Evaluation of Friction Stir Weld Process and Properties for Aircraft Application

MMPDS Initiatives:

Process Path Independence &

In-Situ Fastener Qualification

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Evaluation of Friction Stir Weld Process and Properties for Aircraft Application

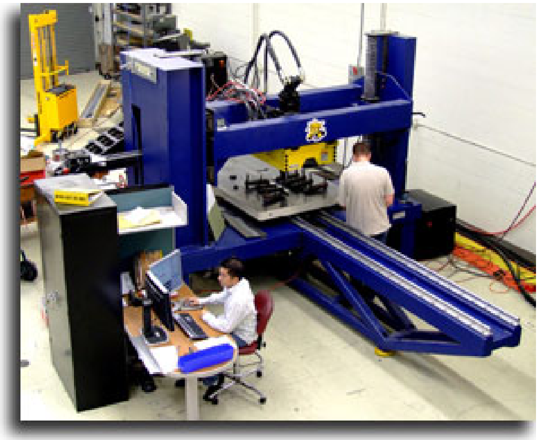
- Motivation and Key Issues
  - FSW & FSSW are emergent joining technologies
    - Aerospace applications are being developed to take advantage of cost, part count reduction, lead-time benefits, the lowered environmental impacts, etc., of these processes
    - However, each lacks sufficient supporting (mature) industry standards & design (allowables) data
- Objective
  - Incorporate FSW & FSSW design allowables data into MMPDS
    - Based on a performance and procedure specification methodology
    - Supported by developing industry standards (e.g. AWS, ISO, etc.)
- Approach
  - Develop & demonstrate protocols for incorporating FSW & FSSW data into the MMPDS Handbook collaboratively
    - Demonstrate process path independence approach for butt & lap joints
    - Develop FSSW as "In Situ" fasteners & qualify as installed fasteners

FAA Sponsored Project Information

- Principal Investigators & Researchers
  - Dwight Burford, PhD, PE
  - Bryan Tweedy, MS
  - Christian Widener, PhD
- FAA Technical Monitor
  - Curt Davies
- Industry Participation
  - Boeing IDS: *John Baumann, St. Louis; David Ogan, Wichita*
  - Bombardier Aerospace: *Ken Poston, Ireland; Bruce Thomas, Montreal; Leo Kok, Toronto*
  - Cessna Aircraft: *Ron Weddle & Ali Eftekhari, Wichita*
  - Hawker Beechcraft: *Byron Colcher & Phil Douglas, Wichita*
  - Spirit AeroSystems: *Casey Allen, Mike Cumming & Gil Sylva, Wichita*

Outline

- ***Qualification Initiatives***
  - ***Performance Specifications***
  - ***Butt & Lap Joint Initiatives***
- ***Path Independent Study***
- ***In Situ Fasteners***



Qualification Initiatives

Performance Spec Model

Customer Requirements | **Acceptance Criteria** | **Supplier Controls**

Process Performance Spec
- Documentation
- Objectives
- Deliverables
- etc.

Process Procedure/Detail Spec
- WPS (welding procedure specifications)
- PQR (procedure qualification record)
- etc.

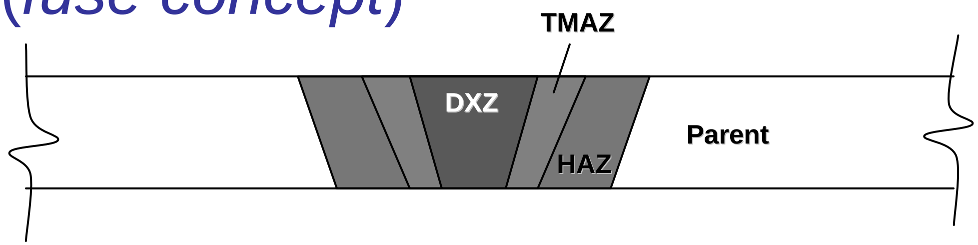
Industry Specs (AWS, ISO, etc.)
MMPDS* Data

*Metallic Materials Properties Development & Standardization (formerly MIL-HDBK-5)

Qualification Initiatives

- <u>Butt Joint Initiative</u>

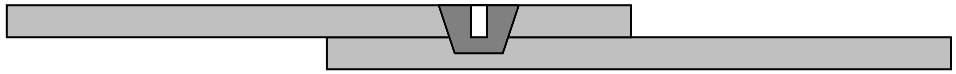
  Qualification supported by a *Path Independence* study (*fuse concept*)



(cross-section)

- <u>Lap Joint Initiative</u>

  Qualification of “friction stir spot welds” as *In Situ* Fasteners (tested similar to *installed* fasteners)



(cross-section)

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Path Independence Initiative

- As established by published work and experience, FSW has a *sufficiently flexible process window* that allows all aluminum alloys to be joined with a wide variety of weld tool designs
- It is hypothesized, therefore, that:
  - an unlimited number of weld tool designs using *independently developed process windows* can be used to make equally sound joints having minimum joint properties/efficiencies
  - any advantage one tool may have over another is expected to be evident primarily in terms of productivity, i.e. welding and processing speeds.

Formulation of Approach

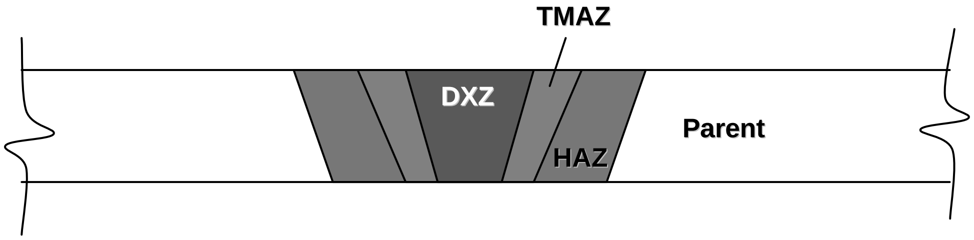
- Mechanical properties of joints linked to parent material properties
  - FSW is <u>an *additional* local thermal-mechanical processing step</u> that 1) refines the local microstructure and 2) retains the bulk chemistry (e.g. filler material is not typically added)
- Due to the local nature of the process, gradients in mechanical properties exist and vary across the joint
  - Different failure modes and/or failure locations in transverse tensile tests may be varied in FSW joints by controlling the process parameters
  - This allows <u>placement of the failure location</u> in a controlled manner (Parent, HAZ, TMAZ, DXZ) to reduce variability in joint properties

Formulation of Approach

- **Approach Summary**
  - Establish a minimum joint efficiency (e.g. static transverse tensile strength) by controlling process parameters and failure location for a given weld tool
  - Confirm the overlap of property results from joints produced by significantly different tools documented in the open technical literature
- **Approach Phases**
  - **Stage 1**: Bounding Welds - Bead-on-plate screening welds
  - **Stage 2**: Initial DOE - develop working process window for IPM, RPM & Forge Load
  - **Stage 3**: Final DOE - optimize parameter set for IPM, RPM & Forge Load (statistically based)

Allowables Prep for FSW

- Variation & Failure Location Control
  - Reduce variation by promoting / controlling failure to a unique failure mode / location through process control
    - Parent
    - HAZ
    - TMAZ
    - DXZ (nugget)



  - Fuse Approach / Concept
    - Place failure in “overaged” parent material (covered by allowables)

Path Independence Study: Tool Configuration & Corresponding Process Parameters*

Classic TWI 5651
(concave shoulder, straight threaded probe)

Tri-flute™
(shoulder: flat, multi-scrolled probe: tapered, threaded, fluted)

Trivex™
(shoulder: flat with cavity probe: tapered, threaded, 3 contoured sides)

TWI

Shoulder: flat, single scroll
Probe: Threaded tapered Tri-Flat

S: small Wiper™
P: Twisted tapered Tri-flat

S: large Wiper™
P: Twisted tapered Tri-flat

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***Fixture, FSW machine, etc. held constant!**

Path Independence: Initial DOE Parameters

WSU Wiper 0.600

RPM	400-800
IPM	10-20
Forge	<u>**4500-5250**</u>

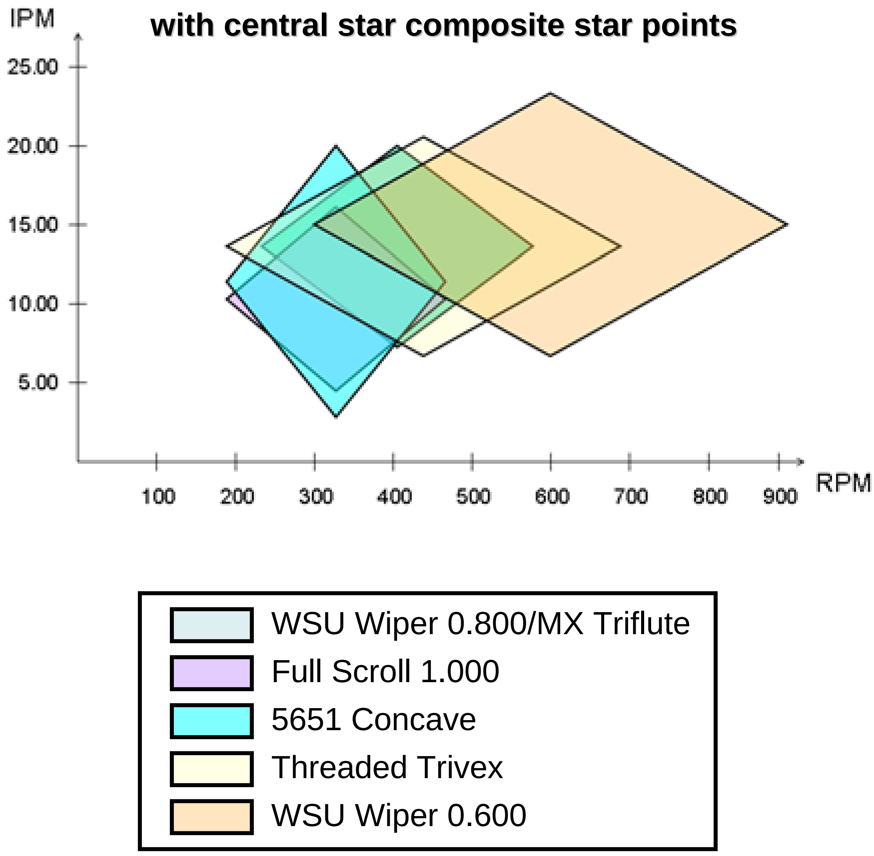
WSU Wiper 0.800

RPM	300-500
IPM	10-16
Forge	7000-8000

MX Triflute 0.800

RPM	300-500
IPM	10-16
Forge	7000-8000

Design of Experiments (DOE) process space with central star composite star points



TWI 5651 1.000

RPM	250-400
IPM	7-16
Forge	<u>**8500-10500**</u>

Full Scroll 1.000

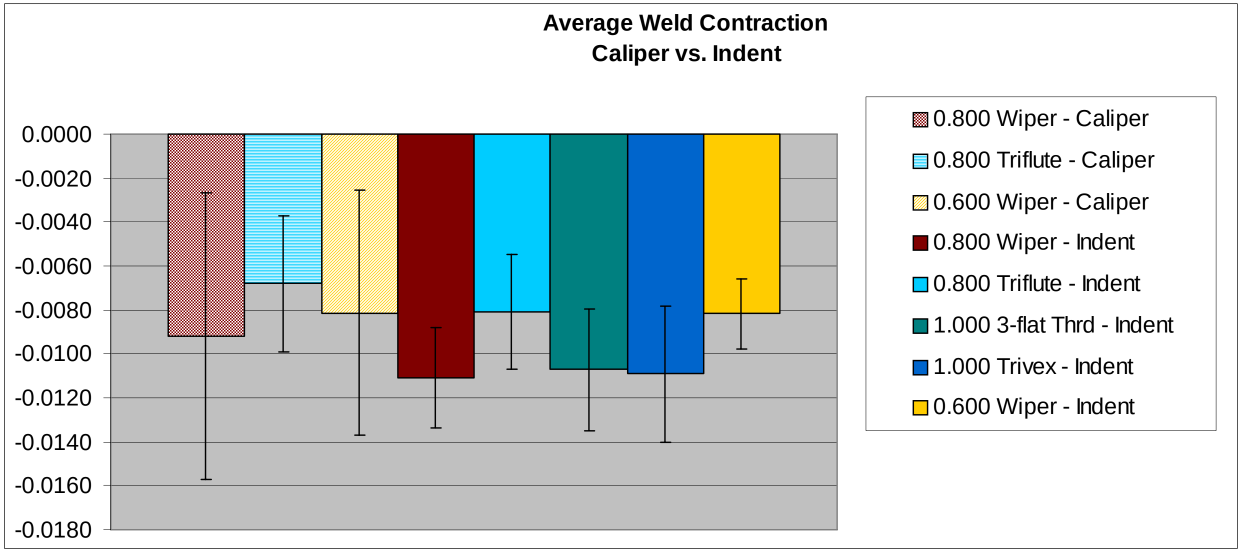
RPM	250-400
IPM	7-13
Forge	7500-9000

Trivex™ 1.000

RPM	300-600
IPM	10-18
Forge	9000-10500

Path Independence: Lateral Contraction

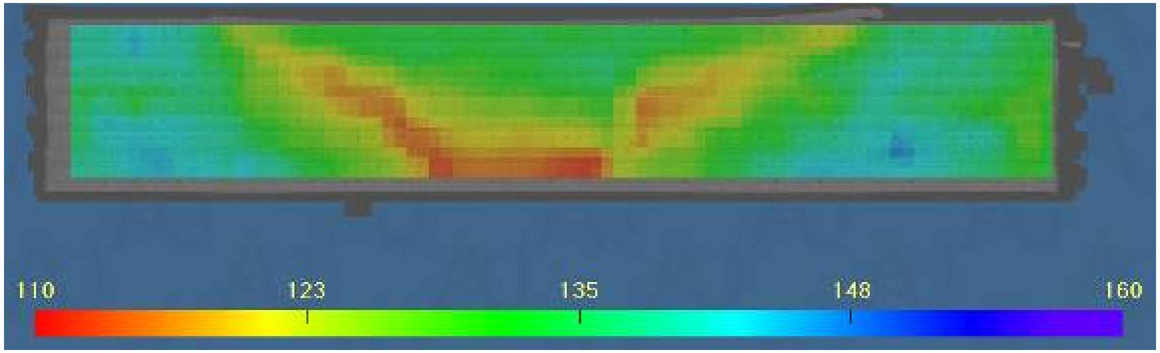
- No statistical difference between contraction measurements for variations in tool design and weld parameters
  - Due to small overall differences and relatively large scatter.
  - However, caliper measurements led to higher standard deviations.



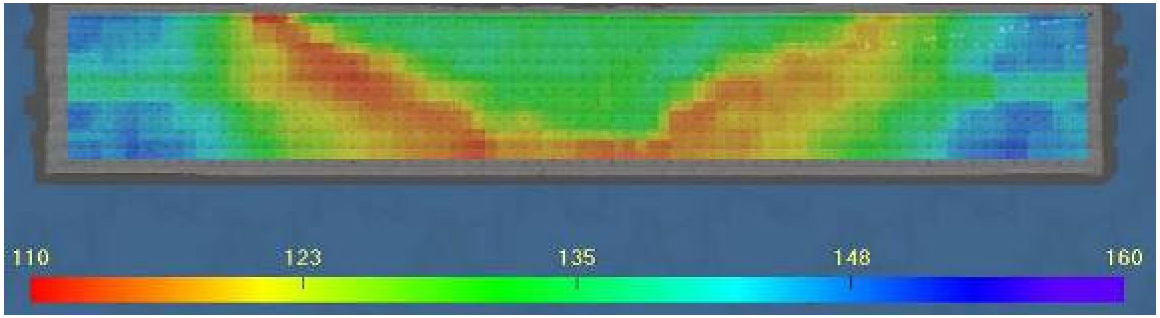
Microhardness Results: 1.0" TWI 5651

Transverse cross-sections of FSW joints (looking in the direction of travel with the advancing side on right)

"Cold"
250/16/8500
55.3 ksi
Nugget failures



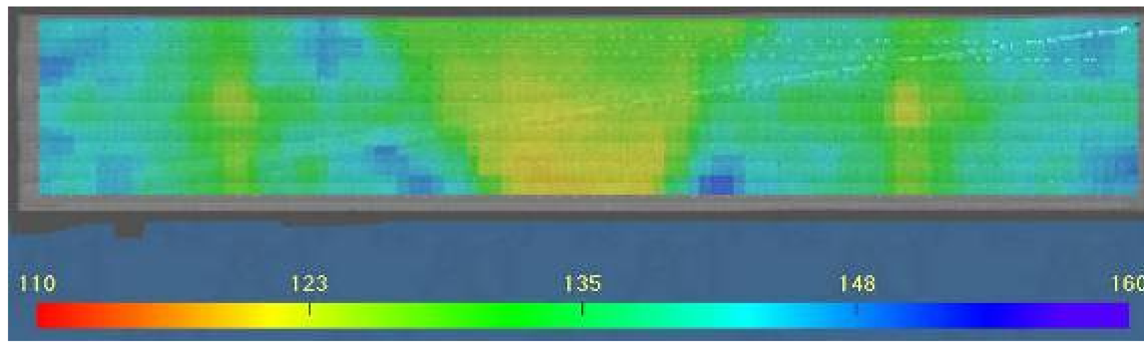
"Hot"
400/7/10500
53.9 ksi
Nugget failures



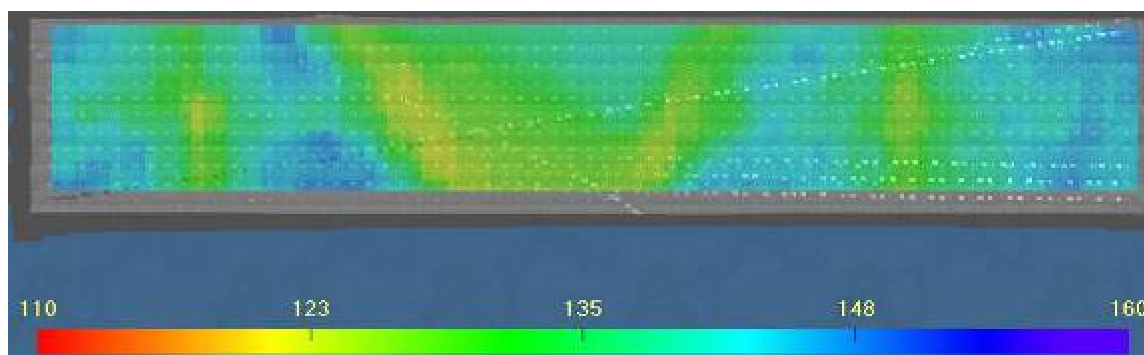
Microhardness Results: 0.6” WSU Wiper™ & Twisted Flats

Transverse cross-sections of FSW joints (looking in the direction of travel with the advancing side on right)

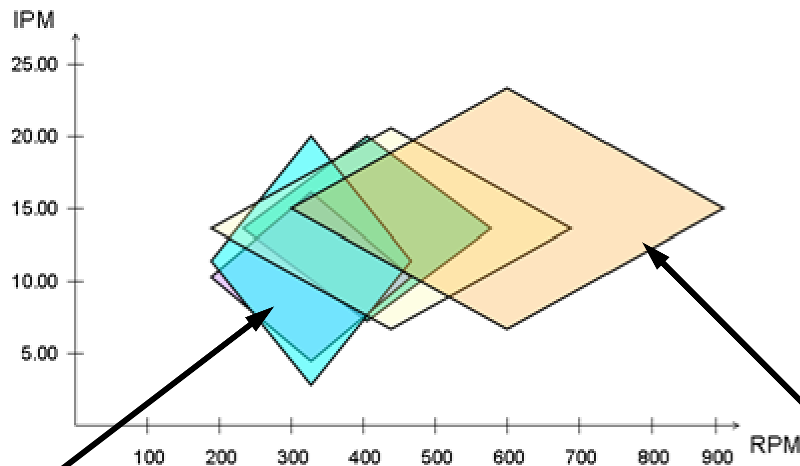
“Cold”
400/20/4500
63.9 ksi
HAZ failures

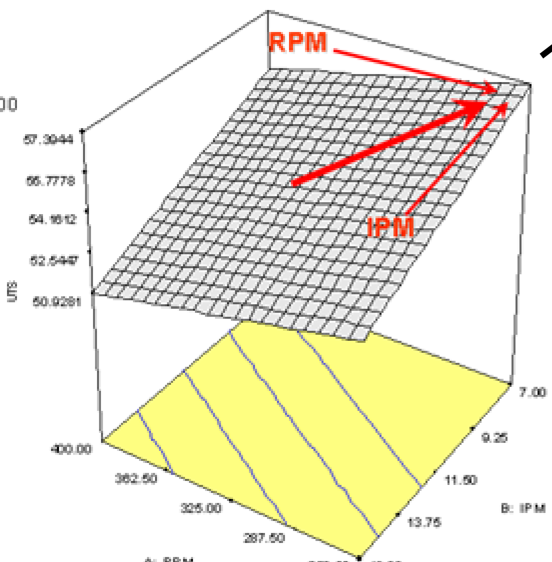


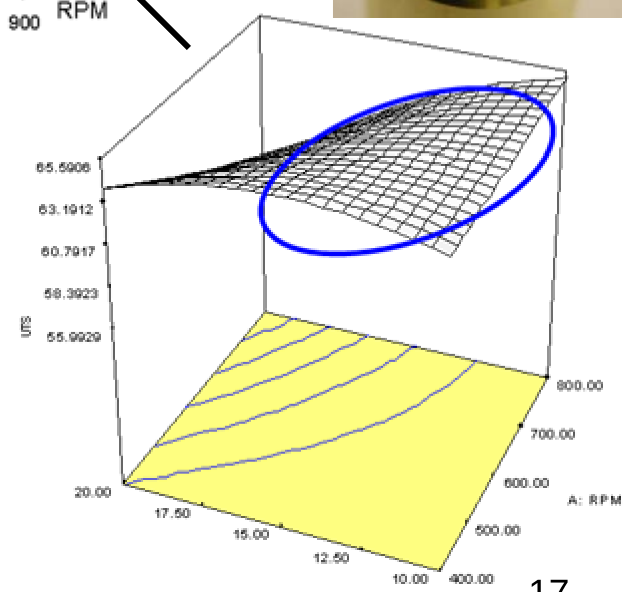
“Hot”
800/10/5250
65.6 ksi
HAZ failures



Initial Process Window Results: TWI 1.0” 5651 vs. 0.6” WSU Wiper



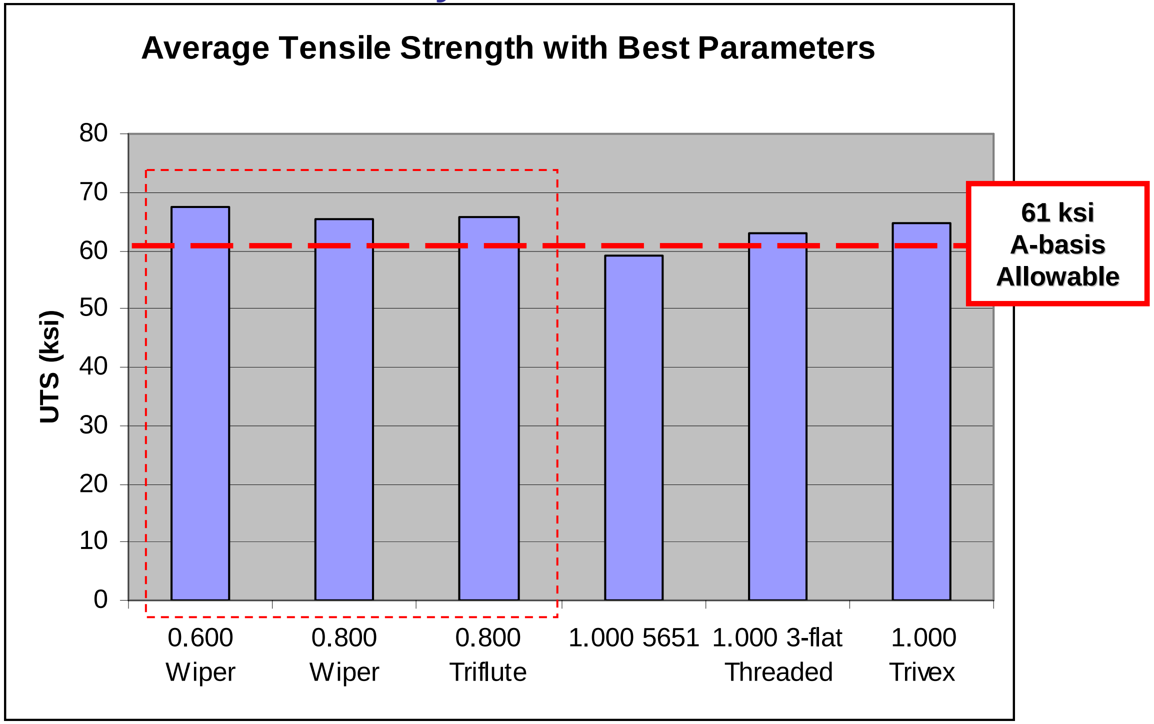




Preliminary Tensile Results: 2024-T3 0.250-in.

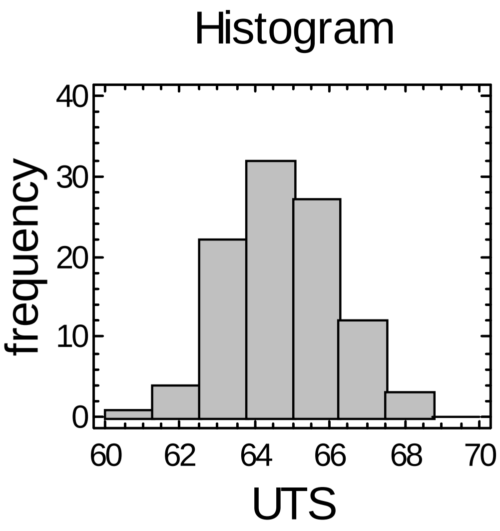
Based on first three tools (preliminary):

- Joint (LT): A-basis: 60.9 B-basis: 62.5
- Parent (LT): A-basis: 64 B-basis: 66
- Joint Efficiency: A-basis: 95% B-basis: 95%



SnapStat: One Sample Analysis

Data variable: UTS
Count = 101
Average = 64.6501
Standard deviation = 1.41777
Coeff. of variation = 2.19299%
Minimum = 61.088
Maximum = 67.928
Range = 6.84
Stnd. skewness = 0.285286
Stnd. kurtosis = -0.525823



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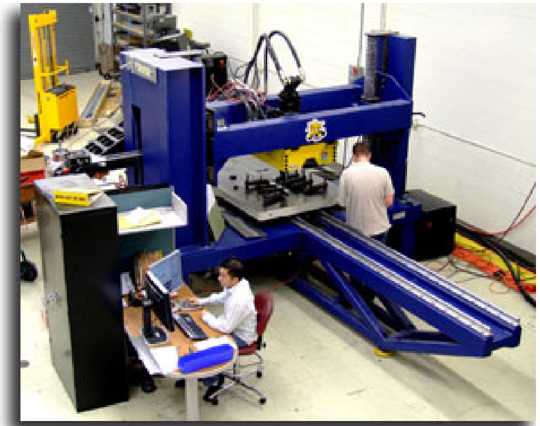
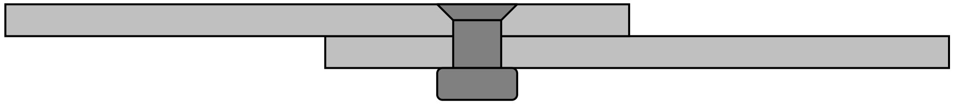


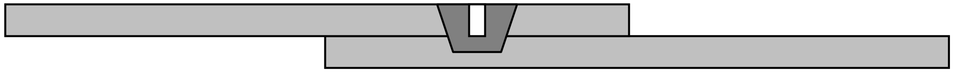
Lap Joint Initiative

Qualification of "friction stir spot welds" as *In Situ* Fasteners tested & analyzed similar to *Installed* Fasteners

Resistance Spot Weld: Bonding surfaces across interface



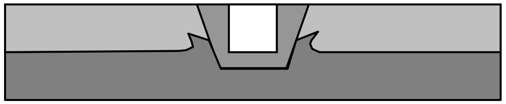
Rivet: installed in hole and compressed to form tight joint



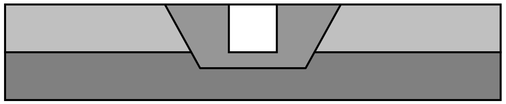
FSSW: Unique fine-grained metallurgical structure extending between components (providing bearing strength)

- Types of FSSW "Spots"
  - Plunge (Poke) Spot (Mazda)
  - Swept Spots
    - Squircle™ (TWI)
    - OctaSpot™ (WSU)
  - Friction (refill) Spot Welding (GKSS)
  - Swing (stitch) Spot
  - High Rotational Speed (HRS) FSSW (WSU)

Plunge (Poke) Spot



Swept Spot



Lap Joint Initiative: In Situ Fasteners

- Benefits of friction stir swept spot joints
  - Discrete fastener locations
    - Separated by parent material (similar to rivets)
    - Discontinuous HAZ along joint line
  - Dual-thickness joint vs. hole with filler (e.g. rivet)
    - “Pad up” effect vs. stress concentration (rivet hole)
    - Long-term stiffness & stress concentration considerations, e.g. in aging aircraft
  - Elimination of filler material, i.e. fastener
    - Fabricate fastener in place by mechanically working parent material (finer grain)
    - Produces integral fastener
    - Leads to part count reduction

Lap Joint Initiative: In Situ Fasteners

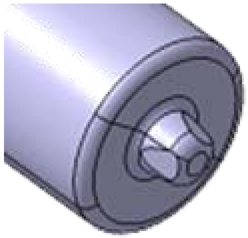
- Benefits of friction stir swept spot joints (cont'd)
  - Tailorable spot size and shape
    - More latitude than with rivets (diameter constraints, etc.)
    - Orient shape to control stress, crack growth, etc.
    - Placement of advancing vs. retreating side on periphery of spot (i.e. in situ fastener)
  - Rapid installation (minimal HAZ)
  - Randomize sequence of installation (to lower distortion)
  - Potentially installed via robot vs. gantry
    - Lower cost solution
    - Field installation & repairs
  - Simplified tooling (lower normal and lateral forces)
  - etc.

In Situ Fasteners Qualified as *Installed* Fasteners

- **Approach**
  - Develop a methodology for qualifying different types of friction stir spot welding (FSSW) joints as ***in situ*** fastener systems.
  - Treat individual "spots" as installed fasteners
    - Parent material is used to form an integral mechanical fastener *in place* between two or more materials joined by a lap joint
- **Notes**
  - In both static and dynamic tests, appropriately designed FSSW (e.g. swept spots) joints are proving stronger than rivets
    - Spots are integral with the parent material
    - Their size and shape of spots can be tailored
    - They appear to provide favorable residual stresses and a pad up effect
  - FSSW joints are expected to be the most straightforward friction stir-related technology to qualify for inclusion in the MMPDS because they are the most like mechanical fasteners, e.g. discrete.

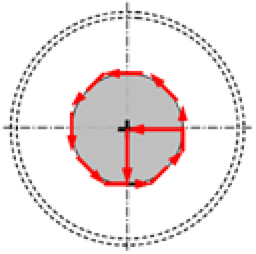
Shear Panel Test: Review of Static Shear Results

FSSW vs. FSW & Riveted – 0.04-in to 0.04-in / 7075 to 2024 24" Square Stiffened Panels (two stiffeners)

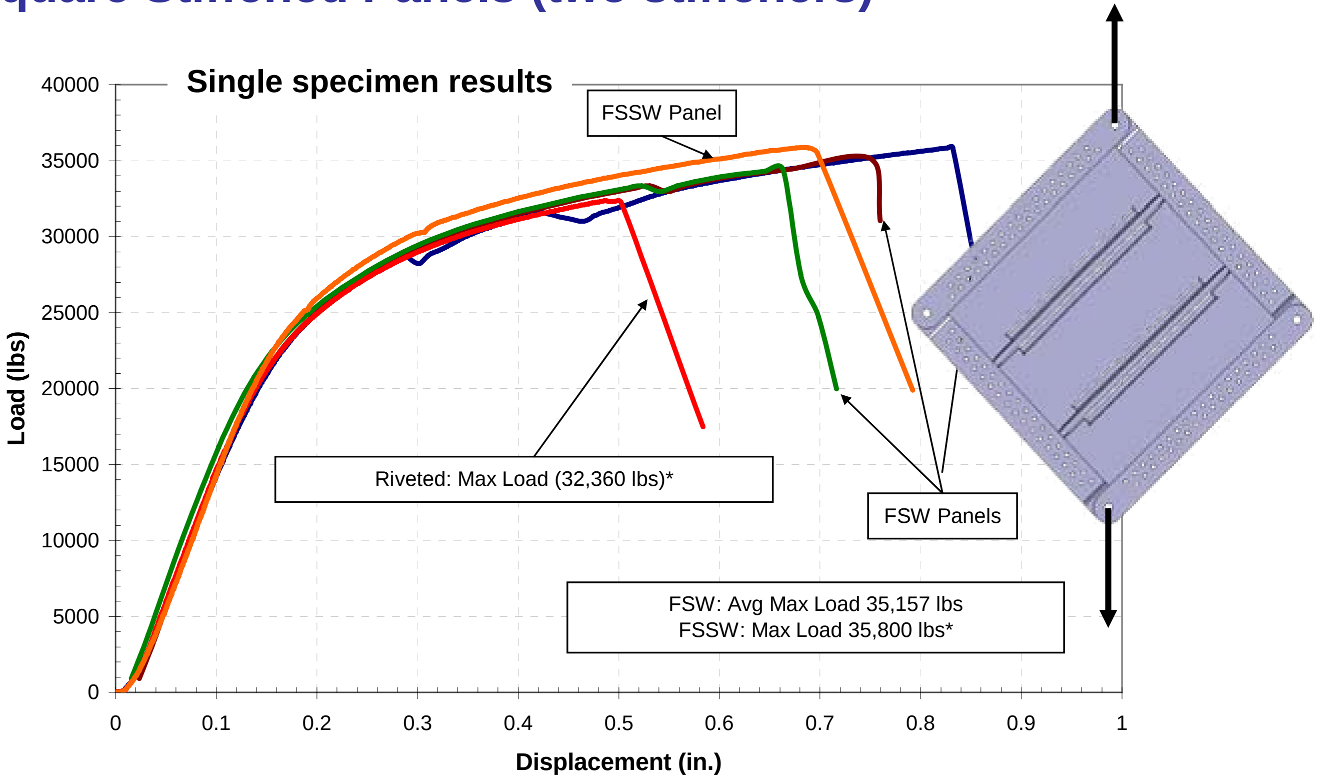


Linear FSW Tool

Psi™ FSSW Tool



OctoSpot™ Tool Path



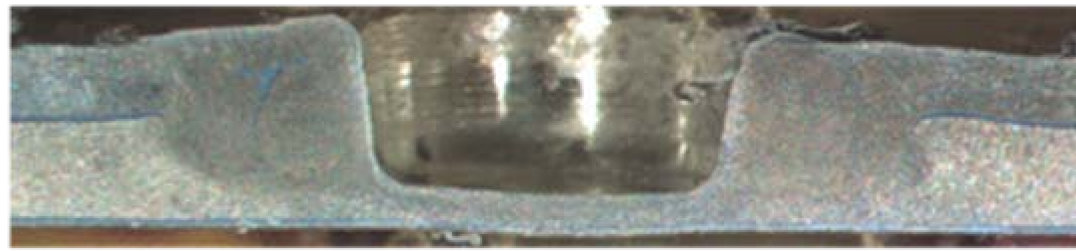
B. Tweedy, et al. ATIO 2006

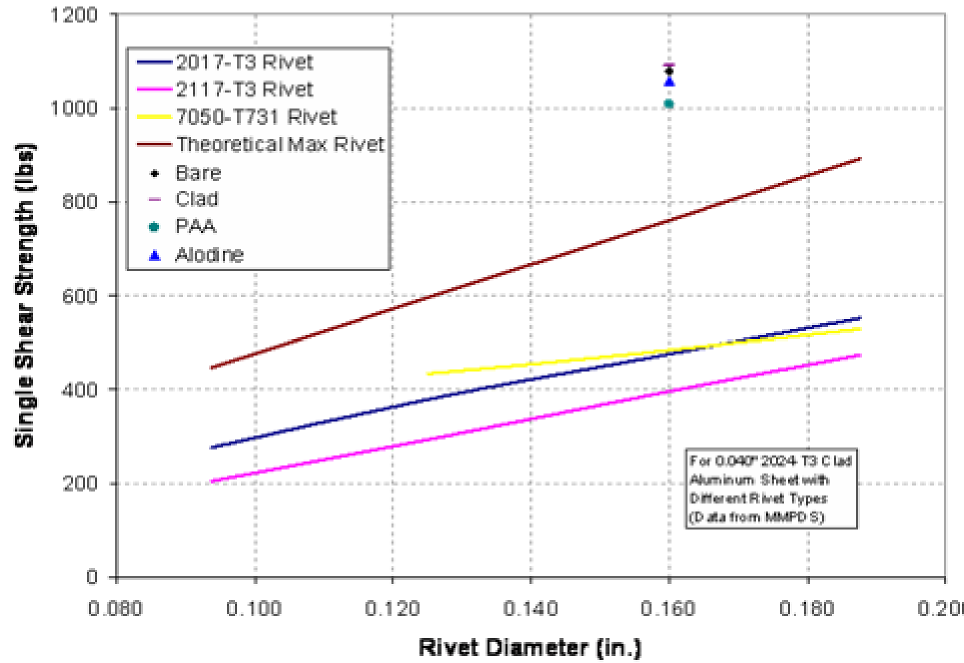
Fay Surface Treatments DOE Results

Run No.	Rotation Speed (RPM)	Travel Speed (IPM)	Plunge Depth (in)
1	1830	10.0	0.006
2	2000	5.0	0.003
3	2500	10.0	0.009
4	2250	18.4	0.006
5	2250	10.0	0.011
6	2250	10.0	0.006
7	2000	15.0	0.009
8	2670	10.0	0.006
9	2250	10.0	0.006
10	2250	10.0	0.006
11	2250	10.0	0.006
12	2500	5.0	0.003
13	2250	1.6	0.006
14	2000	15.0	0.003
15	2250	10.0	0.006
16	2250	10.0	0.006
17	2250	10.0	0.001
18	2250	10.0	0.006
19	2500	5.0	0.009
20	2250	10.0	0.006
21	2500	15.0	0.003
22	2250	10.0	0.006
23	2000	5.0	0.009

- Travel always counterclockwise
- Rotation always counterclockwise
- Advancing side always on outside
- Bare sheet over engineered material
- Central Star Composite generated by Statgraphics

0.04” thick Alclad 2024-T3





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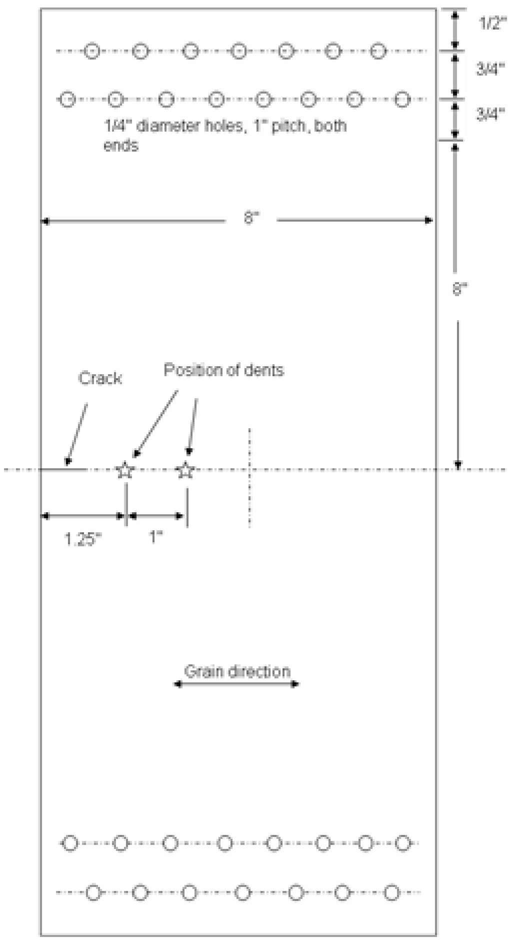
B. Tweedy, et al. TMS 2007

Fatigue Crack Growth Panels



Ref: Previous edge crack growth study in dented and repaired 0.040-in. 2024-T3 panels compared to pristine panels.

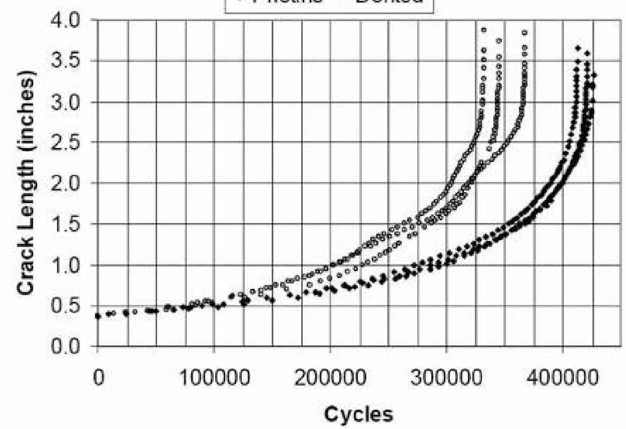
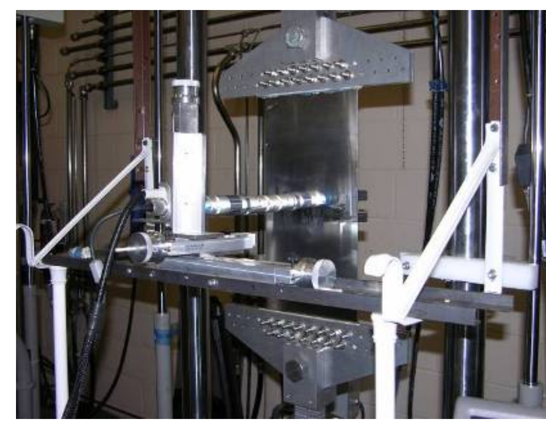


Figure 7. Crack Length vs Cycles (Pristine and Dented Specimens)



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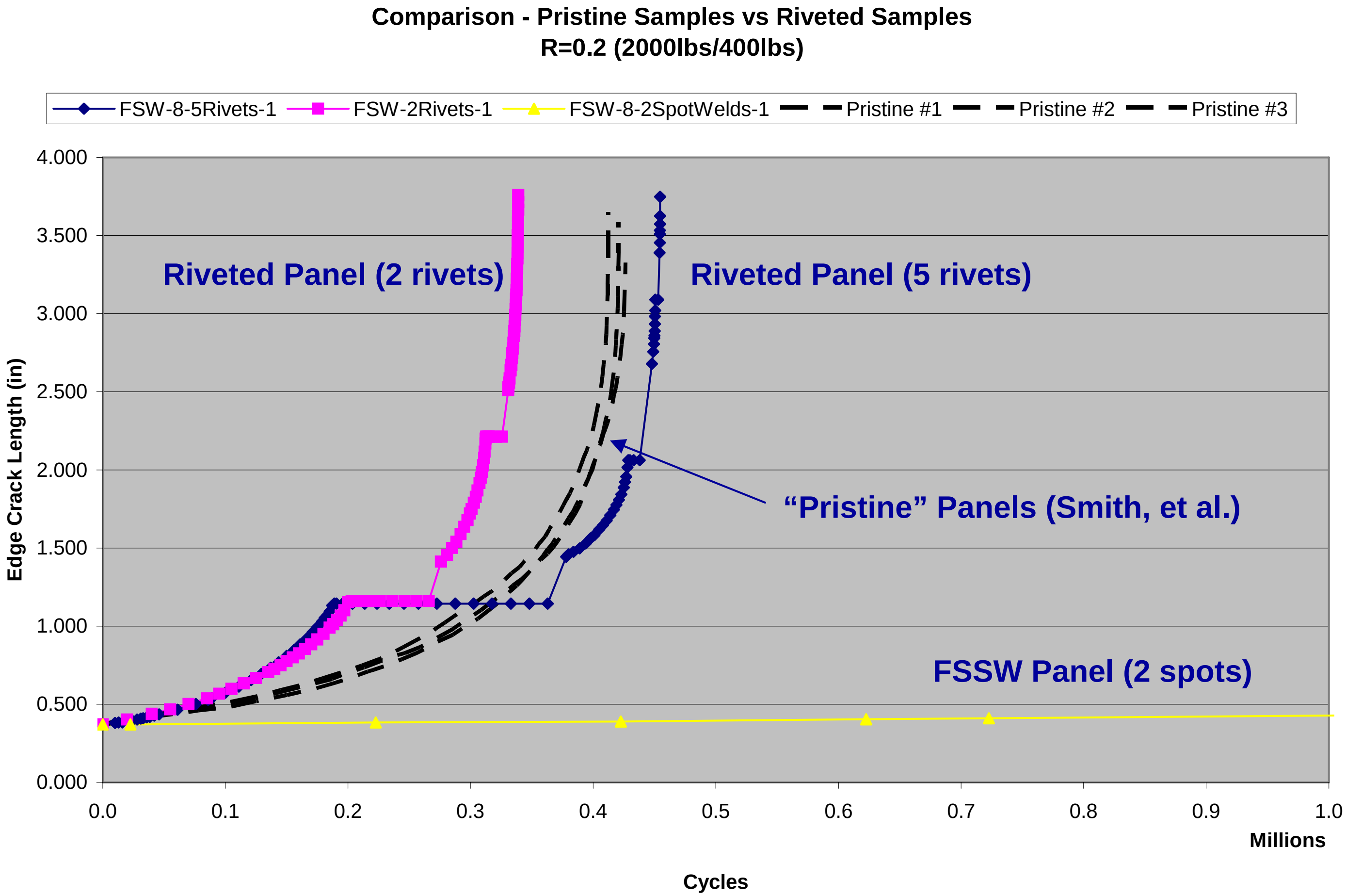
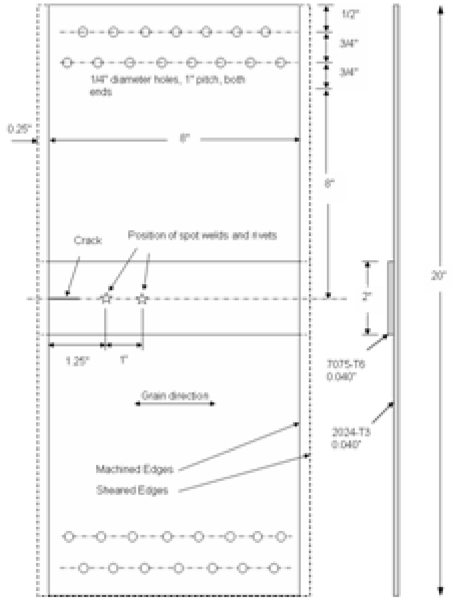
Bert L. Smith, et al.

Fatigue Crack Growth Panels





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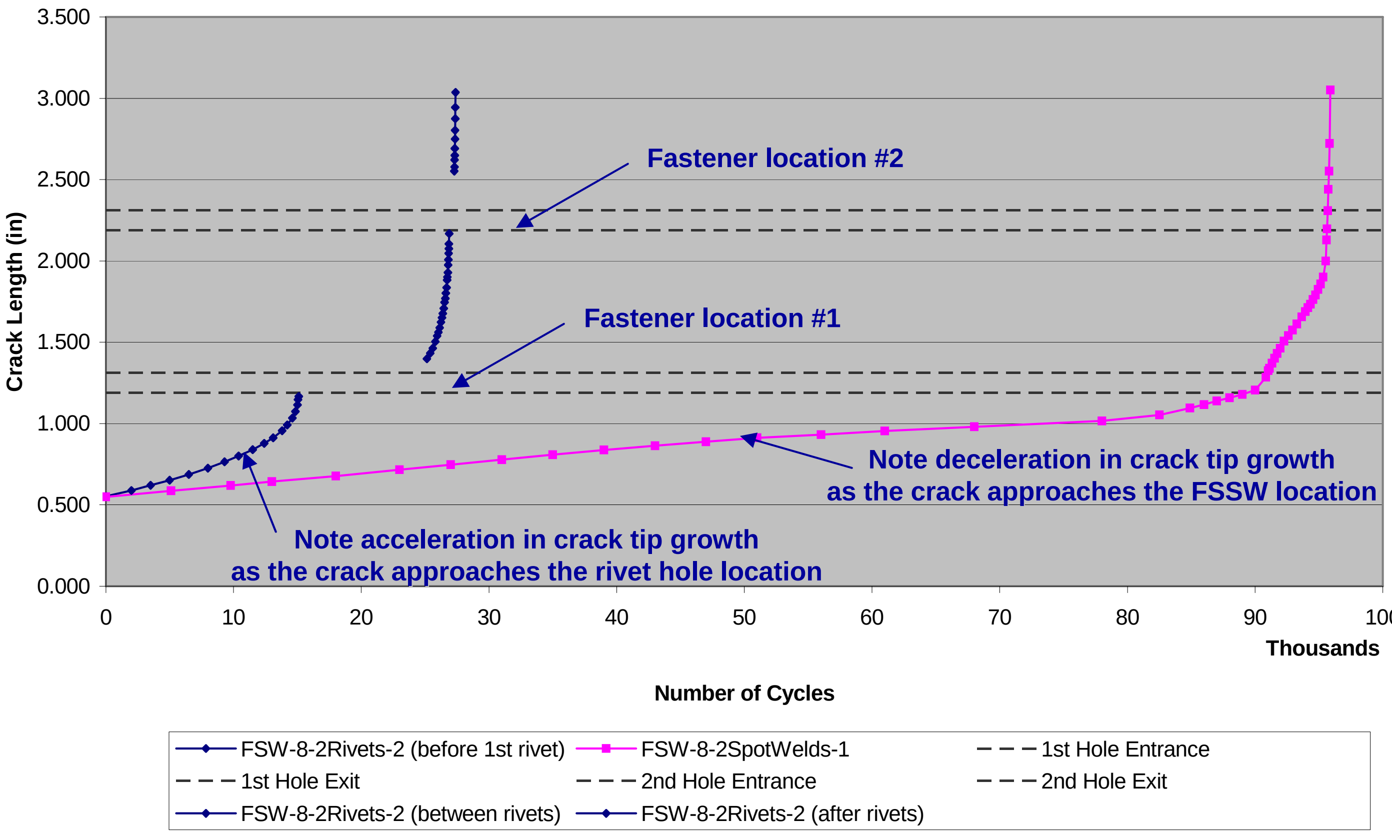
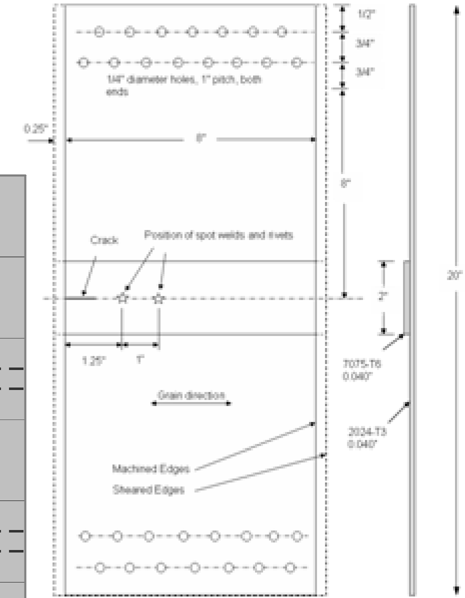
Fatigue Crack Growth Panels

Comparison of Fatigue Crack Growth Rates in Edge Crack Riveted & FSSW Panels
0.040" 7075-T6 (2" x 8") Strap on 0.040" 2024-T3 (8" x 16") Skin
Initial Edge Crack Length = 0.55, R=0.2 (4000lbs/800lbs)
(Note: Loading is double original dent study)





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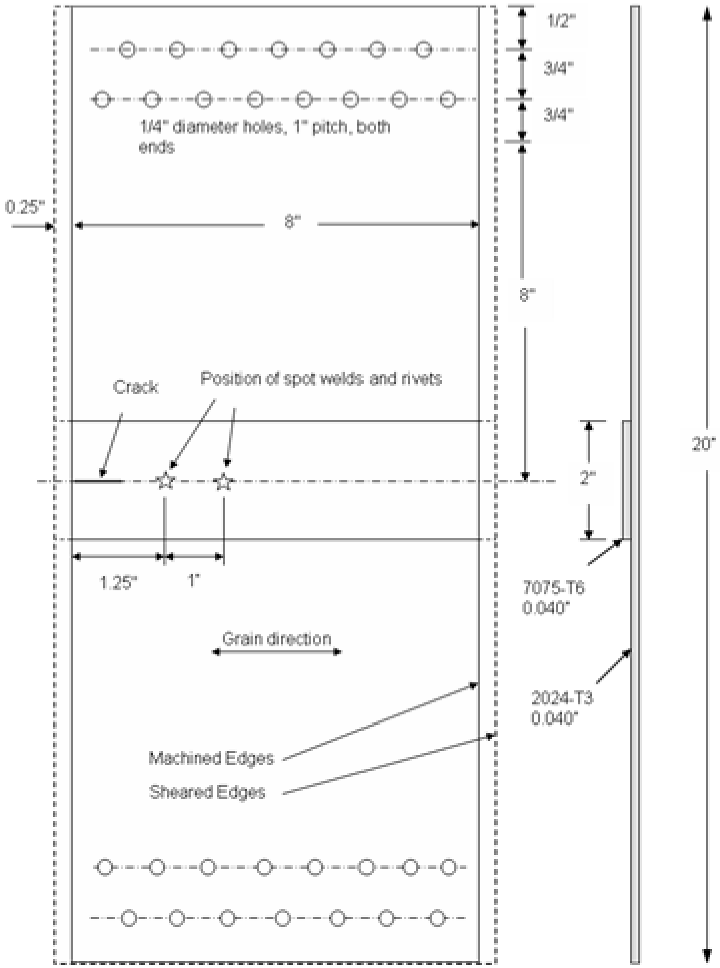
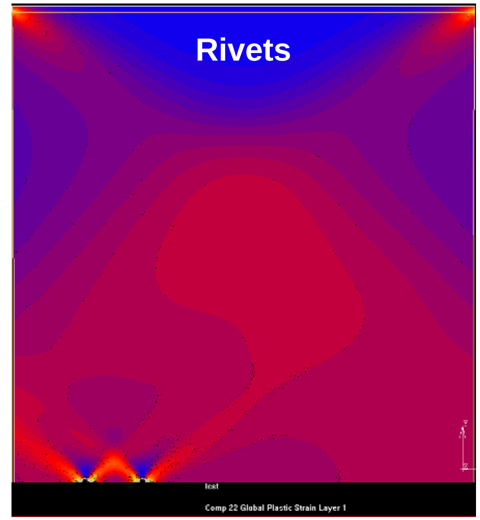
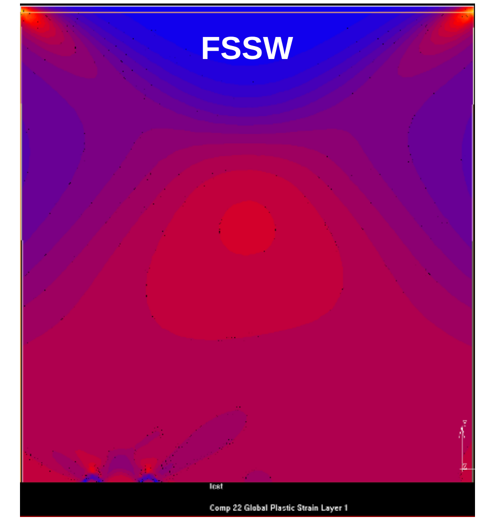
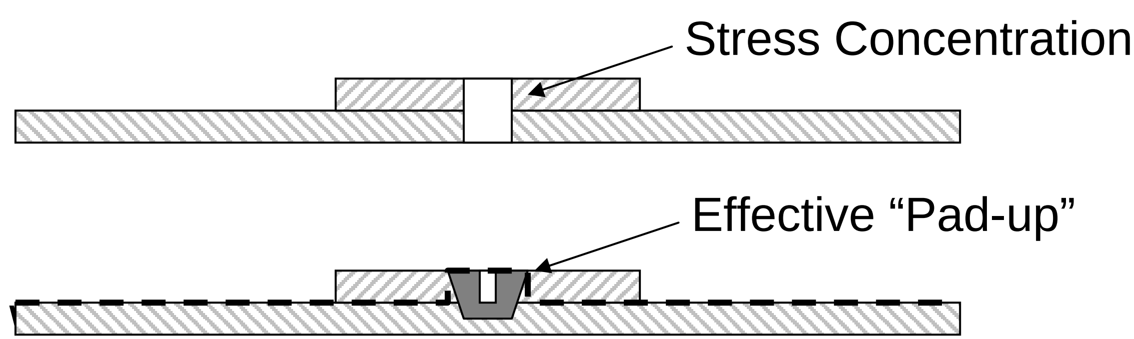
Fatigue Crack Growth Panels: Pad-up vs. Stress Concentration?







Comparison of FEM FSSW Pad-up & Rivet Hole Results Global Plastic Strain, Y-comp0.23” stretch



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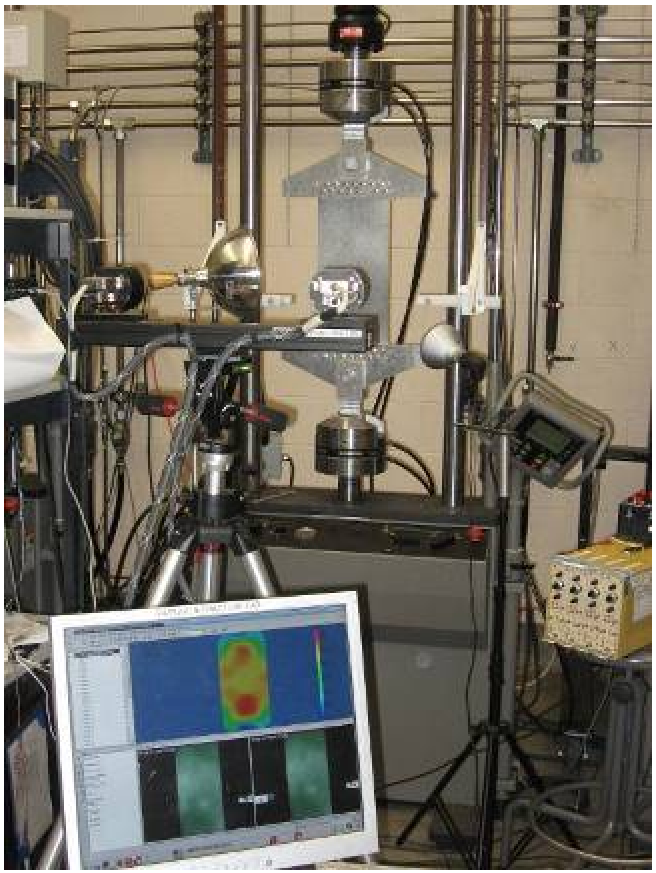
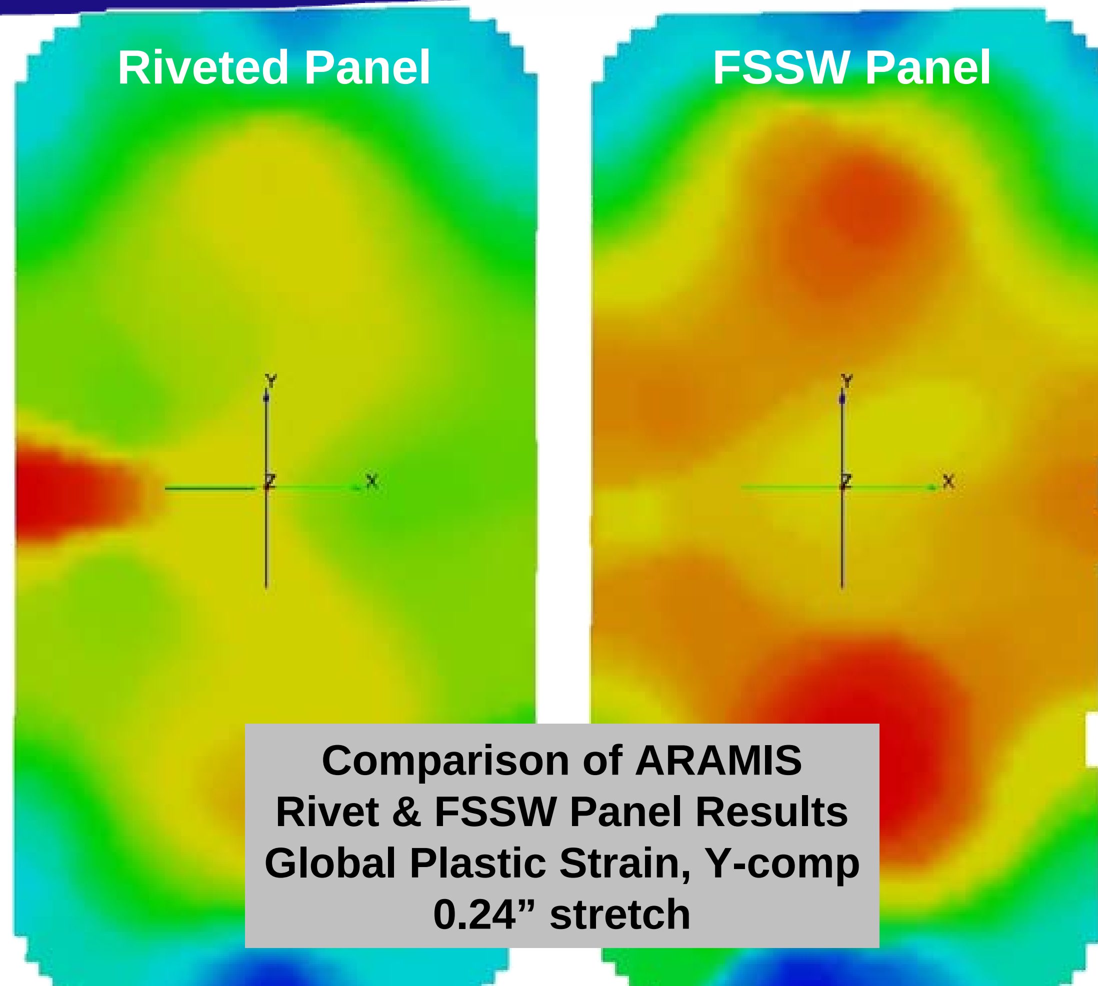
Fatigue Crack Growth Panels: Residual Stress Effect?





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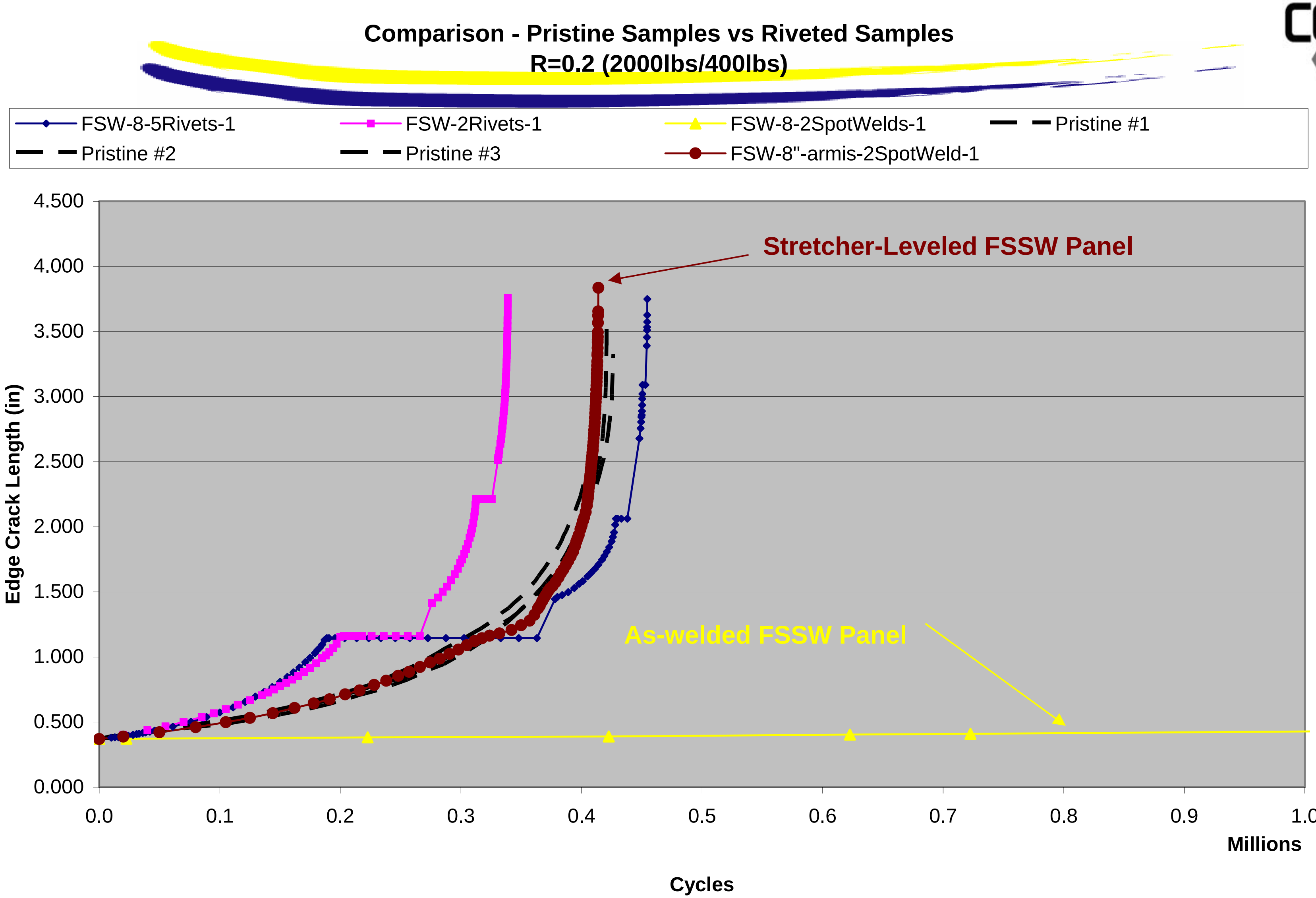

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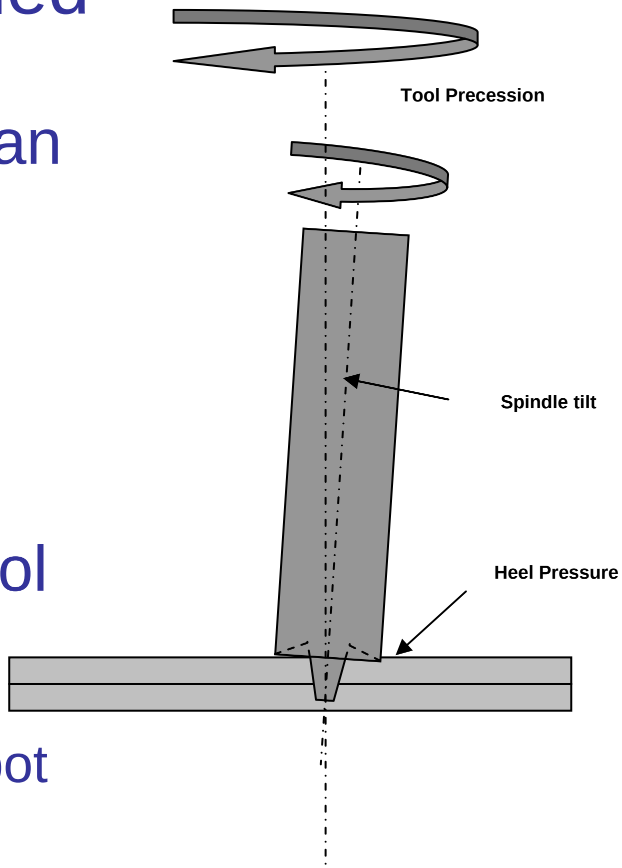
Slow Fatigue Crack Growth Rate in FSSW Panels

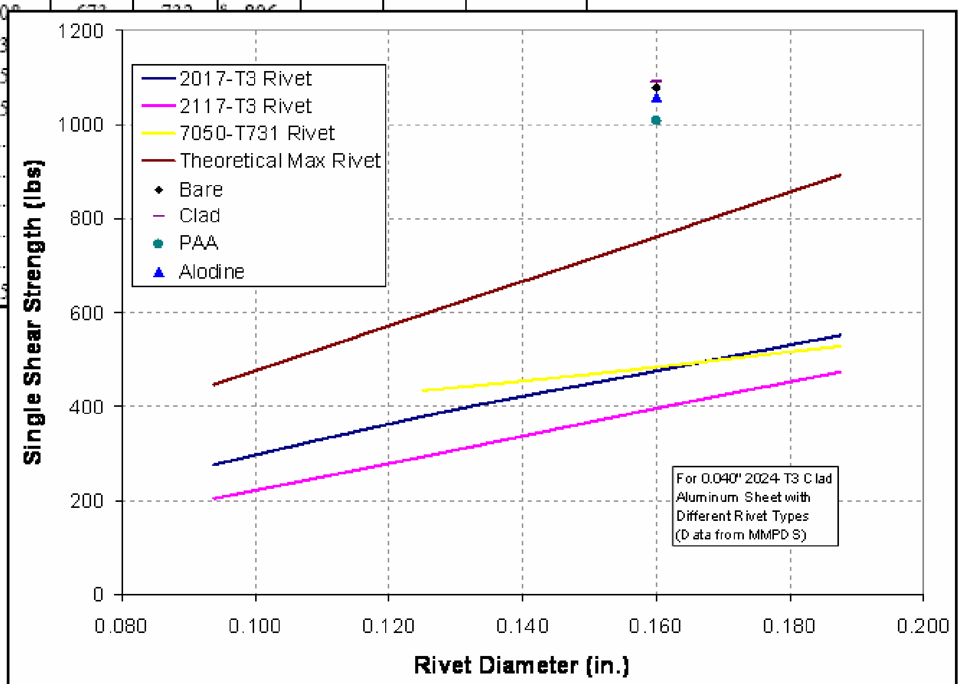
- Observations from stretcher-leveled (stress relieved) FSSW panels
  - Fatigue crack growth rate higher than in as-welded panels
  - Demonstrated similar fatigue crack growth rates to pristine panels
- Possible contributing factors
  - Precession of tool around center of spot with spindle tilt (for concave tool shoulder)
    - Heel pressure
    - Compressed surface region around spot periphery



Handbook Data / Tables

Table 8.1.2.2(m). Static Joint Strength of 120° Flush Shear Head Aluminum Alloy (7050-T731) Solid Rivets in Machine-Countersunk Aluminum Alloy Sheet

Rivet Type	MS14218E[a] (F_{su} = 43 ksi)						
Sheet Material	Clad 2024-T3						
Rivet Diameter, in. (Nominal Hole Diameter, in.)[b]	1/8 (0.1285)	5/32 (0.159)	3/16 (0.191)	7/32 (0.228)	1/4 (0.257)	9/32 (0.290)	5/16 (0.323)
	Ultimate Strength, lbs						
Sheet thickness, in.:							
0.025	215	...	...	...	...	...	...
0.032	307	[c] 346	...	...	...	...	...
0.040	434	478	[c] 529	...	...	...	...
0.050	[illegible]	[illegible]	[illegible]	[c] [illegible]			
0.063	[illegible]						
0.071	[illegible]						
0.080	[illegible]						
0.090	[illegible]						
0.100	[illegible]						
0.125	[illegible]						
0.160	[illegible]						
0.190	[illegible]						
Rivet shear strength[d]	[illegible]						



A Look Forward

- Benefit to Aviation
  - A verified qualification methodology & procedure
    - Testing & certification
    - Controls & acceptance criteria
  - Organized & certified design data
    - MMPDS (Mil HDBK 5) type data
    - S, A, & B basis
  - Design Parameters and Process Guides
    - Process & performance Specifications
    - Comparative data: FSSW vs. resistance spot welds and rivets
  - A cost effective lean/green aerospace technology
    - Low energy use
    - Reduced cycle/manufacturing time
    - Part count reduction
    - Reduced weight
    - Low emissions, environmentally friendly (no sparks, fumes, noise, or harmful rays)
    - Low Ergonomic Impact
- Future needs
  - Continued program support for implementation