AMM
Advanced Methods for Manufacturing

DEC 2 – 3, 2020

All-Position Cladding by Friction Stir Additive Manufacturing (FSAM)

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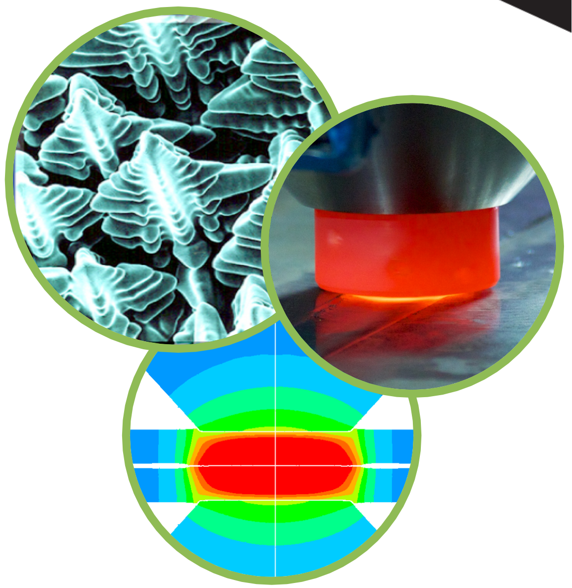


Outline

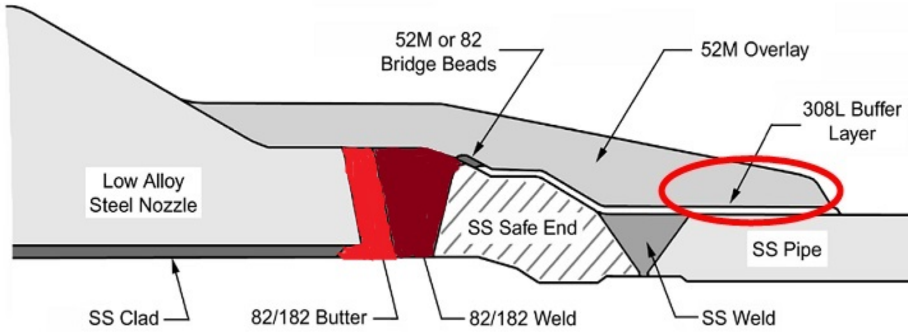
- Project goal/objectives
- Background
- R&D plan
- Progress and status
- Next activities
- Summary

Project Objectives and 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

Background

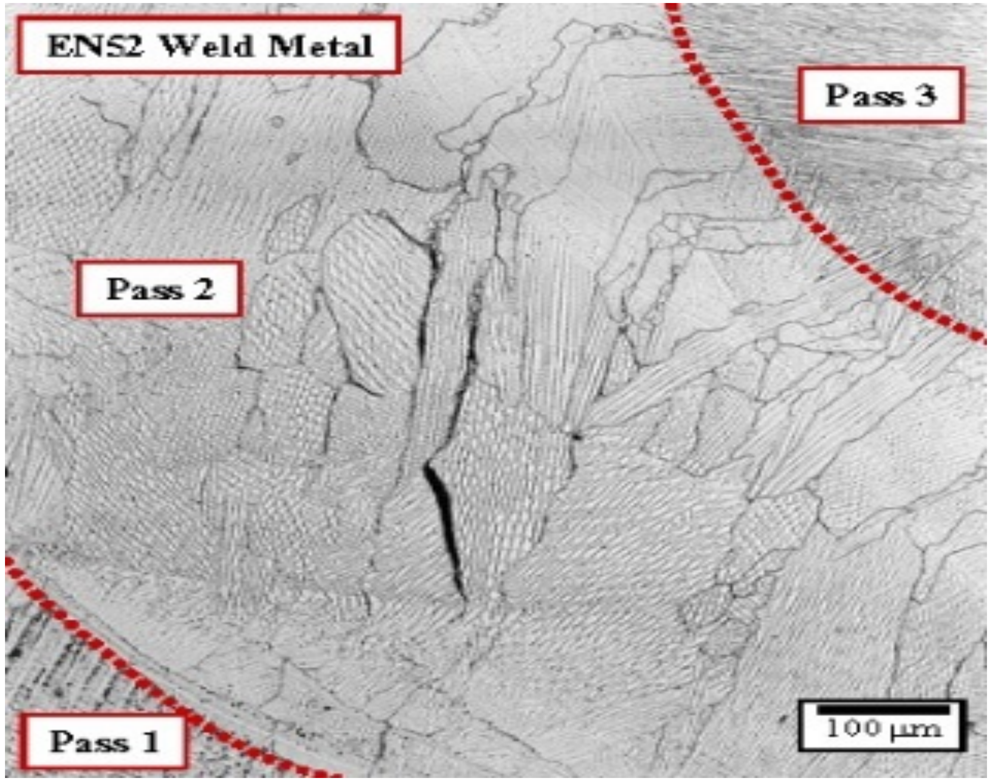
- Cladding and surface modifications are extensively used in fabrication of nuclear reactor systems. It essentially involves adding a layer of different material to component surface.
  - Cladding of reactor vessel internals to improve erosion, corrosion, and wear resistance
  - Build a buffer layer 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

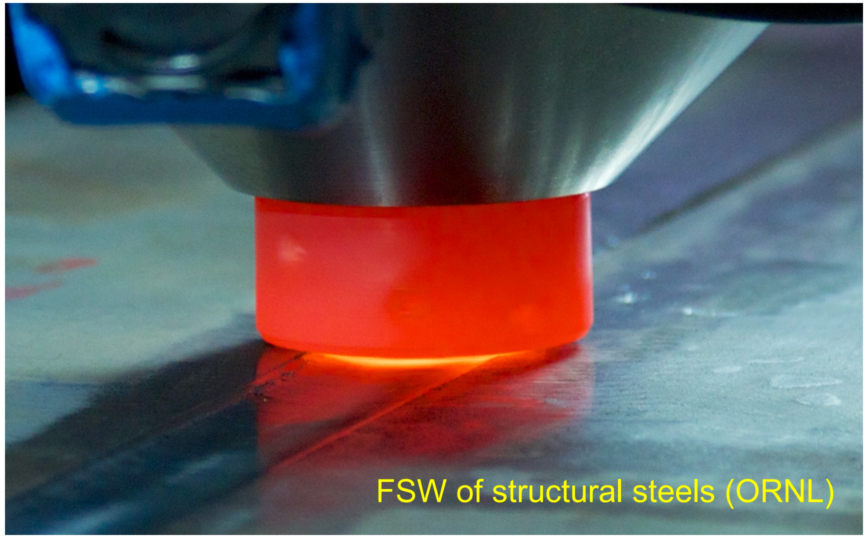
Major barrier in adopting new cladding materials

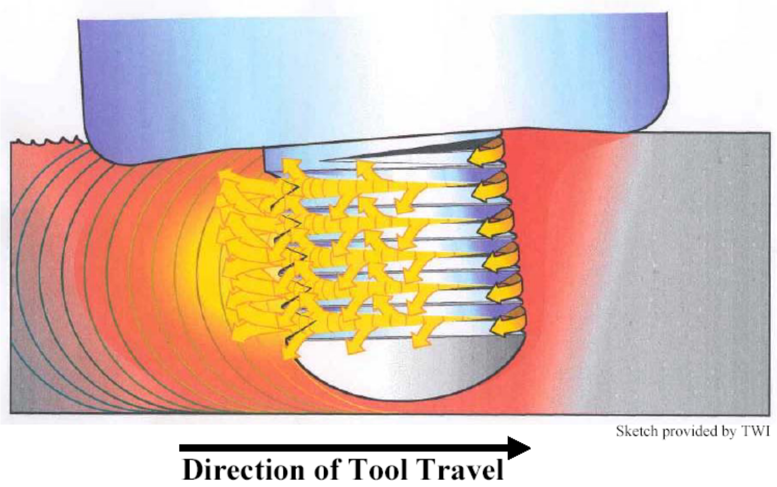
- More SCC resistance alloys (Alloy 52 vs Alloy 82) in the DM weld for piping systems
- Alloy 52 is prone to ductility dip cracking associated with fusion welding processes



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

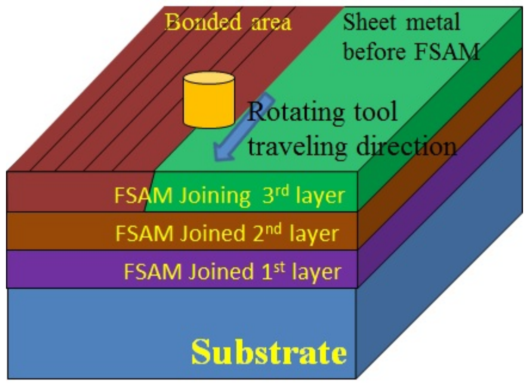
- Friction Stir Welding (FSW) is a novel solid-state joining process. A specially designed tool rotates and traverses along the joint line, creating frictional heating that softens a column of material underneath the tool. The softened material flows around the tool through extensive plastic deformation 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

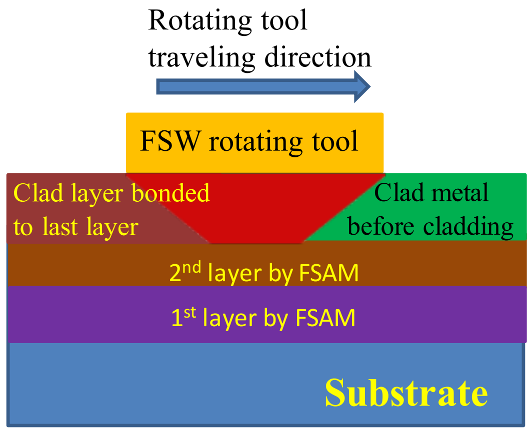




Friction Stir Additive Manufacturing (FSAM)

- 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





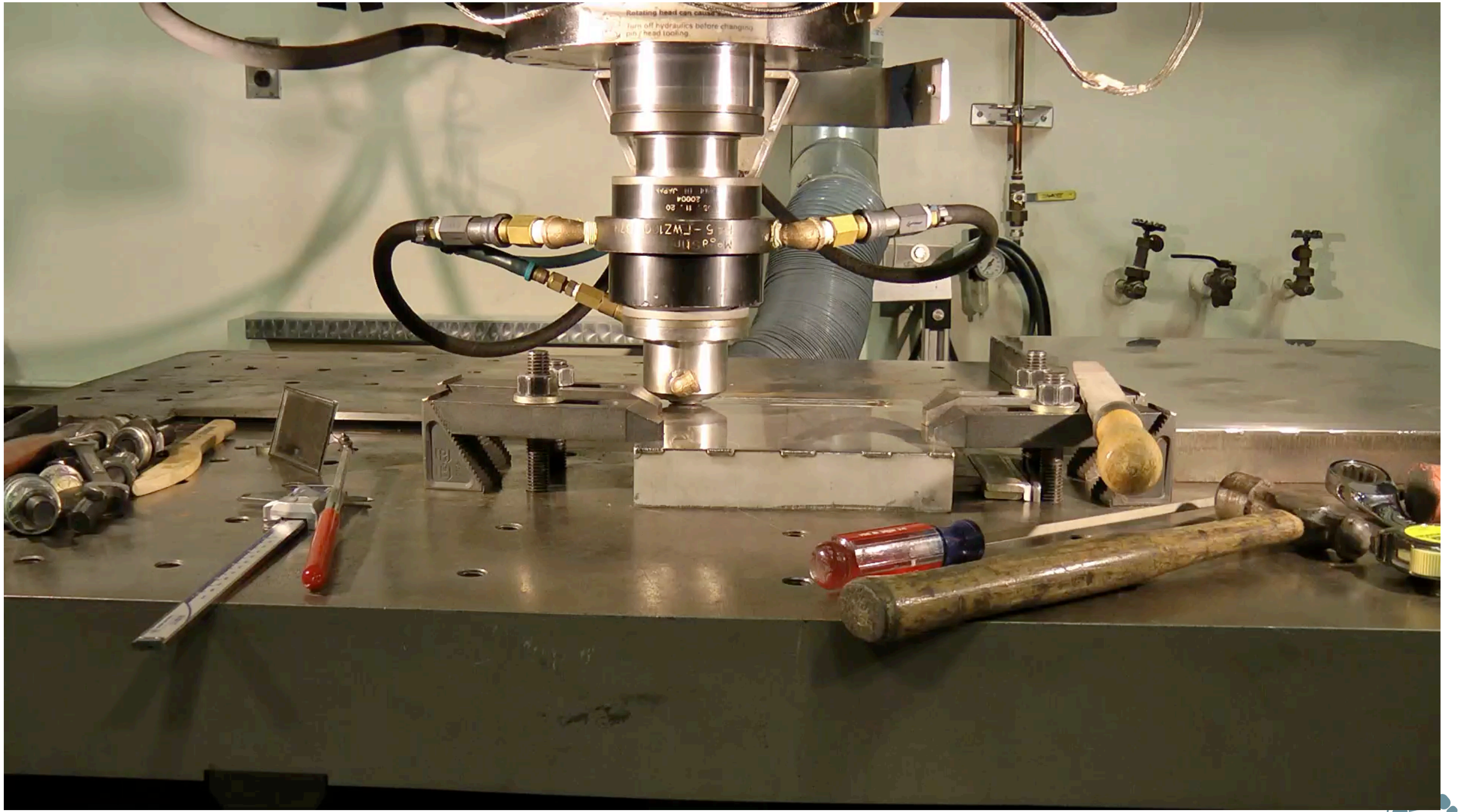
R&D Focuses on

- 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
- 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
- Increasing cladding productivity
- Can we scale FSAM process up for large area cladding?
  - Process parameter/tool geometry design and improvement
  - Robust tool life
- Materials used
  - ASTM A516 pressure vessel structural steel
  - SS304, Alloy 600, Alloy 82/182, Alloy 800 as cladding materials

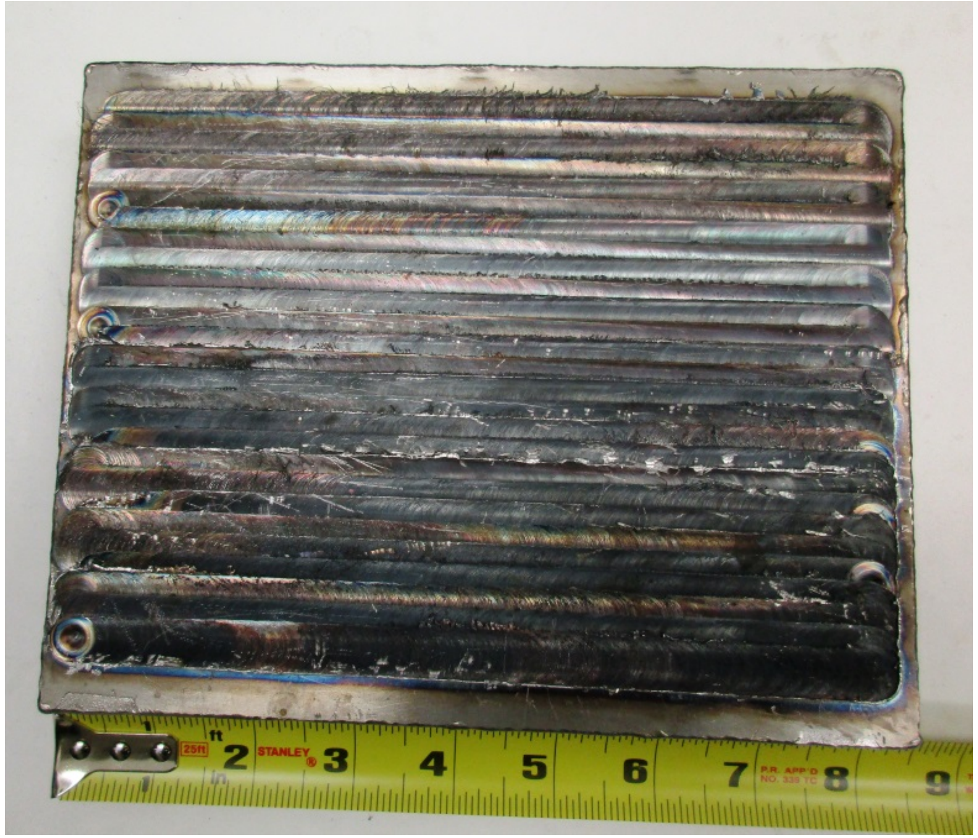
Key Milestones

- 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
- Year 3
  - Complete FSAM cladding parameters optimization. Completed
  - Complete NDE on FSAM coupons. Completed
  - Complete refine processing parameters assisted with numerical modeling. Completed
  - Produce FSAM cladding on prototype mockup nuclear reactor components. On schedule

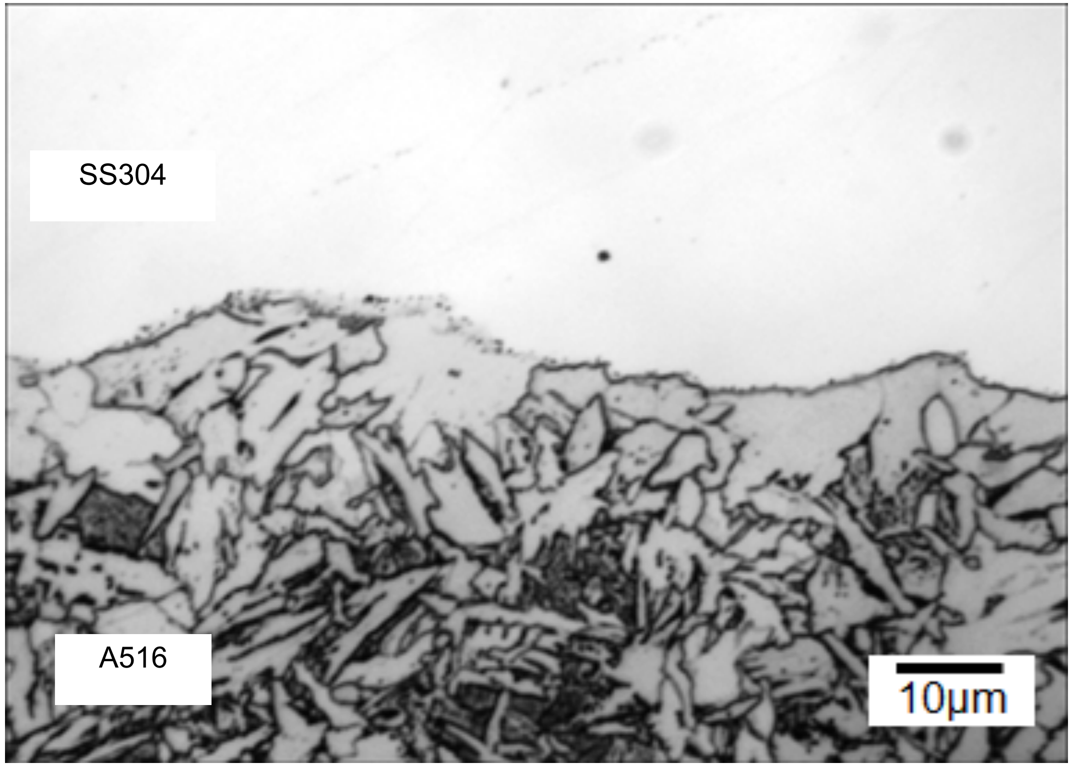
FSAM Process



Single Layer FSAM development

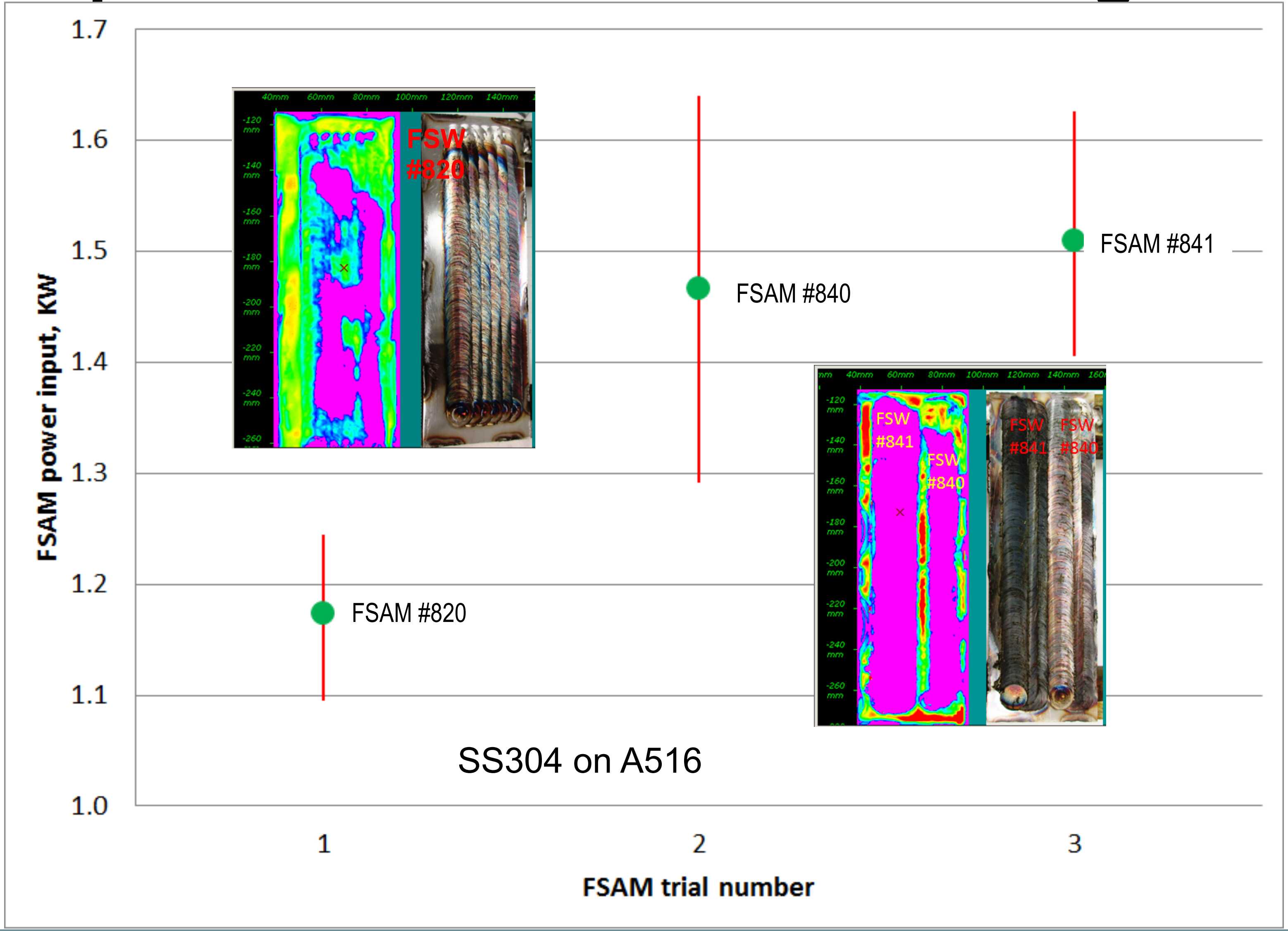


As cladded surface
(surface flush and oxidation, to be addressed)

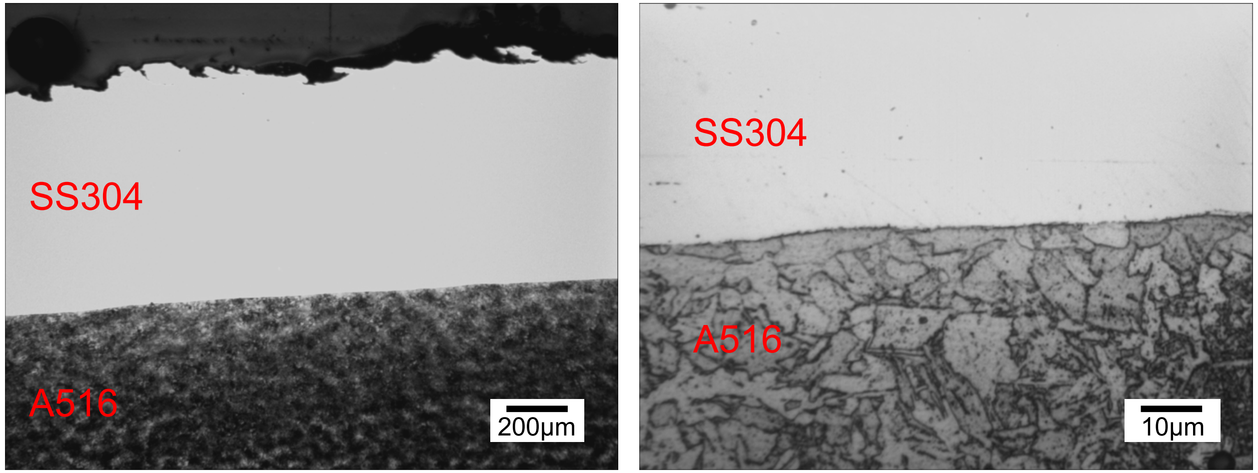


304 SS on structural steel A516

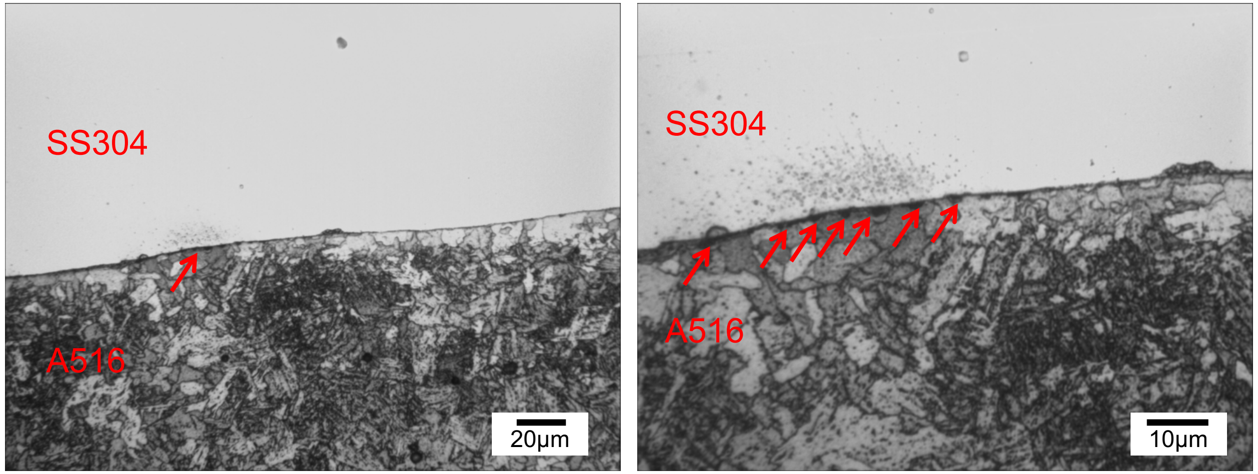
Effect of process conditions on bonding



Interface bond quality from side bend test



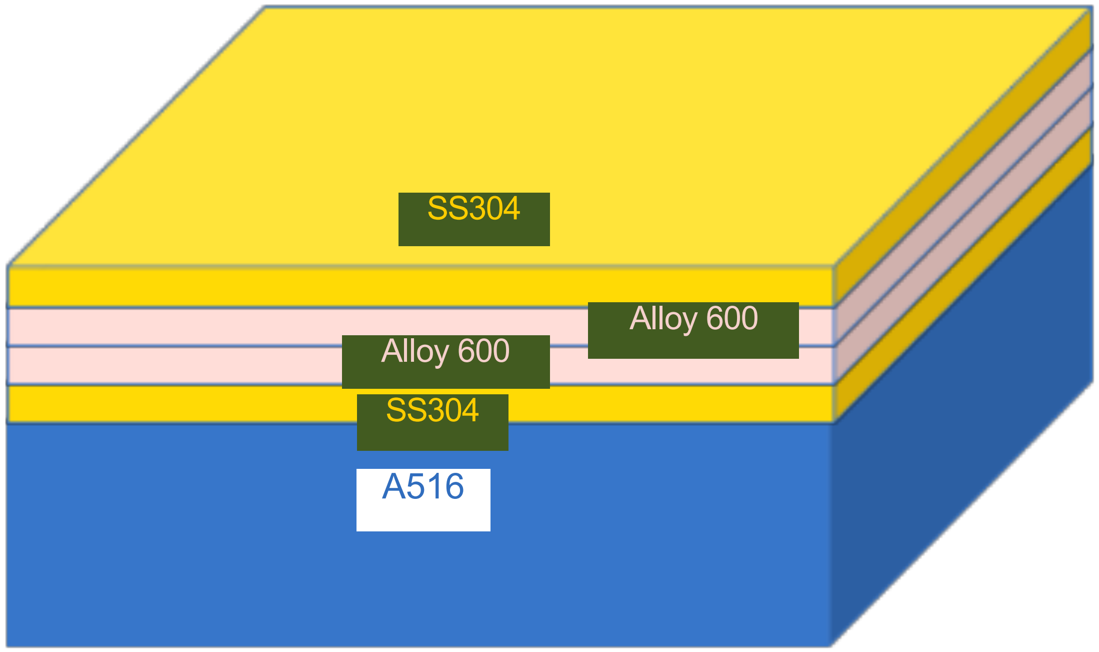
Bonded interface as revealed in the side bend test



Unbonded interface revealed in the side bend test

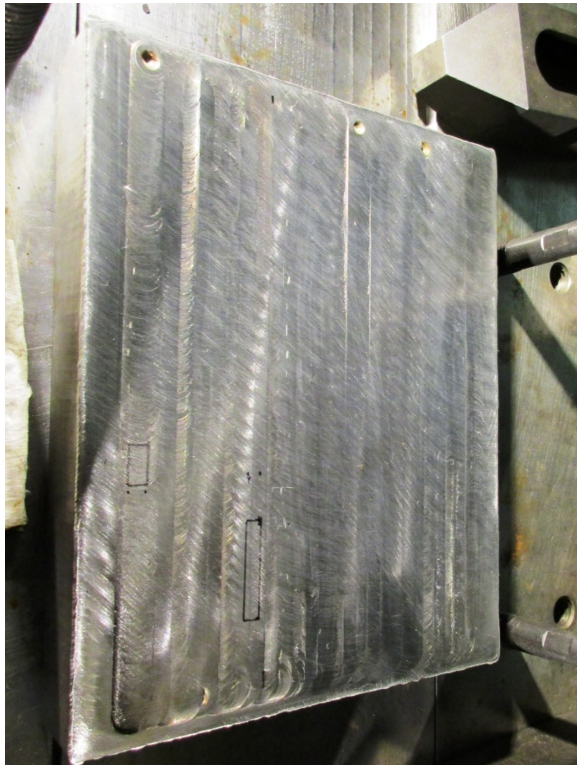
Multi-layer Multi-material FSAM Development

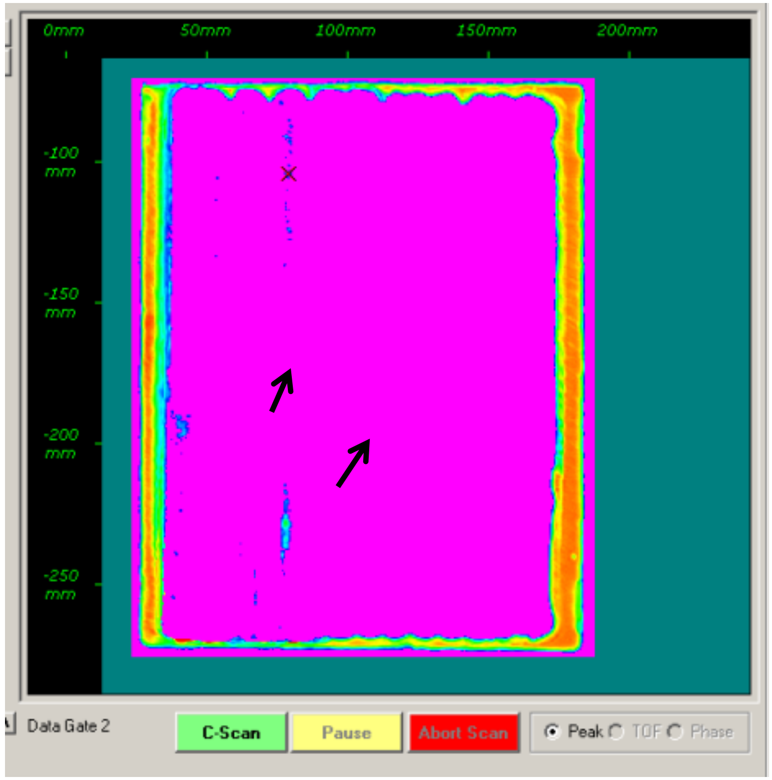
- Materials
  - Substrate: ASTM A516Gr70
  - Layer 1: SS304
  - Layer 2: Alloy 600
  - Layer 3: Alloy 600
  - Layer 4: SS304
- Cladding area: 8x6.5”
- Thickness of each cladding layer: 0.86mm



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)

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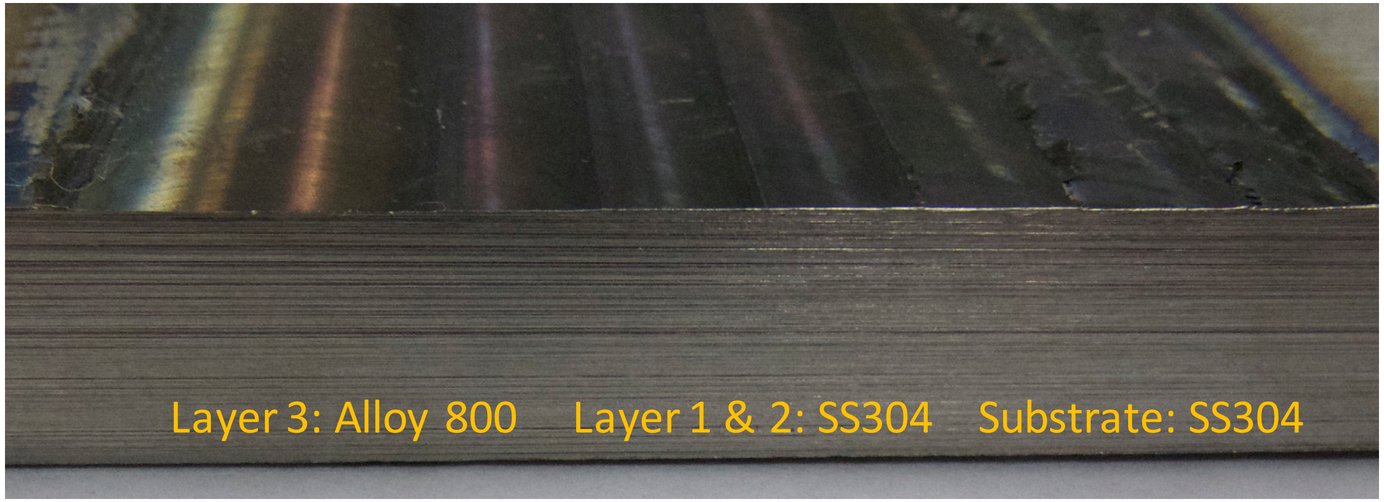
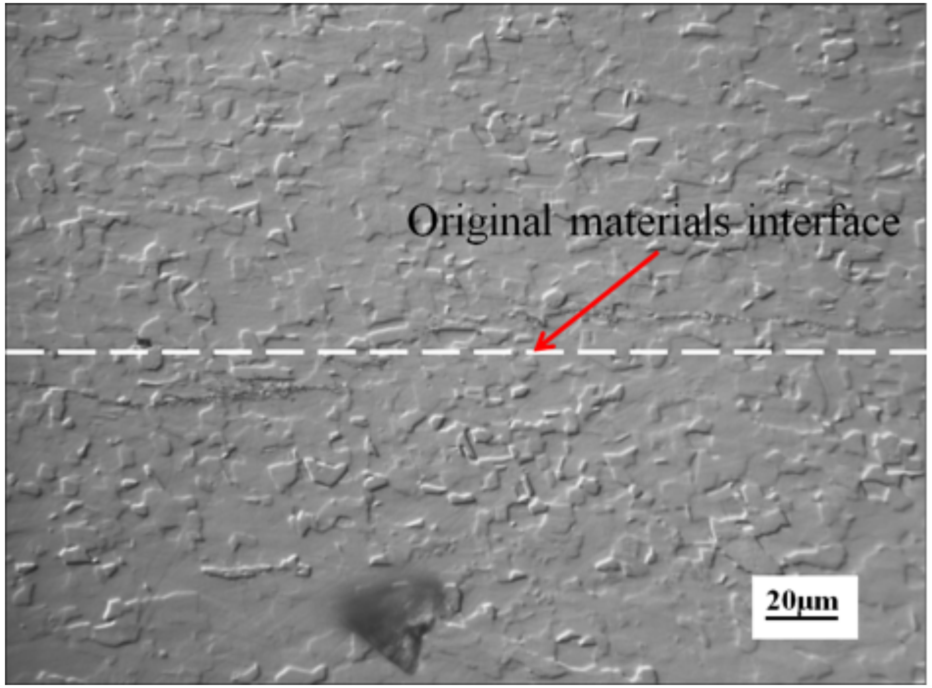
Multilayer FSAM cladding

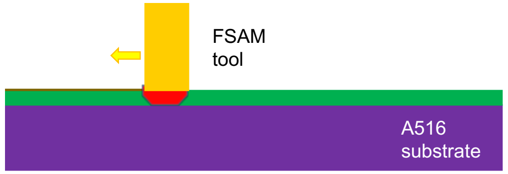


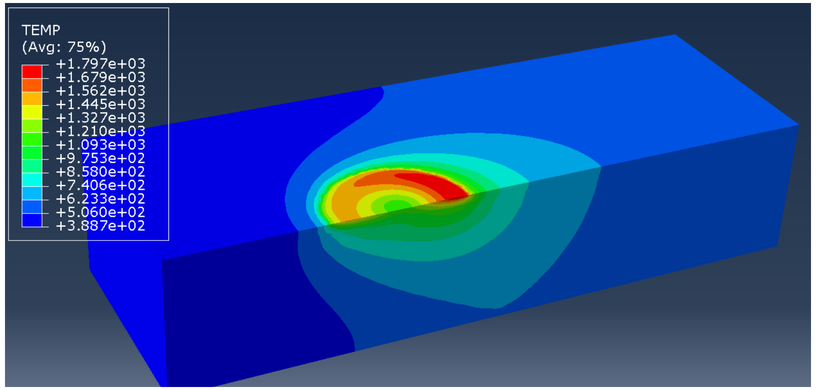
FSAM build of two layers SS304 and one layer alloy 800 on a 304 SS substrate.

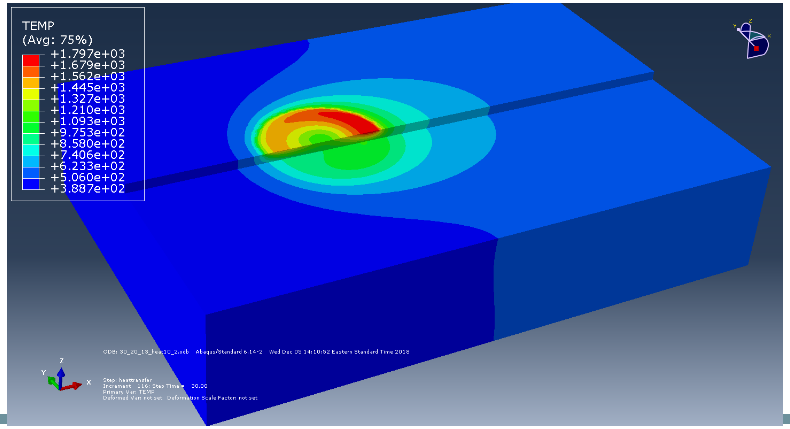


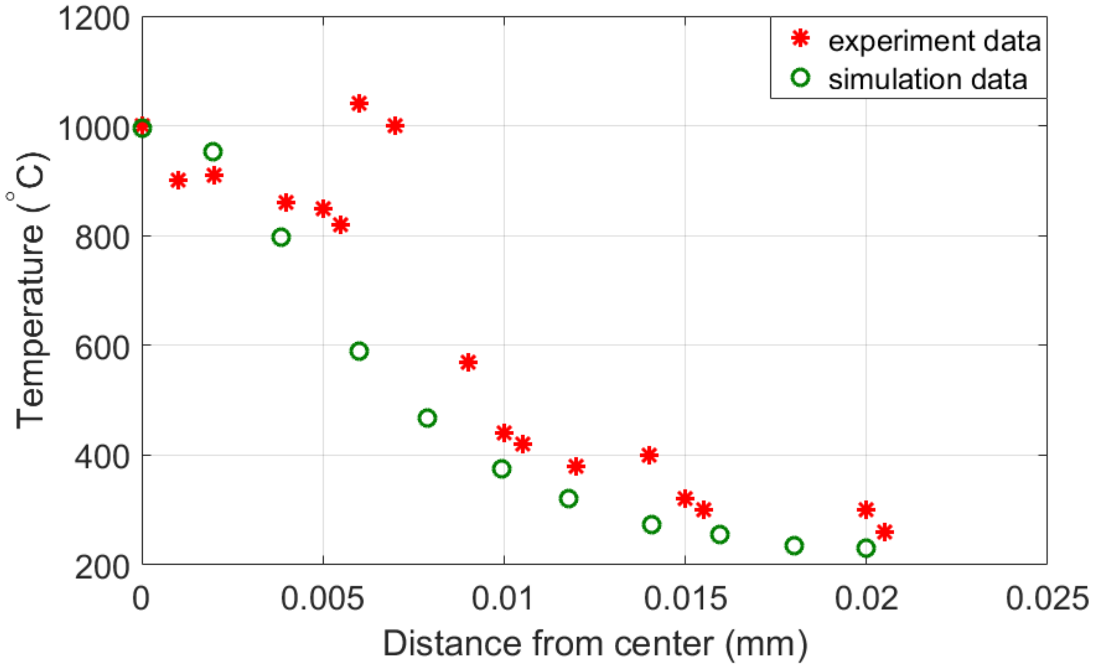
Microstructure near the clad bonding interface between two SS304.

Development of a robust modeling tool for FSAM process development



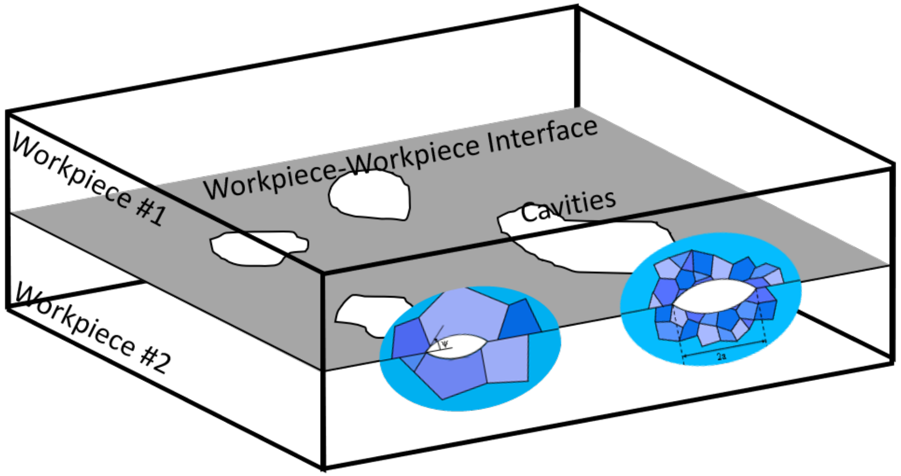






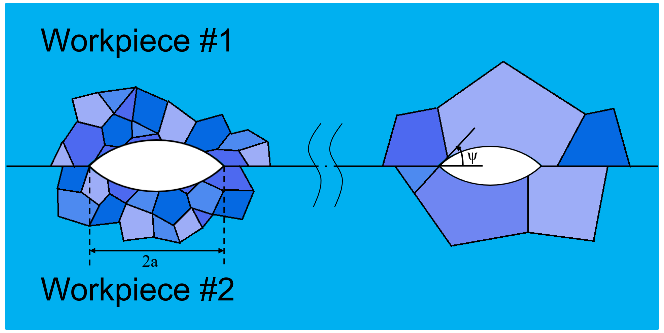
Extend the modeling tool to predict bonding in FSAM

- 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

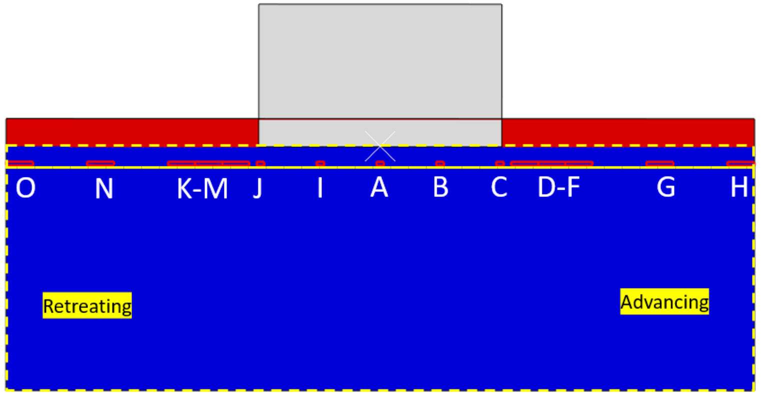


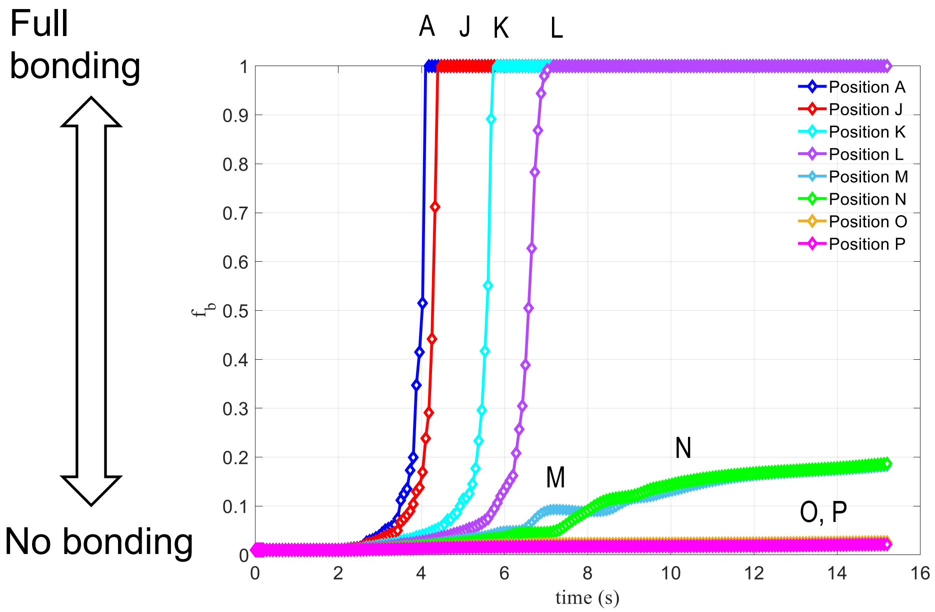
$$\frac{df_h}{dt} = \frac{f_h}{a^3 \ln\left(1/f_h\right)} 2D\sigma_n = \frac{2f_h}{\ln\left(1/f_h\right)} \dot{\varepsilon}_e^c \left(\frac{\sigma_n}{\sigma_e}\right)\left(\frac{L}{a}\right)^3$$

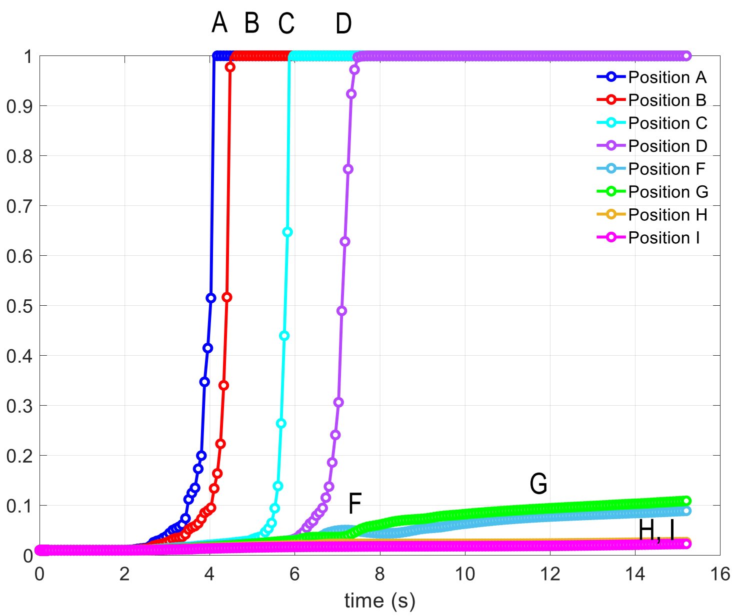
Cocks and Ashby (Prog. Mater. Sci., 1982)



Predicted bonding region during FSAM

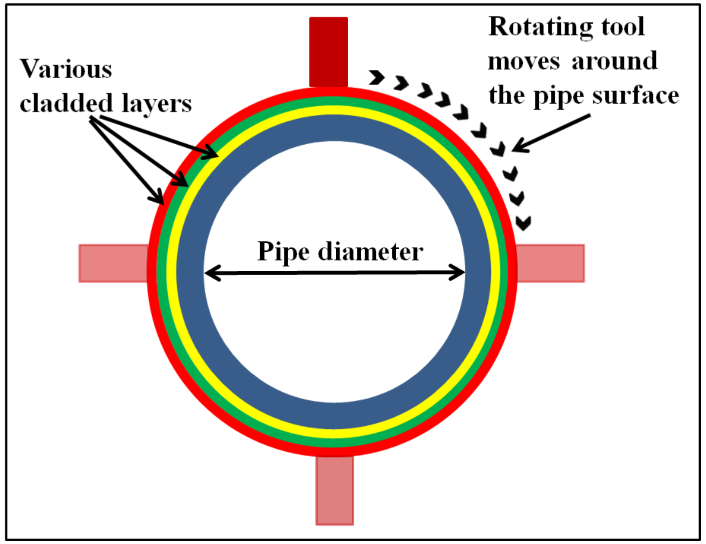




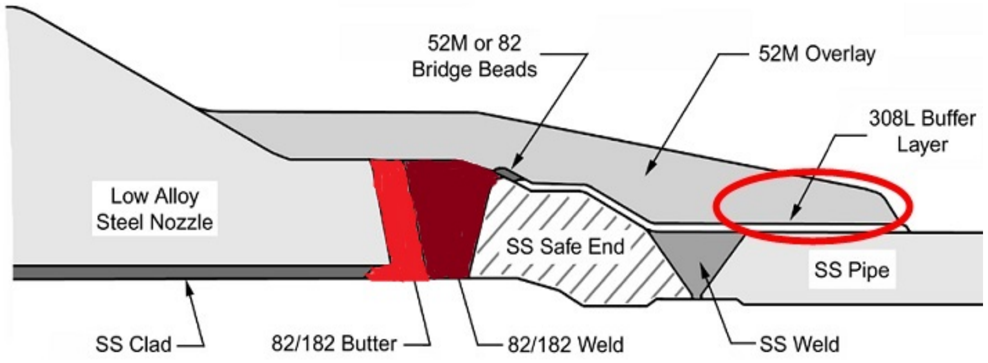


Scale up demonstration

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

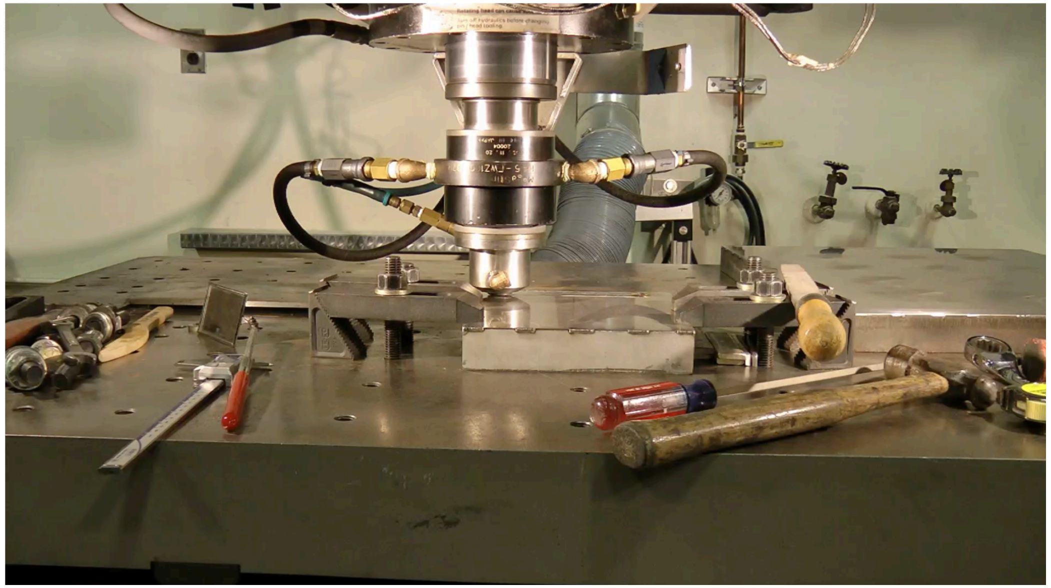


To simulate

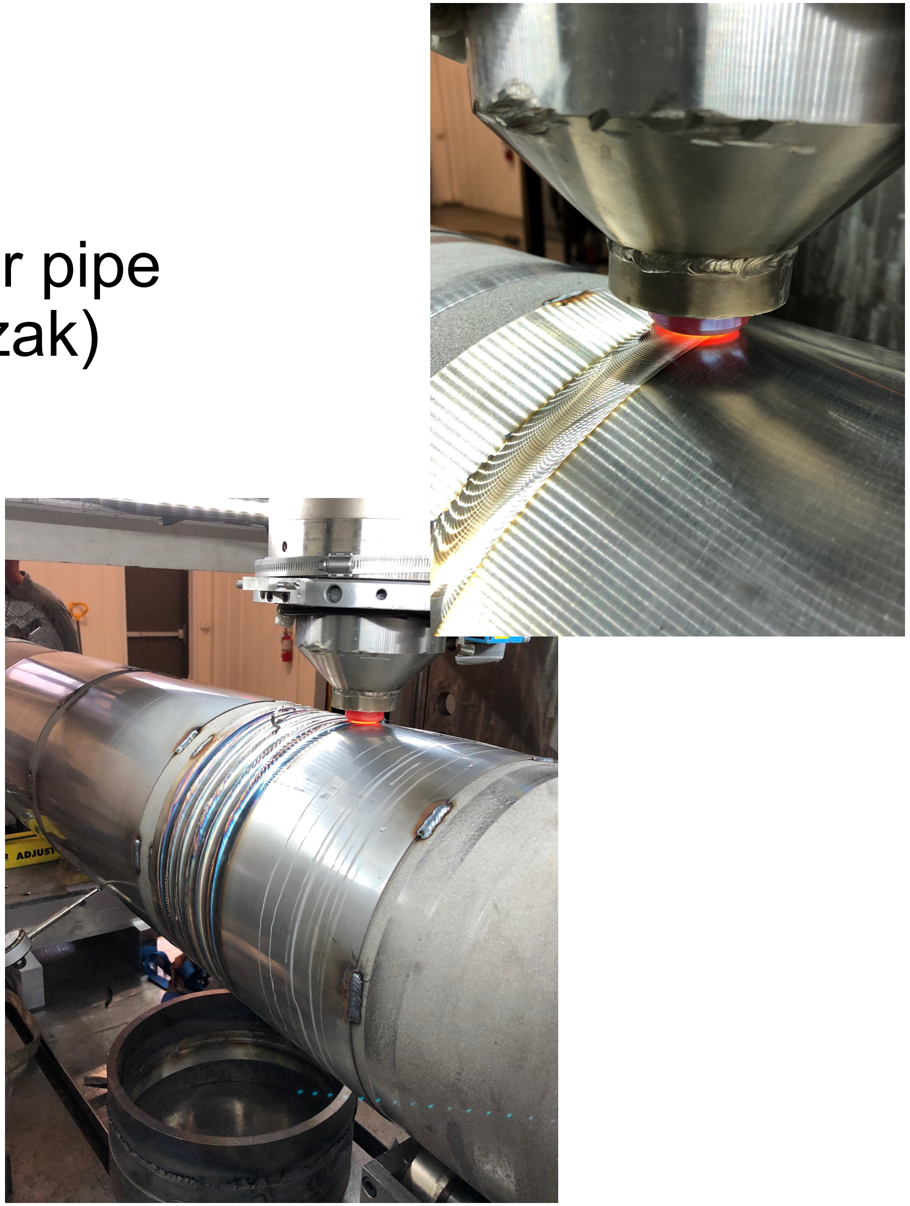


Scale up demonstration

- Transfer baseline FSAM process conditions for pipe cladding at our industry partner (MageStir/Mazak)
- Completed first set of cladding experiments
- Post cladding testing on-going (bond quality, microstructure and interface properties)



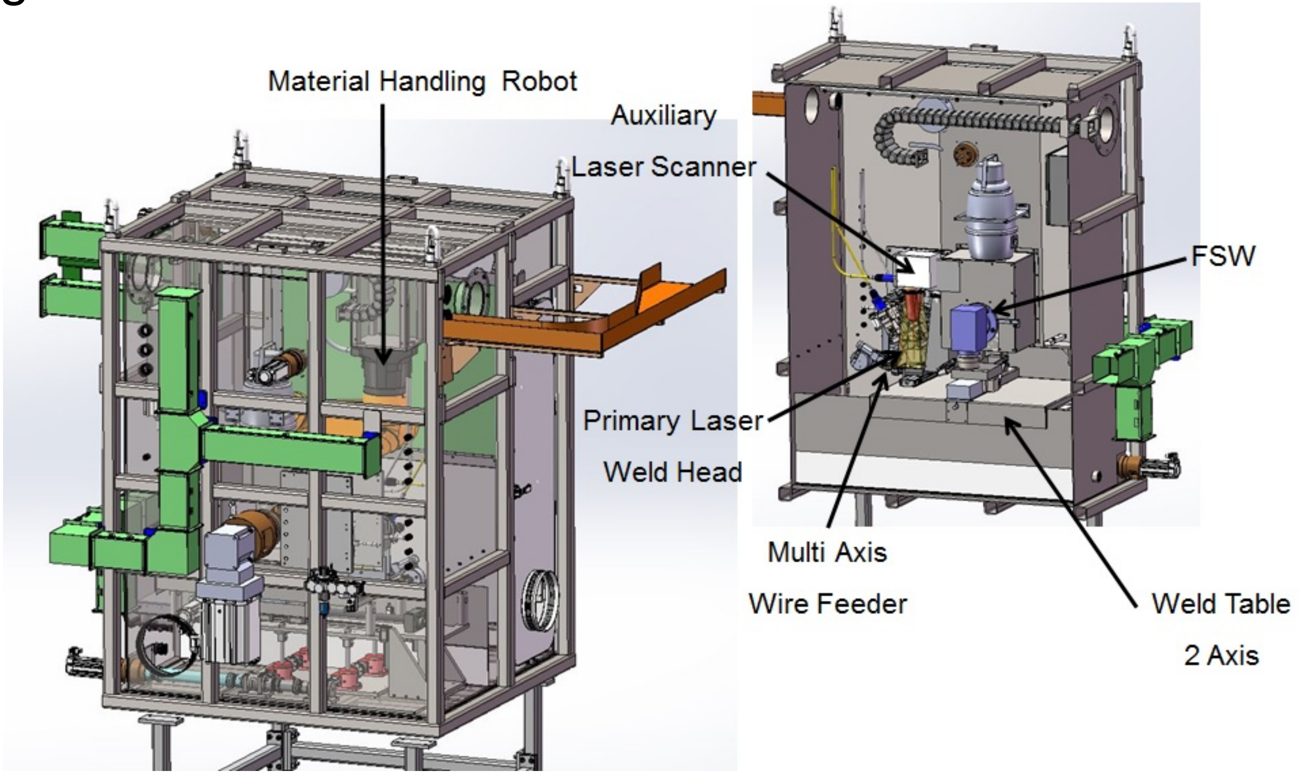
Lab scale R&D at ORNL

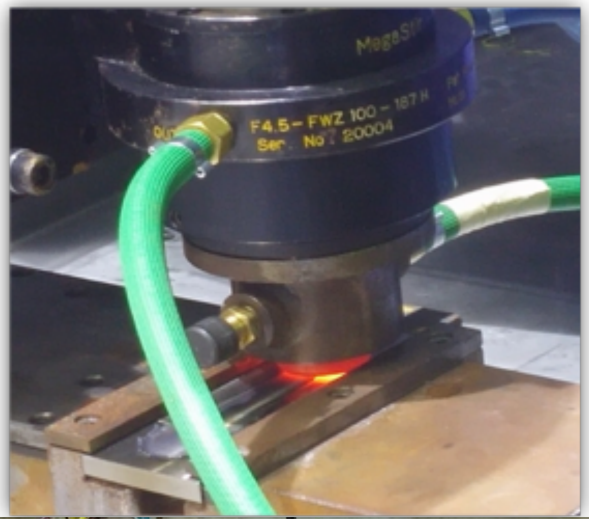


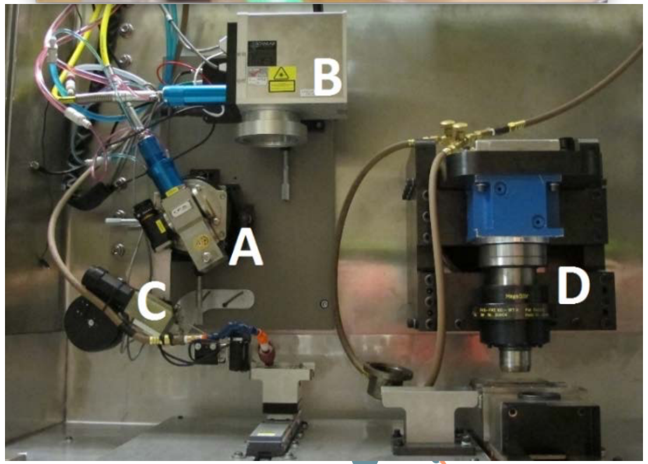
Scaleup/transfer to industry

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







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

Issues and Concerns

- COVID-19 impacts
  - Caused ~9-month delays in scale up and technology demonstration task at the industry site
  - Requested project extension to complete the project (3/2021)
  - Now the issue has been solved and we are on target to complete the project by 3/2021

Acknowledgements

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