Joining Technologies for Coal Power Applications

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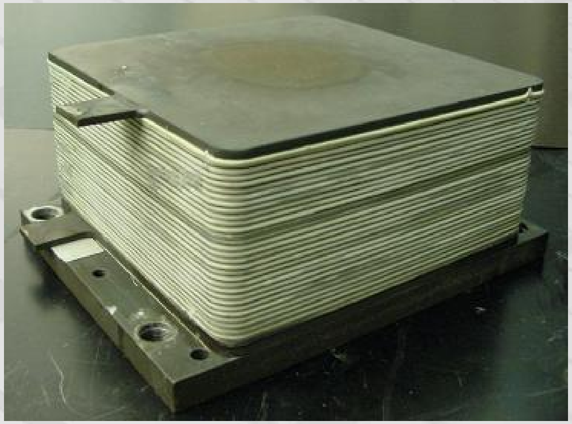
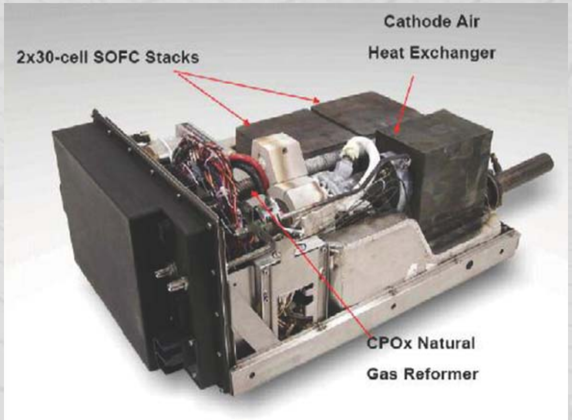
Materials Joining: An Enabling Technology

- **Project Objectives: To develop joining technology that advances the state-of-the-art in coal power generation**
  - Gas separation membranes (oxyfuel combustion, IGCC)
  - Solid oxide fuel cells
  - High-temperature, corrosion-resistant alloys (SC, USC, IGCC plants)
- **Project Accomplishments:**
  - New family of degradation-resistant, high-temperature glasses for ceramic membrane sealing
  - New low-cost process for ceramic-to-metal joining: air brazing
  - Conversion joining process for Al_2O_3 and alumina coated materials
  - Demonstration of the viability of ceramic membrane joining for SOFCs and H_2 and O_2 separation membranes (ASUs and WGS reactors)
  - Initial joining of oxide dispersion strengthened alloys by friction stir welding
- **Present Focus:**
  - Develop joining materials/practices that meet current and future DOE-FE needs on electrochemical devices
  - Optimize solid-state welding processes for current and future alloys of interest in coal power applications
    - Joinability of advanced high-temperature alloys
    - Developing joints with properties equivalent to base metal

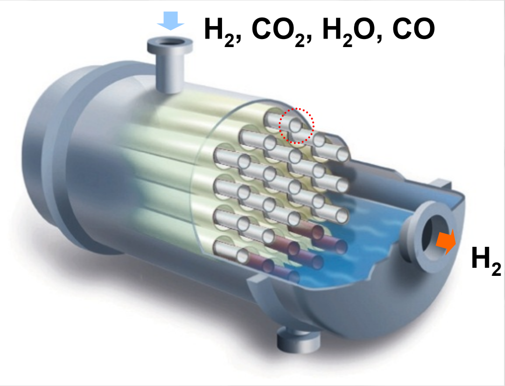
Membrane Joining

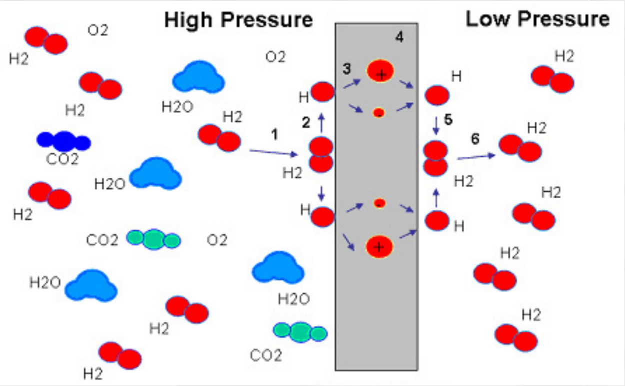
Applications

SOFC

Gas Separation



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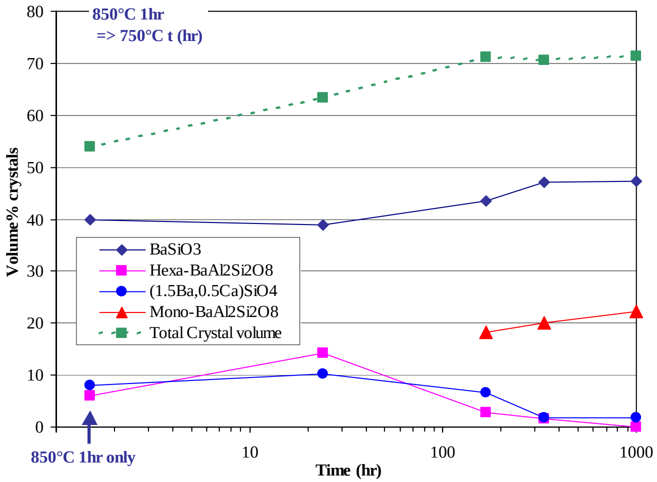
High-Temperature Glass Sealant

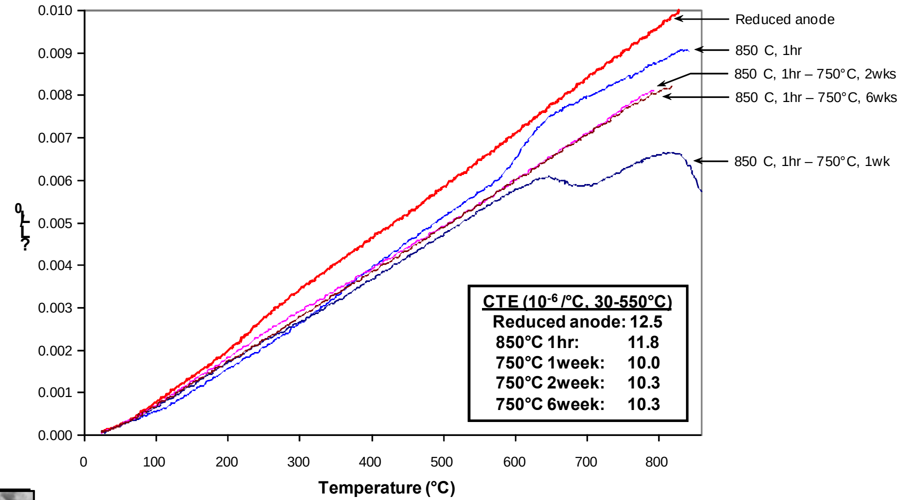
Challenges:

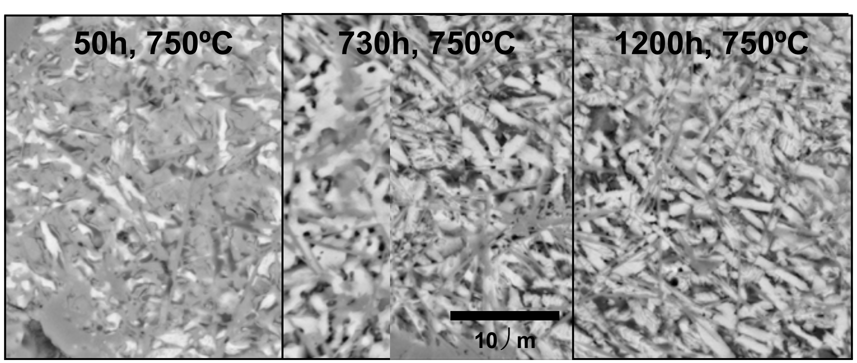
- Controlling crystallization and T_g
- Controlling CTE during joining and subsequent use
- Proper substrate wetting
- Limiting material interactions along the faying interfaces

Crystallization



CTE



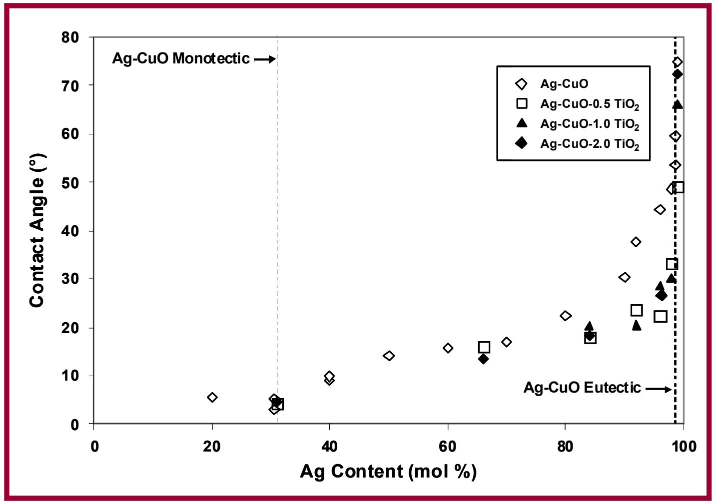


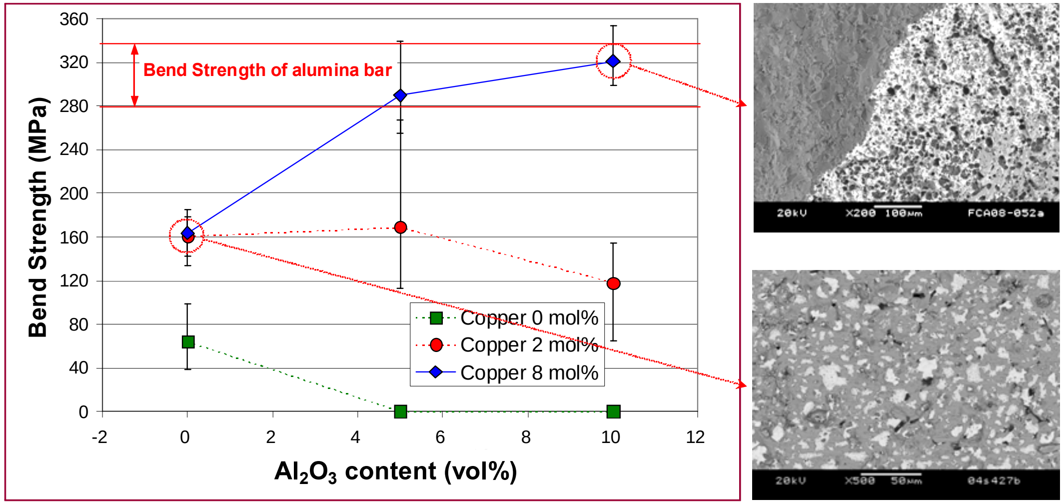
Meinhardt, Kim, Chou, and Weil, *J. Power Sources,* **182** (2008) 188

- $BaO-Al_2O_3-SiO_2$
- Patents:
  - U.S. 6,430,966 – Glass-ceramic material and method of making
  - U.S. 6,532,769 – Glass-ceramic joint and method of joining
- Commercial use: Praxair, Litton, Delphi

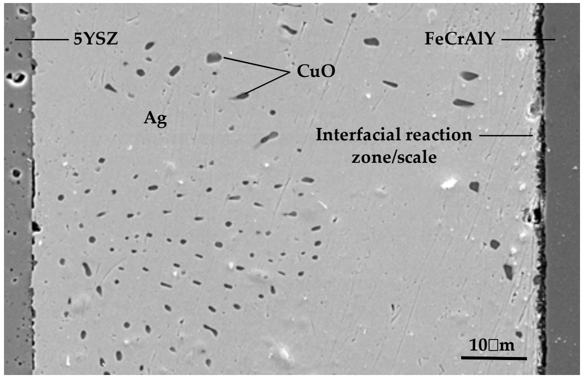
Challenges:

- Proper substrate wetting
- Limiting material interactions along the faying interfaces
- Expand the compositional range of oxide membrane materials that can be brazed





US Patent Pending

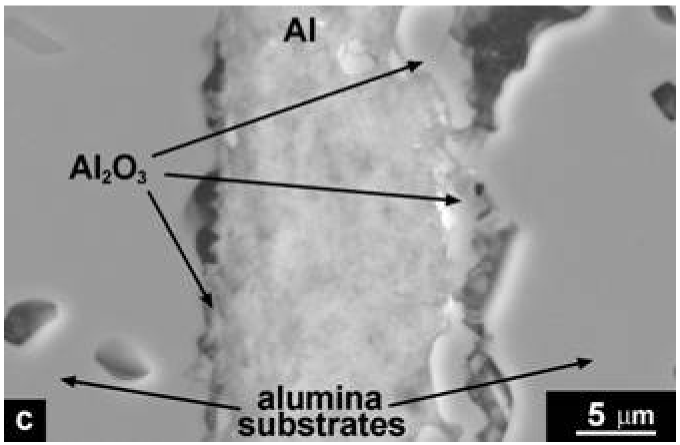


Weil, Kim, and Choi, *J. Mater. Res.*, in review

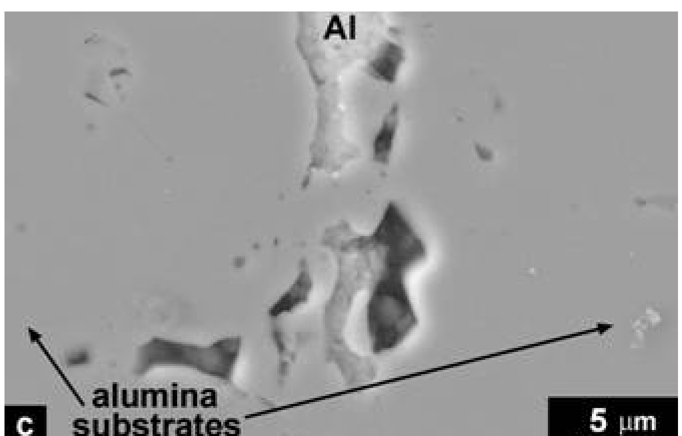
- Ag-CuO (+TiO_2, Pd, Al, Al_2O_3)
- Patents:
  - U.S. 7055733 – Oxidation ceramic-to-metal braze seals
  - WO 059843 – Method of joining ceramic and metal parts
  - WO 54535 – Diffusion barriers in modified air brazes
  - U.S. Patent Pending - High temperature air brazes
- Commercial use: Delphi, Corning, Aegis Technology

Drivers:

- Operational temperature of the seal is equivalent to the base material
- CTE match (avoidance of thermal stresses during thermal cycling)
- Ease of component construction with no property decrement



800ºC, air



1200ºC, air

Kim and Weil, *J. Am. Ceram. Soc.*, **90** (2007) 3830

- Al-based foil/powder
- Patents:
  - U.S. Patent Pending – Ceramic microchannel pyrolyzer
  - U.S. Patent Pending – Ceramic bonding technology for high-temperature ceramics
- Current application: High-temperature microchannel devices

Joining of High-Temperature Alloys

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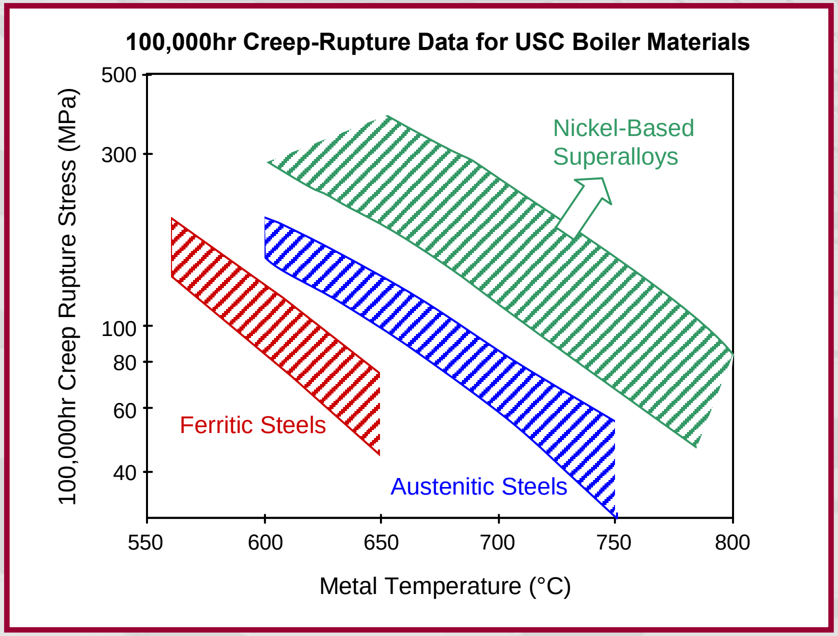
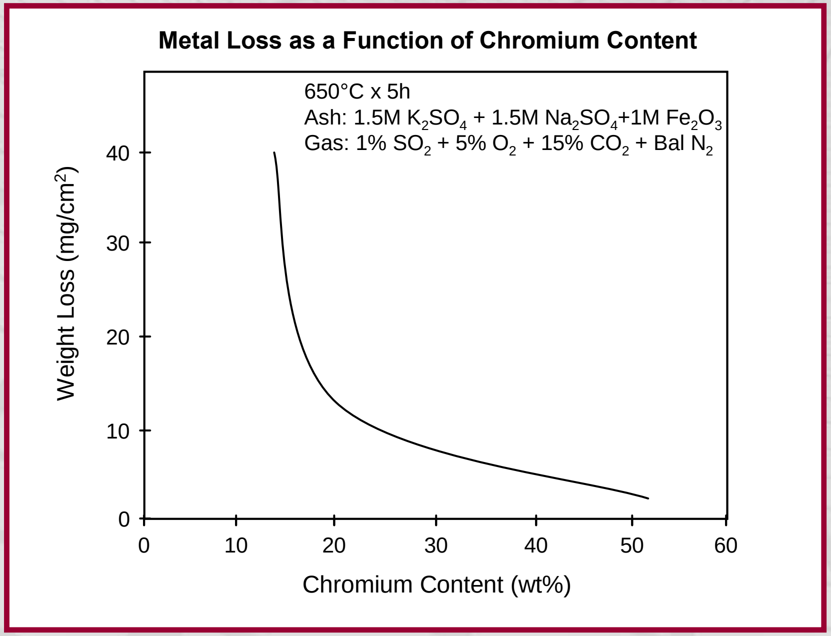
Technology Drivers



From P. J. Maziasz et al., DOE-FE(ARM) 2005 proceedings



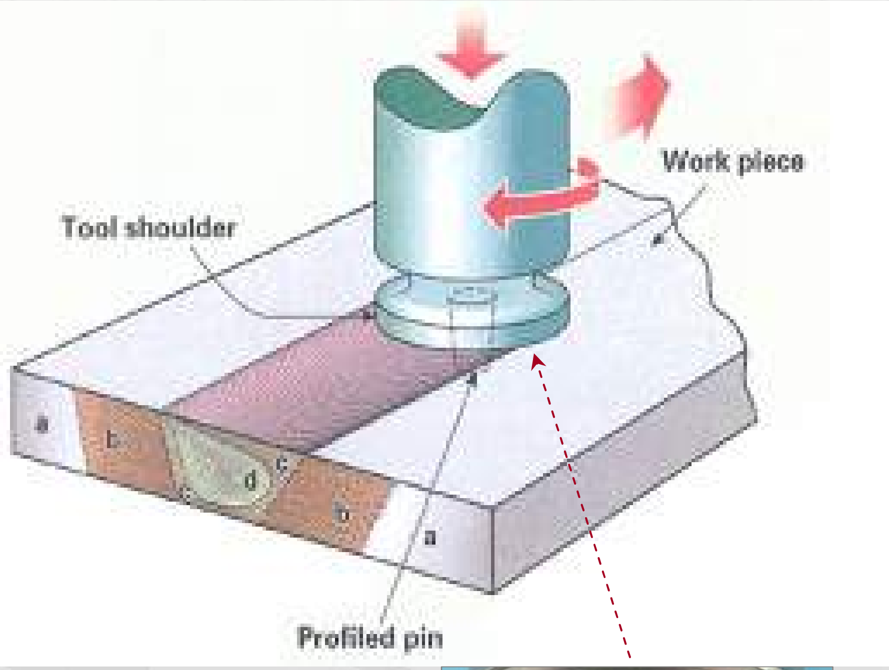
From T. Ikeshima, Bull. Japan Inst. Metals, 22, p. 389

- **Major technology drivers for heavy section components:**
  - Minimize thermal fatigue
  - Attain high creep strength
- **Major technology drivers for superheater/reheater tubes**
  - Steamside oxidation resistance
  - Fireside corrosion resistance
- **Key issues: material and fabrication costs (joining is often a key consideration)**

Solid-state joining process (no material melting)

- **Spinning, non-consumable tool is plunged into the surface of a material**
- **Heat from friction and plastic work lowers material's flow stress**
- **Tool moves through the softened material along the joint line causing material flow from front of the tool to the back into the joint gap**
- **The resulting joint is characterized by:**
  - **Fine-grained "nugget" composed of recrystallized grains (d)**
  - **Surrounded by a mechanically deformed region (c) and a heat affected zone (b)**

FSW was invented by TW, ltd in 1991



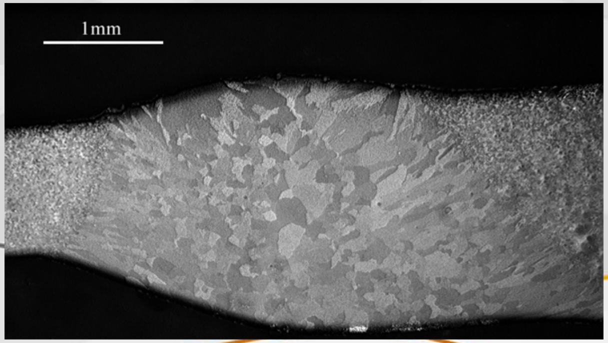
FSW Process Advantages

Technical

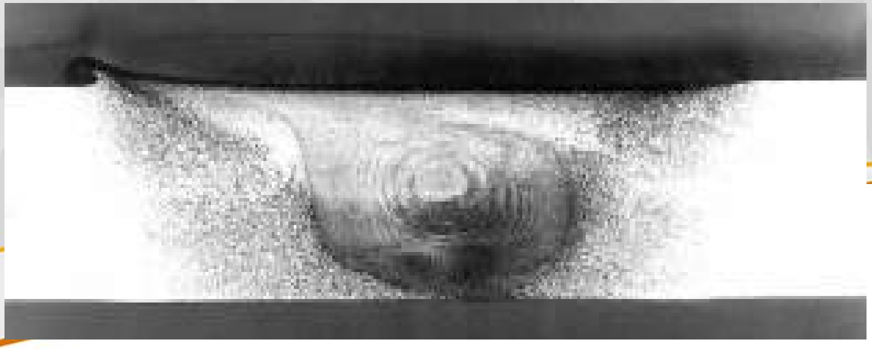
- Higher strength joint
- Improved fatigue performance
- Higher toughness, better damage tolerance
- Fewer defects, nil microsegregation
- Fine grain nugget is more amenable to NDE (x-ray, ultrasonics, etc.)
- Fine grained nugget less susceptible to hydrogen induced cracking
- Lower distortion
- Lower heat input:
  - Reduced residual stress
  - Smaller HAZ
  - Reduced sensitization for corrosion

Economic

- Single pass method – faster on thick section welds
- Fewer consumables
- No environmental emission
- No “expert” operators
- Lower recurring costs (but higher initial capital costs than GTAW/GMAW)
- Lower energy costs



Fusion Weld (Al)


Friction Stir Weld (Al)

Task Objectives

- **Develop joining approaches that improve current materials and enable the next generation of high-temperature alloys**
  - Examine the high-temperature and creep strength of FSW joint vis-à-vis those of the base material
  - Investigate the comparative corrosion properties
- **Develop a feedback process control system algorithm that ensures weld quality is within acceptable design tolerances and can meet certification requirements**
- **Transition joining approach to commercial-scale tube/pipe applications**

Capabilities

- PNNL has a dedicated state-of-the-art friction stir welding facility
  - Capable of achieving peak loads up to 30,000 lbs (z-axis, 8,000 lbs x- and y-) and processing parts as large as 8 x 8 ft
  - Highly instrumented for process parameter development
  - Equipment has high speed data acquisition for statistical process control and load vector variability analysis (weld certification)
  - Includes tool and anvil cooling systems and pre- and post-weld induction heating systems
- Developing a rotary tool to join pipe/tubing
- This work leverages the materials joining experience and capabilities we've established on automotive/heavy vehicle applications, nuclear plant projects, and oil/gas pipe joining programs

Approach: Initial Focus on ODS Steels

- MA 957 - 14% Cr, 0.25% yttria strengthened ferritic fuel cladding steel
  - Source: US DOE Fast Breeder Reactor stockpile (INCO produced)
- ODS Eurofer 97 – 9% Cr, 0.3% yttria strengthened martensitic steel
  - Source: produced by Plansee to FZK specifications using Eurofer 97 (Fe-9CrWVTa) as a base material
- Kanthal APMT – high Cr, 0.2% alumina strengthened ferritic steel
  - Source: Sandvik, Inc.

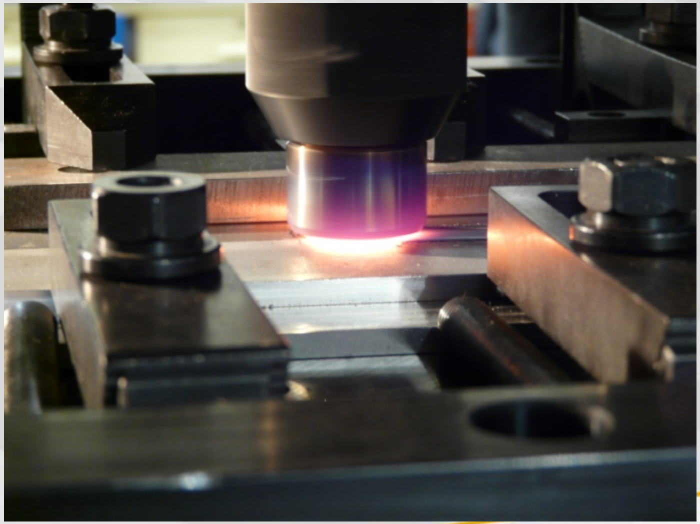
	Cr	Mo	W	Ti	V	Al	Ta	Mn	C	Y_2O_3	Fe
MA957	14	0.3	-	1.0	-	0.1	-	-	0.015	0.25	balance
ODS Eurofer 97	9	-	1.1	-	0.2		0.14	0.4	0.080	0.30	balance
Kanthal APMT	22	3.0	-	-	-	5.0	-	<0.4	<0.05	0.2 Al_20_3	balance

- Explore process parameter space
  - Spindle speed
  - Heat input
  - Weld speed
  - Rake angle
  - Tool design/tool material
- Mechanical property characterization
  - Nanoindention hardness testing across the joint
  - Tensile testing (at room and elevated temperature)
  - Creep testing
- Joint quality assessment
  - Examination of strain localization during tensile testing

Initial FSW Trials on ODS Eurofer 97

- Product form was flat plate 125mmx250mmx6mm
- Bead on plate welds were made at two process conditions using polycrystalline cubic boron nitride tooling with a 1 inch diameter tool with a 0.25 inch pin
- Stepped spiral tool geometry

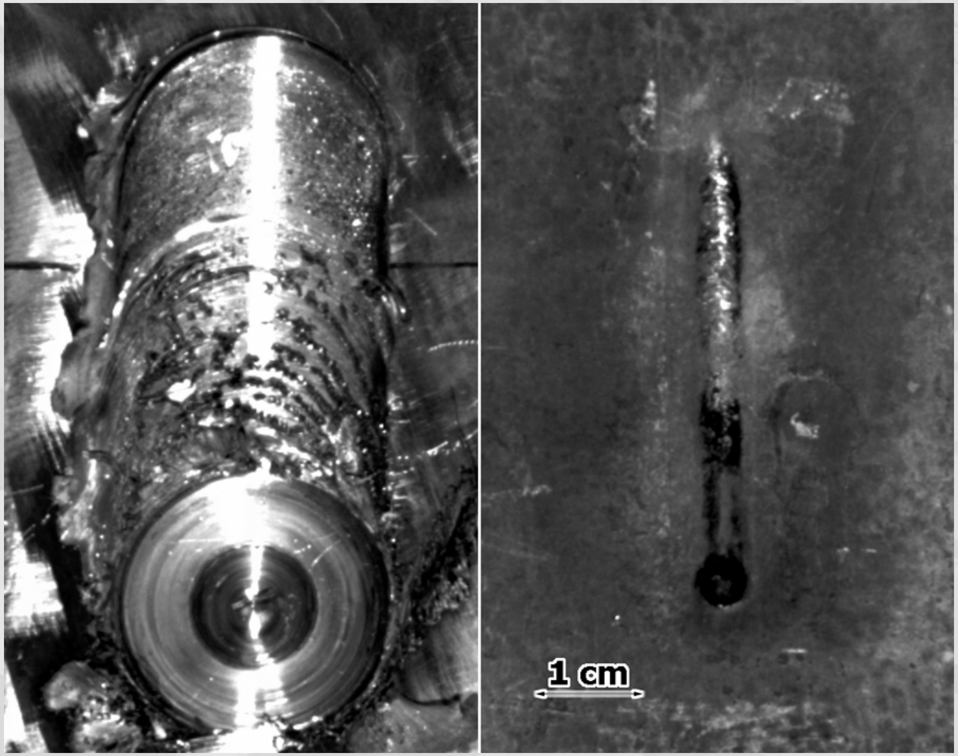
Weld No	Weld Speed (cm/min)	Spindle speed (rpm)	Condition	Peak Temperature (°C)
1	2.5	150	No preheating	758
2	2.5	300	No preheating	915



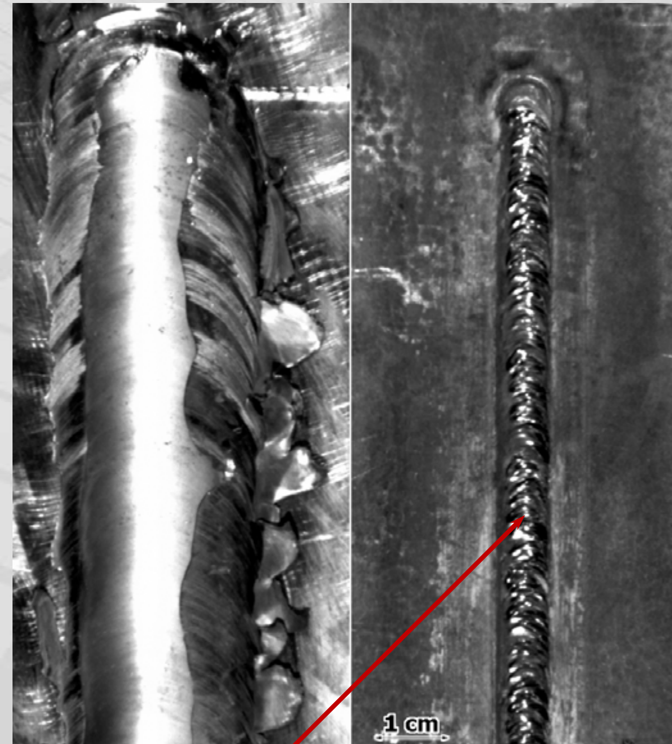
SS 304L Example

Initial FSW Trials on ODS Eurofer 97

150 rpm

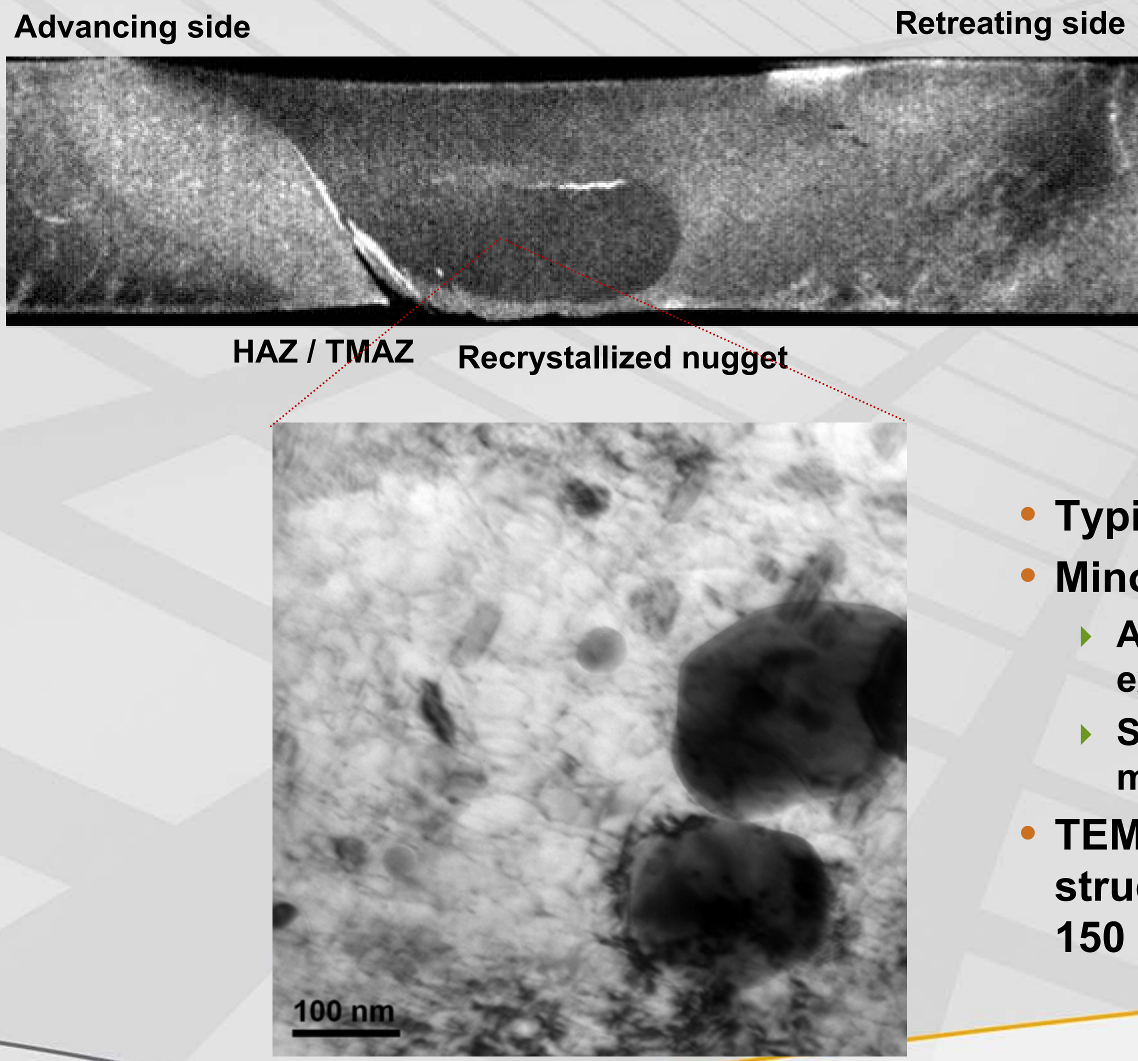


300 rpm



Backside root forged into anvil slightly from pin that is too long

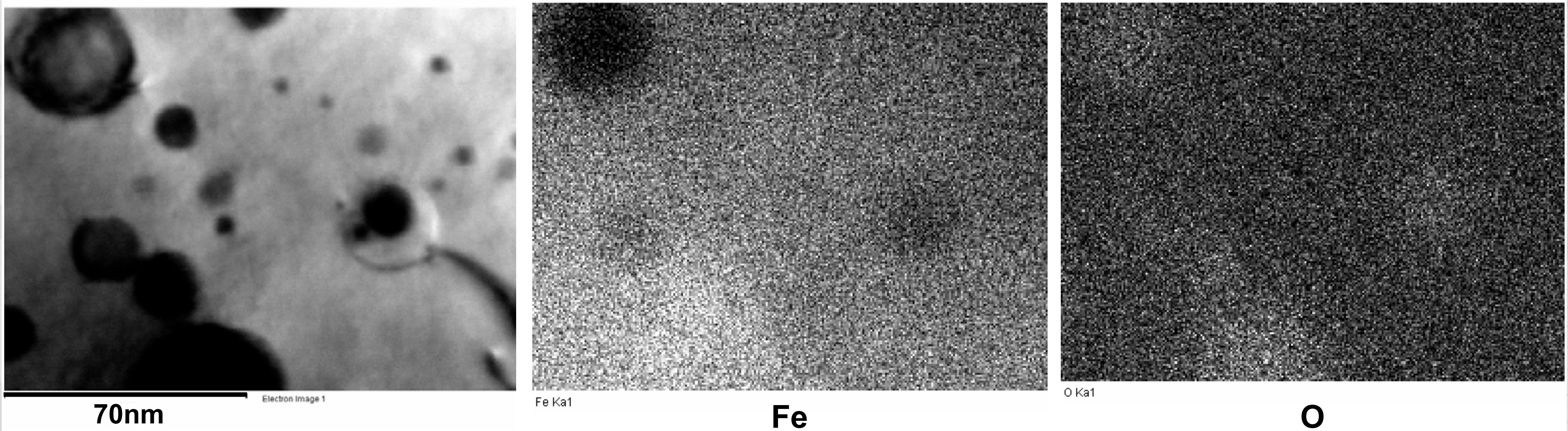
Initial FSW Trials on ODS Eurofer 97

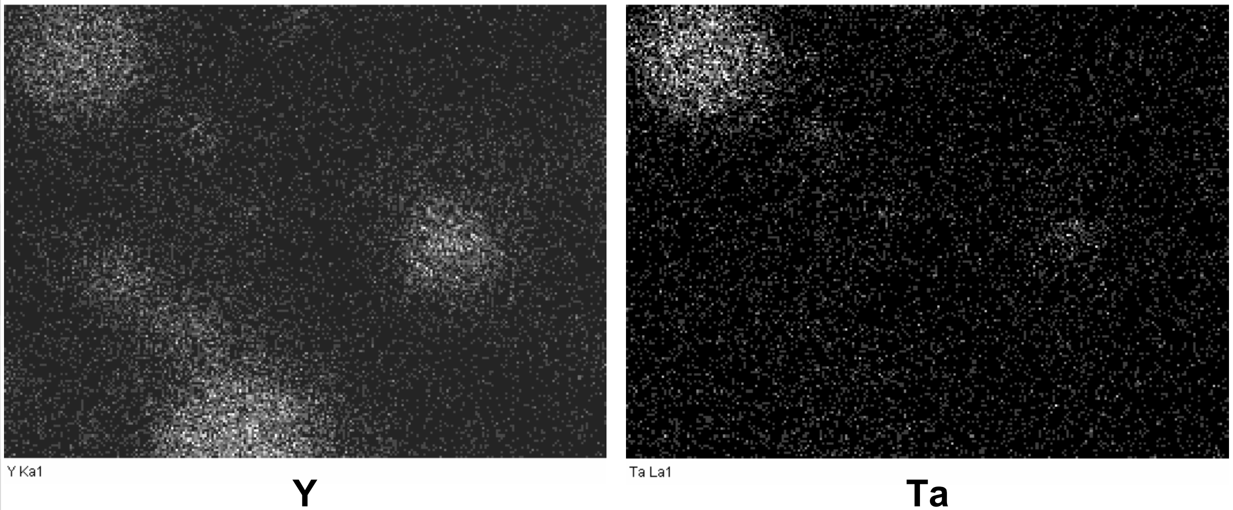


300 rpm

- Typical FSW microstructure
- Minor defects present
  - Advancing side defect from excessive pin length
  - Some material stirred in from mild steel anvil at root
- TEM shows highly dislocated structure with dispersed 50 - 150 nm size particles

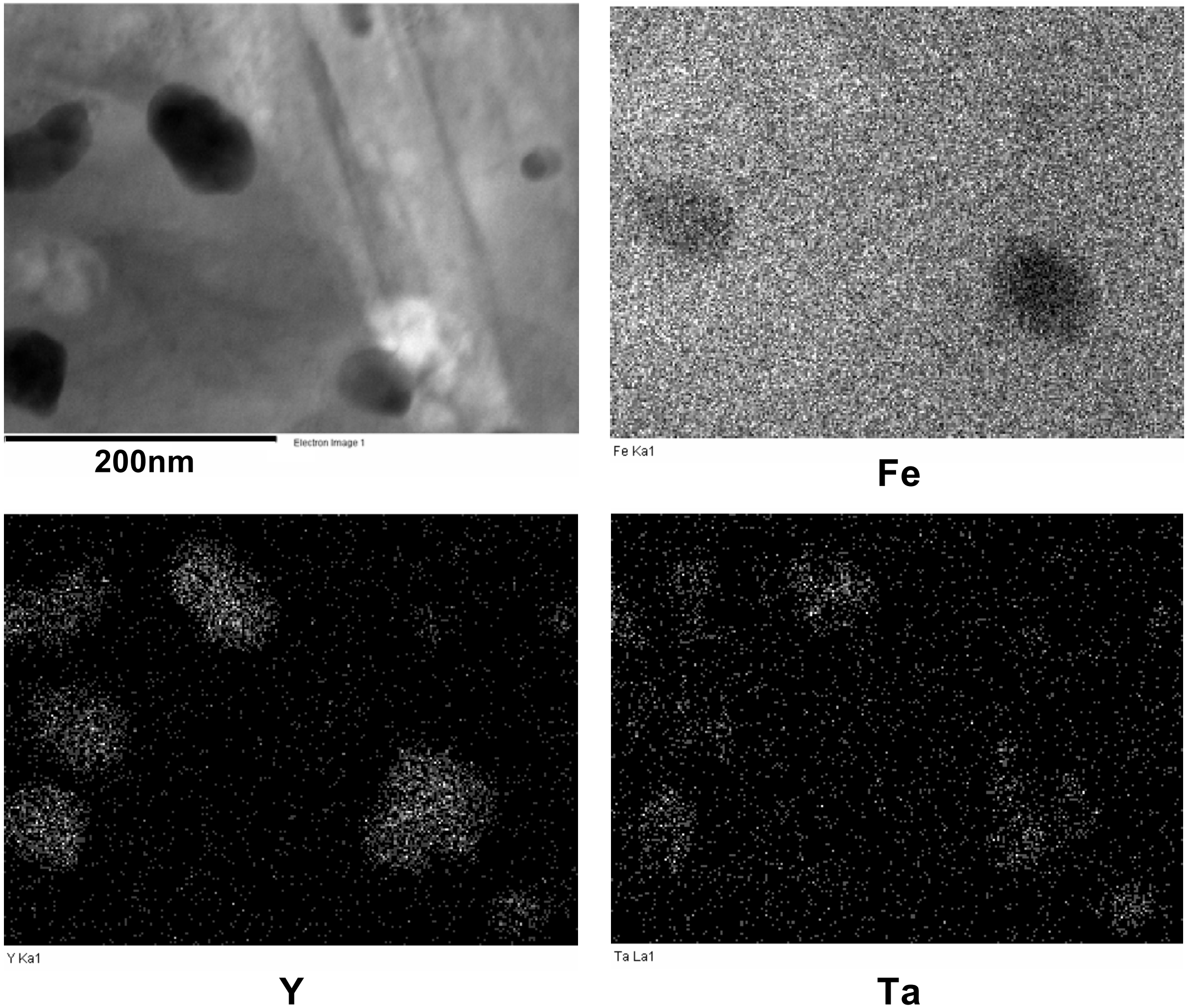
Base Material Microstructure





Y and Ta oxide particles are generally smaller than 50 nm and commonly <10 nm in size

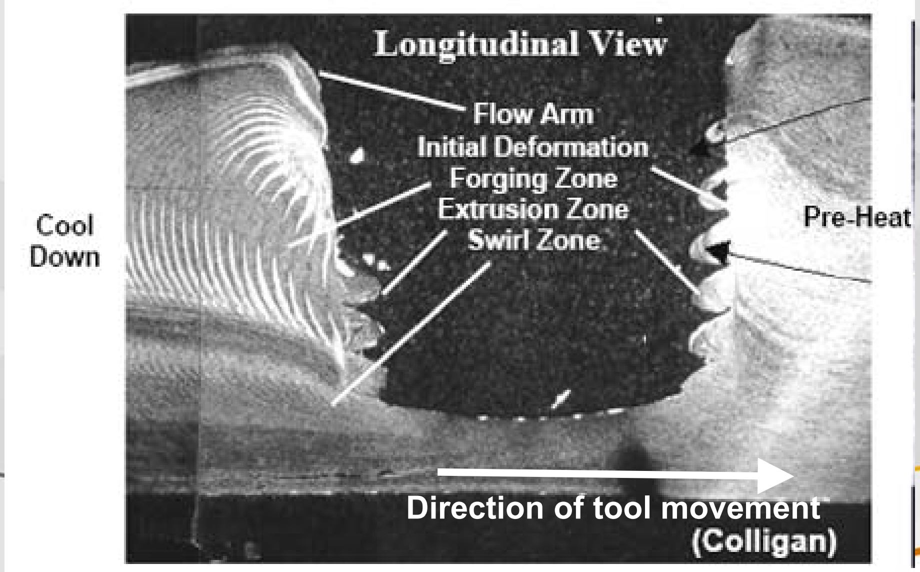
Nugget Microstructure (300rpm)



In contrast to base material, FSW nugget shows a modest increase in yttria particle size to 50 – 100nm

Speculated Mechanism

- FSW Process works by shearing and deforming thin bands of material around the pin and forging them to the back side
- Thin bands are formed that separate regions of high and low angle grain boundaries
- Along the boundaries, second phase particles collect, “pushed” by the banding process and concentrated into particle trails
- The same mechanism may physically move and segregate dispersoids at a very fine scale to create the agglomerated Y_2O_3 particles seen in TEM
- This physical displacement and coalescence of dispersoid, combined with dynamic recrystallization may allow agglomerated particle to form

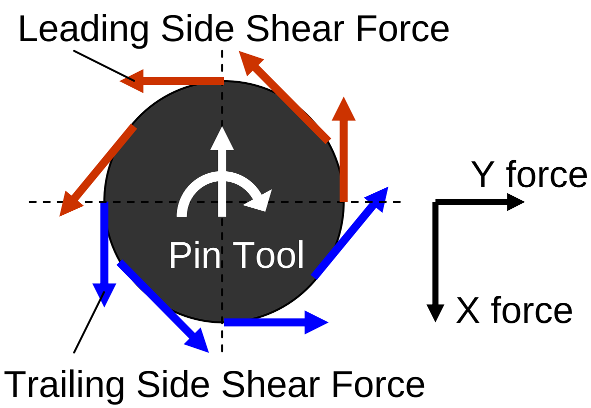


If this is true then the degree to which individual particles might be agglomerated is dependent on weld parameters such as weld pitch, heat input, and tool design.

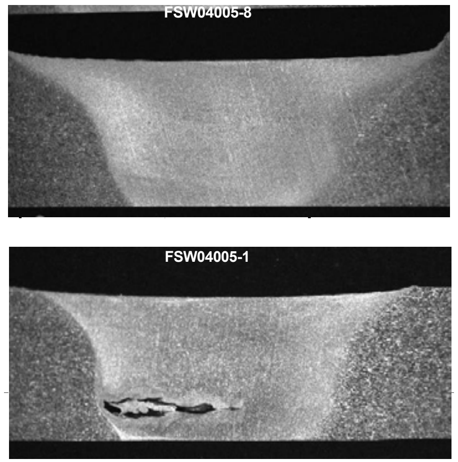
Future Steps

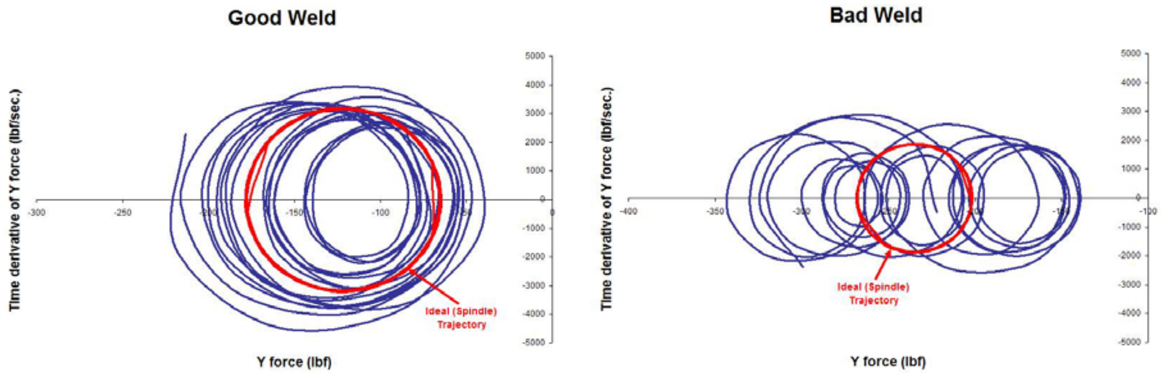
In-Situ Weld Quality Measurement/Control

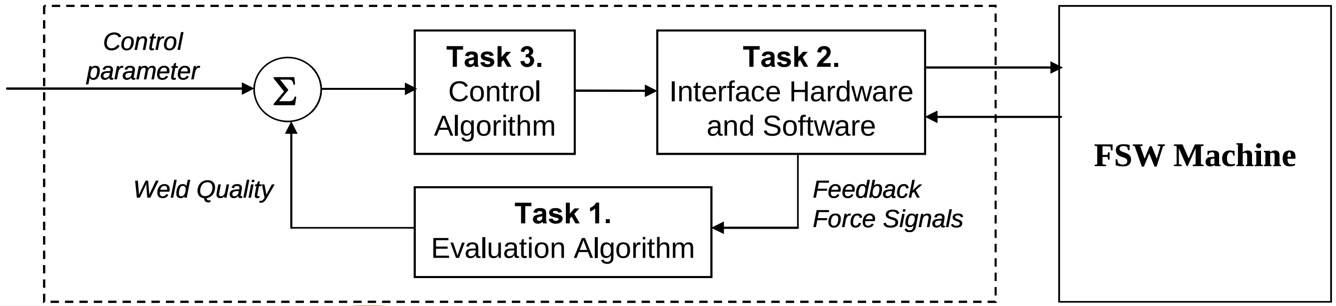
From Corwin and Logar at SDSMT



- **In terms of Y feedback force, the pin tool is exerted by the two competing shear forces – the leading side shear force and the trailing side shear force.**
- **The leading side shear force tends to decrease Y force, while the trailing side shear force tends to increase Y force**
- **These two competing shear forces define the equilibrium point of Y force**







Rotary Weld Development

Megastir, Inc. FSW Pipe Welder

Conclusions

- **Materials joining – processes that enable a wide variety of technologies important to efficient fossil fuel utilization:**
  - **Gas separation (H_2/O_2)**
  - **SOFC and electrochemical sensor fabrication**
  - **Use of alloys with higher creep- and corrosion-resistance → higher plant efficiency**
- **Membrane joining highlights:**
  - **Glass seals that are functional at temperatures up to 1000ºC for 20,000hrs in separated H_2/wet air environments**
  - **High-strength air brazes for ceramic-metal joining at temperatures up to 900ºC+ - simplified joining approach relative to vacuum brazes**
  - **Conversion joining – affords joining of alumina and alumina-coated materials with use temperatures equivalent to that of the base material**
- **High temperature alloy joining:**
  - **Investigating FSW**
  - **Initial work on ODS Eurofer 97 shows successful joining, but some coarsening of oxide dispersoid – in initial stages of development**
  - **Currently working through process parameter matrix and microstructural/mechanical characterization**
  - **FSW offers the potential for in-situ weld control and weld quality measurement**