Novel Technologies for Similar and Dissimilar Titanium Joints

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Not-for-Profit Project Based Development
- Continuous development activities
- Single & group development programs

Facility
- 132,000 ft² manufacturing development

Staff
- 150 dedicated, experienced staff
- Most EWI engineers hold advanced degrees
- Many are well known for their skills in the industry
- Most EWI engineers have significant industrial experience

Engineering Disciplines
- Welding, Material Science, Mechanical, Electrical, Design,
  Manufacturing, Industrial Systems, Ceramics, and Chemistry

Global presence and networking capability.
Novel Joining Technologies

- **Electro-Spark Deposition (ESD)**
  - Typically used for surface crack repair and coating
  - Recently applied as a joining method
    - Typical joint thickness <0.125-in
  - Can be applied to a variety of material combinations
    - Refractory alloys, Ti, steel, Al, Cu, and others

- **Friction Stir Welding (FSW)**
  - Typically used for joining material in a butt- or lap-joint configuration
  - Solid-state process
  - Joint thickness from 0.020- to 1.0-in.
  - Used to join Al, Cu, Mg, steel, Ti, Ni, and some dissimilar combinations
Electro-Spark Deposition (ESD) Process Fundamentals

- **ESD processing characteristics**
  - Repetitive fire of a capacitive discharge power supply
  - Discharge pulse widths are approximately 35 μsec
  - Peak currents are ~100s of amps

- **ESD torch**
  - Hand held or fixed position
  - Rotating electrode

- **Short circuit sparking**

- **Transfer of small metal volumes (microns) to substrate**
Electro-Spark Deposition (ESD) Process Fundamentals

- **ESD deposit characteristics**
  - Deposit layers typically microns thick
  - Deposition rates typically <100 μg/sec
  - Multiple layers used to create a deposit
  - Virtually no heating of the substrate

- **Application to complex materials joining problems**
  - Achieves a fine material grain structure
  - Fast cooling rates (>10^5°C/s)
  - Non equilibrium solidification and suppression of solid-state transformations
Thermal Analysis of Various Localized Deposition Processes

Arc and Laser Processes:

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

ESD:

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

Arc and Laser Processes:

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

ESD:

\[ \frac{dT}{dt} = \frac{2\alpha C_p}{\pi x_{sp}^2 H_m} (T_m - T_o)^2 \]
ESD Welding
Mo-47%Re to Hastelloy X

Procedure included
- Fill of initial groove
- Formation of back groove
- Filling back groove
- Side plates used as “run-on/-run-off

Fill is nominally >99% dense
Splat size nominally 10-μm thick
Fill showed good adhesion to both components
Processing time: 8 hr/specimen

Welded ESD Joint
Cross-section
ESD Welding
Dissimilar Metal Joining

- **Materials**
  - Ti-6Al-4V to 1010 Steel & Ti-6Al-4V to IN718
  - Welding performed in argon-filled glove box
  - Samples ground to 320 finish before welding
  - Samples weighed before and after welding
  - 10 passes (layers) per sample

- **Analysis**
  - Metallographic cross-sections
  - Microscopy
    - Optical, SEM, and EDS

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<table>
<thead>
<tr>
<th>ESD Parameters Used</th>
<th></th>
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<tbody>
<tr>
<td>Pulse Rate</td>
<td>400 Hz</td>
</tr>
<tr>
<td>Capacitance</td>
<td>70 µf</td>
</tr>
<tr>
<td>Voltage</td>
<td>150 V</td>
</tr>
<tr>
<td>Electrode RPM</td>
<td>1200</td>
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<tr>
<td>Primary Amperage</td>
<td>6A</td>
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ESD Welding
Ti-6Al-4V onto 1010 Steel

- Deposit characteristics
  - Extreme cracking and breaking of deposit
  - Inconsistent deposit thickness
  - No distinguishable HAZ

- Multiple constituents present
  - Turbulent mixing of constituents
    - 3-4 constituents seen in deposit
  - Large amount of Fe throughout deposit
  - Ti-6Al-4V was not detected by EDS
    - Suggesting large amounts of dissolution

- Compositional measurements of the constituents
  - Compositions do not show typical solidification patterns
  - Compositions do not correlate to
    - Intermetallics
    - Eutectics

Overlay of ESD Results
ESD Welding
Ti-6Al-4V onto IN718

- Deposit characteristics
  - Some areas free of cracking and porosity
  - No distinguishable HAZ
- Multiple constituents present
  - Less mixing of constituents
    - Mixing mostly seen near the interface
  - Ti-6Al-4V identified in deposit layer
    - Suggesting less dissolution than between the Ti-6Al-4V to steel
    - Likely caused by low thermal conductivity
  - Dissolution still seen near interface
- Compositional measurements made of the constituents
  - Compositions do not show typical solidification patterns
  - Compositions do not correlate to
    - Intermetallics
    - Eutectics

Overlay of ESD Results
### ESD Welding
Differences in Deposition Behavior

<table>
<thead>
<tr>
<th>Material Combination Electrode/Substrate</th>
<th>Subst. Melting Temp. (°C)</th>
<th>Electrode Melting Temp. (°C)</th>
<th>Subst. Thermal Diffusivity (W/m-K)</th>
<th>Pulse Width</th>
<th>Pulse Height (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti 6Al4V/1010 Steel</td>
<td>1500</td>
<td>1604</td>
<td>49.8</td>
<td>90</td>
<td>180</td>
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<tr>
<td>Hastelloy-X/T-111</td>
<td>3080</td>
<td>1355</td>
<td>57.1</td>
<td>55</td>
<td>245</td>
</tr>
<tr>
<td>Hastelloy-X/MarM-247</td>
<td>1452</td>
<td>1355</td>
<td>10-15</td>
<td>55</td>
<td>245</td>
</tr>
</tbody>
</table>

Note the very fine interface from a short pulse width. This suggests pulse width plays a larger role than material properties.
ESD Welding
Current Waveform & Deposit Quality

- **Increased pulse width**
  - Longer pulse widths increase the heat input and decrease the cooling rate
    - Creating longer times at high temperatures
    - Resulting in more substrate melting and mixing with the deposited layer

- **Comparison with previous work suggests shorter pulse widths will decrease or eliminate cracking**
  - Successful deposits have been at less than 60-μs pulse width
  - Current welding was done at pulse widths of 90-100 μs
ESD Welding
Metallurgical Implications for Dissimilar Material Joints

- **Effects of high cooling rates on solidification**
  - Equally high solidification rates
  - Dendritic solidification without segregation
  - Solidification morphology surface tension rather than compositionally driven
  - Elimination of drivers for solidification cracking
  - Potential for a wide range of solid-solution phases

- **Effects on solid-state phase transformations**
  - High cooling rates suppress second phases
  - Allows super-saturated phases to exist at room temperature
  - Potential for complex phase distributions with post-weld heating

- **Parallels in other pulse weld technologies**
  - Magnetic pulse welding
  - Percussion welding

- **Pulse width is a crucial variable in ESD**
  - Large effect on heat input and cooling rate
  - Pulse widths of 90 to 100 μs result in voids and cracking
  - Pulse widths less than 60 μs are more successful for joining dissimilar materials
Friction Stir Welding (FSW)

- Solid-state joining process
- Originally developed for joining aluminum
- Uses a 3rd body tool rotating as the heat source
- Tool rotates and traverses along a joint
- Work has extended the process to welding of hard metals
  - Steel, Titanium, Nickel
FSW Ti-6Al-4V Structural Geometries

Butt, Corner and T-Joint example geometries

60-in. T-Joint

48-in. Butt Joint

>1-in. Penetration

24-in. Corner Joint
Additive manufacturing is now being widely considered

- Opportunity for material savings
- Rapid prototyping method

FSW
Ti-6Al-4V Additive Manufacturing
FSW
Ti-6Al-4V Static Mechanical Properties

- Post-weld heat treatment: 1150ºF, 2 hrs.
- Tested per ASTM E8
  - Sub-size specimens (1.0-in. gauge length and 0.25-in. diameter)
  - Room temperature
- Weld metal failure in the GMAW-P (pulsed) specimens
- HAZ failures in the FSW specimens
Questions
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.