Friction Stir Welding of Aluminum and Titanium alloys

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### Report Documentation Page

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Standard Form 298 (Rev. 8-98)  
Prescribed by ANSI Std Z39-18
Friction Stir Welding and Processing

- Friction stir **welding** will offer structural assemblies with high efficiency (Performance)
  - Examples: Through **lowering of weight** by elimination of fasteners
    - (Large cargo aircraft have approximately 1,000,000 fasteners)
- Many calculations show that cost (Affordability) will be lower with FSW once initial equipment is purchased
- Friction stir **processing** offers a route to
  - Superplastic forming
  - Elimination of cast microstructure and casting defects
Why is USAF doing this work?

• Replace fusion welding for Reusable Launch Vehicles and Next Generation Launch Technology
  – Current fusion welding methods are inadequate
  – Property loss with each repair

• Aging aircraft applications
  – Corrosion at fasteners
    • $1B corrosion costs just for Air Force

• Future Aircraft
  – Unitized Structures
  – Components of UCAV
Background

• FSW was invented at TWI (Cambridge) in 1991 and patented in 1992. Now in use and under study worldwide.
• Process is well established for Al alloys in a wide range of thickness.
• Proof of concept demonstrated for steel and Ti but not in commercial use yet.
Key Process Variables

• Process Control
  – Z-axis force: the forging force normal to the plate
  – Tool rotation rate
  – Welding speed.
  – Lead angle: tool tilt relative to the plate (0°-3°)

• Process response
  – X-axis force: opposing tool motion
  – Y-axis force: perpendicular to tool motion in the plane of the plate
  – Torque (power)

• Other
  – Plate thickness (1mm-75 mm, depending on material).
  – Plate composition (flow properties).
  – Tool geometry (shoulder and pin).

Good welds may be made with large variation in any or all of these variables; however, the best* weld requires careful choice.

*What is this?
Typical FSW Tools

W-Re tool in collet-style tool holder. Used for welding steels and $Ti$ alloys

Tools for conventional welding of al-alloys

3-piece self-reacting tool

Shoulder 25 mm $\phi$

Pin 10 mm $\phi$

CBN tool for welding steel sheet

Courtesy: Professor Tony Reynolds, University of South Carolina
FSW Terminology

Microstructure

No solidification structure or defects and max T may be considerably below the solidus.

Dynamically recrystallized zone (Jata & Semiatin: Scripta Materialia, 2001)
Superplastic formable (Reynolds: Materials Science & Engineering, 2003)
Typical Hardness Profiles after FSW

Schematic for Al alloys

Weld Centerline

Refined structure

OA

SHT

Overaged

O-temper, 5XXX alloys, stainless steels, ferritic steels.

Most precipitation hardened alloys.

Distance

Hardness

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FSW Defects
(un-)Commonly Encountered

- Reduction in sheet thickness: simple loss of load bearing cross-section.
- Lack-of-Penetration, LOP/cold lap/kissing bond
- Advancing side wormhole or tunnel.
- Surface lack of fill.
Wormhole Defect Production

- Weld, ≈ 0.67m long in 2219, 9 mm thick plate.
- 1.7 mm/s welding speed.
- rpm varying continuously from 90-900.
- Advancing side defects observed at very high and very low advance per revolution (low and high RPM).

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FSW is being applied to A/C

Large Cargo A/C floor
Corrosion needs to be proven

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Low residual stresses in FSW

X-Rays
CT Coupons

Residual stress, MPa (longitudinal component)

Distance from center line of weld, mm

Al-Li-Cu alloy: C458-T8
as-FSW
Low residual stresses in FSW

![Graph showing residual stresses in FSW for Al-Li-Cu alloy C458-T8 as-FSW to top and back side of weld.](image-url)
Fatigue crack growth in Al-Li alloy C458

Al-Li-Cu alloy C458-T8
As friction stir welded

Fatigue crack growth in Al-Li alloy C458-T8 as friction stir welded.
Fatigue in the weld; Nugget vs. HAZ

C458-T8 (TL)
R=0.3; dry air
EC(T)

ΔK, MPa-m^{1/2}

da/dN, m/cycle

weld nugget
Heat Affected Zone
Effect of specimen geometry on FCG?
Ti alloys
Joining Considerations for Ti

- Joining of Ti alloys is complicated by their high reactivity and low thermal diffusivity
- Embrittlement resulting from the absorption of interstitial elements (O, N, and H)
- Formation of porosity in fusion welds
- Strong dependence of microstructure and properties on processing history
Joining Considerations for Ti

- Solid-state process eliminates problems associated with melting and resolidification.
- Uses cylindrical tool with cylindrical pin extending from shoulder.
- Tool is rotated to desired RPM and plunged into joint.
- After short dwell time, tool is traversed along joint.
- At end of joint, tool is lifted and rotation is stopped.
Experimental Procedures

- ~ 1/4” (~6mm) Ti-6Al-4V plate in mill annealed condition
- FSW at 4 ipm (100 mm/min) using inert gas shroud
- Optical microscopy: Etch with 3% HF & 10% H₂O₂ in water.
- Microhardness testing: 1 kg load & 15 seconds dwell time.
- Bend testing and transverse tensile testing at room temperature
FSW of Ti-6Al-4V
Top View of the FSW Butt Joint
Optical Macrograph

Transverse cross-section of FSW on Ti-6Al-4V
Optical Microscopy

Ti-6Al-4V Base Metal:
mill annealed condition
Microhardness Indentations

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Microhardness Test Results

Microstructural Analysis by SEM
BEI images of FSW in Ti64

HAZ

Stir Zone

-60 µm
40 µm
240 µm
440 µm
3000 µm

500 µm

20 µm
Stir Zone (Nugget) Microstructure

Base metal

Nugget
Transformed $\beta$ volume fraction versus position

![Graph showing transformed $\beta$ volume fraction versus position with data points and line graph. The x-axis represents position from HAZ/Nugget Boundary (µm) ranging from -500 to 3500, and the y-axis represents Volume Fraction (%) ranging from 0 to 100. The graph includes a line for Volume Fraction and a dashed line for True Vol Fract at T. Jata/US Air Force]
Vertical section in Ti-Al-V Phase Diagram

Stir Zone
HAZ

Temperature, °C

Weight Percent V
Results - Bend Test

ε > 12%

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Ti64: Tensile Test Specimens
## Tensile Properties: Ti-6Al-4V

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<th>Base Metal</th>
<th>FSW</th>
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<td>895</td>
<td>912</td>
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<td>Tensile Strength: (MPa)</td>
<td>957</td>
<td>1012</td>
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<td>% Elongation:</td>
<td>12.7</td>
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Summary

• BM was equiaxed $\alpha$ with gb $\beta$
• % prior $\beta$ in HAZ increased with decreasing distance from stir zone
• Stir zone contains acicular $\alpha$ in fine prior $\beta$ grain size
• Weld tensile tests exhibit excellent joint efficiency and ductility
• FSW of Ti alloys is feasible
Research Areas

• Research Gaps
  – Need an Al alloy that is friction stir weldable and has all the good mechanical properties !!!!
  – How do you make the HAZ of ppt hardened Al alloy less corrosion susceptible?
  – A Model that will predict FSW properties for all Al alloys without extensive testing
  – Need a good FSW tool for Ti alloys