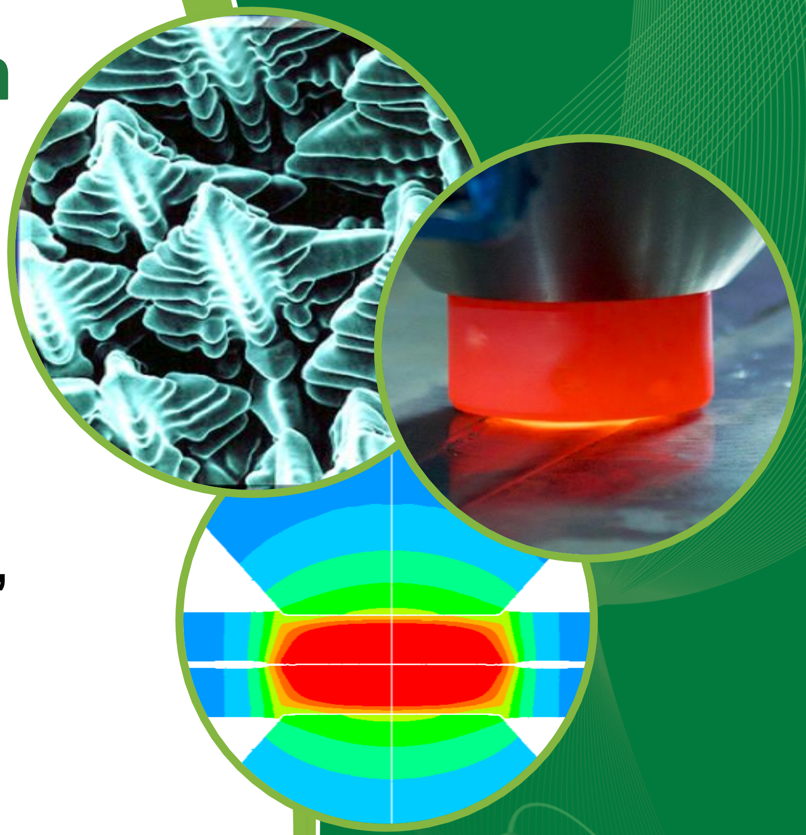
All-position surface cladding & modification by solid-state friction stir additive manufacturing (FSAM)



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Oak Ridge National Laboratory

Electric Power Research Institute

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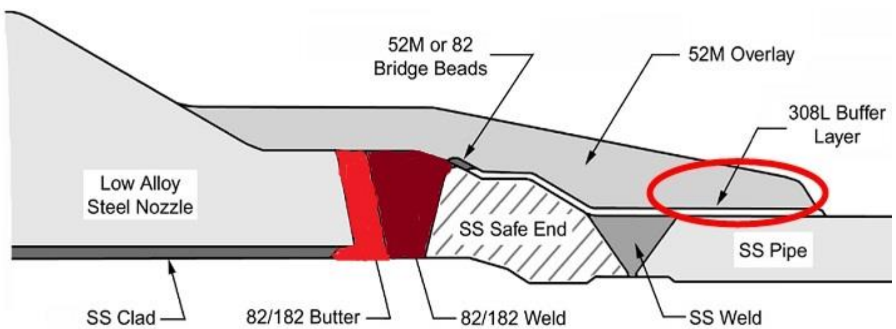
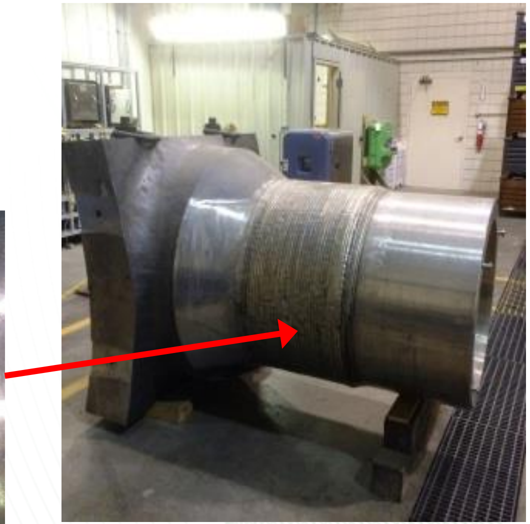
Objectives

- 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

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
  - 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

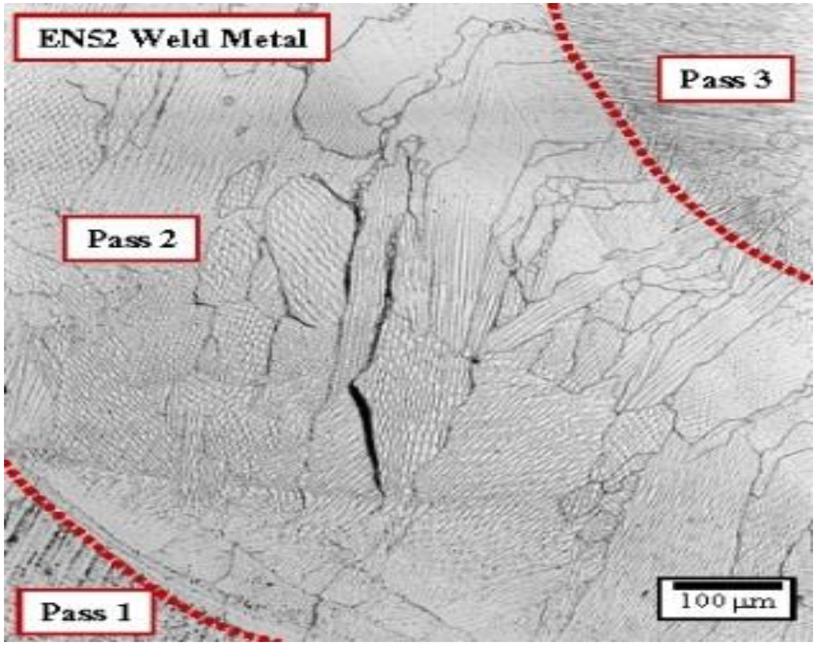
Detrimental effect on substrate properties

- The excessive heat, especially from the high heat input cladding processes, would degrade the microstructures in the substrate underneath the clad layer
  - Often require costly post cladding heat treatment
  - Especially detrimental to high temperature materials (creep resistance steels etc)
- Reducing the heat in cladding process would be beneficial
  - Especially important to on-site repair

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



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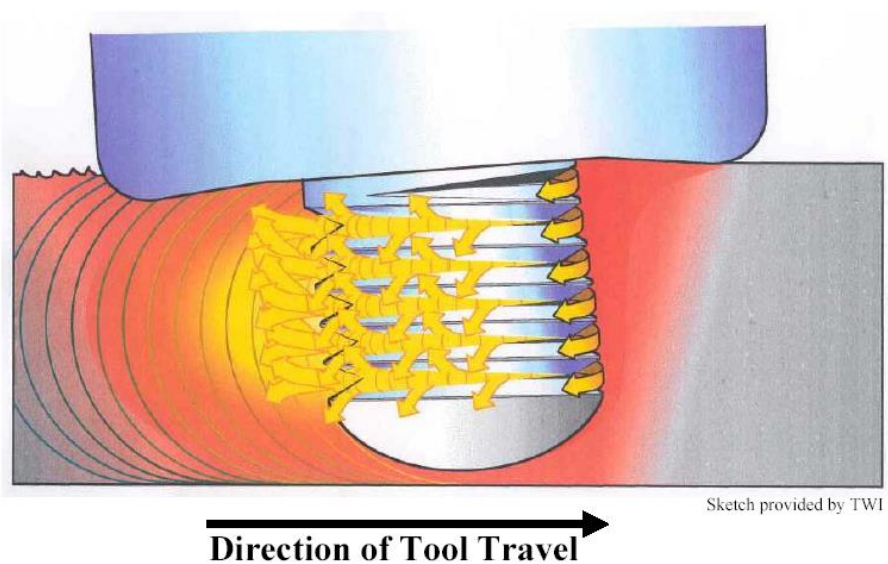
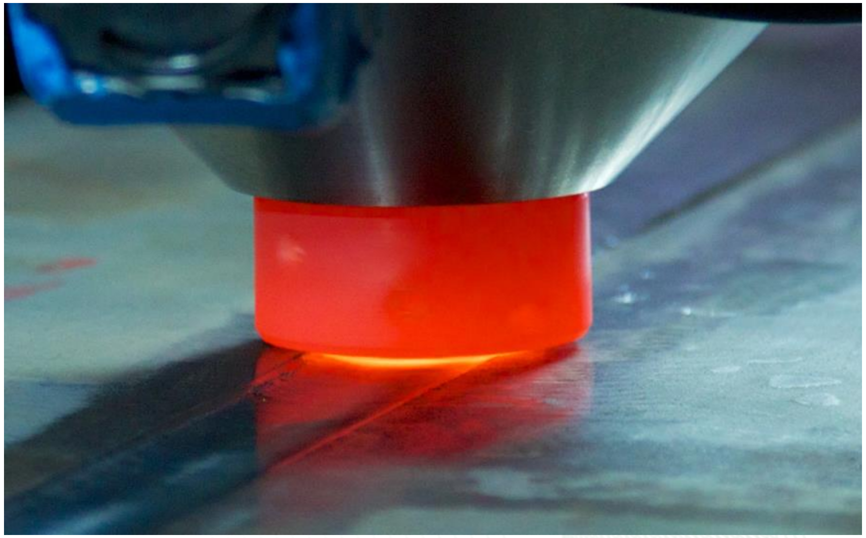
Friction stir welding process

- Friction Stir Welding (FSW) is a new, 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.
- Demonstrated success in Al structure welding (NASA, Auto, transportation)





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FSW at ORNL

- Light-weight materials for automotive/aerospace applications
  - Al, Mg, Ti alloys
- Concerted effort on FSW of high temperature materials for nuclear and fossil energy applications
  - High-strength steels, ODS alloys, and Ni-based superalloys
  - Tool materials for high-temperature materials (steels, nickel alloys, Ti alloys)
  - ***Patented multi-layer multi-pass FSW for thick-section structures*** (reactor vessel, hydrogen storage, etc)
- Modeling
  - Residual stress, Materials flow, Microstructure, Weld performance
- Microstructure characterization

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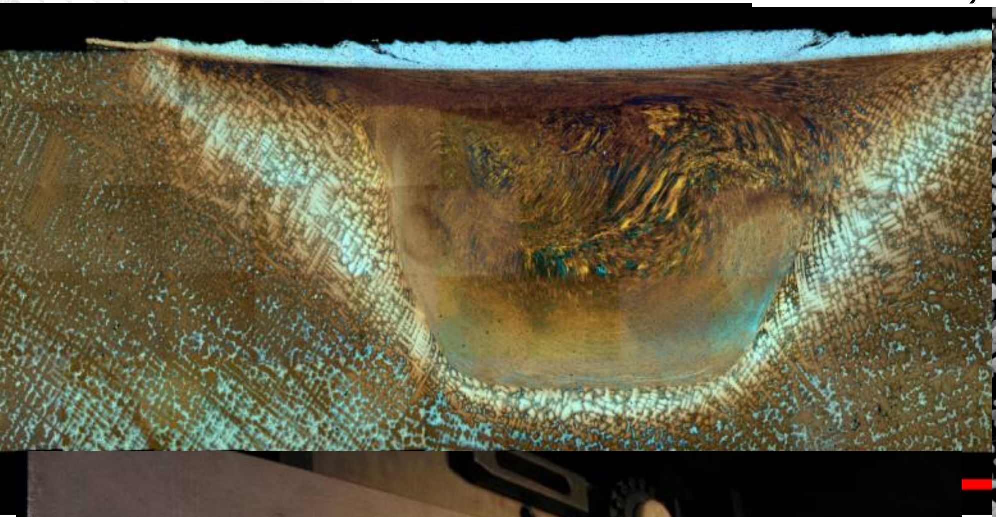
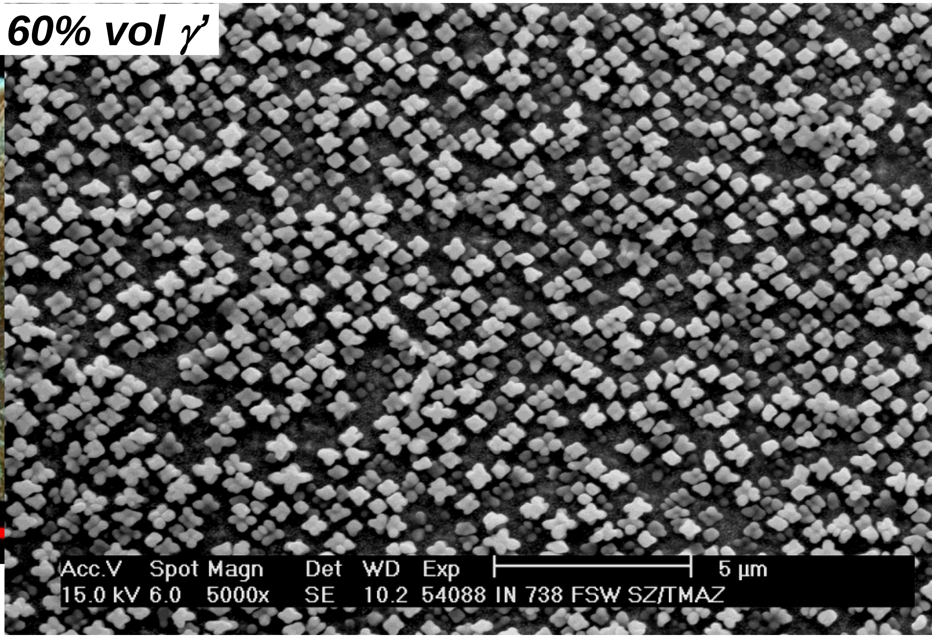
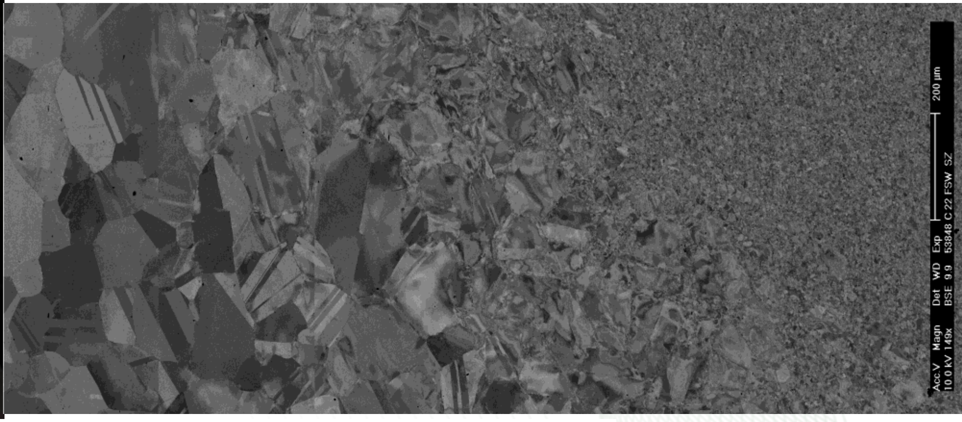
FSW of Superalloys

Cast IN738, 60% vol γ'



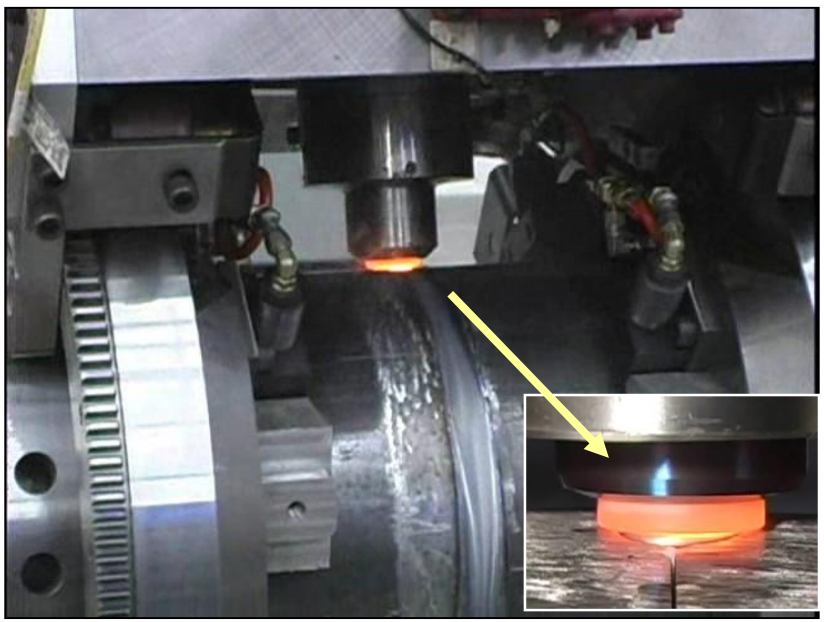




Alloy C22, solution strengthened corrosion resistance

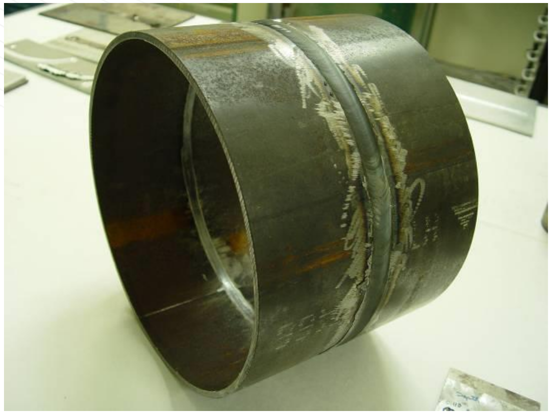
Friction stir welding system for on-site welding of steel pipeline

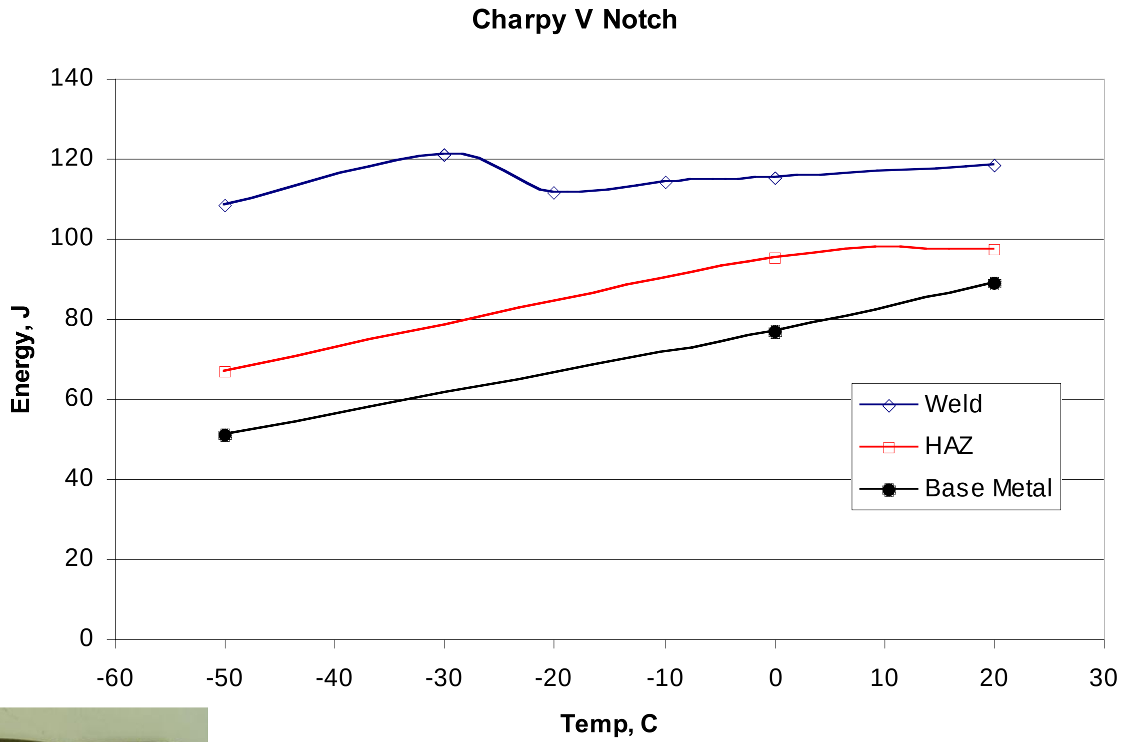
- Develop and apply the friction stir welding to steel piping systems
- Industry partners: ExxonMobil, MegaStir
- Sponsor: DOE EERE AMO



FSW Improves Properties of Pipeline Steels

- Girth weld of API X65 steel for natural gas transmission pipelines





Feng and Packer et al., 2005

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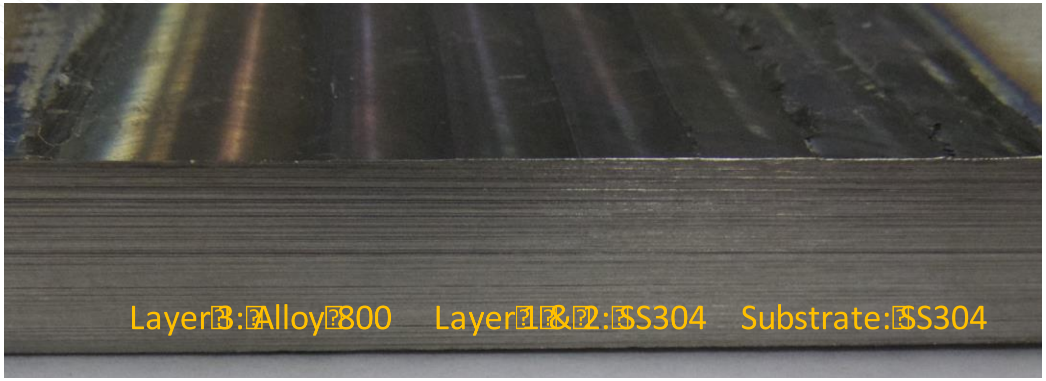
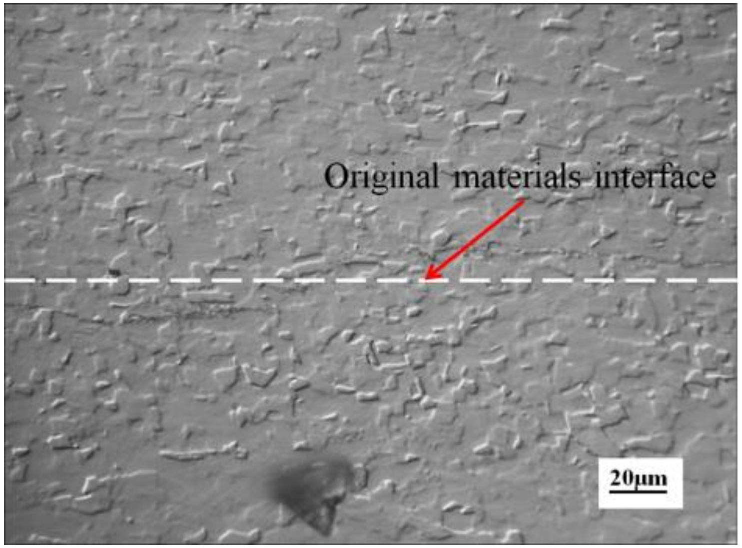
Technology development in this project: Friction Stir Additive Manufacturing (FSAM)

- 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 process innovations have 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

Preliminary results of FSAM cladding



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



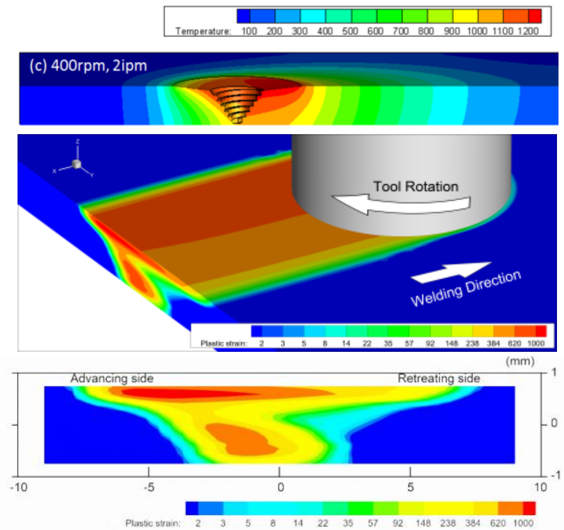
Microstructure near the clad bonding interface between two SS304.

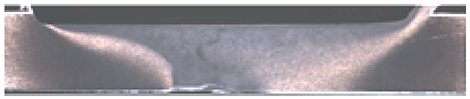
Focus of R&D in this project

- Increase cladding rate to 5 to 10 times higher than the all-position GTAW/GMAW cladding processes
- Reduce the number of cladding layers to reach required cladding layer thickness for intended service. Expecting another 50-60% increase in ”effective” productivity
- Demonstrate all-position cladding with mechanized FSAM prototype system
- Achieve or exceed the 20% cost reduction target for component fabrication set forth in this FOA

Research Plan

- Task 1 FSAM process optimization and scale-up for cladding
  - Process optimization for common reactor structural materials
    - Structural steels (SA508), CSEF steels (P91), nickel based super alloys (Alloy 82 and 52), and austenitic stainless steels (308 and 309L)
  - Initial developed on 10x10” surface.
  - Scale up to 30x30” surface later on
  - Ensure complete cladding bonding
  - Demonstrate target high cladding rate
  - Demonstrate adequate tool life (wear, failure and cost)
- Task 2 Microstructure characterization, property testing and NDE Quality
- Task 3 Fundamentals on thermal-mechanical conditions in FSAM
  - Combined experimental and modeling effort to understand the fundamental factors in FSAM cladding: temperature and material deformation





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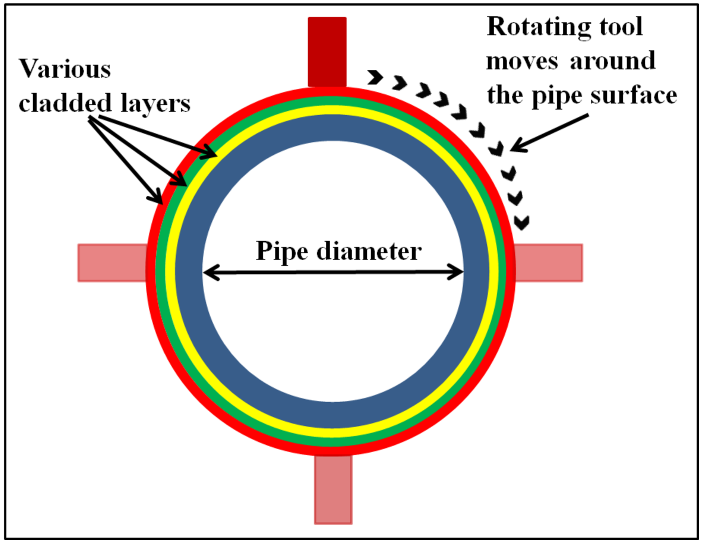
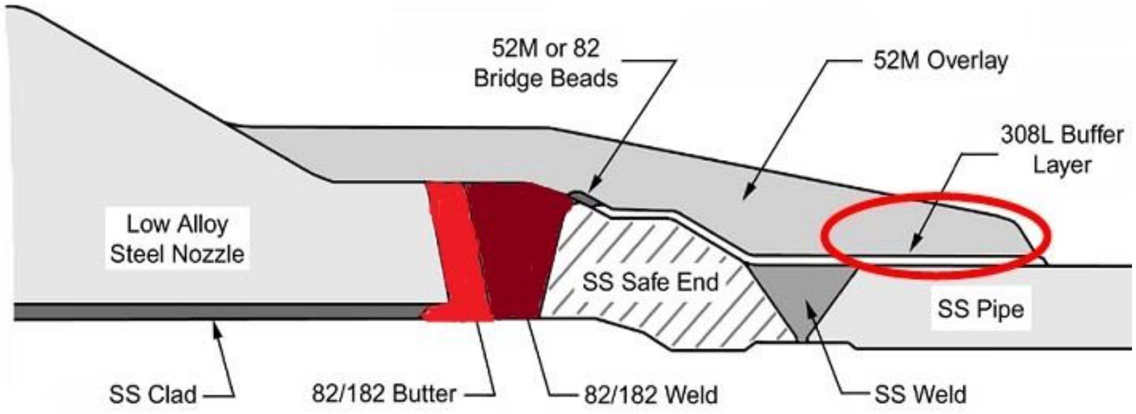
Research Plan (Cont'd)

- Task 4 Technology Demonstration: Prototypical mock up components production
  - Surface cladding on steel pipe
  - Buttering layer of DM weld





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Schedule

Tasks	Year 1				Year 2				Year 3			
Task1: Solid-phase cladding feasibility demonstration and process development	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
Feasibility demonstration	■	■										
Process development	■	■	■	■	■	■	■	■	■			
Task 2: Solid-phase cladding quality examination and characterization												
NDT			■	■	■	■	■	■	■	■		
Mechanical properties test			■	■	■	■	■					
Microstructure characterization	■	■	■	■	■	■	■	■				
Tool wear study		■	■	■	■	■	■	■	■	■		
Task 3: Understanding FSAM Fundamentals												
Experimental investigation	■	■	■	■	■	■	■	■				
FSAM process modeling		■	■	■	■	■	■	■	■	■		
Task 4: Prototypical mock up components production												
Surface Cladding Mockup										■	■	
Fabrication of DM Weld Transition Layer											■	■