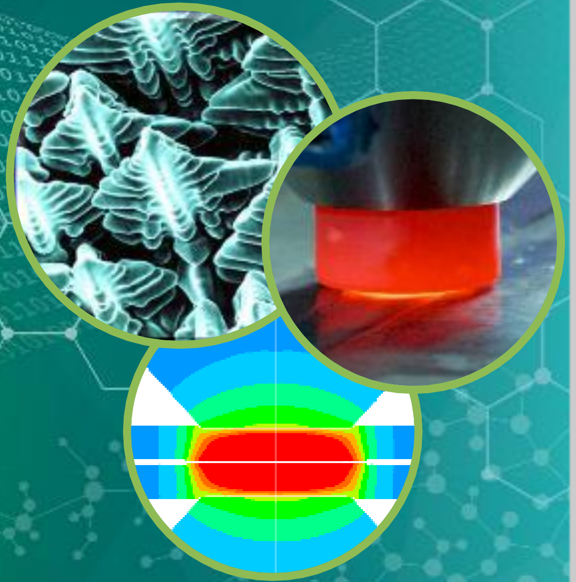
All-position cladding by friction stir additive manufacturing (FSAM)



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Oak Ridge National Laboratory
Electric Power Research Institute

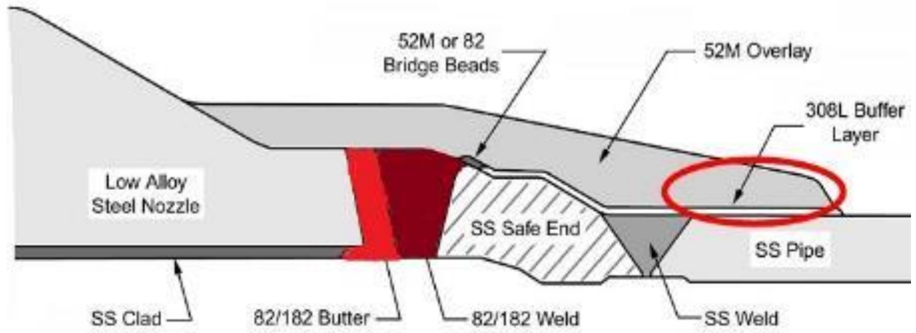
DOE NE AMM Annual Review
December 4-6, 2018
Oak Ridge, TN

Outline

- Background
- Project goal
- R&D plan and tasks to address technical challenges
- Progress and status
- Planned 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

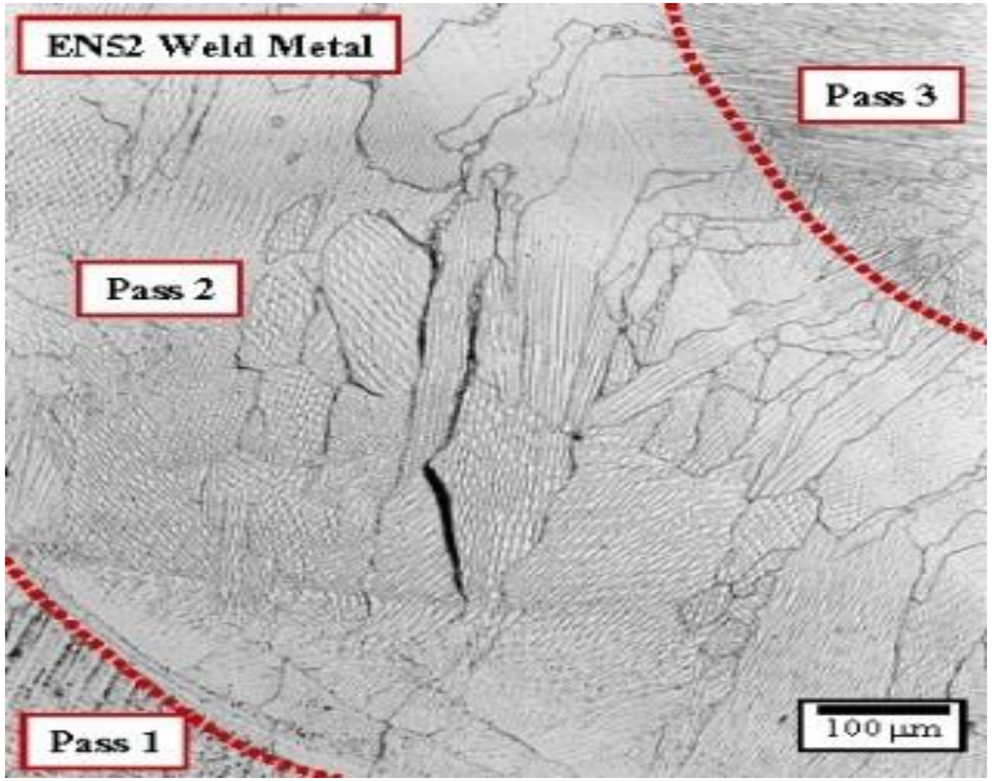
Relatively low productivity and high cost

- Cladding rate
  - All position cladding is limited to low deposition rate processes (GTAW, GMAW) due to gravity effect on the molten weld pool, 2-4lbs/hr
  - High deposition rate processes (ESW, SAW) are limited to flat position.
    - Requires special equipment to rotate large and heavy components.
    - Limited to components with rotating axis
- Multiple layers (3-5 layers typical) to progressively reduce the "dilution" in the top layer for intended service
  - High deposition rate processes have higher dilution and requires more layers
  - Compounding effect on the productivity and increase in material and labor cost

Limitations of today's cladding process

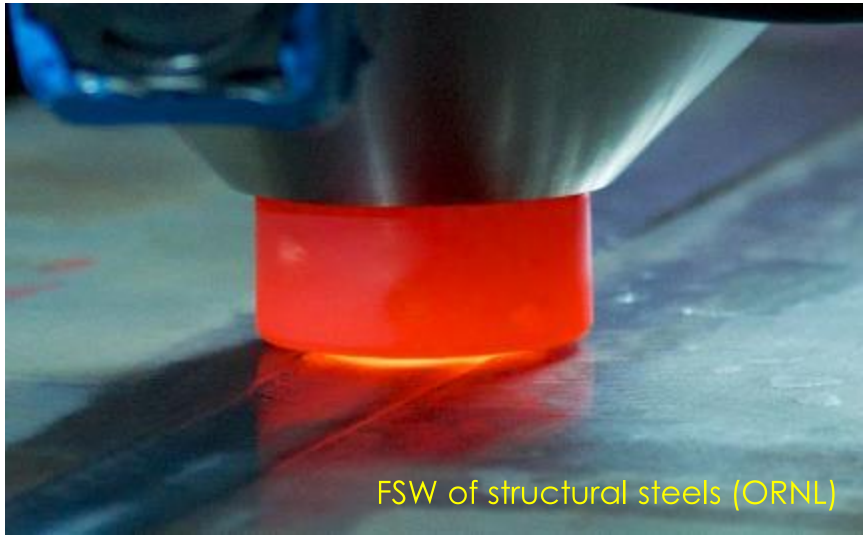
Major barrier in adopting new cladding materials

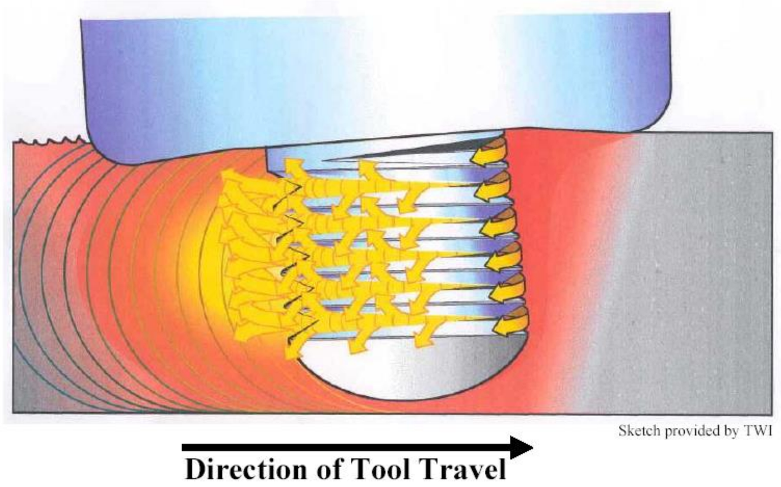
- More SCC resistance alloys (Alloy 52 vs Alloy 82) in the DM weld for piping systems
- Alloy 52 is prone to ductility dip cracking associated with fusion welding processes



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

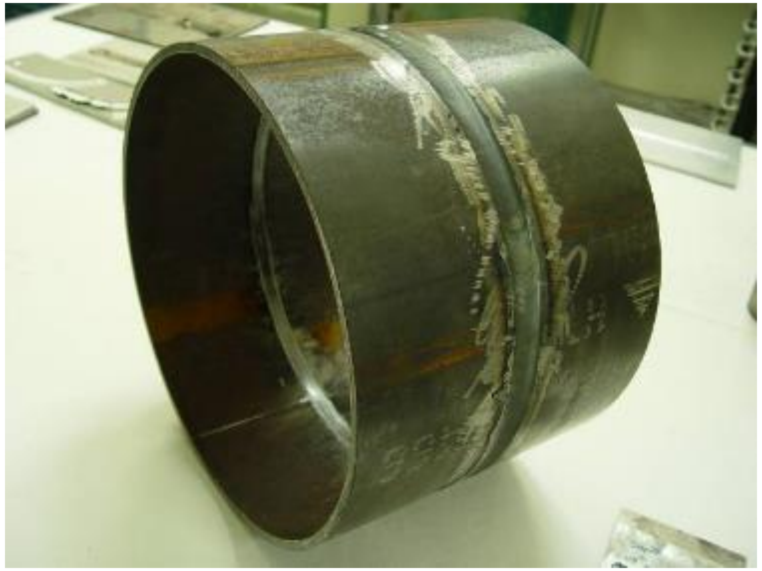
- Friction Stir Welding (FSW) is a novel solid-state joining process. A specially designed tool rotates and traverses along the joint line, creating frictional heating that softens a column of material underneath the tool. The softened material flows around the tool through extensive plastic deformation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

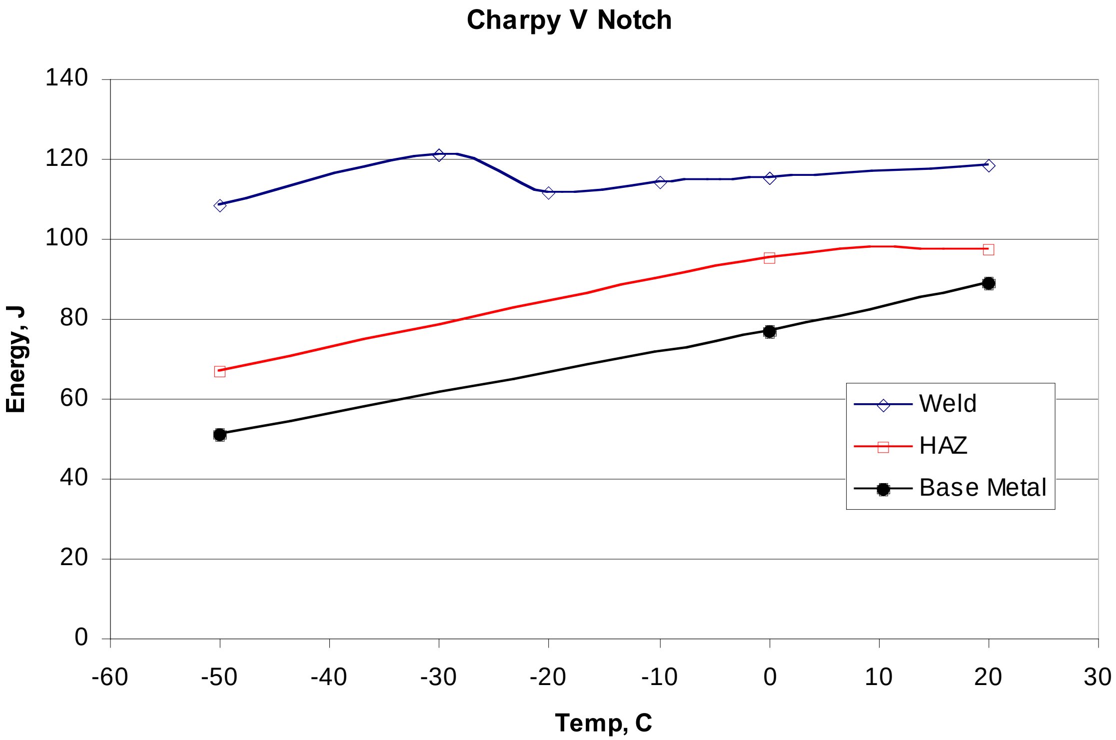




FSW Drastically Improves Dynamic Impact Properties of Pipeline Steels

- Welding of API X65 steel for oil/gas transmission pipelines

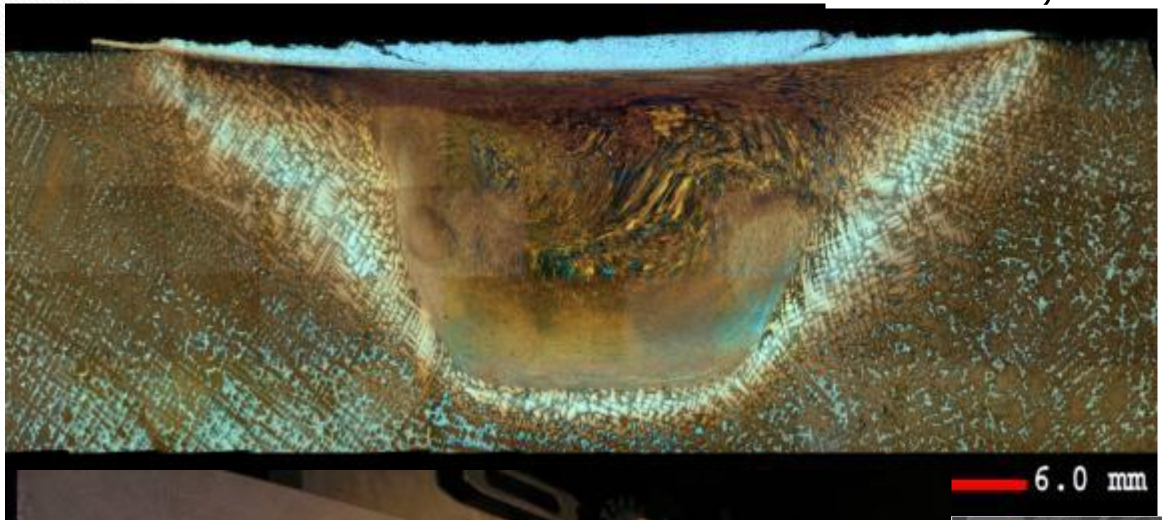


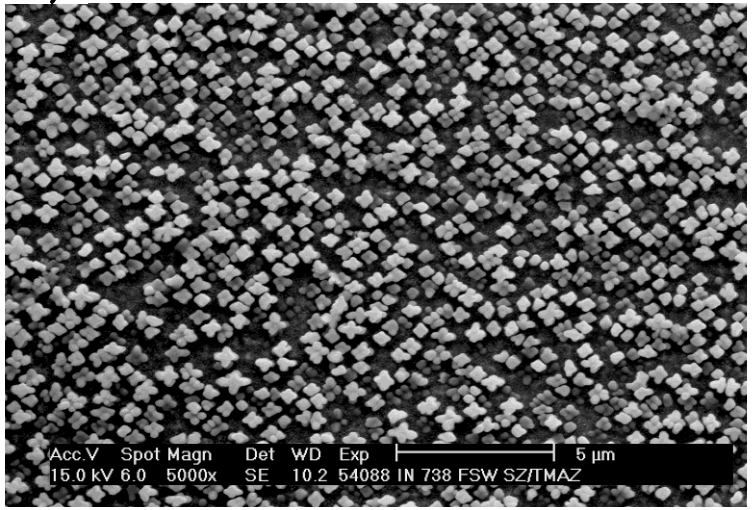


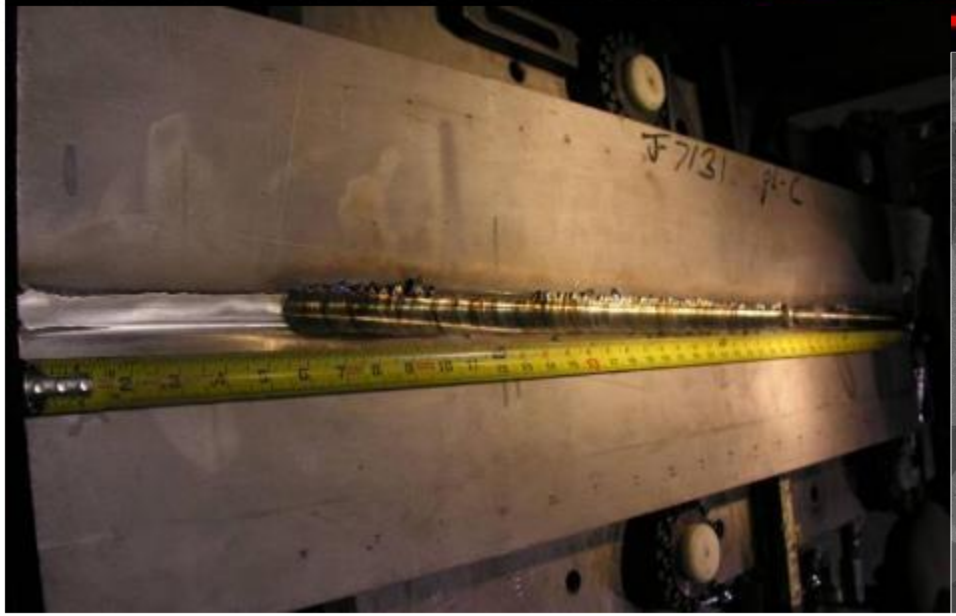
Feng and Packer et al., 2005

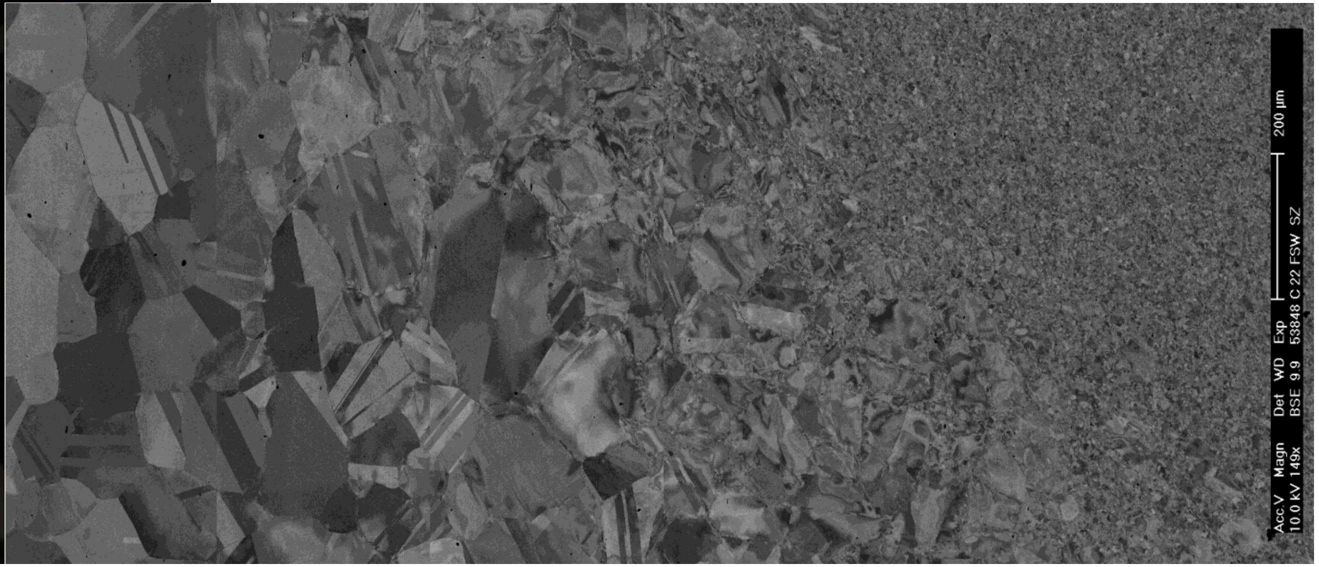
FSW of Superalloys

Cast IN738, 60% vol γ'









Alloy C22, solution strengthened corrosion resistance

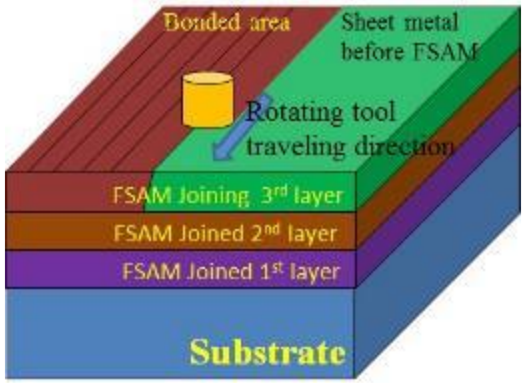
Feng and Gandy, ORNL/EPRI, 2006

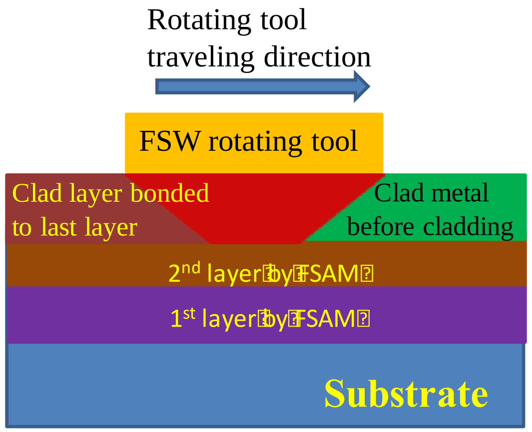
Goals

- 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

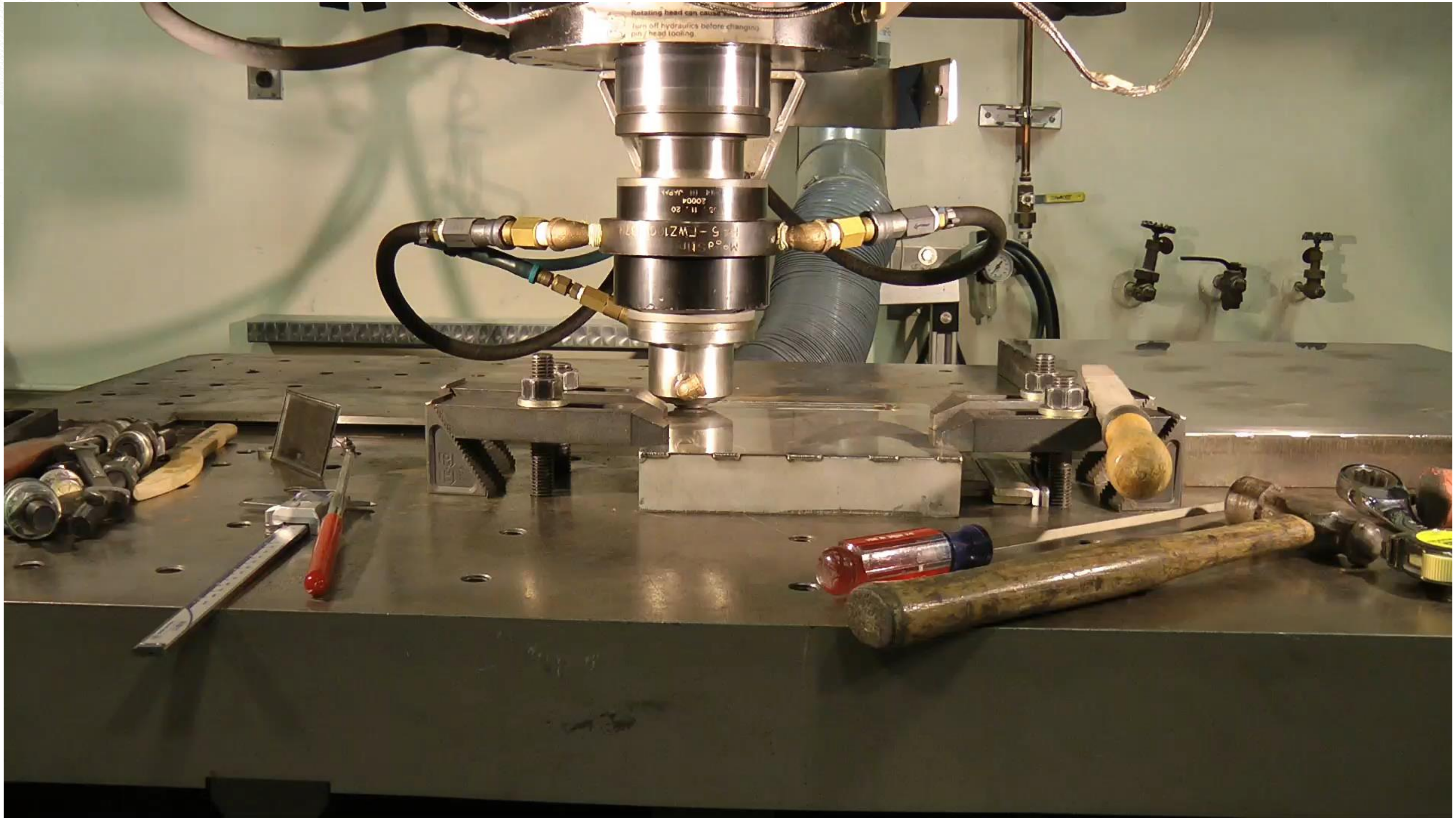
Friction Stir Additive Manufacturing (FSAM)

- 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





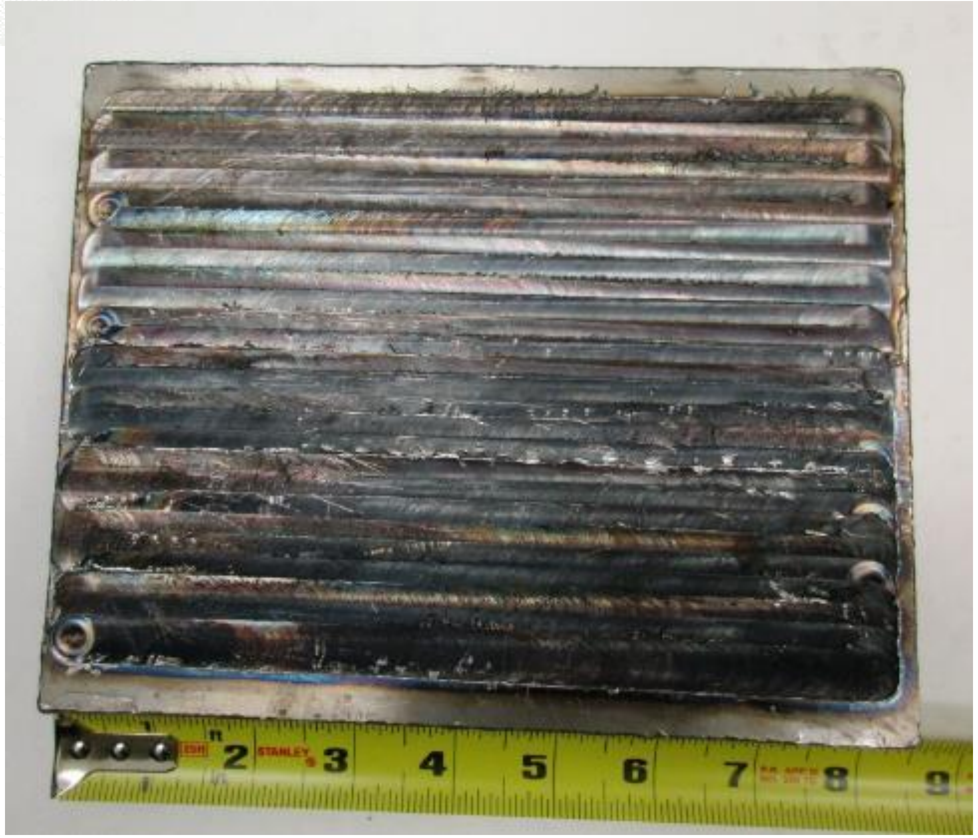
Technology Innovations in FSAM



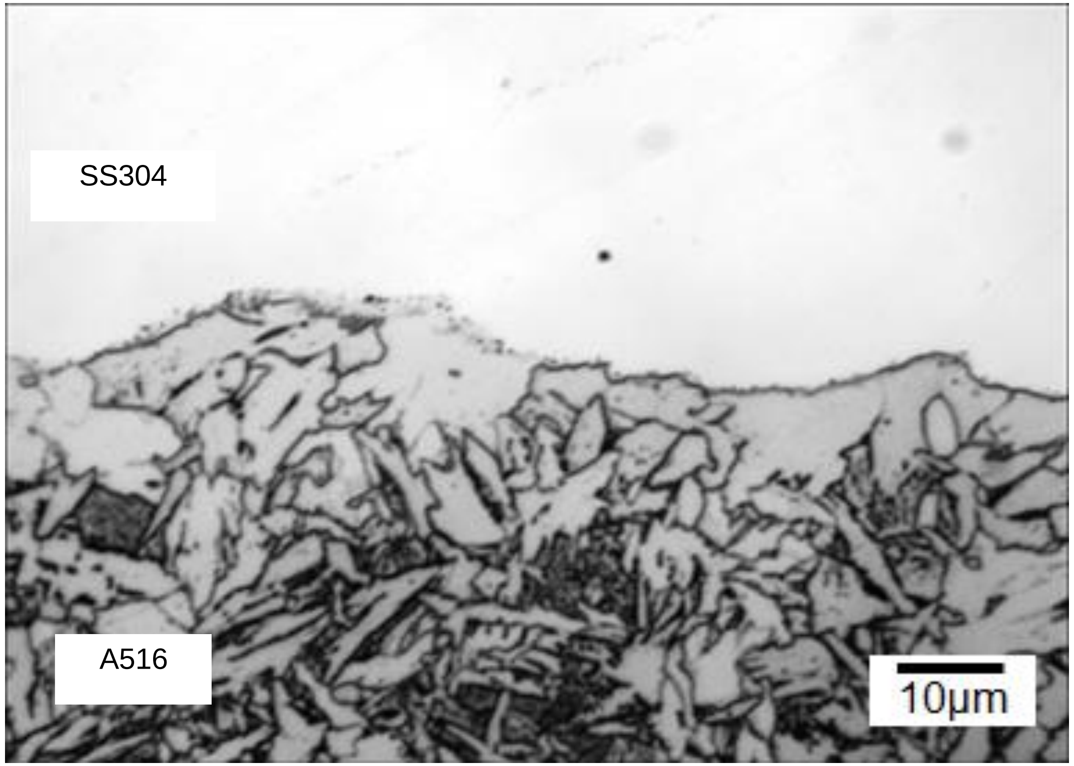
R&D Focuses on

- 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 appropriate temperature range for solid-state bonding in FSAM?
  - Temperature measurement at the bonding interface
- 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



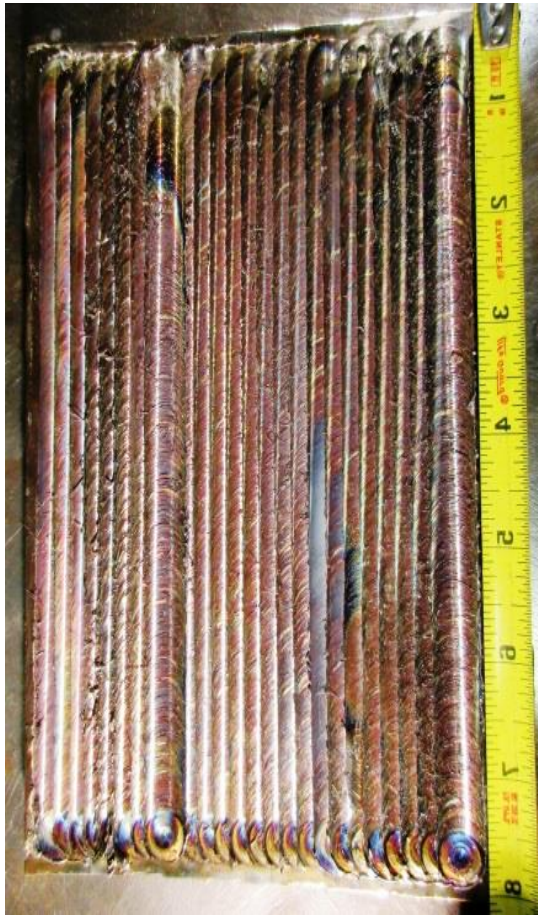
As cladded surface
(surface flush and oxidation, to be addressed)

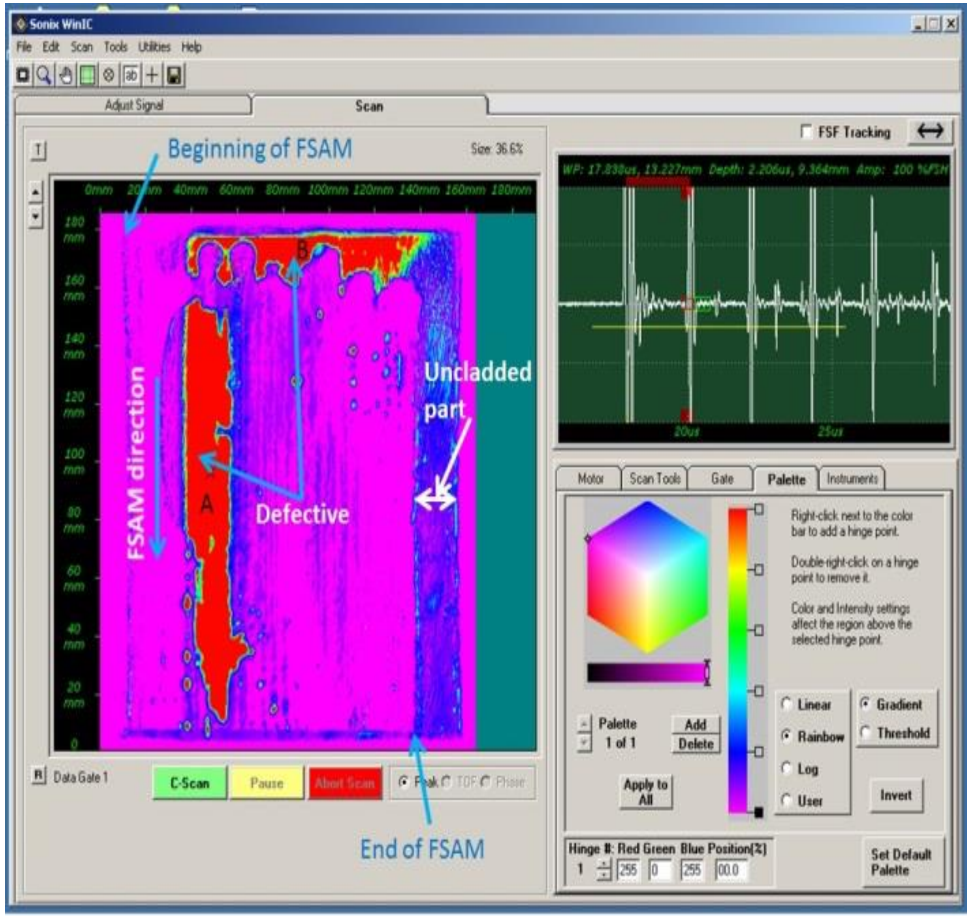


304 SS on structural steel A516

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

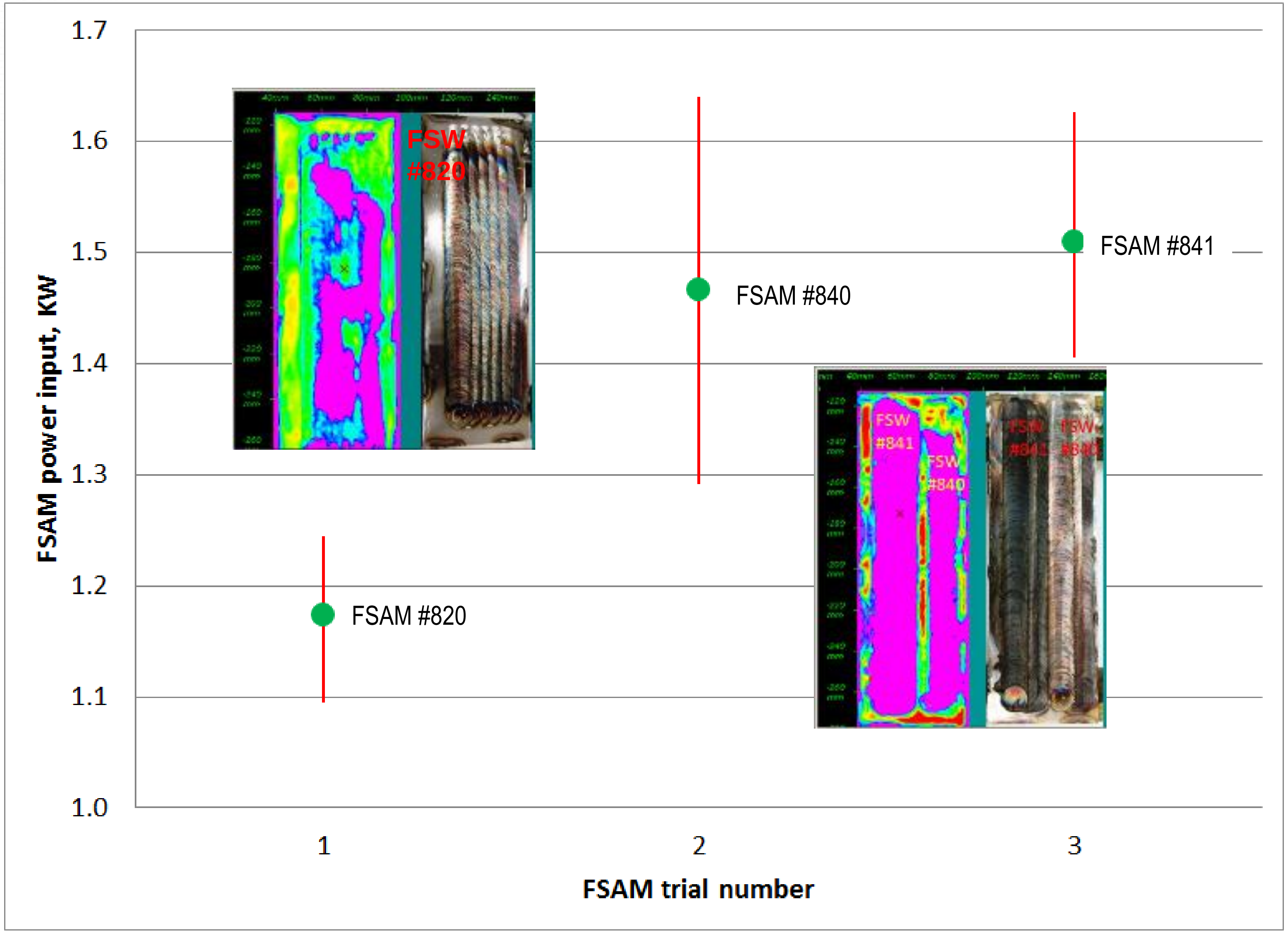
- Enable us to examine an large area quickly to assist process development





SS304 on A516

Effect of process conditions on bonding

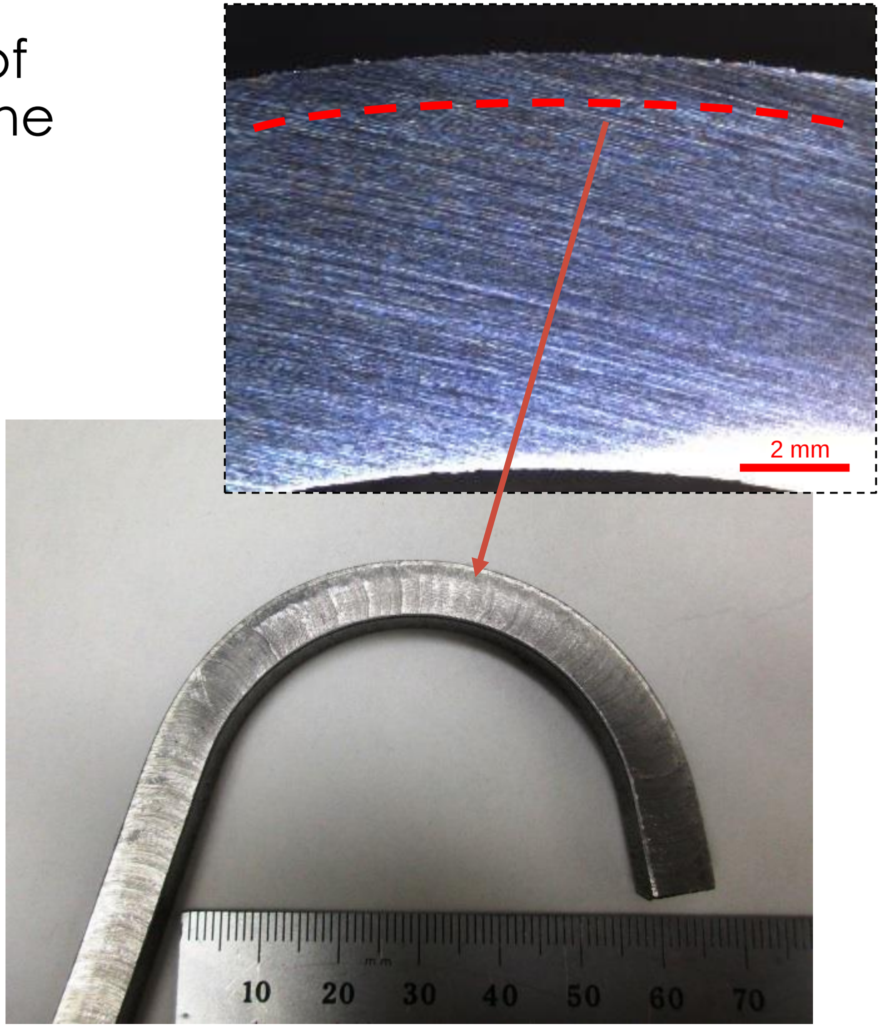


SS304 on A516

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

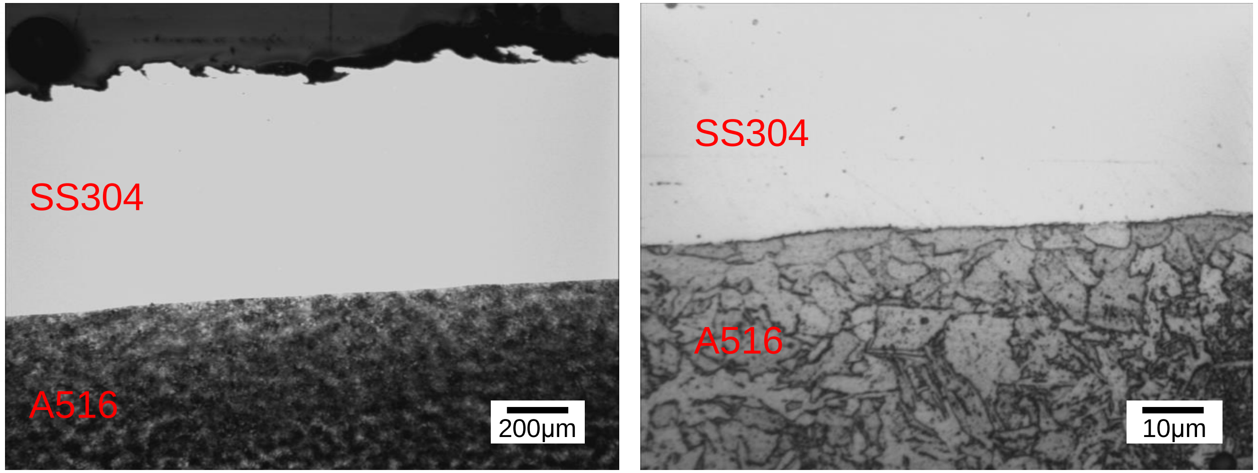
(a) 3” roller (5% elongation)



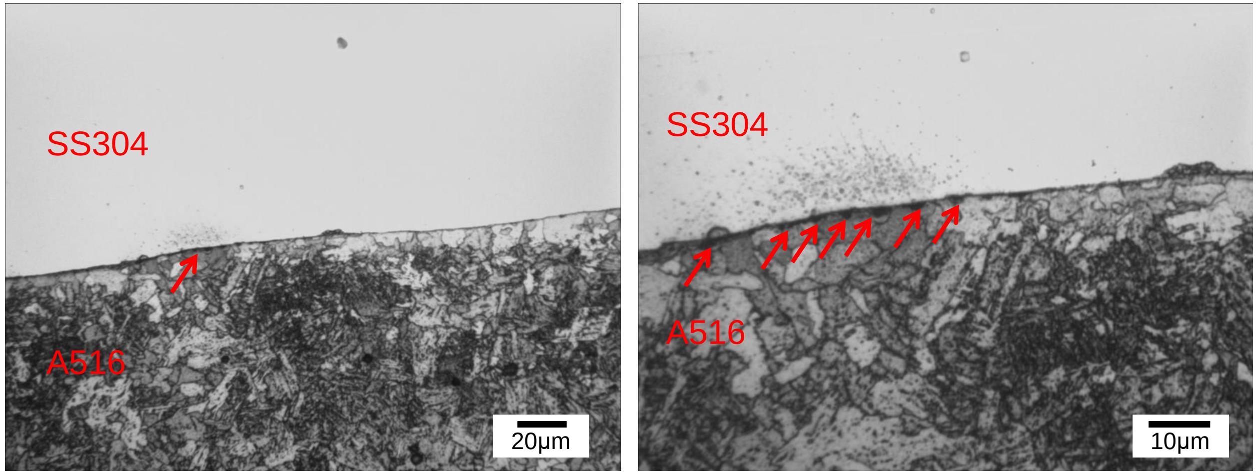
(b) 2” roller (10% elongation)

SS304 on A516

Interface bond quality from side bend test

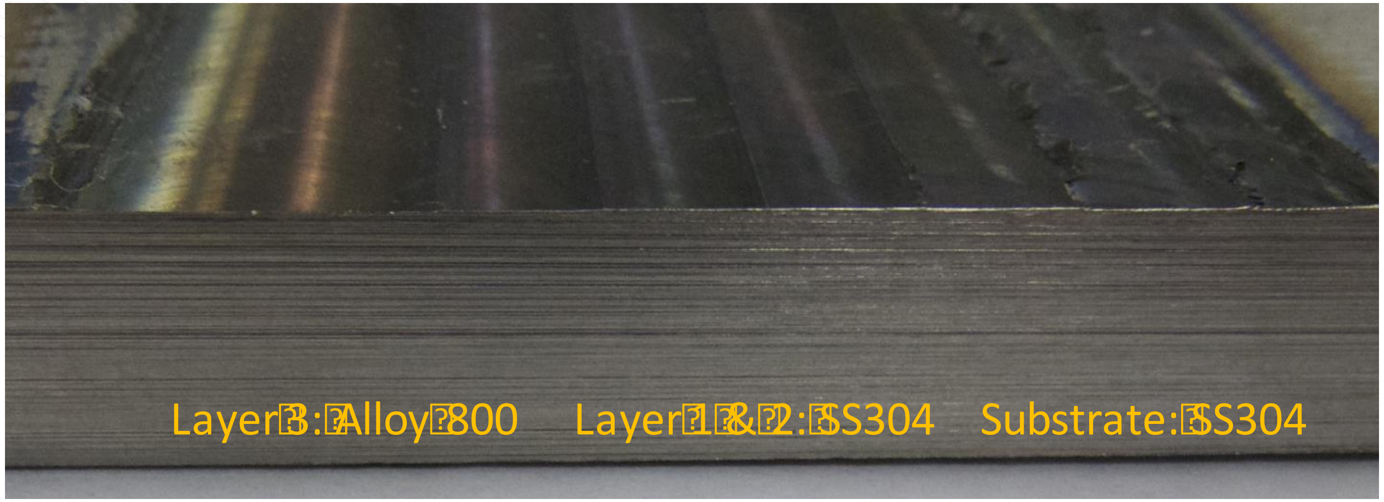


Bonded interface as revealed in the side bend test

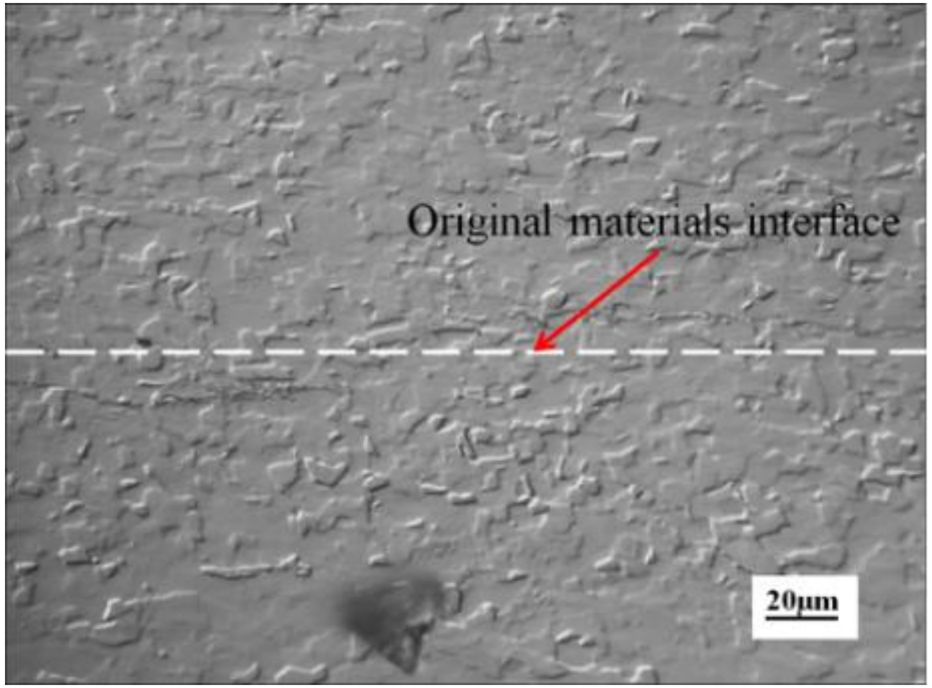


Unbonded interface revealed in the side bend test

Multilayer FSAM cladding



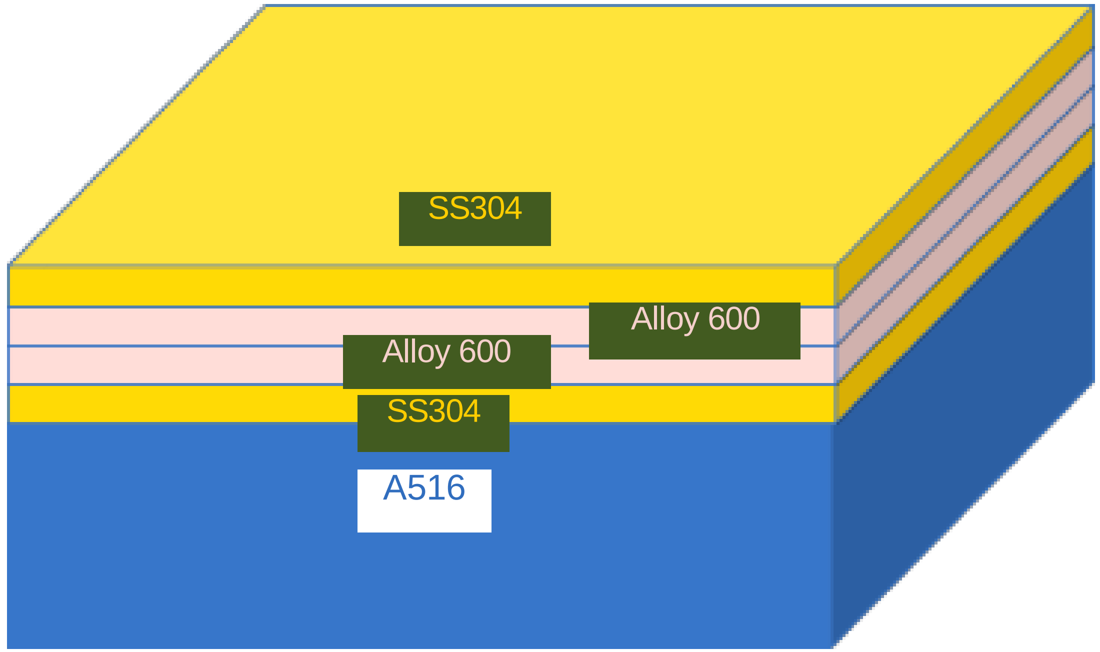
FSAM build of two layers SS304 and one layer alloy 800 on a 304 SS substrate.



Microstructure near the clad bonding interface between two SS304.

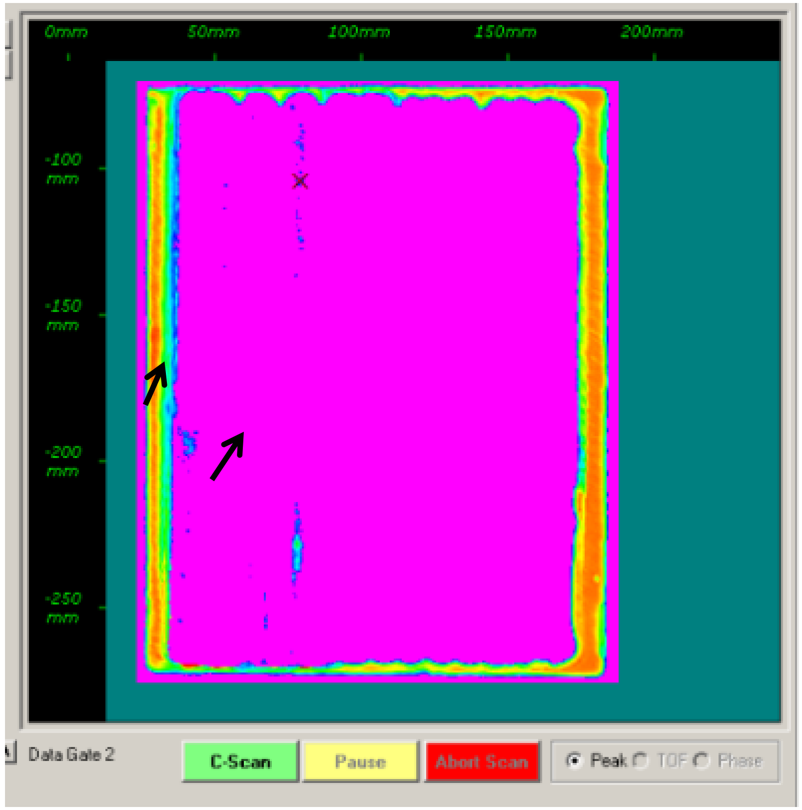
Multi-layer Multi-material FSAM Development

- 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)

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

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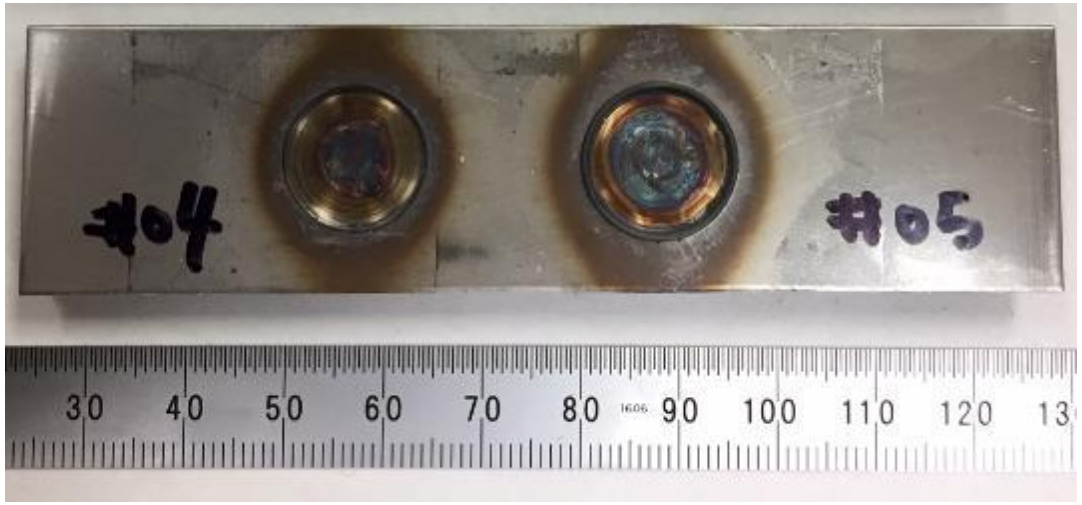
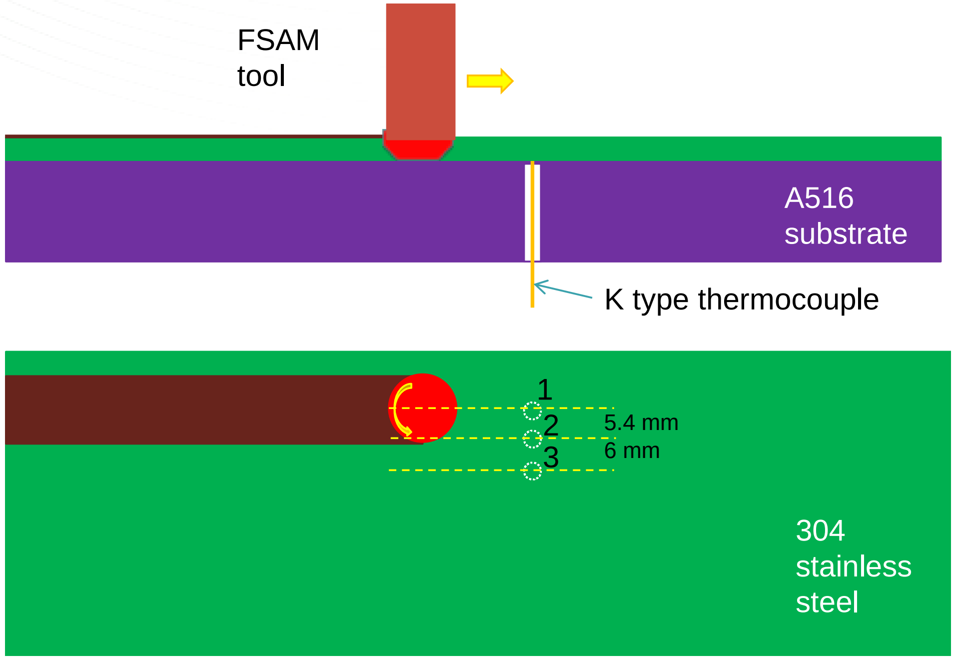
Tool Wear and Life

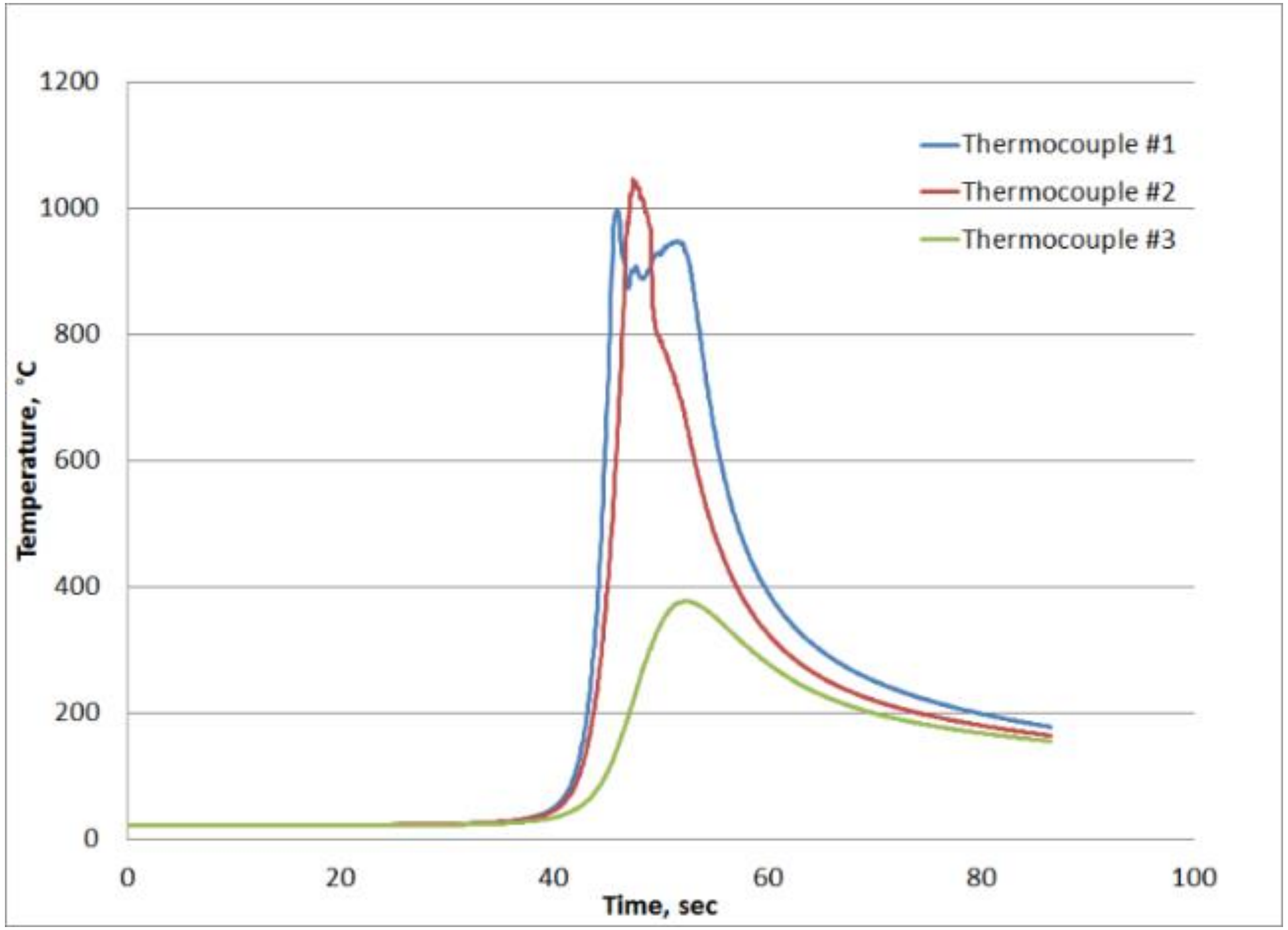
- Our innovative tool design and FSAM process approach have resulted in excellent tool wear performance
  - Only two W based tools were used in all the experimental trials and they are still performing well now.
  - Opens possibility to consider other “low cost” tool materials
  - Possibility for add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



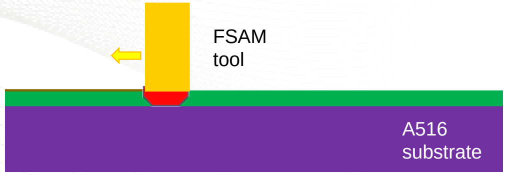
Understanding the process conditions to form Solid-state bonding

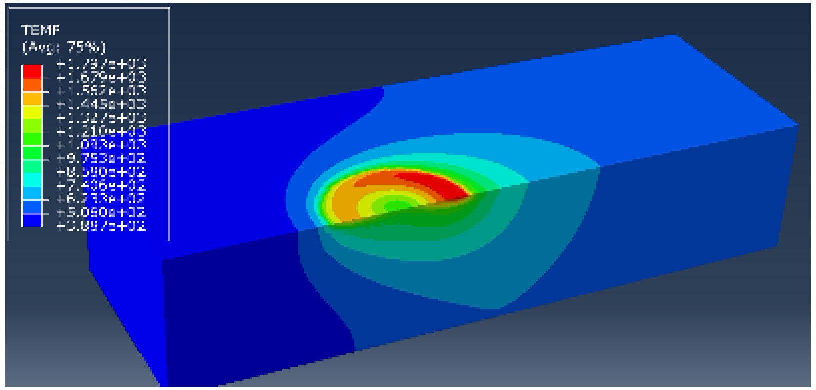
- Temperature measurement at the bonding interface
- Solid state metallurgical bonding forms in the range of 900 - 1100C

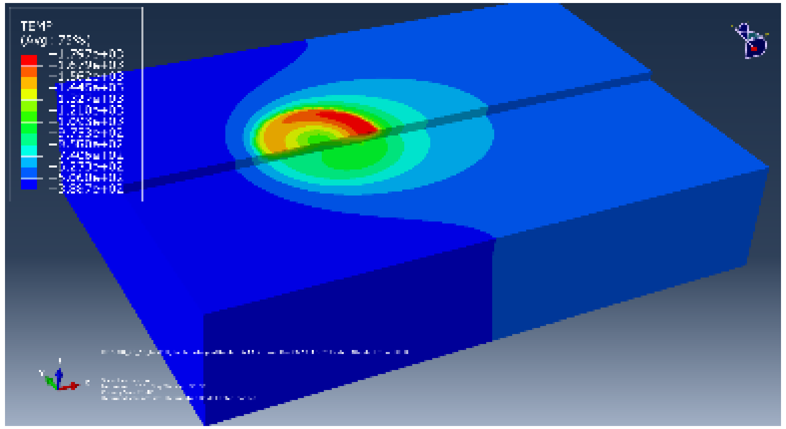




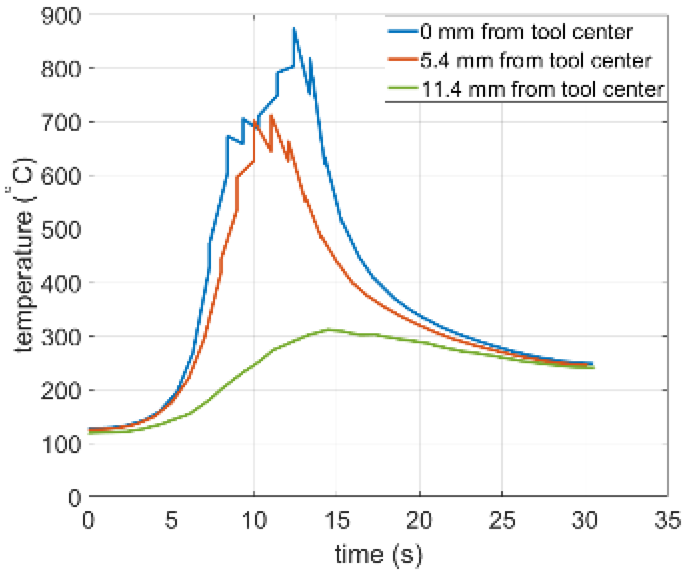
Development of a robust modeling tool for FSAM process development (on-going)

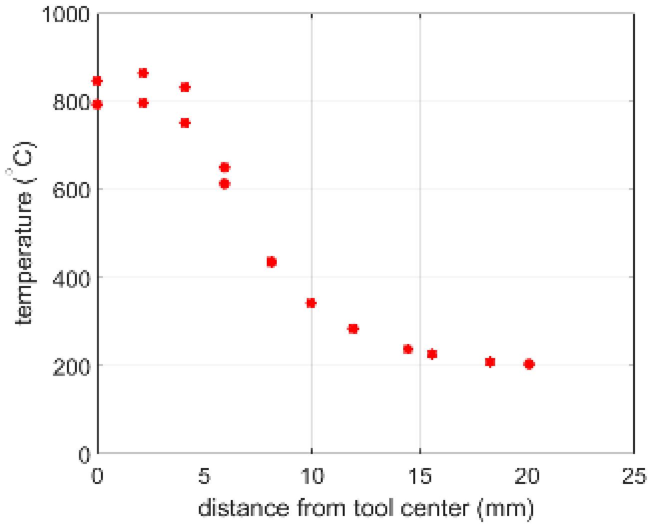




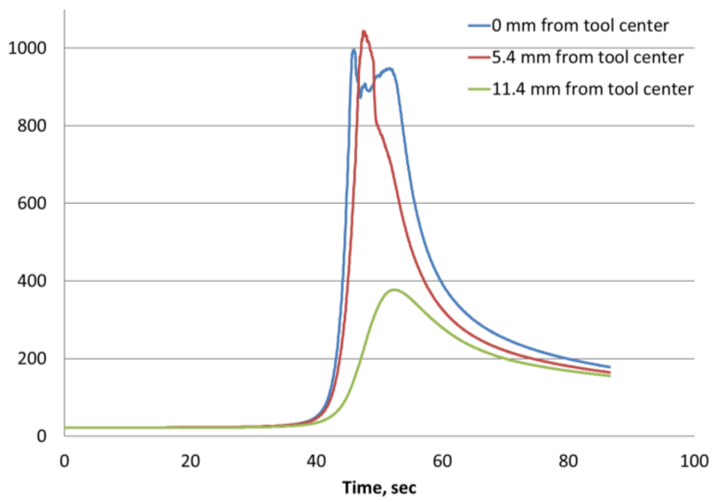


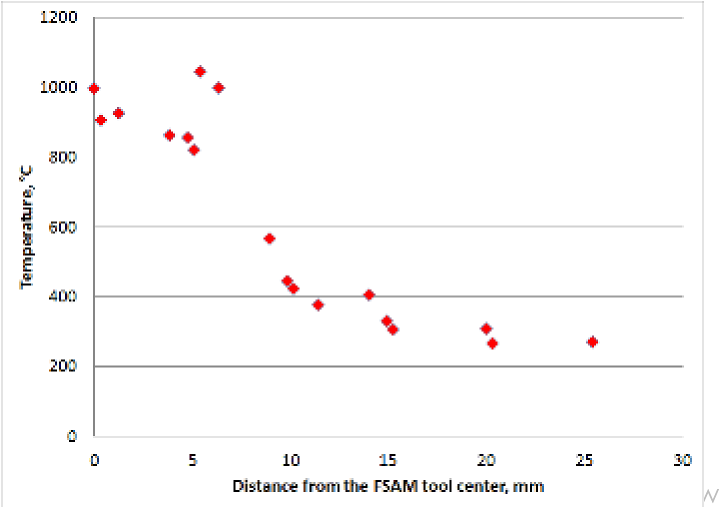
Modeling





Experimental





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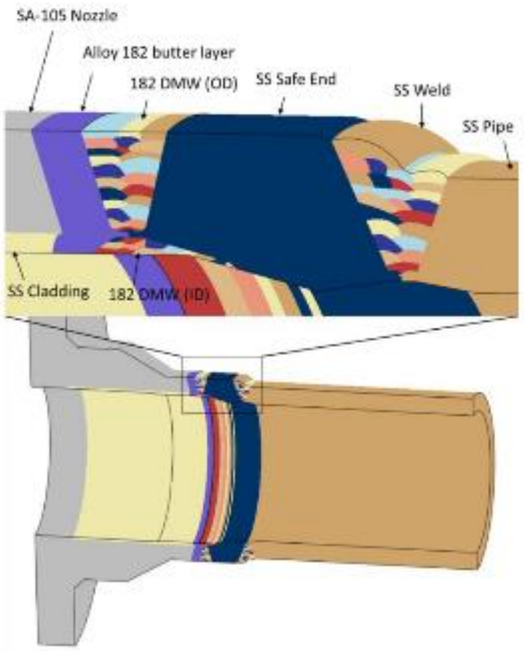
Breakthrough HPC code for welding & additive manufacturing

HPC4 MANUFACTURING

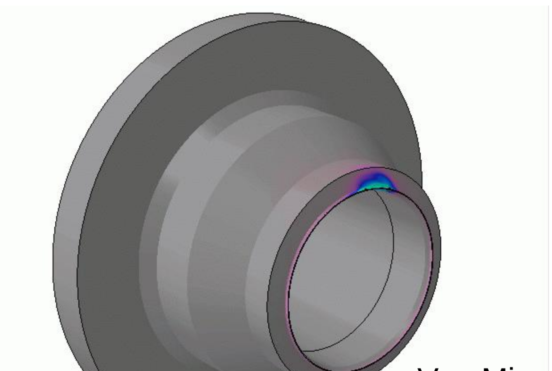
- ORNL/GM/EPRI recently developed an in-house GPU based FEM code that is 1000x to 2000x times faster than today's commercial codes for welding and AM simulations (patent pending)
- Example: 3D simulation of large multi-pass dissimilar weld in nuclear reactor piping

Computation Time Comparison on Same Computer

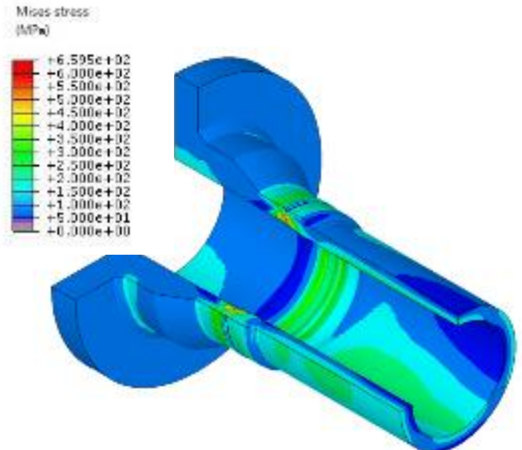
Software	Abaqus	In-house code
Analysis of 20 sec welding	3.5 days	388 sec
Full weld analysis	8.5 years#	3.2 days



Full 3D simulation by ORNL in-house code revealed residual stress patterns that can't be obtained from widely used axisymmetric simplifications



Von Mises stress evolution

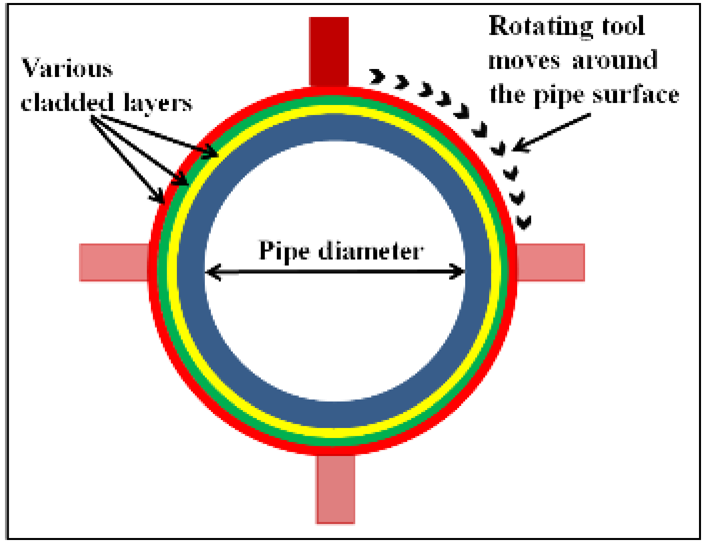


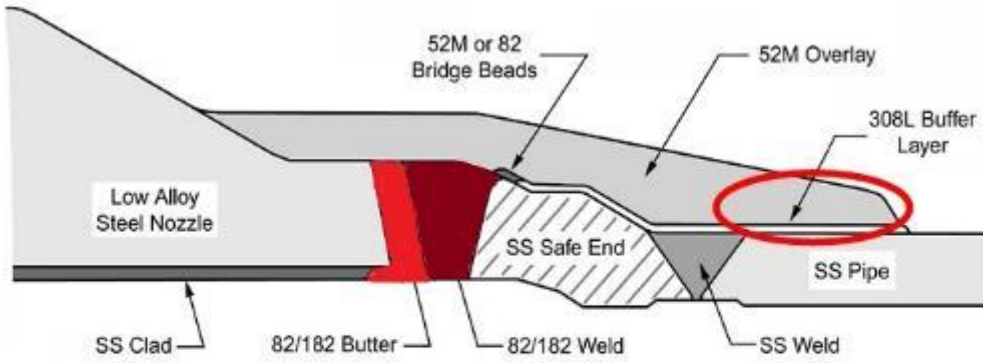
Hoop stress (MPa)

Hui Huang, Jian Chen, Zhili Feng, 2018

Planned Activities

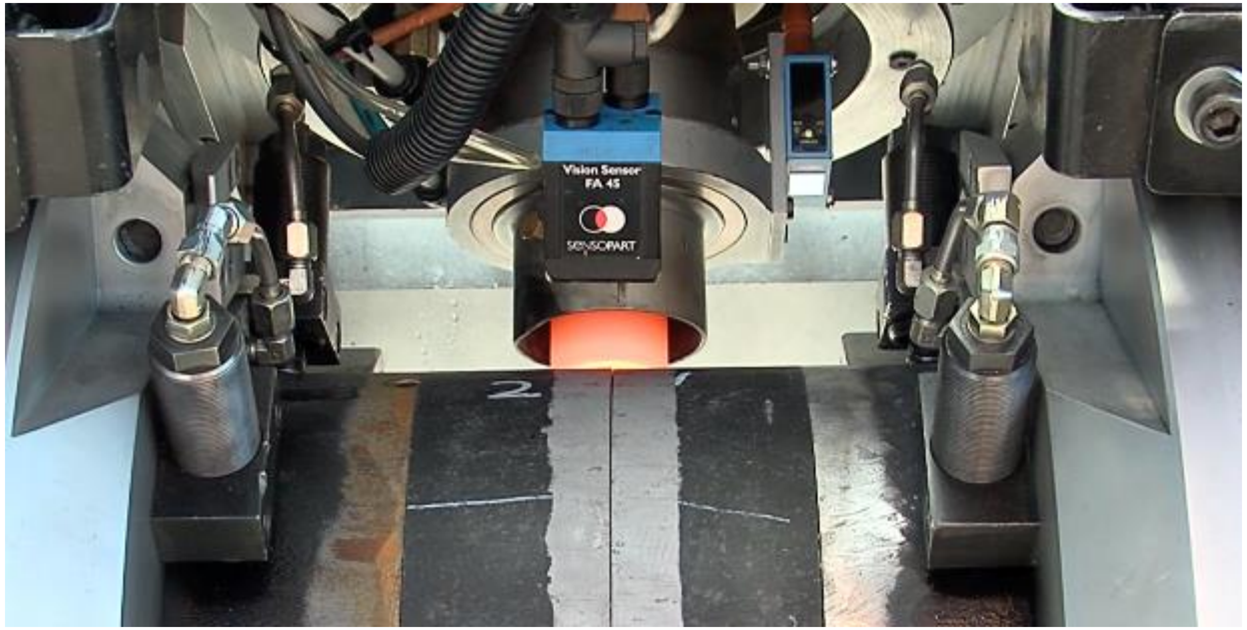
- Further improve productivity by
  - Increasing travel speed, increase clad thickness
  - Tool material and geometry optimization
  - Computational modeling tools to assist process development
  - Increase cladding rate to 20 lb/hr, about 5 to 10 times higher than the all-position GTAW/GMAW cladding processes
- Demonstrate on cladding materials for MSR
  - Hastelloy N, Ni, W?
- Scale up and demonstrate all-position cladding
  - Prototypical mock up components production
    - Surface cladding on steel pipe
    - Buttering layer of DM weld
- Feasibility demonstration of solid-state additive manufacture of nuclear reactor structural materials with improved properties





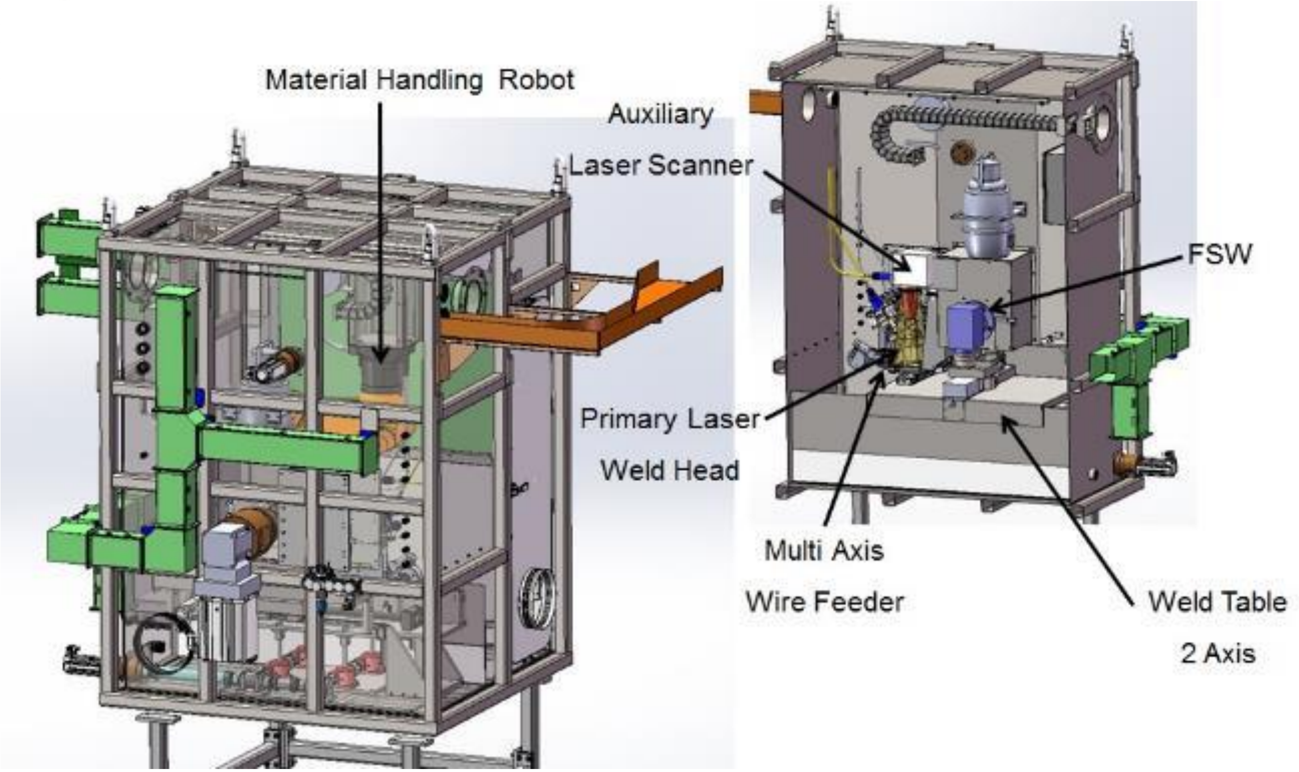
Technology Demonstration

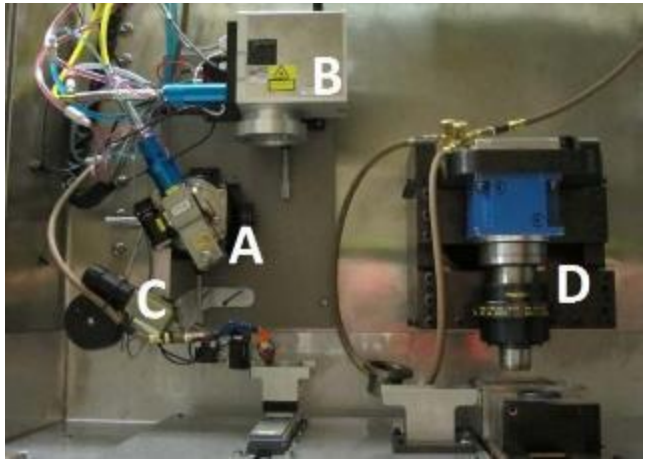
- Effectively utilize our existing industry partnership and equipment from past FSW R&D for oil/gas pipeline construction & maintenance (ORNL, ExxonMobil, MegaStir)



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

- Current processes
  - Laser with proactive stress management
  - Friction stir welding
- Planned (for 2020-2021)
  - FSAM for high helium containing irradiated scenarios





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
  - Improve productivity
  - Scale up and demonstration of all-position cladding

Acknowledgements

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