilar material cladding by FSAM
  - Established baseline FSAM process window for cladding SS304 and Alloy 600 on structural steel A516
  - Determined suitable FSAM temperature range for bonding
  - C-scan ultrasonic NDE is effective to examine clad bonding quality by FSAM
- On-going research to
  - Complete validation of FSAM modeling tools for process applications
  - Scale up and demonstration of all-position cladding

Acknowledgements

- This research was sponsored by the US Department of Energy, Office of Nuclear Energy, for Nuclear Energy Enabling Technologies Crosscutting Technology Development Effort, under a prime contract with Oak Ridge National Laboratory (ORNL). ORNL is managed by UT-Battelle, LLC for the U.S. Department of Energy under Contract DE-AC05-00OR22725.