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Non-Rotating Solid-State Welding Technologies

◆ Process definitions
  – Adaptable to non circular sections
  – Heating stage
  – Forging stage
  – Development of a solid-state bond
  – Single shot processing

◆ Advantages of solid-state processing
  – Properties
  – Product metallurgy
  – Productivity

◆ Typical process variations
  – Flash butt welding
  – Resistance butt welding
  – Resistance projection welding
  – Hot pressure welding
  – Linear friction welding
Characteristics of Upset Welding (UW) Processes

- **Mature technology**
  - Transformer and timer based
  - Single direction forging systems
  - Widely used in industry today
  - Implicit low scrap rates

- **Process inputs**
  - Current
  - Force
  - Time

- **Advantages**
  - Well established technology
  - Rapid (seconds) cycle times
  - High productivity
  - Well adapted to carbon steels
  - Application of temper cycles

- **Disadvantages**
  - Limited widths and areas
  - Uni-directional forging
  - Large upset volumes
  - Max strains on the order of 1000%
  - Sensitive to material resistivity
  - Not adaptable to a wide range of materials
Characteristics of Linear Friction Welding (LFW)

- **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 (~10’s of thousands of percent) along bond line
  - Weld morphologies similar to other friction welds
  - Rapid (seconds) cycle times
  - High productivity
  - Highly localized upsets
  - Adaptable to a wide range of materials

- **Disadvantages**
  - High equipment costs
  - Complexity of controls and tooling
  - Equipment scale
  - Final part alignments
  - Inability to apply post weld heat treatments

Linear friction welding system. Courtesy Thompson Friction Welding Machines

Titanium alloy linear friction welds. Courtesy Thompson Friction Welding Machines

Definitions of Translationally Assisted Upset Butt Welding (TAUW)

- Translationally assisted upset butt welding (TAUW)
  - Mechanistically similar to Upset Butt Welding
  - Introduction of lateral motion
  - Process heating largely accomplished through resistance mechanisms
  - Lateral motion to add a second degree of freedom during deformation
  - Relatively low lateral motion frequencies
  - Equipment costs comparable to UBW
  - Bond line strains (and weld quality) approaching LFW
  - Reductions in material loss compared to UW

- Scope of the current program
  - Adapt an existing UW system for translational action
    - Design and acquisition of a lateral motion system
    - Integration into the existing machine
    - Development of necessary tooling
  - Definition of a candidate application
    - Identification of program stakeholders
    - Review of existing and potential applications
    - Selection of materials and geometries for study
  - Process demonstrations
    - Manufacture of sample welds
      - Without translation
      - With translation
    - Assessment of processing requirements
    - Microstructures of resulting joints
Candidate Applications and Materials

- **Specific applications**
  - Blisks
  - Aircraft structural elements
  - Wheels

- **Materials**
  - Titanium alloys
  - Nickel base alloys
  - Steels

- **Down-selected applications**
  - Ti-6Al-4V
  - 1018 steel
  - Nominal 6-mm x 50-mm cross section

Blisk assembly with LFW attached blades. Courtesy MTU Aero Engines

Stamped and welded truck wheel rims. Courtesy Accuride Wheels
Design and Integration of the Translational Motion System

- **Definition of system requirements**
  - Based on the selected application
  - 36-kN upset force
  - 70-kN lateral force
  - 6-mm lateral displacements

- **Base welding system**
  - Thompson F3 welding frame
  - 40-kN max upset force
  - 3ΦDC power supply

- **Translational action**
  - Parker Hannfin system
  - Compax3F control/drive
  - VPak power unit
  - 100-mm diameter cylinder
  - D3FH proportional valve
  - Probe and linear alignment coupler for feedback control

Electric servo-drive system. Courtesy Parker-Hannifin Corporation

Thompson F3 upset butt welding frame available at EWI
Tooling and Software Developed for Allowing Translational Motion

- **Tooling developed for TAUW**
  - Translational slide assembly built onto existing platens
  - Support brackets to accommodate reactive translational torques
  - Integrated conductive path on the translating clamp
  - Simplified clamps for restraining test workpieces

- **Software integration for the final system**
  - Translational motion software provided by Parker-Hannifin
  - Interface for programming displacement, frequency, and numbers of motions
  - System initiated from the main welding control
  - Sequencing between current and the translational and upset motions

- **Instrumentation for monitoring**
  - Weld current
  - Lateral displacement
  - Forge displacements
**Upset Butt Welding (UW) Trials on Ti-6Al-4V**

- Ti-6Al-4V coupons
- 6-mm x 50-mm cross sections
- Iterative welding trials
- Initial practices based on steels
  - 5 to 15-mm stickout
  - 75 to 150 MPa upset stresses

<table>
<thead>
<tr>
<th>Weld no.</th>
<th>Force (kN)</th>
<th>Stickout per side (mm)</th>
<th>Current (kA)</th>
<th>Up-slope time (ms)</th>
<th>Weld time (ms)</th>
<th>TAUW</th>
<th>Motion delay (ms)</th>
<th>Upset dist. (mm)</th>
<th>Comments</th>
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Upset Butt Welding (UW) Trials on Ti-6Al-4V

- Full faced bonding
  - Width
  - Through thickness
- Non-uniform heating across the width
- Differential flash profile
  - Bifurcated at the center
  - Continuous at the edges

- $\alpha+\beta$ base material
- Partially transformed HAZ in the forge region
- Narrow $\beta$-transformed zone along bond line
- Bond area ~3x the base material thickness
- ~240% bond line strain
- Extensive flash removal required
Translational Upset Butt Welding (TAUW) Trials on Ti-6Al-4V

- Quality measures primarily through bend testing
- Heating times varied from 750-ms to 3000-ms
- Translational action at the end of the heating cycle

<table>
<thead>
<tr>
<th>Weld</th>
<th>Stickout (mm)</th>
<th>Weld Force (kN)</th>
<th>Upslope (ms)</th>
<th>Weld time (ms)</th>
<th>current (kA)</th>
<th>offset</th>
<th>strokes</th>
<th>upset (mm)</th>
<th>Bend test (kN)</th>
<th>Comments</th>
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<td>4.57</td>
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<td>Sample used for both met and bend testing</td>
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<td>1000</td>
<td>10.8</td>
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<td>3</td>
<td>-</td>
<td>-</td>
<td>Tensile test performed on this sample</td>
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</table>

*Sample sectioned lengthwise, 1/2 used for bend testing, 1/2 for met evaluations. The reported bend strength is for this half sample width.
General Characteristics of TAUW on Ti-6Al-4V

<table>
<thead>
<tr>
<th>Ultimate Strength (MPa)</th>
<th>0.2% Yield Strength (MPa)</th>
<th>Elongation (%)</th>
<th>Reduction of Area (%)</th>
<th>Failure Location</th>
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<tr>
<td>321</td>
<td>312</td>
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<td>784</td>
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<td>14.8</td>
<td>Weld</td>
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</table>

![Current (kA) vs. Displacement (mm) graph]

![Magnified view of weld region]
Visual Observations During TAUW of Ti-6Al-4V
Microstructural Characteristics of TAUW on Ti-6Al-4V
# Translational Upset Butt Welding (TAUW) Trials on 1018 Steel

- **Practices based on UW for steels**
- **Use of a 4-kA, MFDC power supply**
- **Preliminary quality evaluations through manual bend testing**
- **Higher currents compared to Ti-6Al-4V**
- **Reduced stroke lengths**

## Weld Stickout, Weld Force, Upslope, Weld time, Current, Offset, Strokes, Upset, Bend test, Comments

<table>
<thead>
<tr>
<th>Weld</th>
<th>Stickout (mm)</th>
<th>Weld Force (kN)</th>
<th>Upslope (ms)</th>
<th>Weld time (ms)</th>
<th>Current (kA)</th>
<th>Offset (mm)</th>
<th>Strokes</th>
<th>Upset (mm)</th>
<th>Bend test (kN)</th>
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<td>3</td>
<td>0</td>
<td>-</td>
<td>repeat of conditions from sample 19 for tensile test</td>
</tr>
</tbody>
</table>
# General Characteristics of TAUW on 1018 Steel

## Table of Results

<table>
<thead>
<tr>
<th>Ultimate Strength (Mpa)</th>
<th>0.2% Yield Strength (Mpa)</th>
<th>Elongation (%)</th>
<th>Reduction of Area (%)</th>
<th>Failure Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>607</td>
<td>486</td>
<td>5.0</td>
<td>21.8</td>
<td>Weld</td>
</tr>
<tr>
<td>617</td>
<td>488</td>
<td>6.2</td>
<td>23.9</td>
<td>Weld</td>
</tr>
</tbody>
</table>

![Graph](image1.png)

![Image](image2.png)
Visual Observations During TAUW of 1018 Steel
Hardness Distributions – Tensile Behavior Relationships on the Steel Samples

- Yield strengths comparable to the base material
- Relatively limited elongation compared to the base material
- Impact of metallurgical notches around the weld
- Very narrow HAZ
- Hardness values maximize around 350-VHN to 375-VHN
- Through thickness uniformity in hardness variations
Analysis of Resistance Heating During TAUW

- Thermal analysis based on previous activity for resistance spot welding
- One dimensional analysis
- Pure resistive heating
- Sinusoidal temperature distribution between the dies
- Peak temperature at the end of resistance heating
- Influence of thermal conductivity

\[ \Theta = \Theta_p \frac{1 + \left( \frac{1}{5\pi} \right) \left( \frac{k_e}{k_w} \right) \cos \left( \frac{\pi}{2\Delta x} x \right)}{1 + \left( \frac{1}{5\pi} \right) \left( \frac{k_e}{k_w} \right)} \]
Temperature Dependent Yield Strengths of Ti-6Al-4V and 1018 Steel

- Temperature dependent yield strength data collected from the literature
- Extensive softening at higher temperatures
- Ti-6Al-4V typically stronger at all temperatures
- Data fit with sigmoidal equations
- Equations can be integrated with developed thermal solutions

\[
\sigma_{\text{steel}} = 62 \times \text{Asinh} \left( \frac{570 - T}{40} \right) + 255
\]

\[
\sigma_{\text{Ti}} = -420 \times \text{Asinh} \left( \frac{T}{450} \right) + 850
\]
Temperature and Yield Strength Variations for TAUW on Ti-6Al-4V and 1018 Steel

\[
\begin{align*}
\Theta_p\text{-steel} &= 1100 \, ^{\circ}\text{C} \\
\Theta_p\text{-ti} &= 1450 \, ^{\circ}\text{C} \\
k_e &= 367 \, \text{W/m-K} \\
k_s &= 41.9 \, \text{W/m-K} \\
k_{\text{Ti}} &= 6.7 \, \text{W/m-K} \\
\text{stickout} &= 7.6 \, \text{mm}
\end{align*}
\]
Translationally Assisted Upset Butt Welding – Conclusions

- TAUW a new technology
  - Augmented strains compared to UW
  - Bonding at reduced upset distances
- Hardware development to add translational action
- Comparisons with conventional UW
- Demonstrations using both Ti-6Al-4V
- Primary upset occurring during translational action
- Current flow providing preheating
- Elimination of “shear peaks”
- Limited translational action required
- Modeling demonstrating differences in heating for the two material systems
Questions?

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