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

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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
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)
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
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

Charpy V Notch

Feng and Packer et al., 2005
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
Research Plan (Cont’d)

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

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