Advances in Solid-State Joining at EWI

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Resistance and Solid-State Technologies

- **Resistance Welding**
  - Spot
  - Thin materials
  - Conductive heat
  - Embossed projection
  - Seam
    - Pipe cladding
  - Mash seam
    - Dissimilar materials
  - Flash butt
  - Resistance butt
    - TAUW
  - Electro-spark deposition
  - Percussive
  - Brazing

- **Solid-State Welding**
  - Friction
  - Friction stir
  - Inertia
    - Aluminum to steel
  - Hot upset
  - Cold pressure
  - Friction stir
  - Solid projection
  - Magnetic pulse
  - Diffusion
  - Stud

- **Ancillary Technologies**
  - Design-of-experiments methods
  - Instrumentation and control
  - Mechanical fastening
  - Modeling and simulation
Inertia Friction Welding Large Section Aluminum to Steel Joints

- Friction welding Al to steel a production process
- Production applications tin walled tube
- Need for scaling to pipe sections
- Work here on 120-mm-diameter pipe
- 8-mm pipe wall
- Al-6061 to 1010 Steel

Aluminum and steel samples prepared for welding

Welded specimen extracted from fixture

Welded sample with OD and ID Turned

Segment removed for tensile testing
Process and Metallurgical Response of Case Welds

- Process designed to achieve low overall cycle times
- Improved weld quality with
  - Shortened weld times
  - High specific weld force
  - Coarse texture 0.06-mm amplitude
- Bend and tensile testing - joint fails in the parent aluminum

Average Tensile = 306 Mpa

280 Milliseconds
Translationally Assisted Solid-State Joining Processes

- **Technologies using lateral forging as a mechanism to assist bonding**
  - Translational friction welding
  - Translationally assisted upset welding

- **Candidate applications**
  - Blisks
  - Aircraft structural elements
  - Wheels
  - Pipe connections
  - Rail road rail
  - Non circular sections

- **Materials**
  - Titanium alloys
  - Nickel-based alloys
  - Steels
Linear Friction Welding

- **New technology**
  - Concepts derived from direct-drive friction welding
  - Young technology, developed only ~15 years ago
  - Modern systems largely hydraulically based

- **Process inputs**
  - Normal force
  - Translational frequency
  - Translational displacement
  - Deceleration sequence for aligning parts

- **Advantages**
  - High deformations (~10s of thousands of percent) along bond line
  - Weld morphologies similar to other friction welds
  - Rapid (seconds) cycle times
Linear Friction Welds in Titanium Alloys - Characteristics

Macrosection of a Ti-6Al-4V Linear Friction Weld. Note the localized deformation zone and high apparent bond line strains. (Courtesy APCI Inc.)

Microstructure of a Ti-6Al-4V Linear Friction Weld Bond Line. Note the refined microstructure along the bond line as well as apparent resolutionizing. (Courtesy APCI Inc.)
Linear Friction Welds in High Carbon Steels - Characteristics

Macrosection of a 1080 Steel Linear Friction Weld. Note localized cracking at the weld edges related to high residual hardness. (Courtesy APCI Inc.)

Microstructure of a Ti-6Al-4V Linear Friction Weld Bond Line. Note the rapid transition from pearlite to martensite at the far HAZ boundary. (Courtesy APCI Inc.)
Translationally Assisted Upset Welding (TAUW) – New Generation Solid-State Welding

- Technology based on resistance butt welding
- Translational action to improve bond line strains
- Independent forging and scrubbing cylinders

- Independent action of
  - Current pulse
  - Translational action
  - Upset action

- Independent control of surface strains and heat content
Translationally Assisted Upset Welding - Characteristics

As Welded Specimen Showing Minimal Flash Curl

Bond Line Macrograph Showing Flash Curl and Bond Line Profile

Details of the Bond Line Showing Re-Solutionized Microstructure
Development of Multi-Material Thermal Protection Systems - Introduction

- **Large area TPS application**
- **Large temperature gradient application**
- **Core of resistance welded bimetallic honeycomb panel**
  - High thermal resistance
  - Low density
  - Secondary fabricability
- **Bi-material solution to accomplish desired temperature gradient**
  - High-temperature refractory material outer
  - Lower temperature material inner
- **Metallurgical considerations for dissimilar material joints**
  - Must be welding compatible
  - Must avoid thermal transitions at weld line

Candidate refractory materials: ceramics, C-C composites, refractory metals
Candidate honeycomb (hot side) materials: Moly alloys, Ta alloys, Nb alloys
Candidate honeycomb (cold side) materials: stainless steels, Ti alloys
Candidate PMCs: thermoset composites
Development of Multi-Material Thermal Protection Systems - Fabrication Steps

1. Foil manufacturing
2. Foil forming
3. Honeycomb manufacturing
4. Ceramic to refractory metal
5. Refractory metal to refractory core brazing
6. Ti (SS) sheet to core brazing
7. Adhesive bonding
8. Prototype TPS section
Electro-Spark Deposition (ESD) Process

- **ESD processing characteristics**
  - Repeat fire capacitive discharge power supply
  - Discharge pulse widths on the order of 35 μs
  - Peak currents on the order of 100s of amps

- **ESD torch**
  - Hand held
  - Rotating electrode

- **Short circuit sparking**

- **Transfer of small metal volumes (microns in diameter) to substrate**
Thermal Analysis of Various Localized Deposition Processes

Arc and Laser Processes: 

\[ T = \frac{Q}{2\pi KR} e^{\frac{V}{2\alpha x}} + T_o \]

ESD: 

\[ T = T_m - T_o \left[ \text{erf} \left( \frac{x}{x_{sp}} \right) \left( \frac{C_p}{H_m} \frac{T_m - T_o}{H_m} \right) \left( \frac{1}{\sqrt{\pi}} \right) \right] \]

Arc and Laser Processes: 

\[ \frac{dT}{dt} = 2\pi K \frac{V}{\dot{q}} (T - T_o) \]

ESD: 

\[ \frac{dT}{dt} = 2\alpha C_p \frac{\dot{q}}{\pi x_{sp}^2 H_m} (T_m - T_o)^2 \]
Electro-Spark Deposition Welding Trials

- Welding of ½ tensile specimens
- Weld prep
- Deposition practice:
  - Hastelloy X electrode (1.5-mm diameter)
  - 40-μF capacitance
  - 120-V charging voltage
  - 500-Hz firing rate
- Three specimens for materials combination
  - One for metallographic sections
    - Fill patterns
    - Internal fill quality
    - Intermetallic formation
  - Two samples each for mechanical testing
Electro-Spark Deposition Welding – Mo-47%Re to Hastelloy X

- **Procedure included**
  - Fill of initial groove
  - Formation of back groove
  - Filling back groove
  - Sideplates used to improve joint geometry
- **Fill nominally >99% dense**
- **Splat size nominally 10-μm thick**
- **Fill showed good adhesion to both components**
- **Processing time: 8 hr/specimen**

**Final Geometry of a ESD Joint**

**Cross Section of a Mo-47%Re to Hastelloy X ESD Weld**

**Microstructural Details of the Hastelloy X Deposit**
Electro-Spark Deposition Welding – Mo-47%Re to Hastelloy X

- **Hastelloy X/deposit interface**
  - Good adhesion of deposited material
  - No degradation of base material noted
  - Splat size in deposit on the order of the BM grain size

- **Mo-47%Re/deposit interface**
  - Good deposit adhesion noted
  - Little or no dilution with base metal
  - No evidence of second phases

Details of the Hastelloy X/Deposit Interface

Details of the Mo-47%Re/Deposit Interface
Electro-Spark Deposition Welding – Mo-47%Re to MarM 247

- **Joint macrostructure**
  - Fill characteristics similar to that for other ESD welds
  - Apparent adherence to both the Mo-47%Re and MarM 247 materials
  - Two-side deposition evident

- **MarM 247/deposit interface**
  - Good adhesion of deposited material
  - Apparent reaction zone between the base metal and deposited splats
  - Interface morphology similar to that seen for magnetic pulse welds
  - Reaction zone on the order of microns thick
Use of Thermal Constructs for Preliminary Cost Scaling of New Technologies

- **Application**: High-speed indirect resistance brazing of internally reinforced panels
  - Thin-gauge construction
  - Automotive customer

- **Development of roll brazing technology**
  - Resistively heated rolls
  - Flood cooling to control overall thermal cycle

- **Integration of low-cost materials**
  - Mild and AHSS steels
  - Galvanized coating as the braze alloy

- **Preliminary trials on resistance brazing using the galvanized coating**
  - Reflow with single point resistance heating
  - Joint strengths ~50% that of full spot welds

Zinc re-flow at the center of a braze joint at best practice conditions (Courtesy CellTech Metals)

Zinc re-flow at the edge of a braze joint at best practice conditions (Courtesy CellTech Metals)

Strengths for Joints made at Increasing Currents Showing the Transition from Brazing to Welding (Courtesy CellTech Metals)
Preliminary Assessments of the High-Speed Manufacturing System for Automotive Panel

- **Thermal analyses for predicting strip heating and cooling**
  - Closed form solutions
  - Geometric and material property effects
  - Estimates of heating and cooling dynamics
  - Temperature-time relationships at each interface

- **Estimates of processing requirements**
  - Total thermal cycles on the order of 10s of milliseconds
  - Speeds in the range of m/min
  - Influence of panel design
  - Estimates of currents and voltages

- **Demonstration trials underway**

\[ \theta = \theta_w - \frac{4 \theta_w}{\pi} \sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1} \exp\left( -\frac{\alpha (2n+1)^2 \pi^2 x}{4 (\xi_1 + \xi_2)^2 v} \right) \]

Equation Defining Conductive Heating Associated with the Hot Roll Technology (Courtesy CellTech Metals)

\[ \theta = \theta_0 + (\theta_h - \theta_0) \exp \left[ \left( \frac{v}{2 \alpha} - \sqrt{\left( \frac{v}{2 \alpha} \right)^2 + \frac{H}{K_1 (\xi_1 + \xi_2 R)}} \right) x \right] \]

Equation Defining Cooling Associated with the Hot Roll Technology (Courtesy CellTech Metals)

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Heating and Cooling Profile for a 1.5-mm Thick Panel During Resistance Roll Brazing (Courtesy CellTech Metals)

Relationships Between Panel Geometry Factors and Line Speed for Resistance Roll Brazing (Courtesy CellTech Metals)
Friction Stir Welding of High-Temperature Alloys

- Third body friction welding process
- Necessary interactions between tool and substrate materials
- Refractory metal and ceramic tool systems
- Bond line strains defined by plastic zone

- Thermal cycles defined by processing speeds
- Initial work done on titanium alloys
- Current focus is on steels
- Preliminary studies on nickel base alloys

FSW on 13-mm Ti 6Al-4V
FSW Corner and T-Joints
- Single pass (no inter-pass cleaning issues)
- Low distortion
- Cycle time reduction (1 pass ~100-mm/min versus 4 passes at ~500-mm/min w/GMAW)
- Simple joint preparation

FSW Corner Joint 13-mm Ti 6Al-4V
Tool Evaluations for Welding X80 Steel

- **Tungsten-based tool materials**
  - 99% W, 1% La$_2$O$_3$
  - 75% W, 25% Re
  - 70% W, 20% Re, 10% HfC

- **Extreme tests**
  - Hot processing conditions
  - No external cooling
  - Intended to exacerbate wear

- **Mechanisms of wear**
  - Deformation
  - Twinning
  - Intergranular failure

- **Best demonstrated material** – 70% W, 20% Re, 10% HfC
  - Negligible deformation
  - Minimal abrasive wear
  - Excellent tool shape stability

Matl. C Tool After Welding
Matl. C Edge Effect
Matl. C Digital Profilometry Data
# Resistance and Solid-State Technologies – Summary

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Questions?

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Since the early 1980s, EWI has helped manufacturers in the energy, defense, transportation, construction, and consumer goods industries improve their productivity, time to market, and profitability through innovative materials joining and allied technologies. Today, we also operate a variety of centers and consortia to advance U.S. manufacturing through public/private cooperation.