Friction Stir Welding of Aluminum and Titanium alloys

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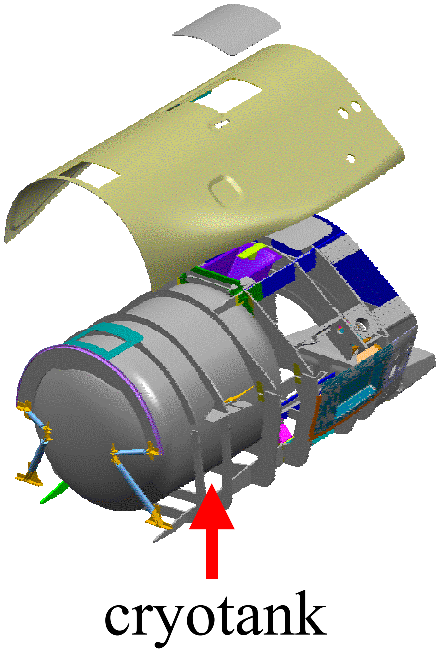
Prescribed by ANSI Std Z39-18

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

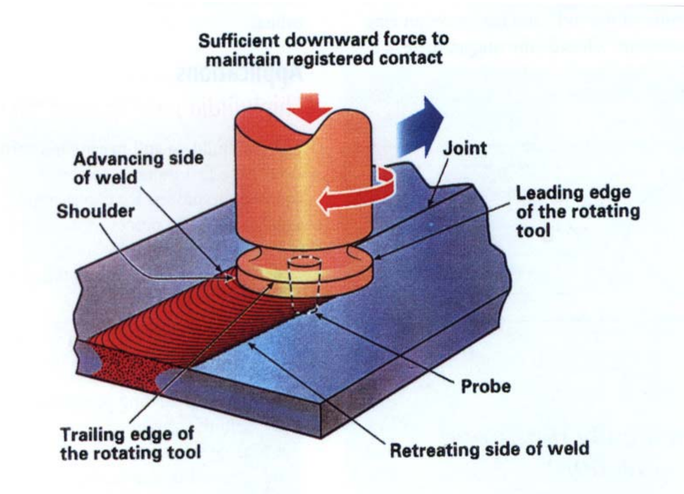


- Aging aircraft applications
  - Corrosion at fasteners
    - $1B corrosion costs just for Air Force
- Future Aircraft
  - Unitized Structures
  - Components of UCAV

Background

- FSW was invented at TWI (Cambridge) in 1991 and patented in 1992. Now in use and under study world wide
- 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.

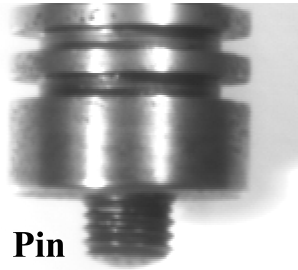
*What is this?

Typical FSW Tools

Tools for conventional welding of al-alloys

3-piece self-reacting tool

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

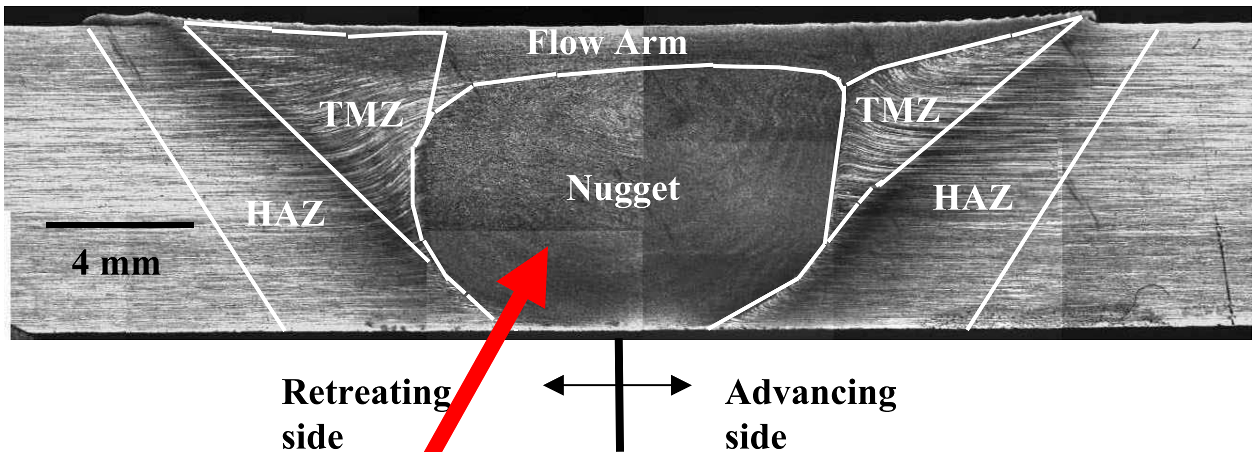


CBN tool for welding steel sheet

Courtesy: Professor Tony Reynolds, University of South Carolina

FSW Terminology

Microstructure

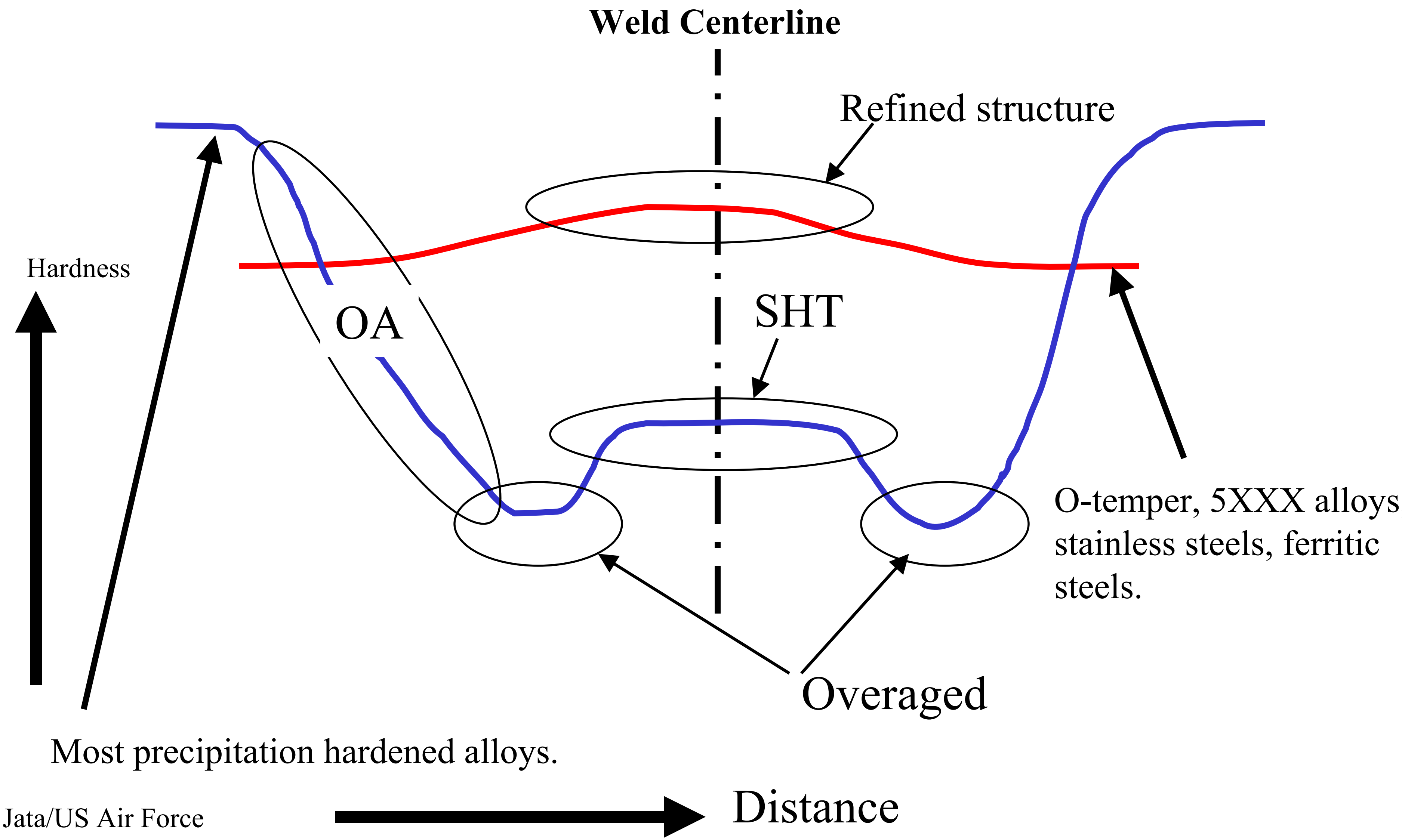


No solidification structure or defects and max T may be considerably below the solidus.

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

Typical Hardness Profiles after FSW

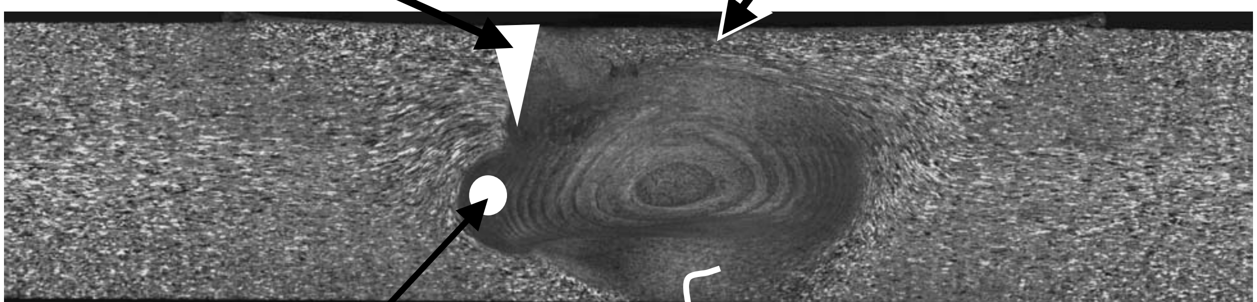
Schematic for Al alloys



FSW Defects (un-)Commonly Encountered

Surface lack of fill.

Reduction in sheet thickness: simple loss of load bearing cross-section.



Advancing side wormhole or tunnel.

Lack-of-Penetration, LOP/cold lap/kissing bond

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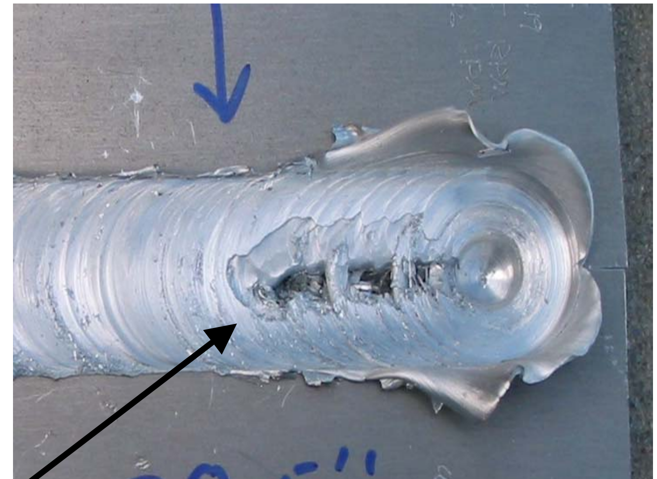
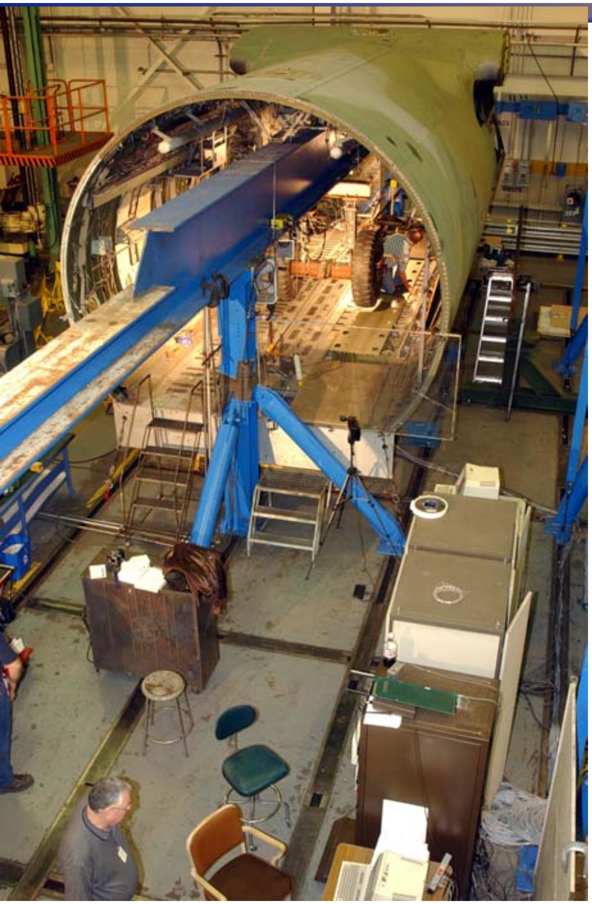
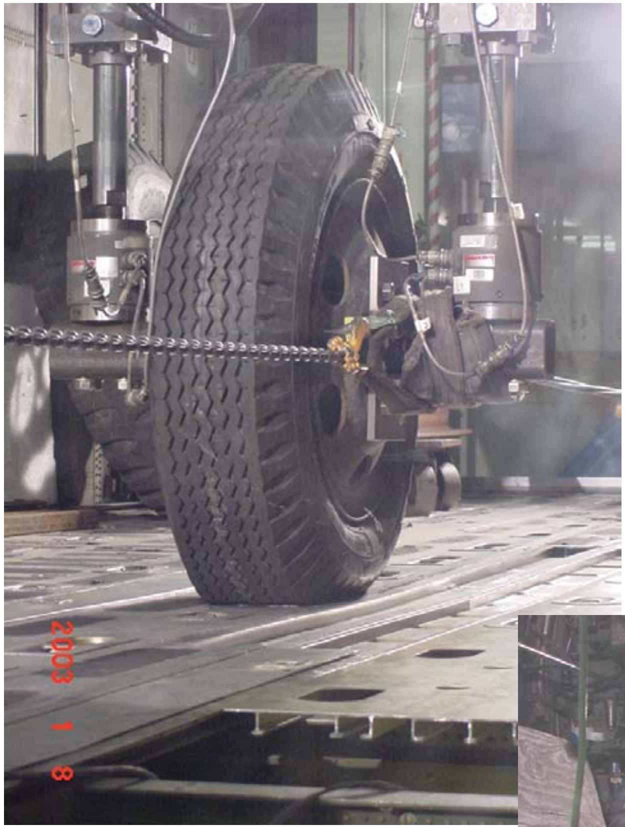
Wormhole Defect Production



- 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).

FSW is being applied to A/C





Large Cargo A/C floor

Corrosion needs to be proven

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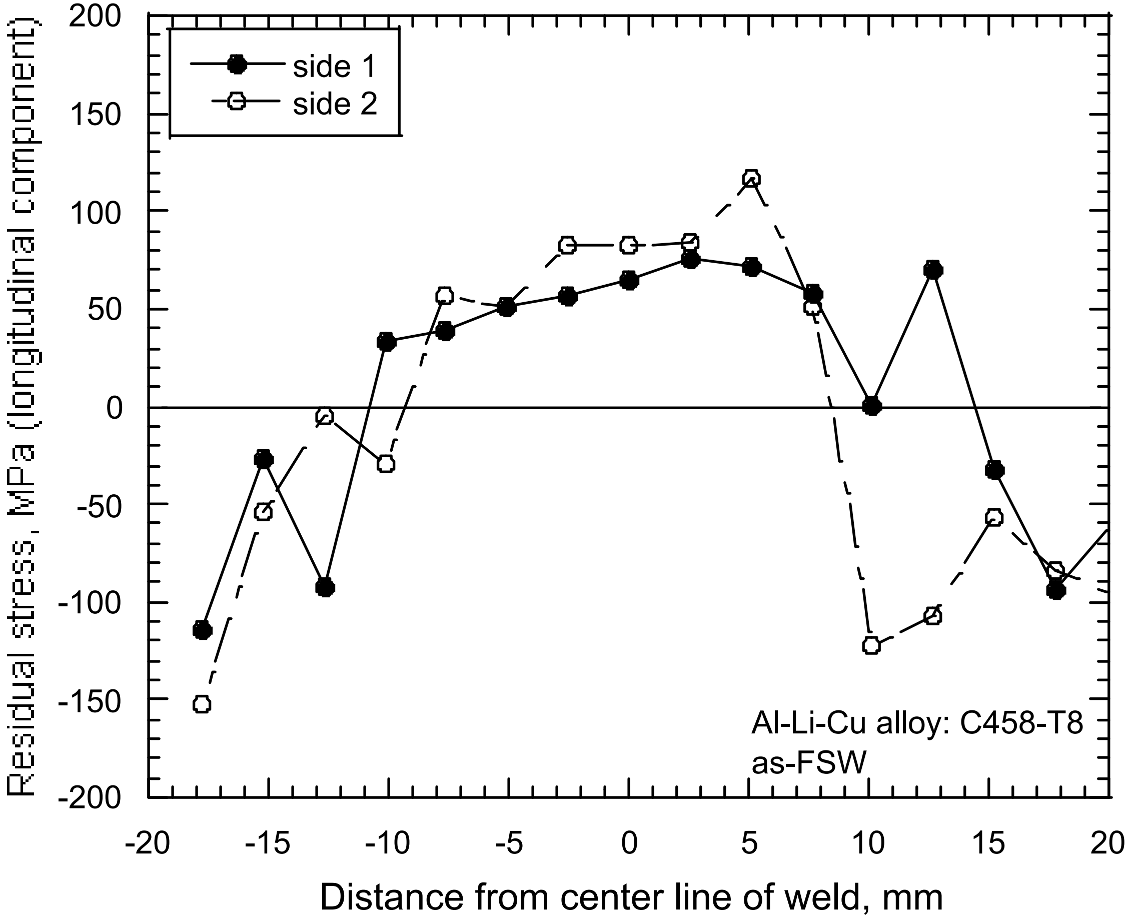
Low residual stresses in FSW

X-Rays
CT Coupons



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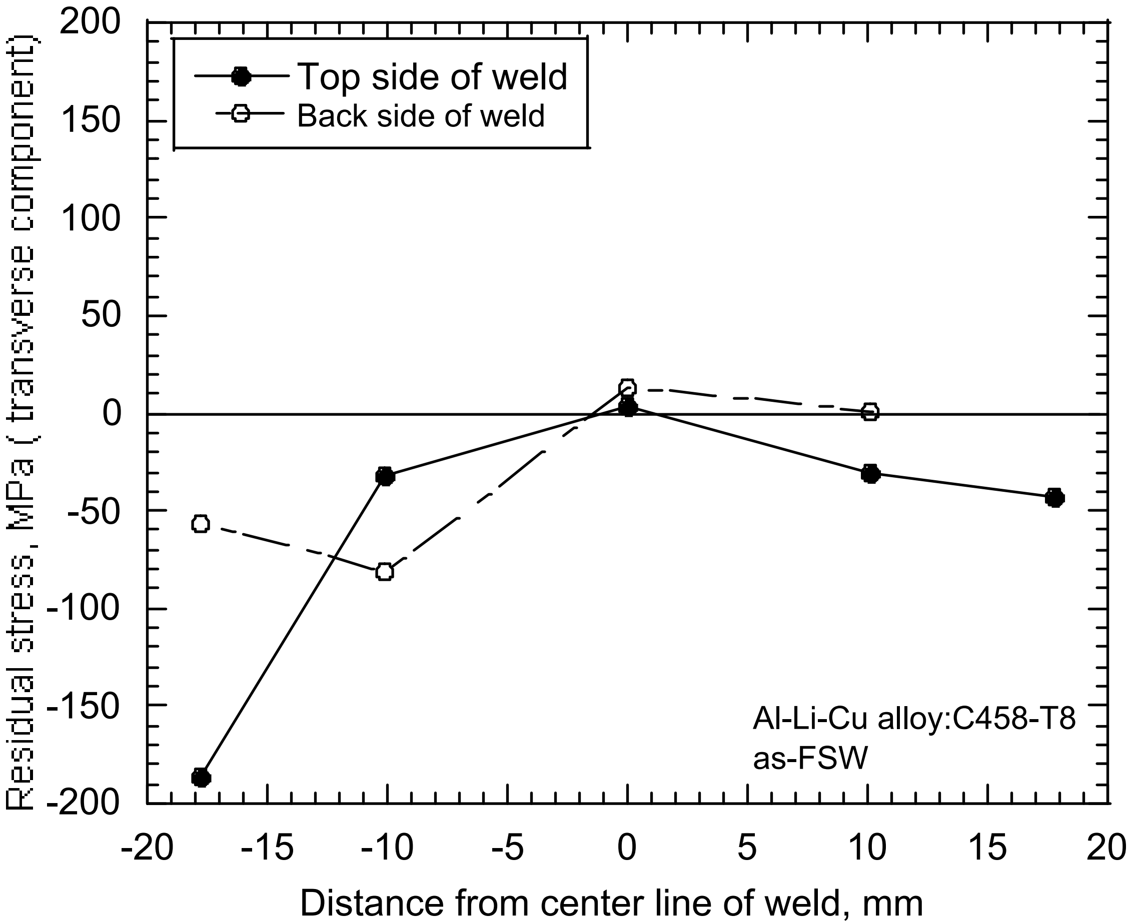
Low residual stresses in FSW



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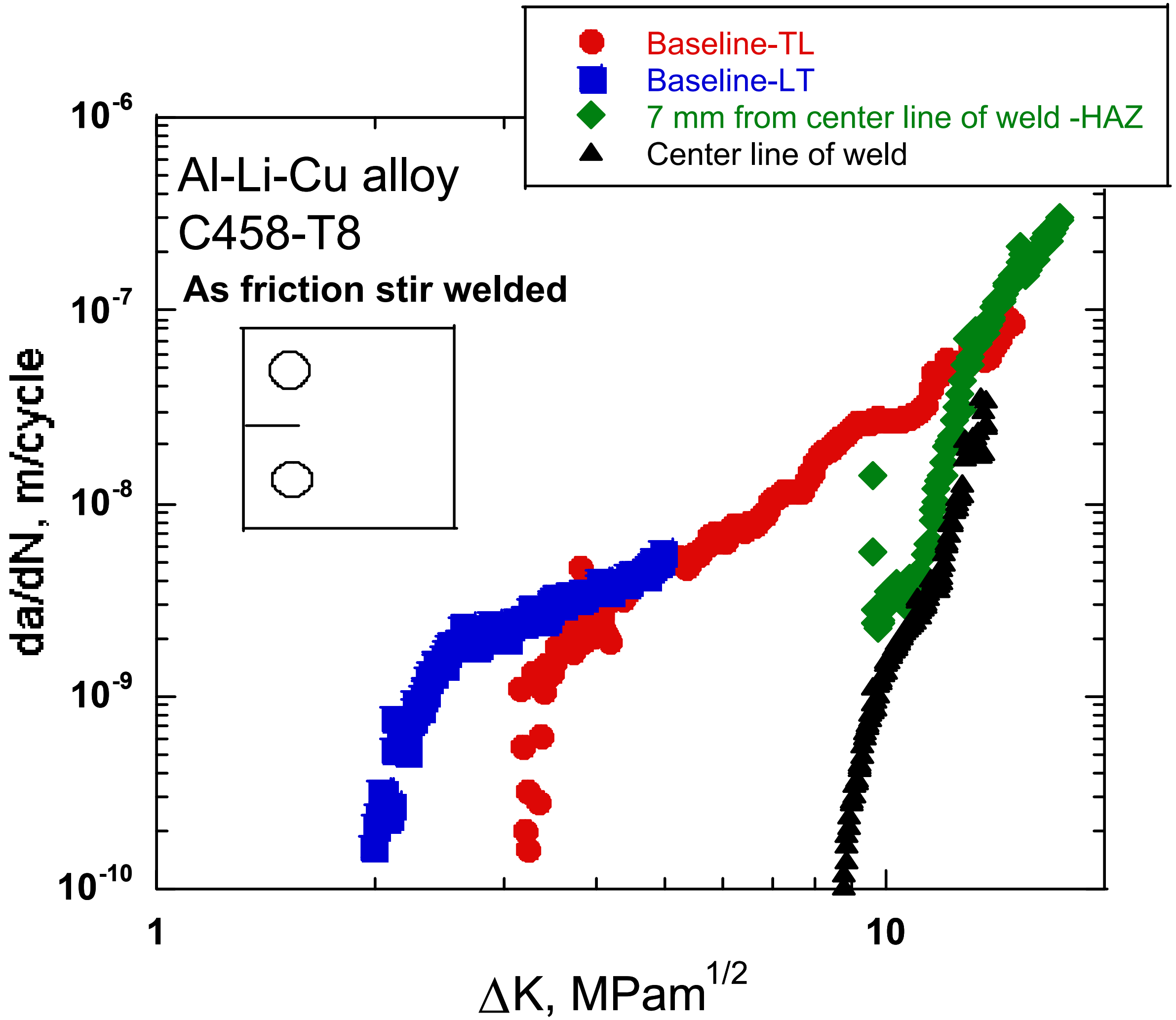
Fatigue crack growth in Al-Li alloy C458



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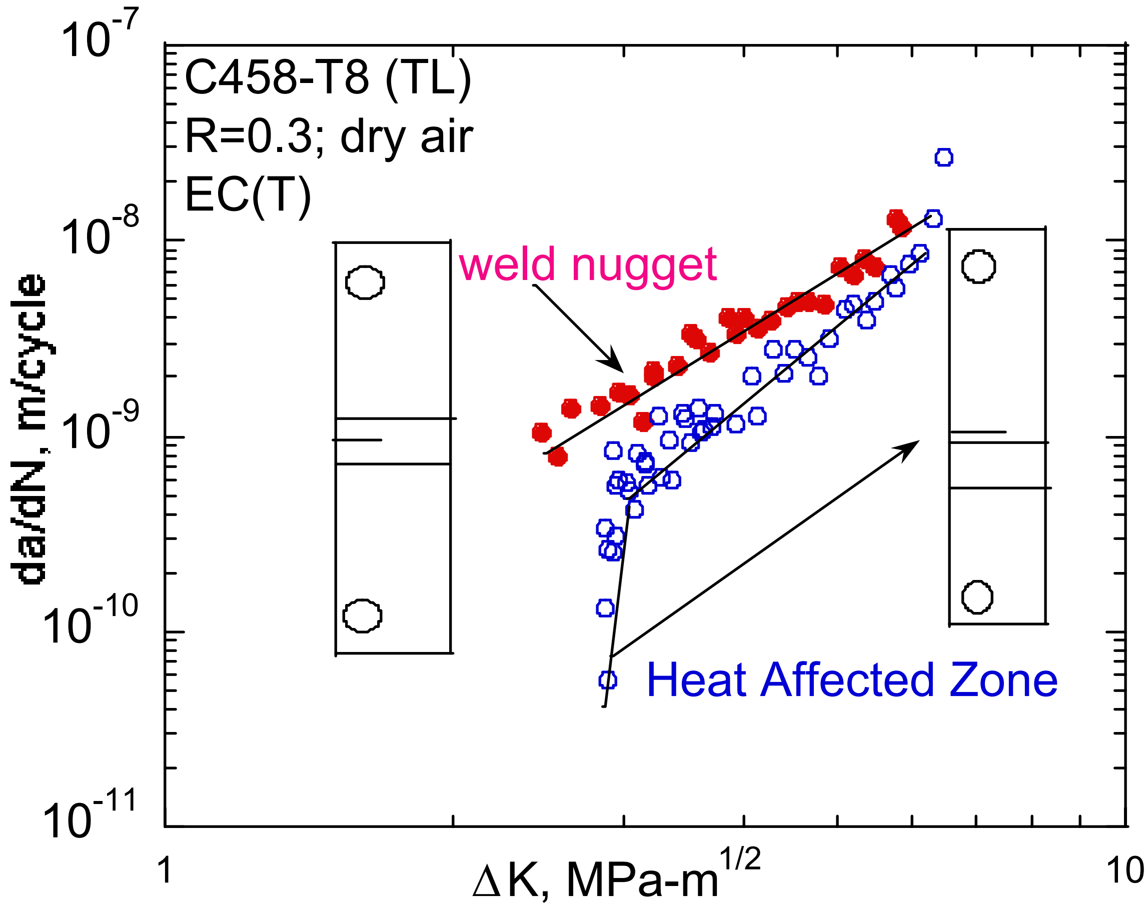
Fatigue in the weld; Nugget vs. HAZ



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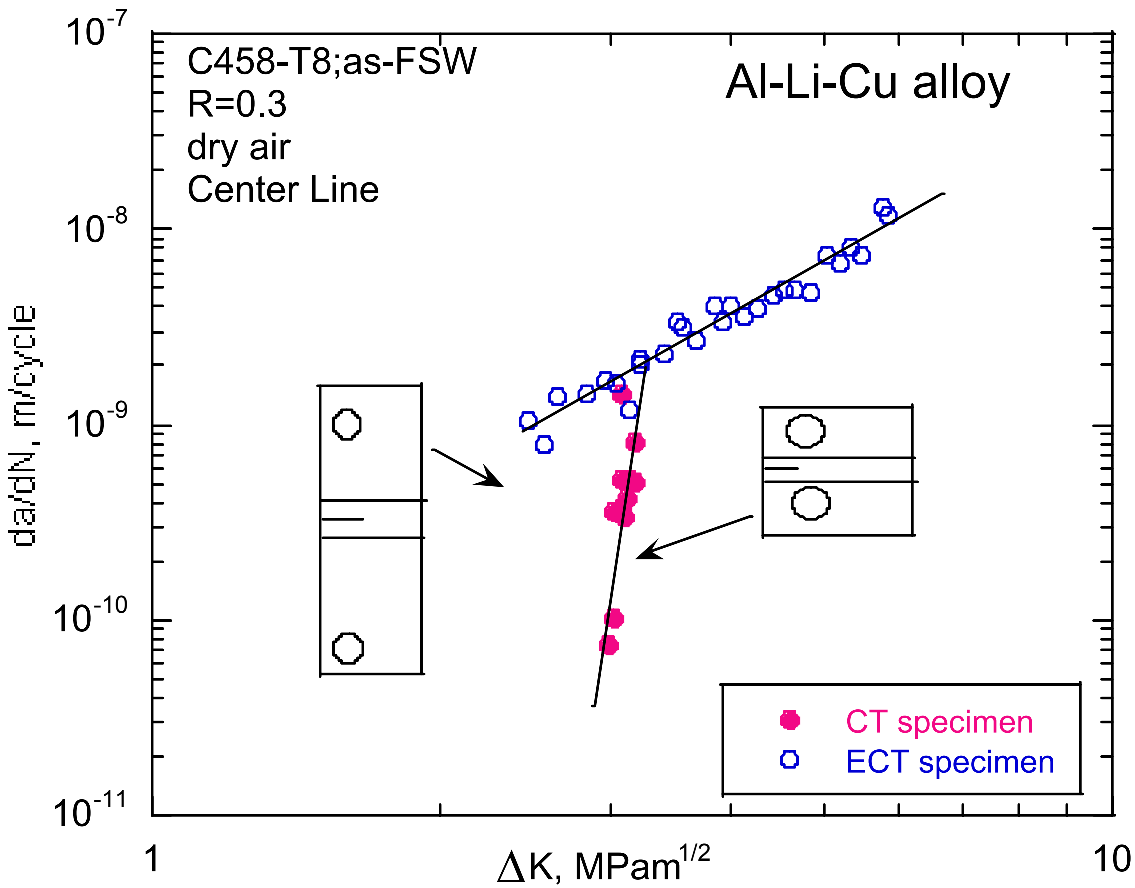
Effect of specimen geometry on FCG ?



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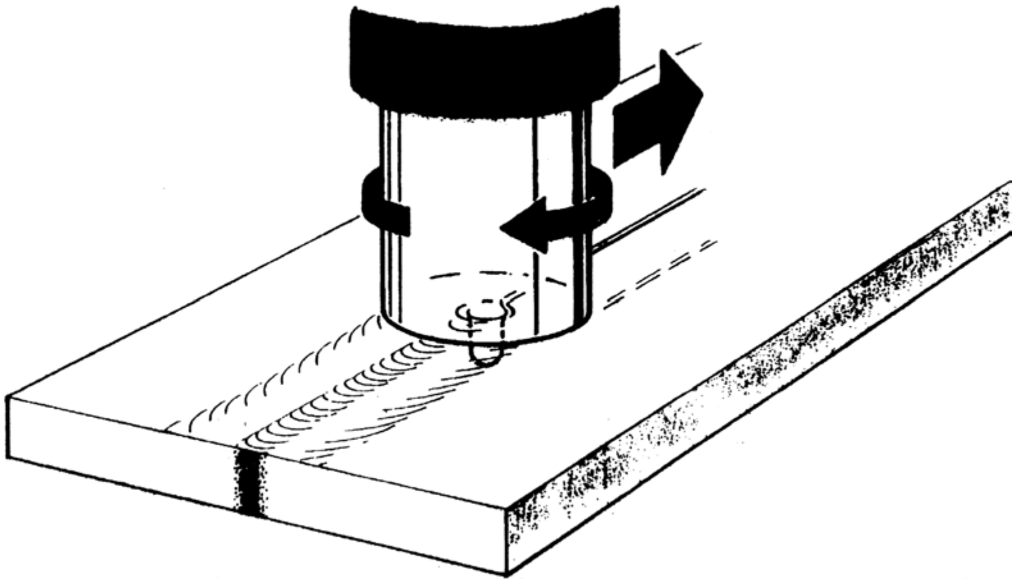
Ti alloys

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

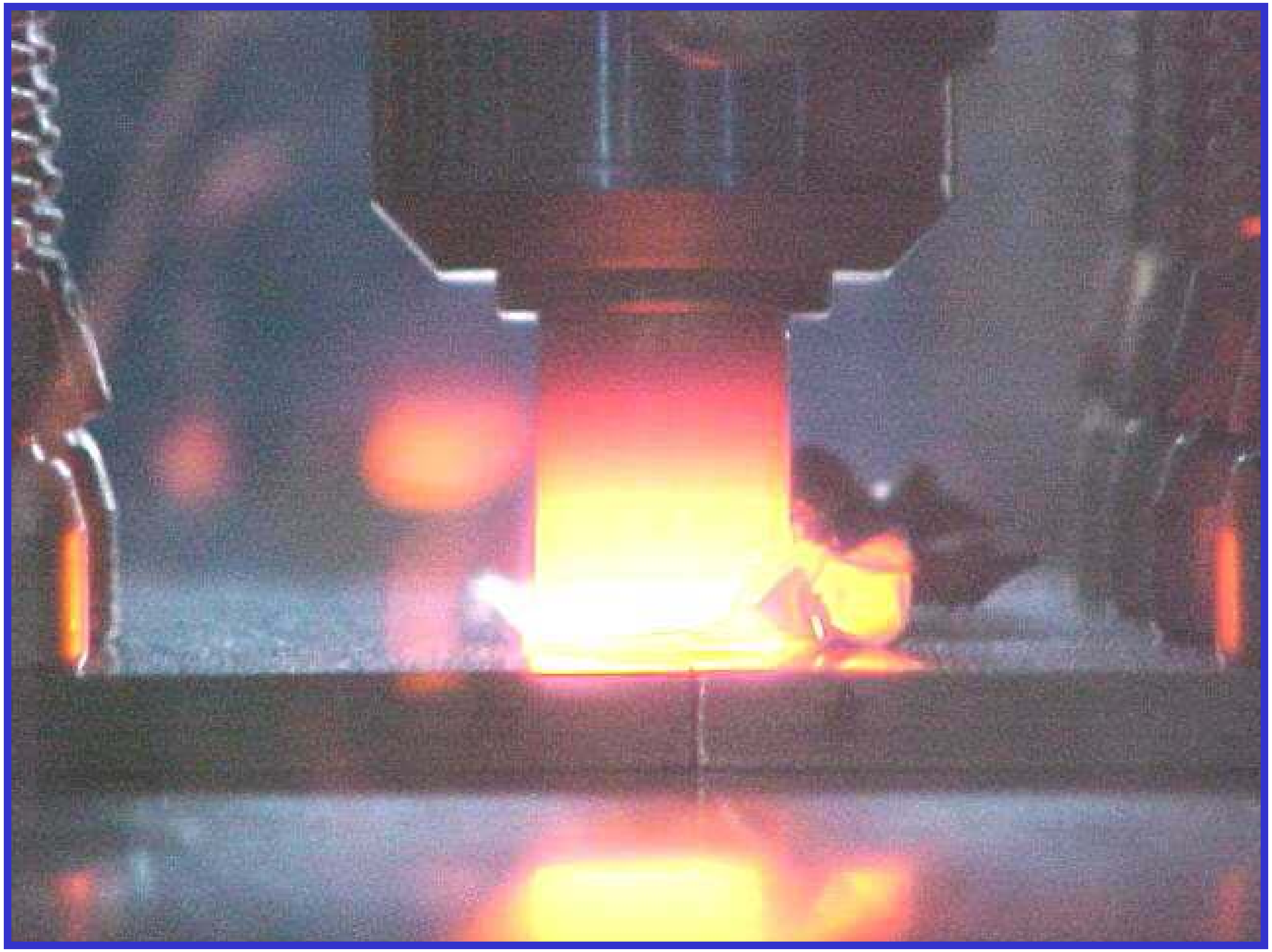


- **Solid-state process eliminates problems associated with melting and resolidification.**
- **Uses cylindrical tool with cylindrical pin extending from shoulder.**
- **Tool is rotated to desired RPM and plunged into joint.**
- **After short dwell time, tool is traversed along joint.**
- **At end of 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% H_2O_2 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



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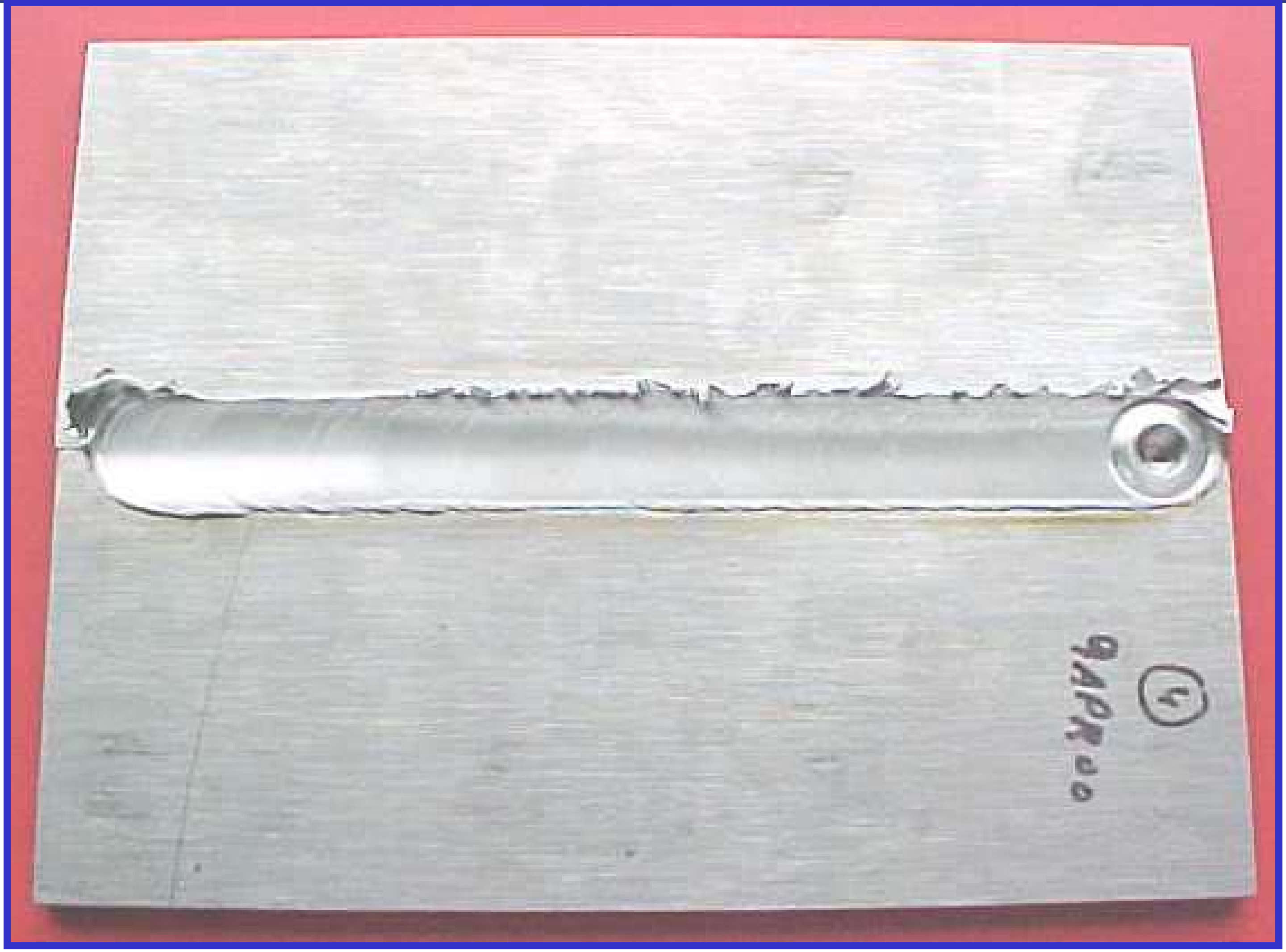
Top View of the FSW Butt Joint



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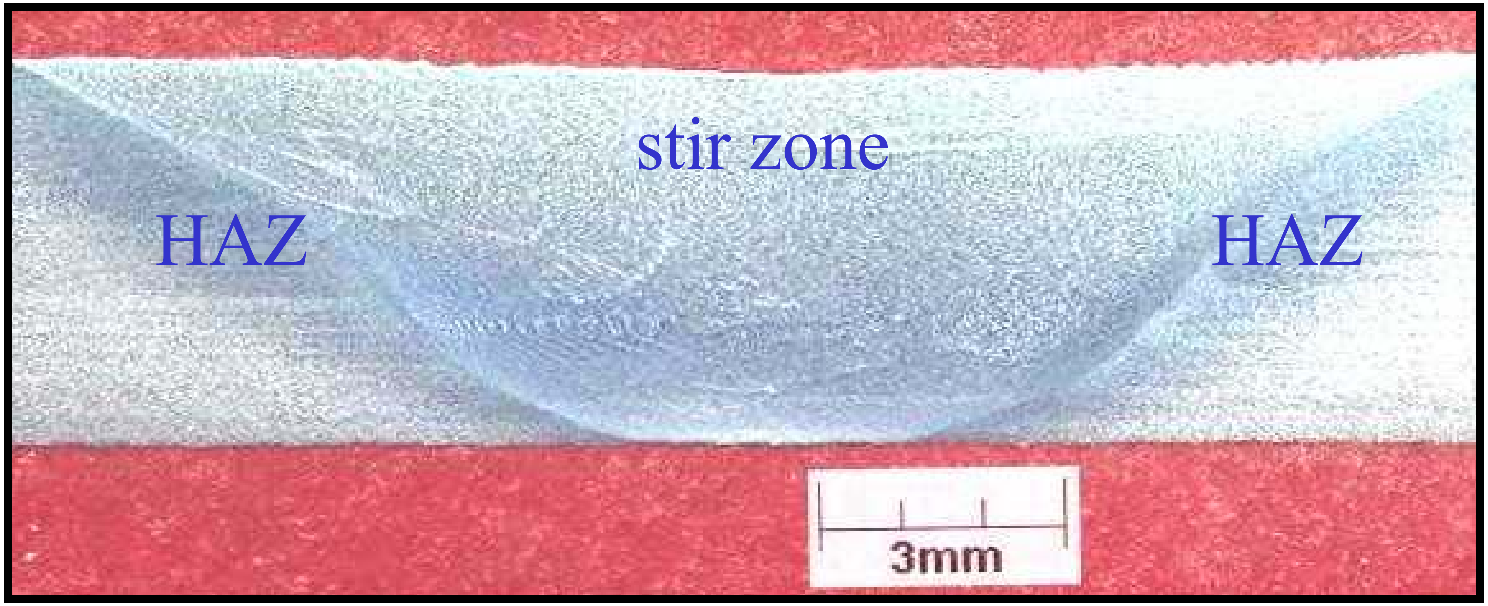
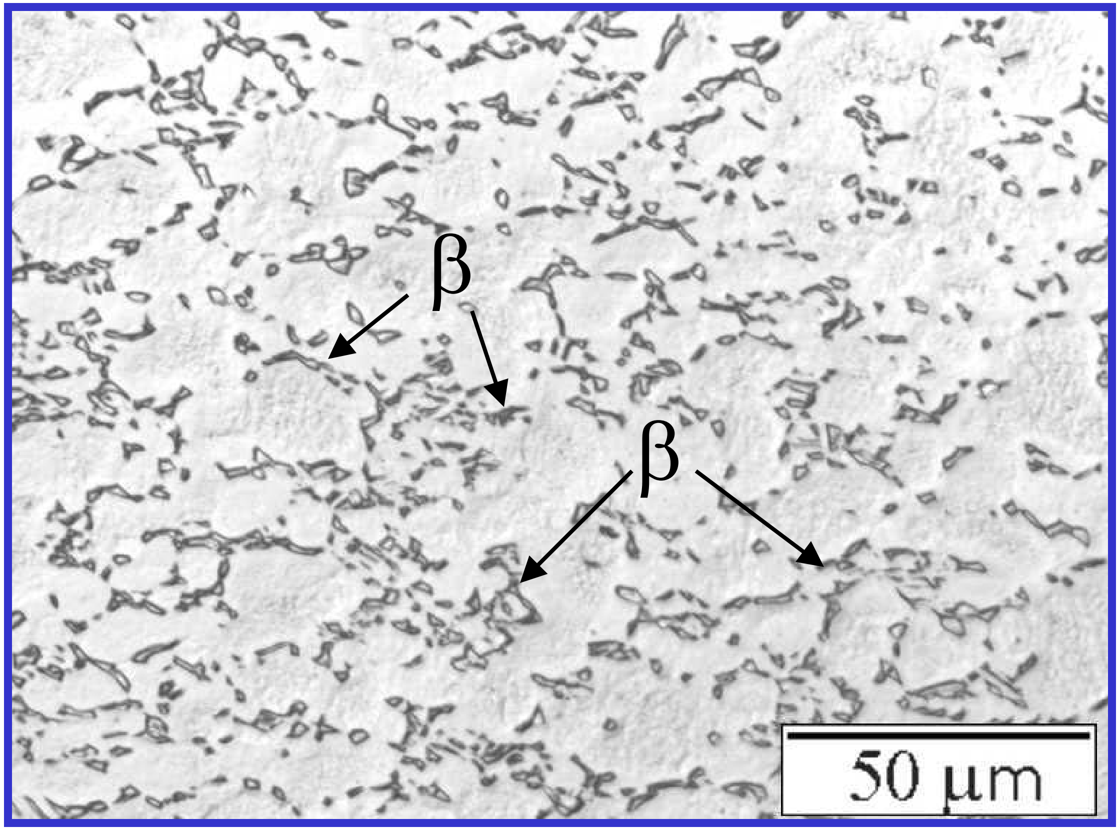
Optical Macrograph



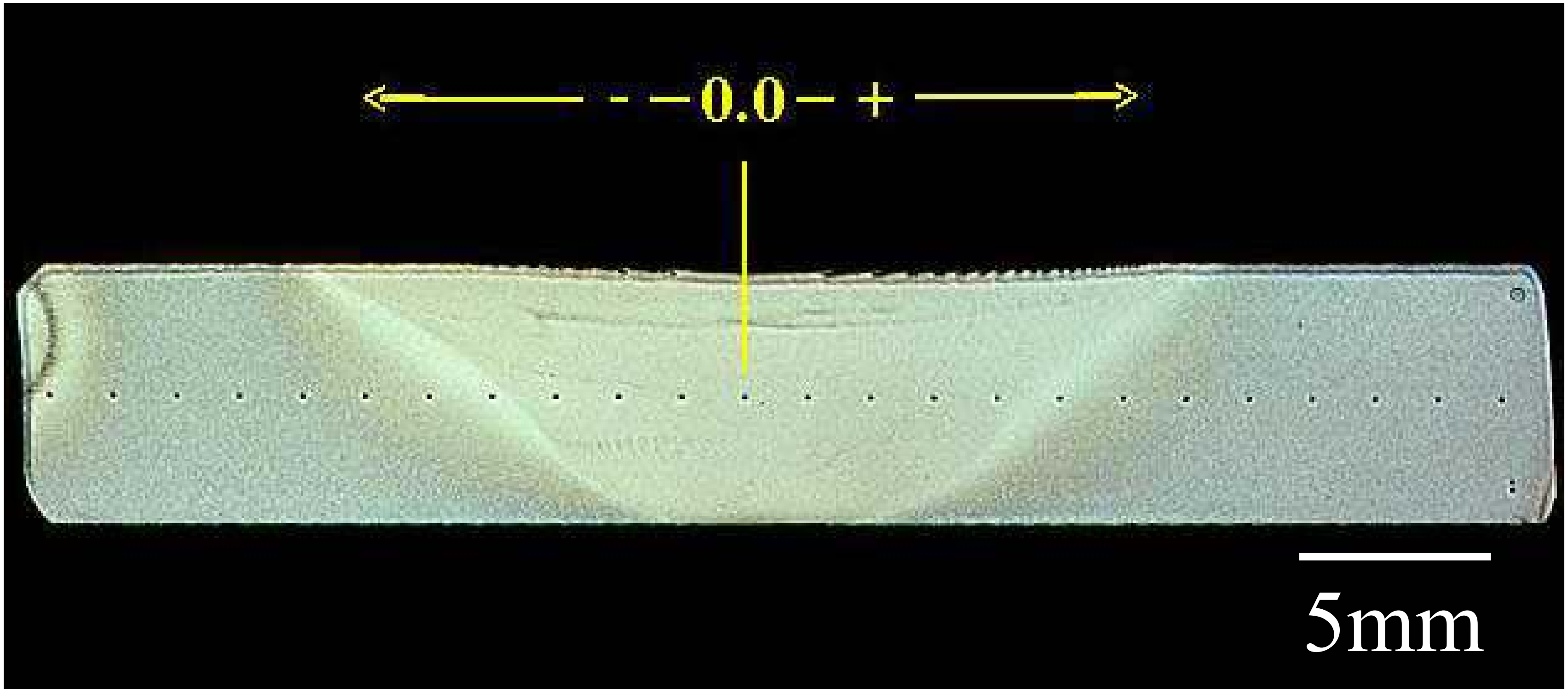
Transverse cross-section of FSW on Ti-6Al-4V

Optical Microscopy



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

Microhardness Indentations



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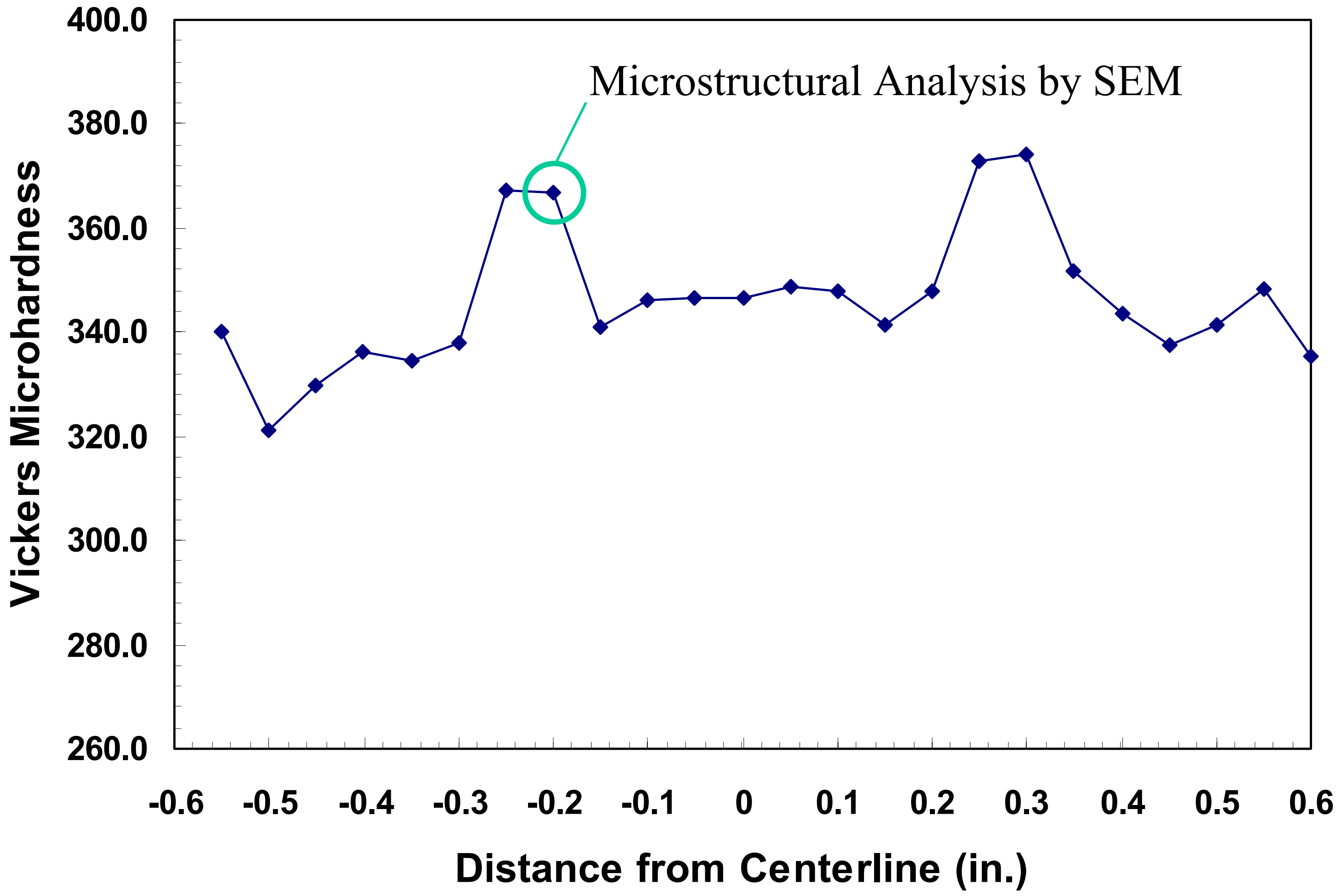
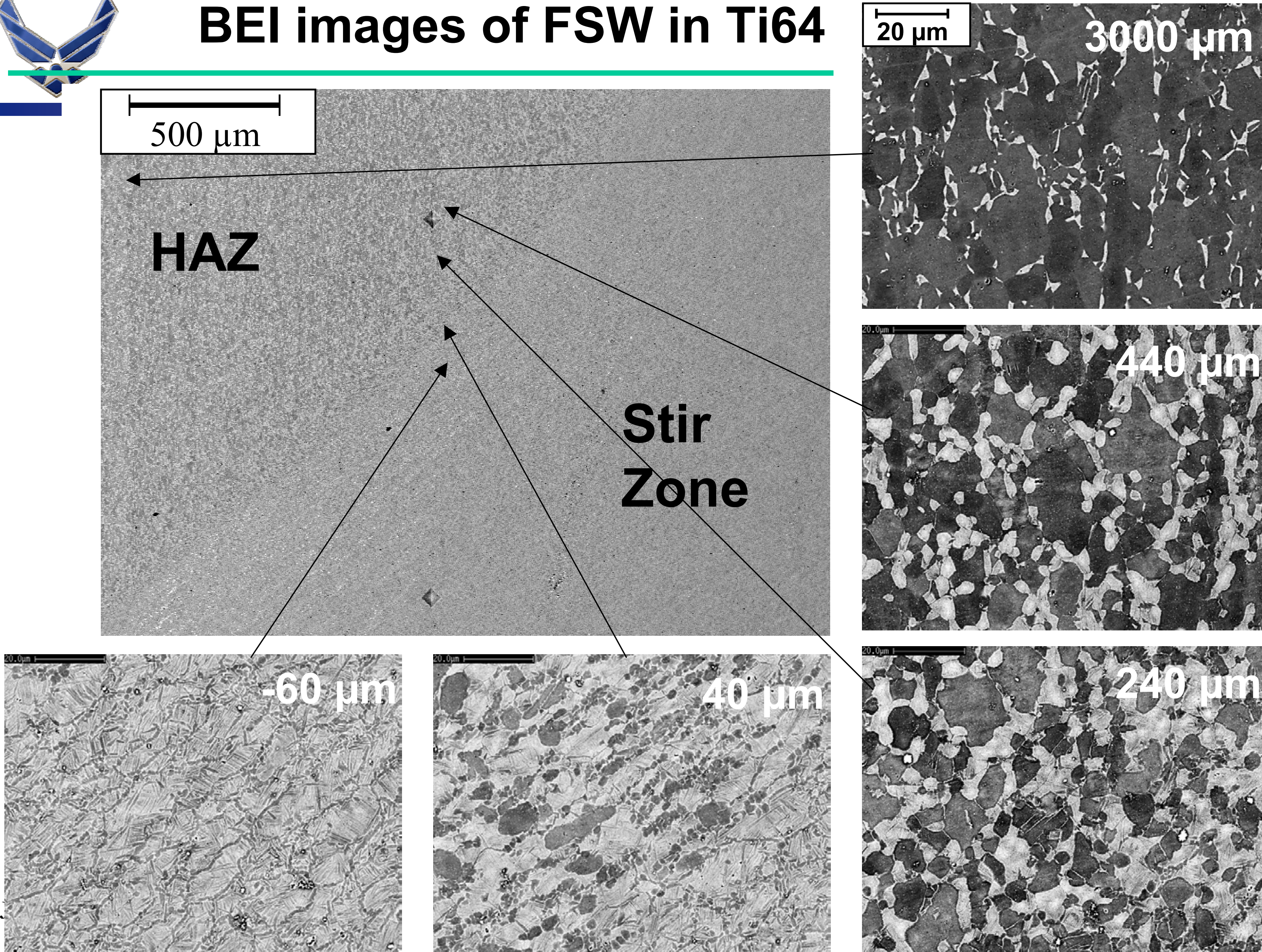
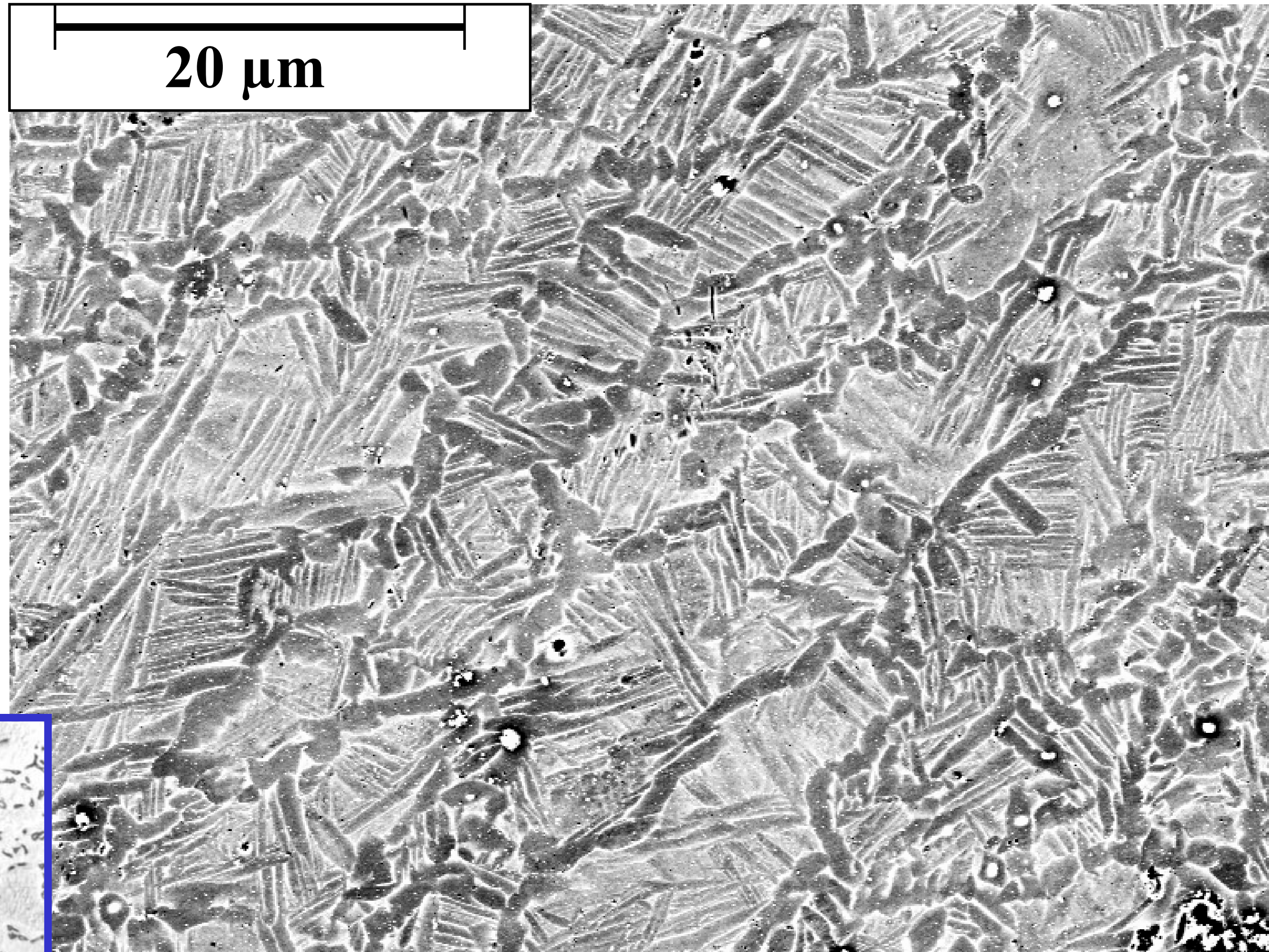
Microhardness Test Results



BEI images of FSW in Ti64

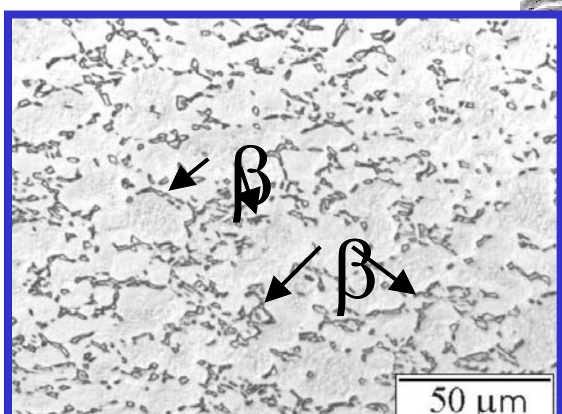


Stir Zone (Nugget) Microstructure



Nugget

Base metal



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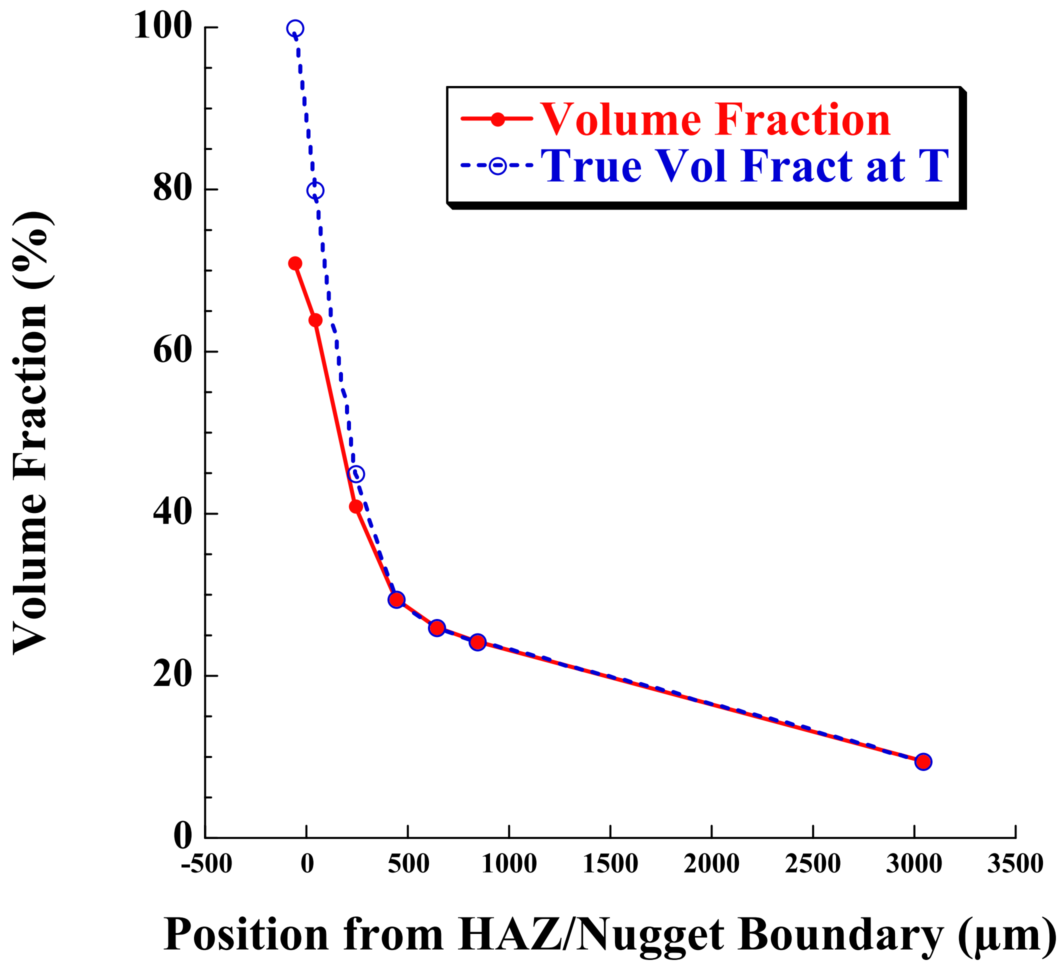
Transformed β volume fraction versus position



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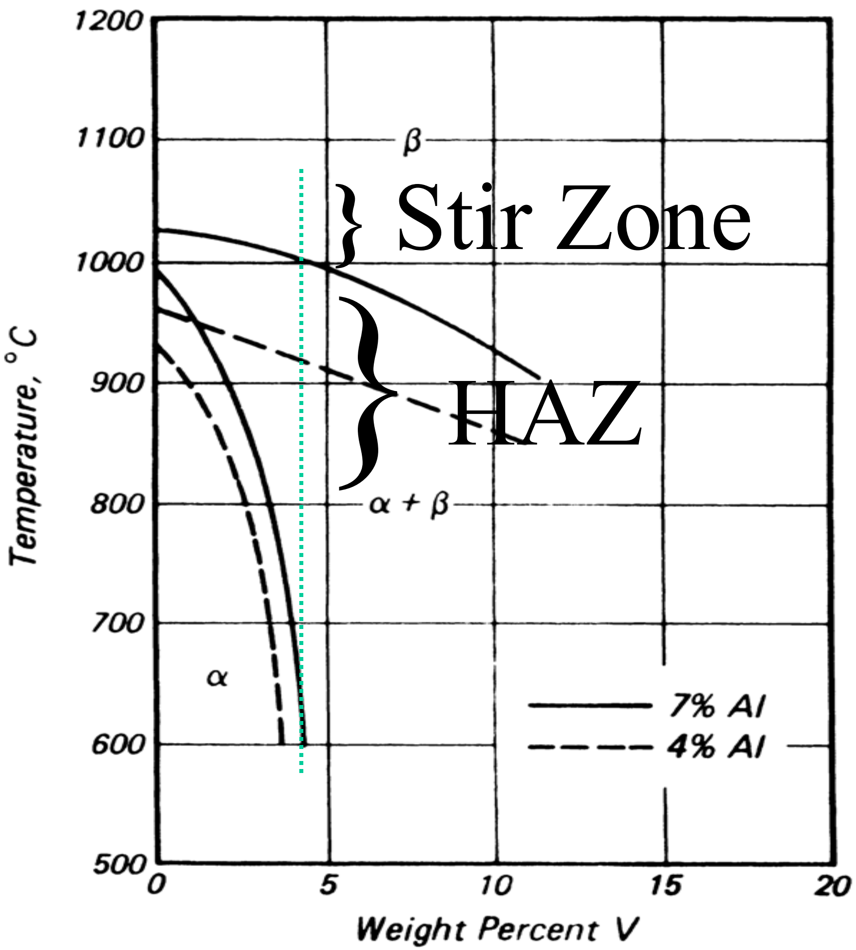
Vertical section in Ti-Al-V Phase Diagram



Results - Bend Test

$\varepsilon > 12\%$

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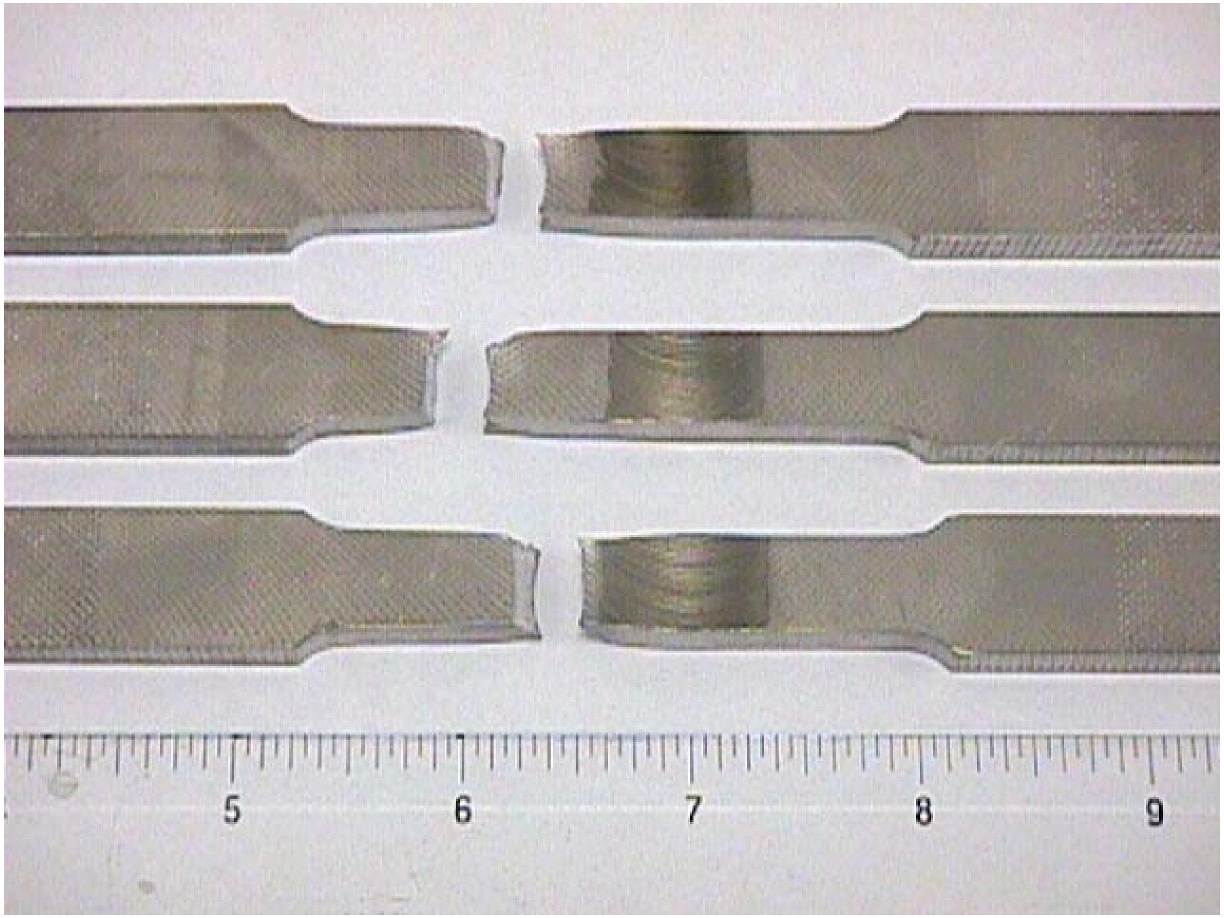
Ti64: Tensile Test Specimens



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Tensile Properties: Ti-6Al-4V

	Base Metal	FSW
• Yield Strength: (MPa)	895	912
• Tensile Strength: (MPa)	957	1012
• % Elongation:	12.7	12.7(0.9)
• Failure Location:	NA	BASE

Summary

- BM was equiaxed α with gb β
- % prior β in HAZ increased with decreasing distance from stir zone
- Stir zone contains acicular α in fine prior β 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