Evaluation of Friction Stir Weld Process and Properties for Aircraft Application

MMPDS Initiatives:

Process Path Independence &

In-Situ Fastener Qualification

A Center of Excellence AMTAS Advanced Materials in Transport Aircraft Structures

WICHITA STATE UNIVERSITY

CECAM center of excellence for composites and advanced materials

The Joint Advanced Materials and Structures Center of Excellence

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 benefits, part count reduction, lead-time flexibility, lowered environmental & ergonomic impacts, etc., of these joining processes
    - However, each lacks sufficient supporting industry standards & design allowables data for safe, consistent industry-wide implementation
- 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
  - Christian Widener, PhD
  - Jeremy Brown, M.S.
- 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; Richard Meeske, Wichita*
  - Cessna Aircraft: *Ron Weddle & Ali Eftekhari, Wichita*
  - Hawker Beechcraft: *Byron Colcher & Phil Douglas, Wichita*
  - Spirit AeroSystems: *Casey Allen, Mike Cumming, Mark Ofsthun, & 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)

Purpose

- The key to developing allowables for any material or process is that the expected variation must be understood and controllable within certain limits.

- Friction Stir Welding (FSW) is a relatively new thermo-mechanical processing and joining technique under investigation for its potential inclusion in the MMPDS or other similar standard properties data reference.

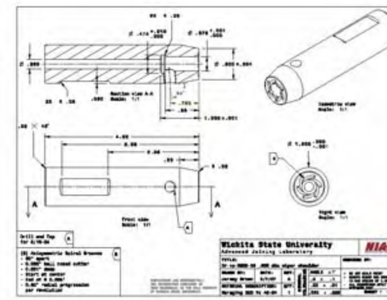
Path Independence Tools

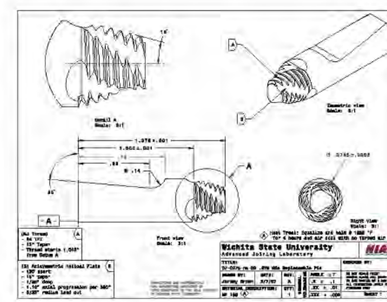
Classic TWI 5651 tool

Tri-flute™

Trivex™

Example drawings





Scroll

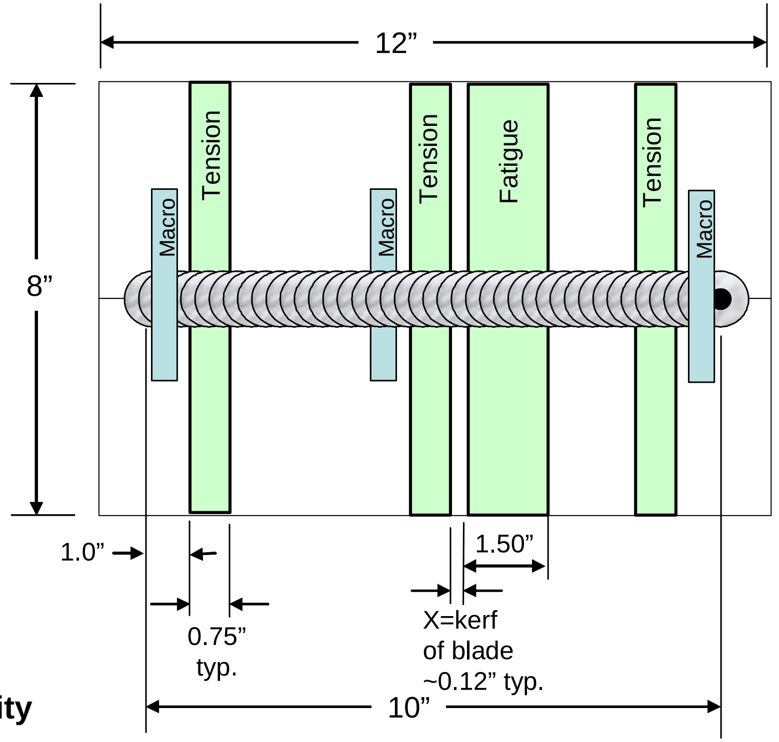
Wiper™ - small

Wiper™ - large

Path Independence Coupon & Fixture

- Material
  - 0.250 inch 2024-T351 bare
  - Provided by Cessna Aircraft
  - Three heat lots, randomized
  - Machined into 4” x 12” coupons
- Test Fixture
  - Side clamps
  - 4000 series anvil

- Test Coupons
  - (3) Tensile *(ASTM E-8)*
  - (3) Metallography
  - (1) Fatigue



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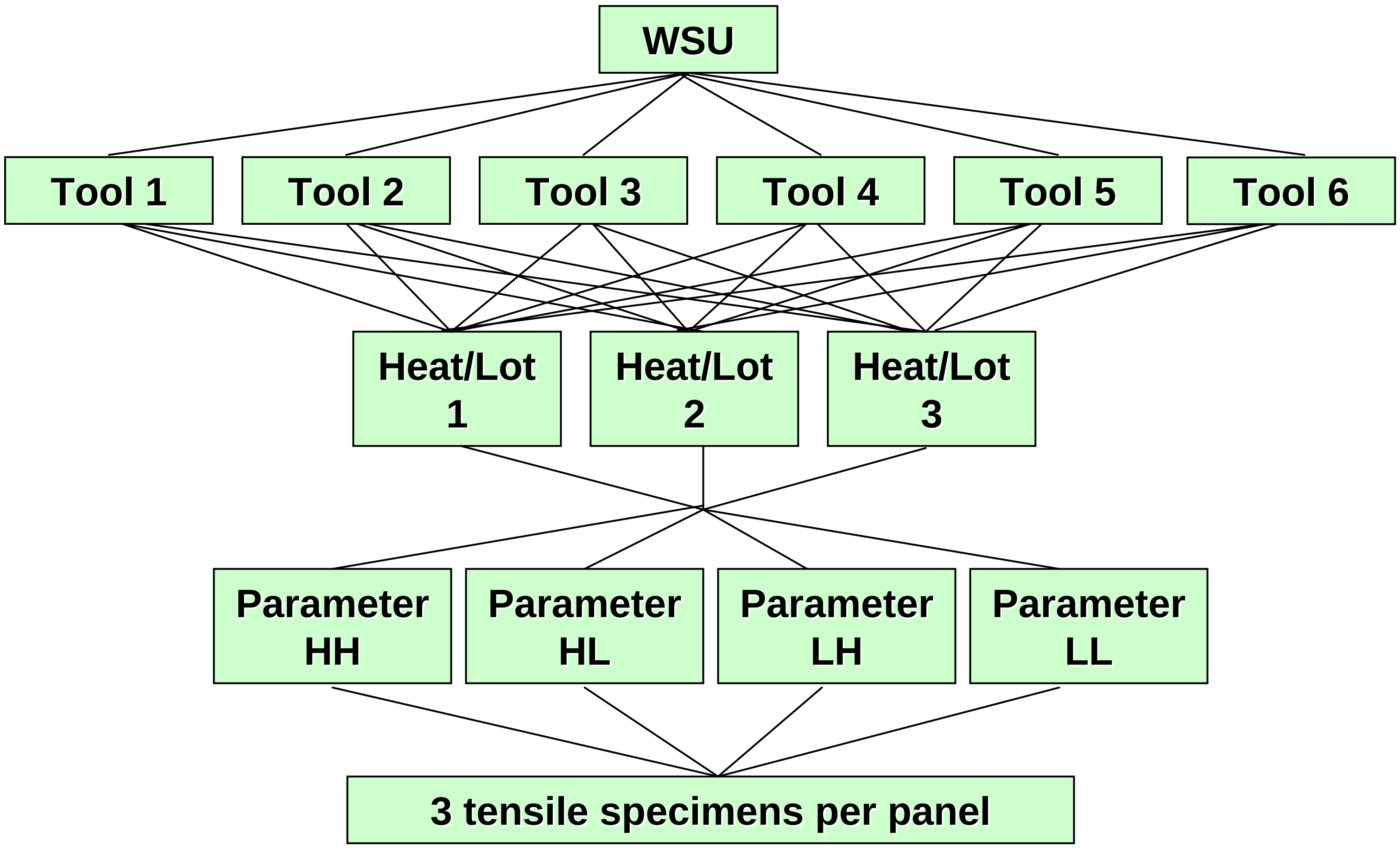
Design Allowables for FSW

- ***FSW Allowables***
  - Statistically calculated minimum strength values that can be used for design.
- ***What is needed to calculate allowables?***
  - An understanding of the expected variation.
    - Random variation
    - Process controlled variation
  - A statistical procedure for calculating allowables.
  - A sufficient number of representative samples to gain the necessary confidence that the process is repeatable, reliable, and under control.

Sources of Variation for FSW

- Welding Parameters
  - Strength varies from Low (<50% Joint Efficiency) up to the theoretical maximum for a given tool.
- Tool Design
  - Affects the theoretical maximum for a given alloy/thickness combination.
- Site / Facility
  - Varies up to theoretical maximum, and is affected by fixturing, machine type, control system tuning, operator, lab conditions, etc.
- Base Material
  - Joint strengths can be affected by large variations in parent material strength and material thickness.

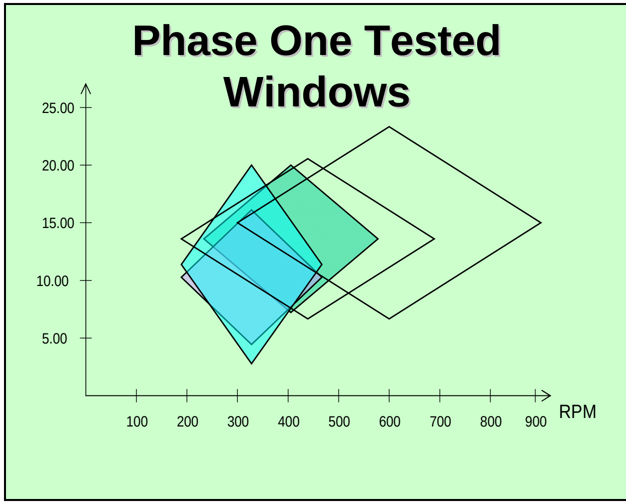
Path Independence Study – Tool Variability

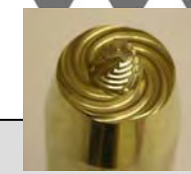


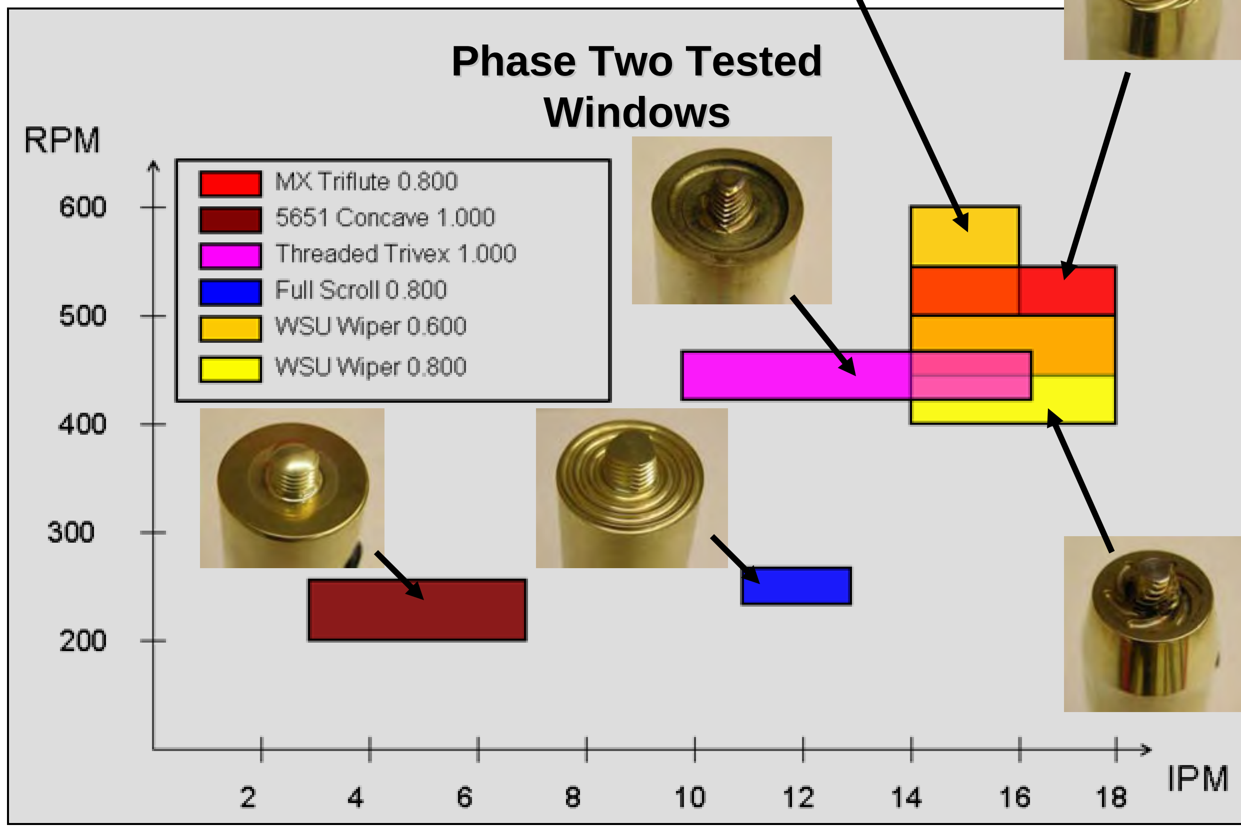
Results

- Stable process zones were identified for three of the tools during the second round DOE
  - S-basis values were calculated for each tool
  - T_{99} and T_{90} values were calculated for pooled data from the three tools.
- Acceptable parameters were found for the remaining tools, but were not fully optimized.

Process Windows





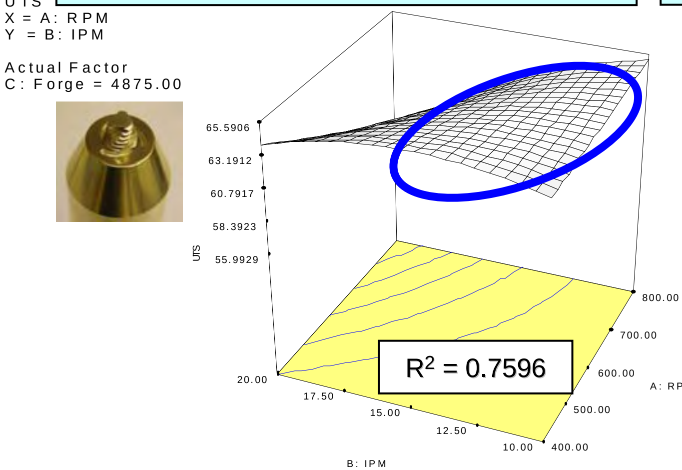


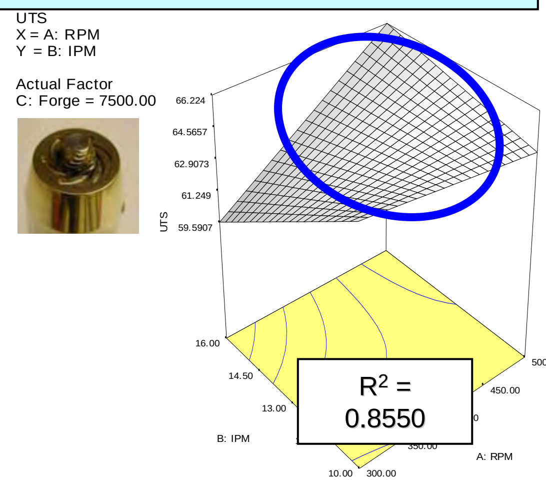
Tensile Test Results

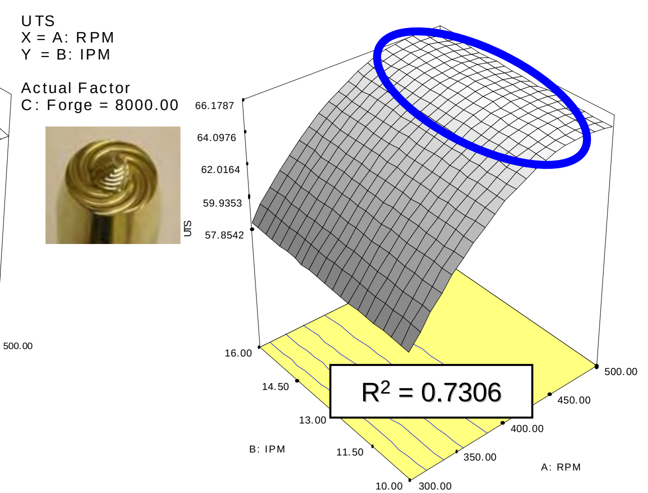
- 11 welds, 5 parameter sets
- 30 tensile coupons
- S-basis = 59.5 ksi

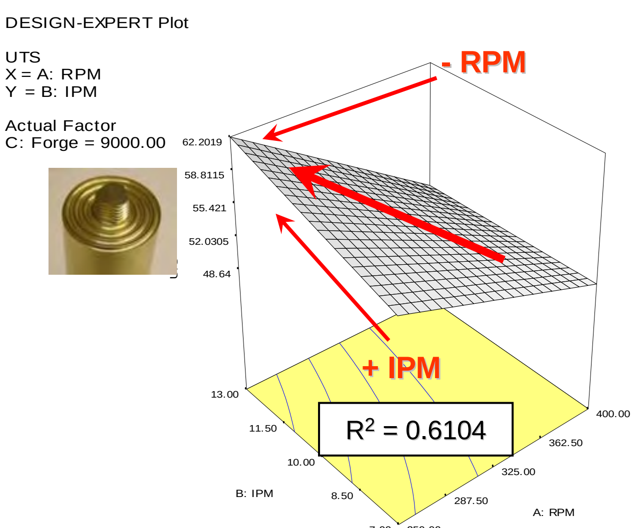
- 13 welds, 11 parameter sets
- 39 tensile coupons
- S-basis = 60.9 ksi

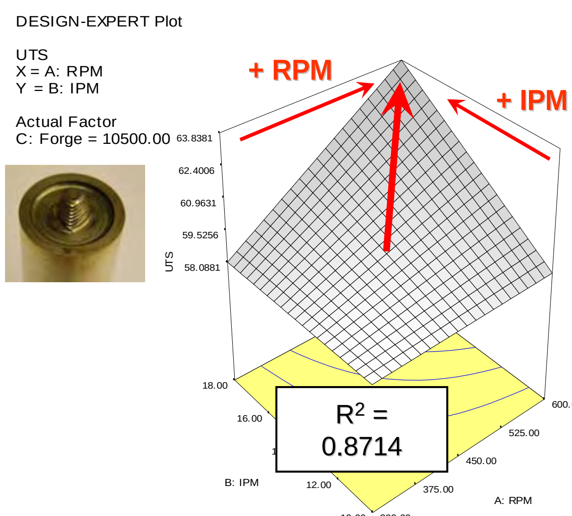
- 10 welds, 10 parameter sets
- 32 tensile coupons
- S-basis = 59.7 ksi

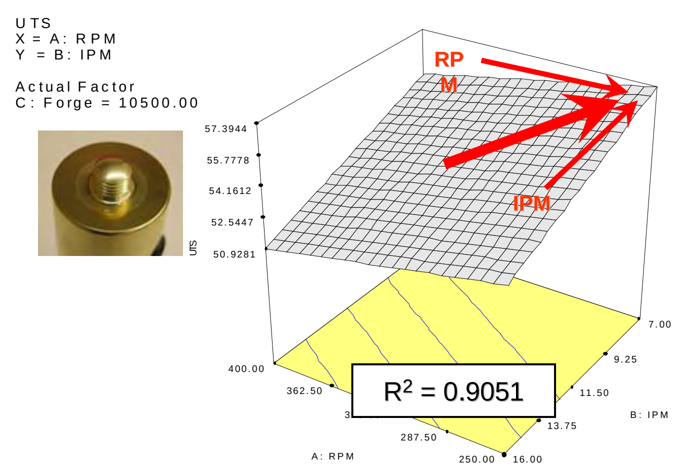






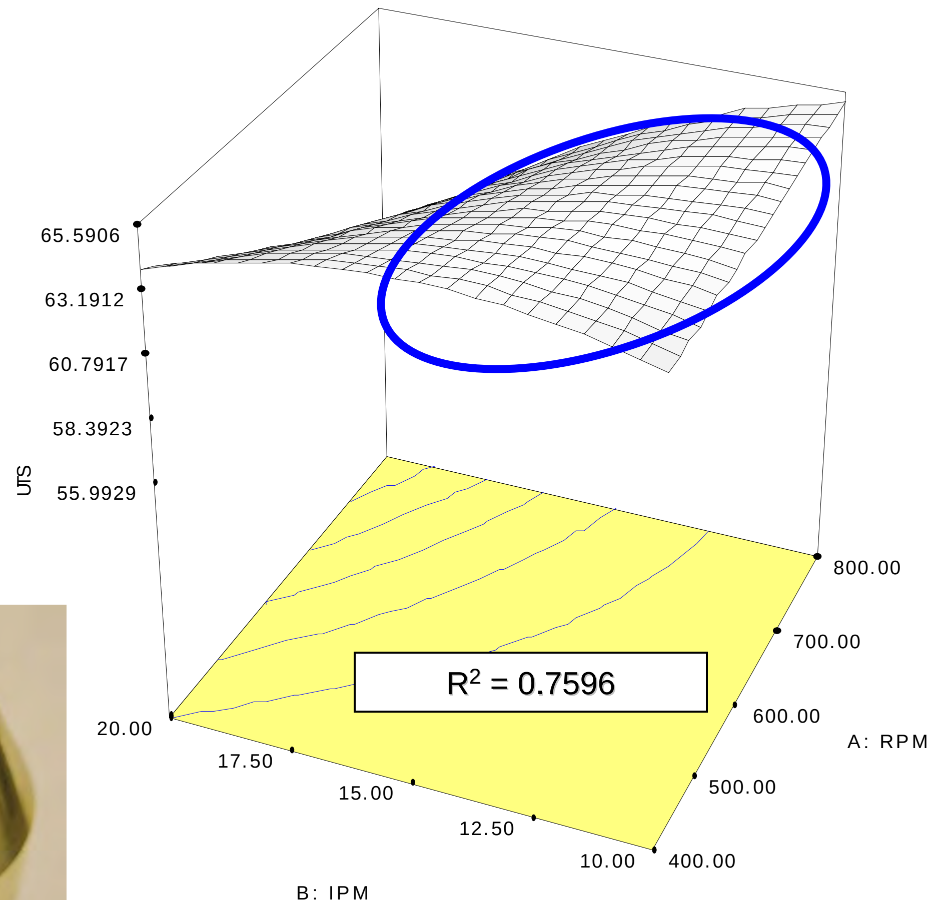




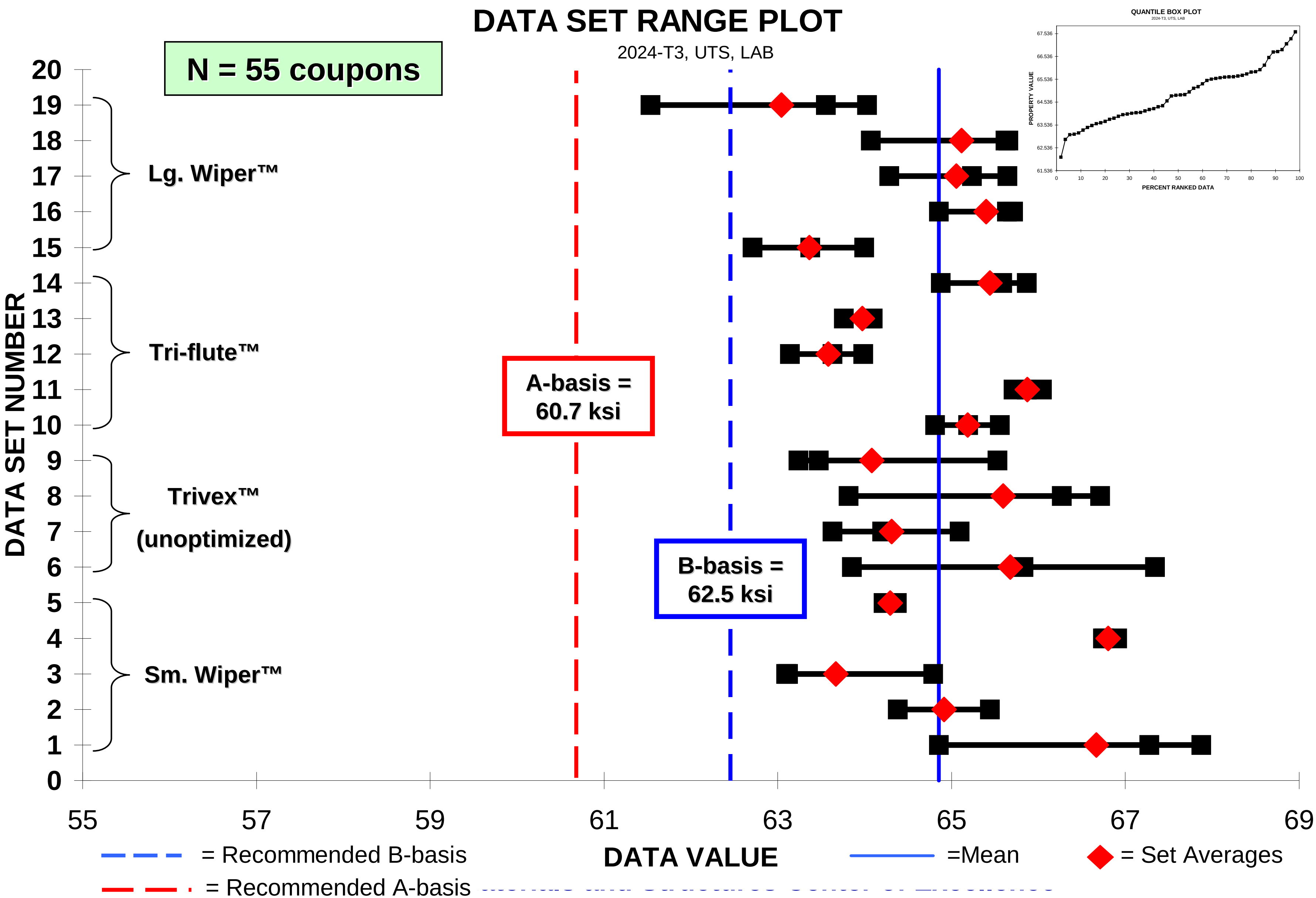


Tensile Results: 0.6” Small Wiper

- Optimized zone
  - RPM: 300 – 800
  - IPM: 6.6 – 15
  - Forge load: 4500 – 5500
  - 1 tool, 11 welds, 5 parameter sets, 30 tensile coupons
  - Max. 67.9 ksi
  - Min. 61.1 ksi
  - Avg. 65.1ksi
  - Stdev 1.833 ksi
  - $K_{99} = 3.064$
  - $S_{basis} = 59.5$ ksi



ANOVA Analysis using 4 – FSW Tools



Reported Data on 2024-T3

Table 1: Reported Tensile Results for As-Welded 2024-T3*

Material Thickness	Ultimate Tensile Strength	Weld Elongation (%)	Ref.
0.040-in. (1 mm)	*58.9 ksi (406 MPa)*	*6.0*	*5*
0.064-in. (1.6 mm)	*66.9 ksi (461 MPa)*	*11*	*6*
0.080-in. (2 mm)	*64.7 ksi (446 MPa)*	*13.0*	*7*
0.080-in. (2 mm)	*64 ksi (441 MPa)*	*16.3*	
0.090-in. (2.25 mm)	*53 ksi (366 MPa)*	*- -*	
0.100-in. (2.5 mm)	*71.1 ksi (490 MPa)*	*17*	
0.125-in. (3.2 mm)	*63.5 ksi (438 MPa)*	*12.2*	
0.l60-in. (4 mm)	*62.7 ksi (432 MPa)*	*7.6*	
0.200-in. (5 mm)	*59.5 ksi (410 MPa)*	*5.1*	
0.250-in. (6.35 mm)	*60.9 ksi (420 MPa)*	*--*	
Average	***62.5 ksi (431 MPa)***	***11***	
Std. Dev.	***4.90 ksi (33.8 MPa)***	***4.5***	

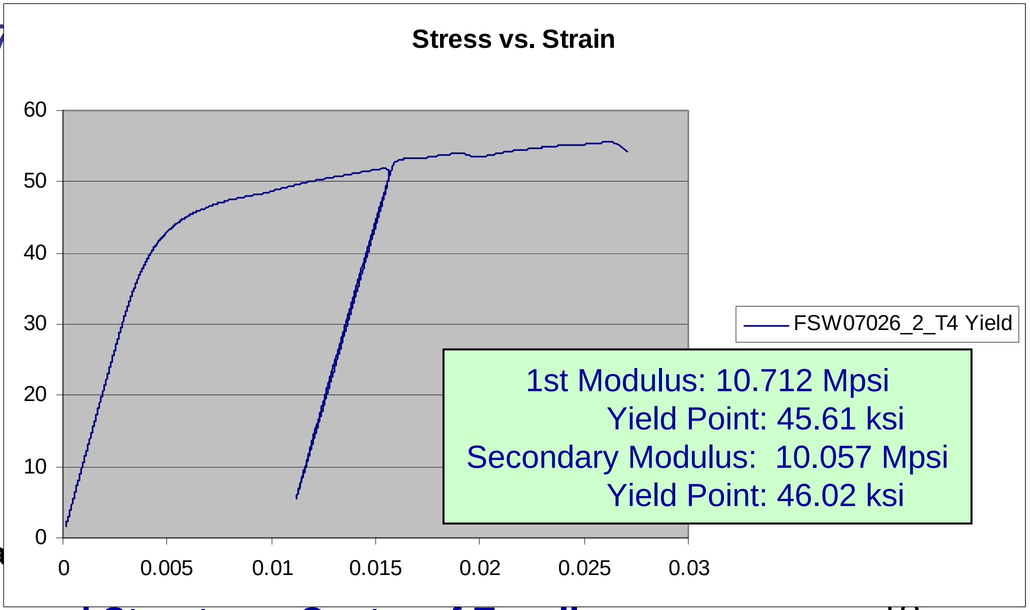
- 70% of the averages reported in literature would meet these calculated T99 values.
- 60% of the averages reported in literature would meet these calculated T90 values.

***2024 is a precipitation strengthened Al alloy that naturally ages to a stable temper within 96 hrs**

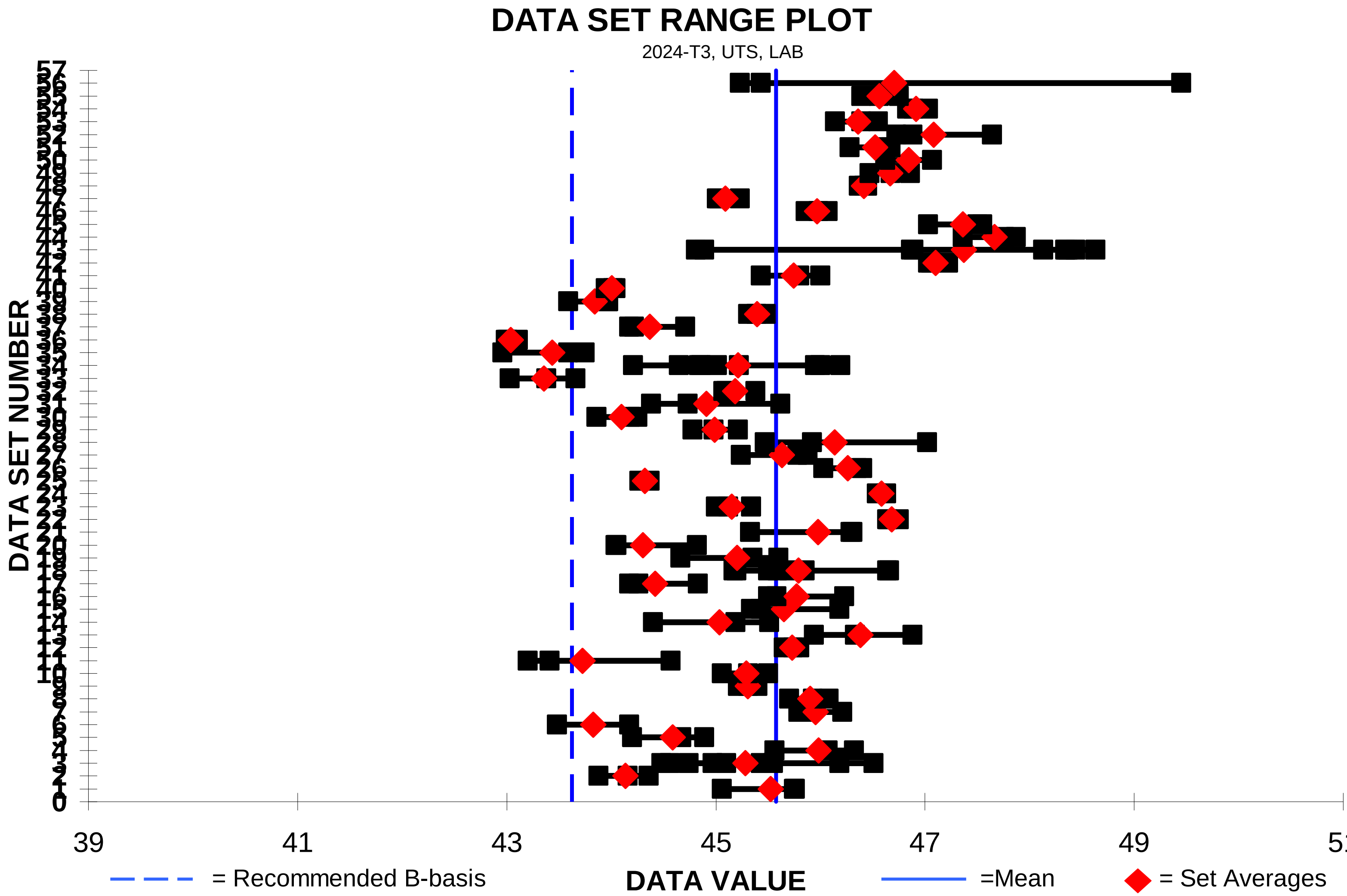
Calculated Path Independence T_{90} value was also 62.5 ksi

Yield Strength

- Yield strength appears to be much less sensitive to welding parameters.
- For the large Wiper™ tool (FSW07026) over the entire DOE (17 welds):
  - UTS = 62.9 ± 3.46 ksi
  - YS = 45.1 ± 0.84 ksi
- For the Triflute™ tool (FSW07
  - UTS = 62.2 ± 5.21 ksi
  - YS = 45.5 ± 0.90 ksi

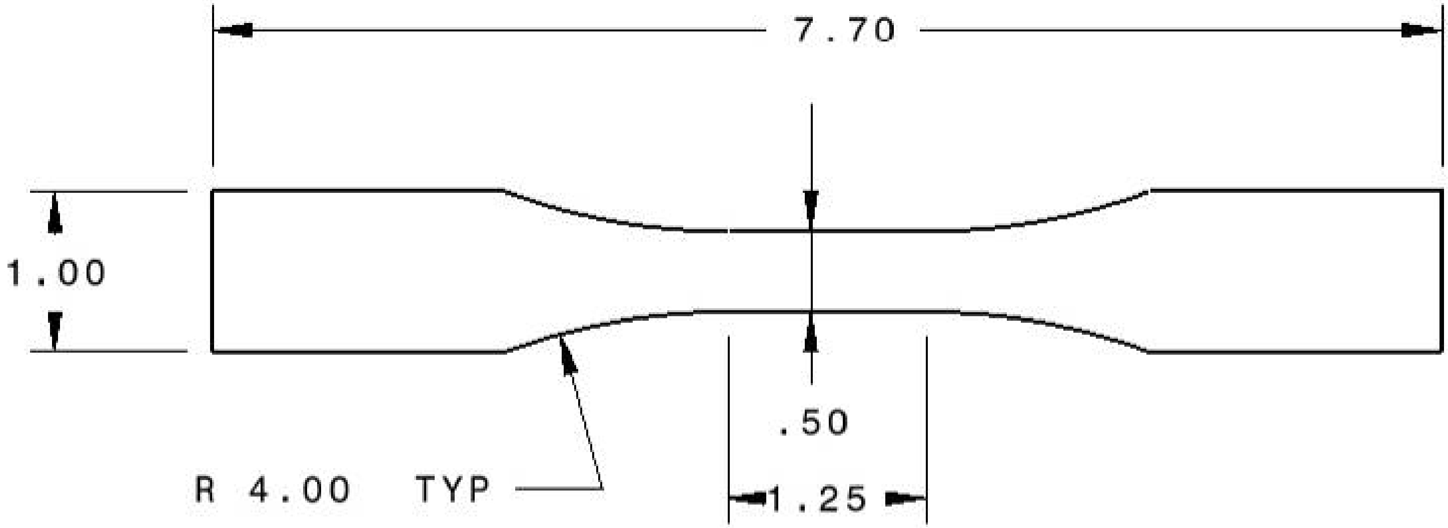


Yield Data – Four Best Tools – Over the Entire Parameter Range



Fatigue Testing

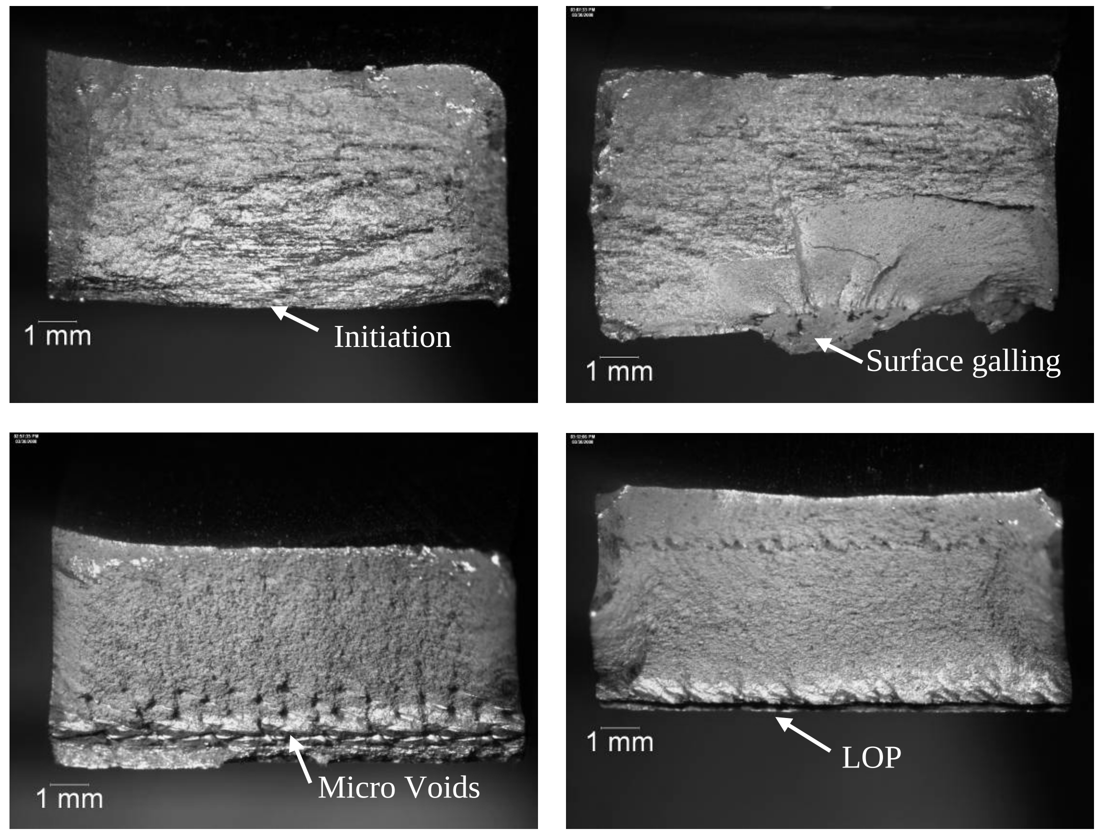
- Screening Tests
  - Stress level targeted for $10^4 – 10^5$ cycles.
  - Load 5000 lbs, R = 0.1, 20 Hz
  - Purpose to evaluate if optimum parameters based on strength and failure mode are also optimum for fatigue.



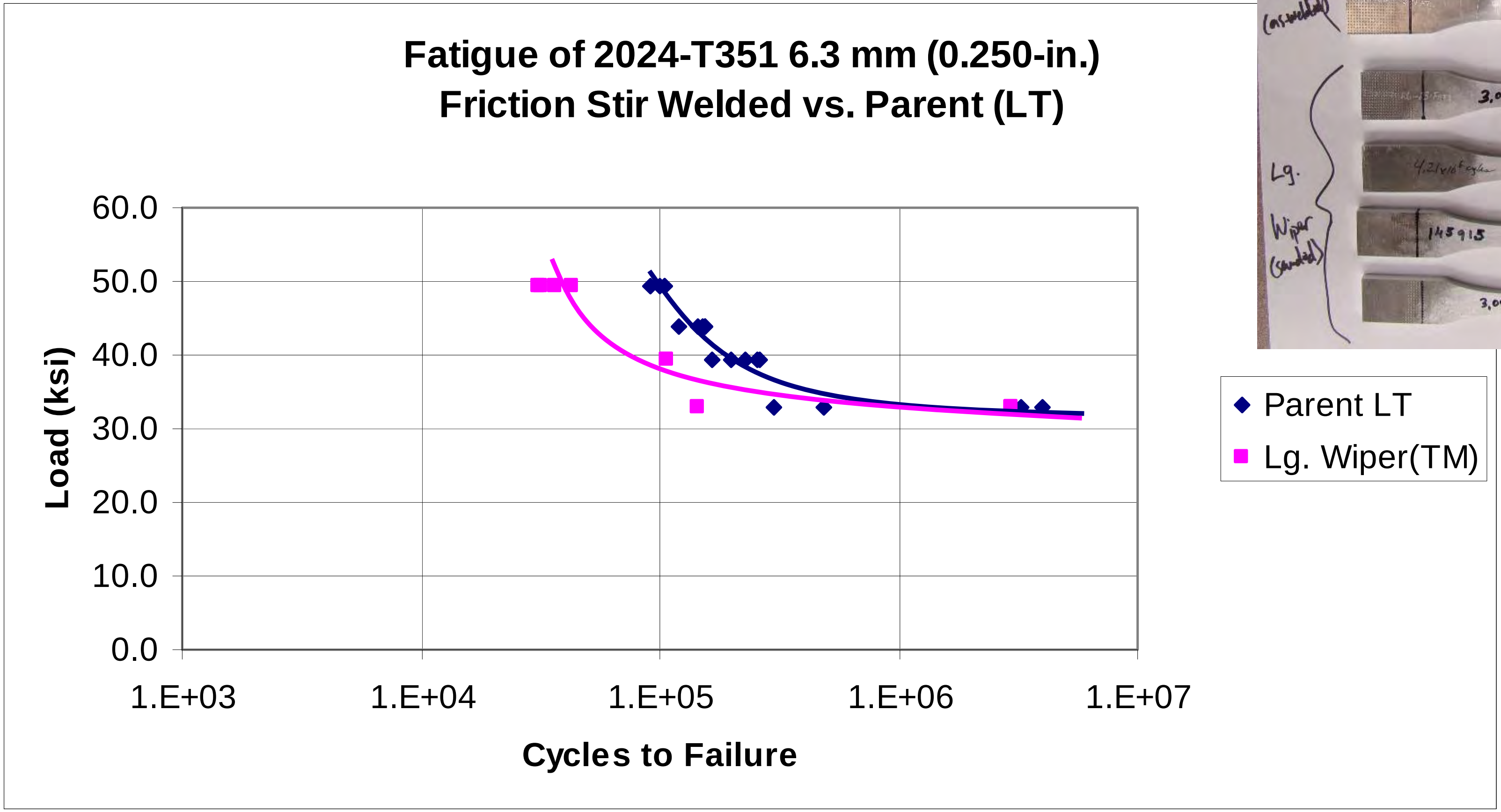
Typical Fatigue Failures from Screening Test

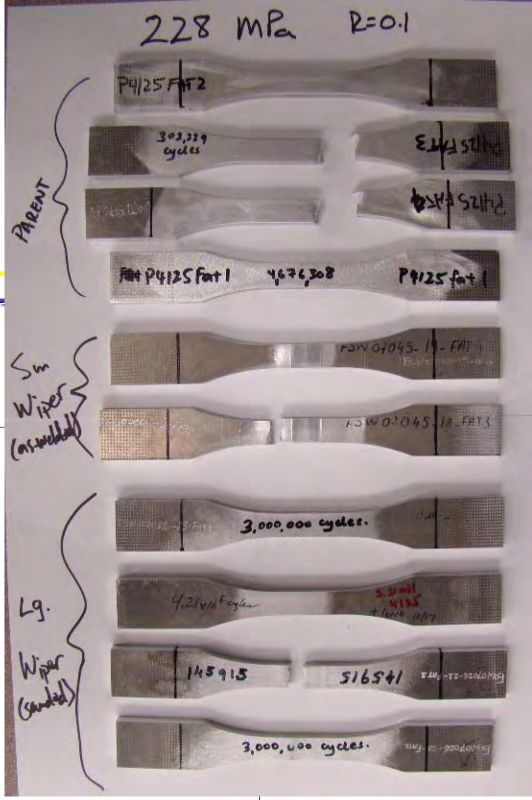
- Welding defects can be readily identified in the fracture surface of welded coupons

- When defects were not present, the fatigue performance was observed to be close to parent material.

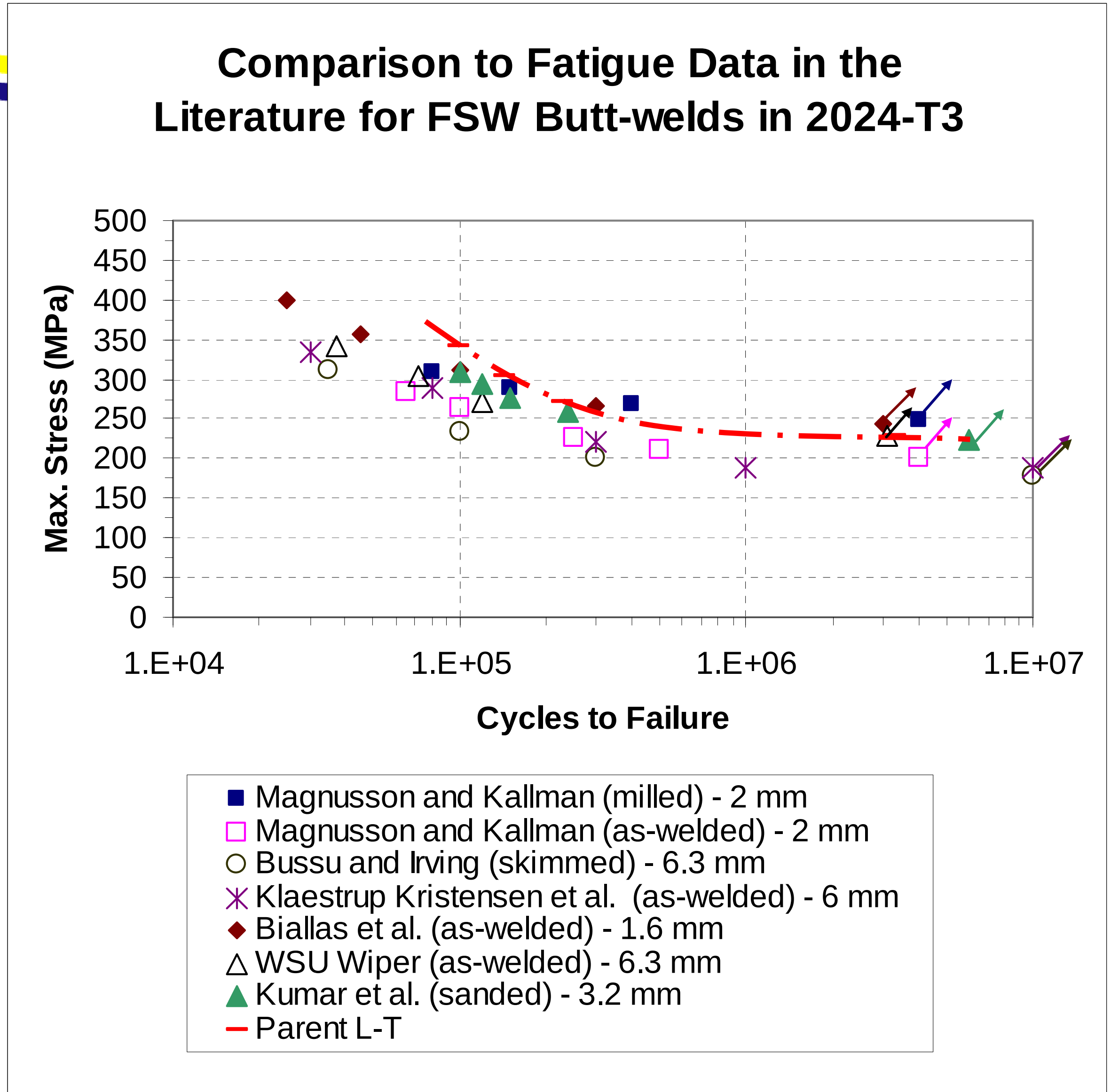


Fatigue Results



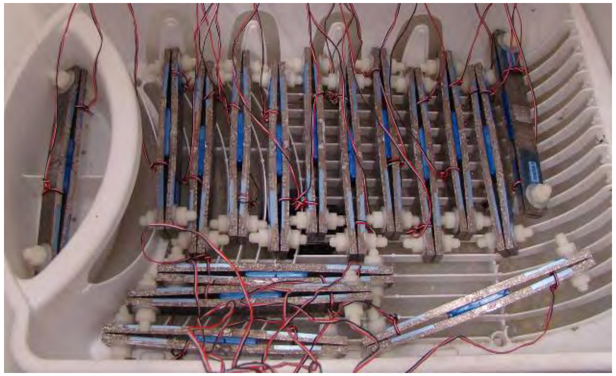


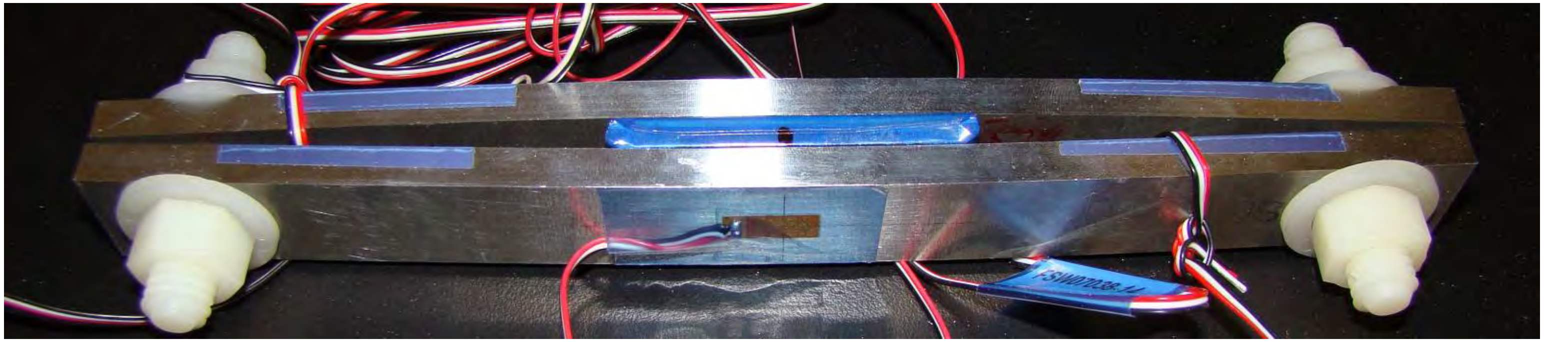
Survey of Other Reported Fatigue Results



Path Independence – SCC Testing

- SCC Testing – 32 samples – PER ASTM G64, G47, and G58
  - 4 point bend – 2-in. apart - 23 ksi – verified by strain gauge
  - Alternate Immersion – 3.5% NaCl
  - As-welded – tested to parent material rating 50% of Y.S. for LT
  - TEST COMPLETE - After 40 days – No Failures – Meets Parent Specification





Summary & Conclusions

- It has been demonstrated that a number of different tool designs can be used to produce a sound friction stir welded joint in 0.250-in. 2024-T351.
- These results are in reasonable agreement with reported results for 2024-T3 in a range of thicknesses.
- This is not to suggest that one tool may not provide any particular advantage over another in terms of productivity, fatigue, etc.
- For allowables or a performance specification, it is unnecessary to define exact tool geometries.
  - Tool geometries would be found in the weld process specifications of individual suppliers or producers, but should not be a requirement to meet performance goals
- The next phase is round robin testing…

Road Map for FSW Allowables Development…

FAA/NIS "Evaluation of Friction Stir Weld Process and Properties for Aircraft Application"

Path Independence– tool and process variation

Conducted at Wichita State University

Round Robin Testing – site to site variation

Underway – Expected completion April 2009

A performance-based specification approach

Report the Path Independence final results to the FAA via a DOT/FAA/AR

Does FSW belong in the MMPDS?

STOP

Draft new sections for inclusion in the MMPDS for FSW

Begin testing for allowables

Wichita State University

Outline

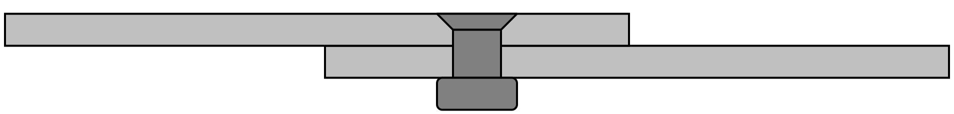
- *Qualification Initiatives*
  - *Performance Specifications*
  - *Butt & Lap Joint Initiatives*
- *Path Independent Study*
- ***In Situ Fasteners***

Lap Joint Initiative

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

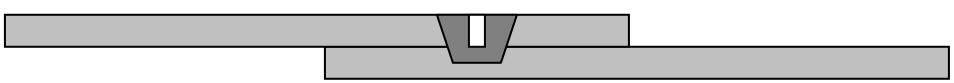
(Not compatible with faying surface sealants)

Resistance Spot Weld: joining surfaces across interface



(Compatible with faying surface sealants)

Rivet: installed in hole and compressed to form tight joint



(Compatible with faying surface sealants)

FSSW: unique fine-grained metallurgical structure extending into components

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
    - Supports 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)
  - Compatible with faying surface sealants

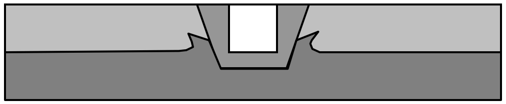
In Situ Fasteners Qualified as *Installed* Fasteners

- **Approach**
  - Develop & test 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
- **Background**
  - In both static & 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 can be tailored to support design
    - They appear to provide favorable residual stresses & 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.

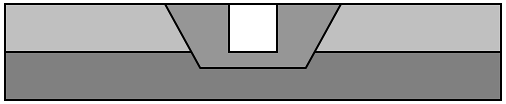
Background

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

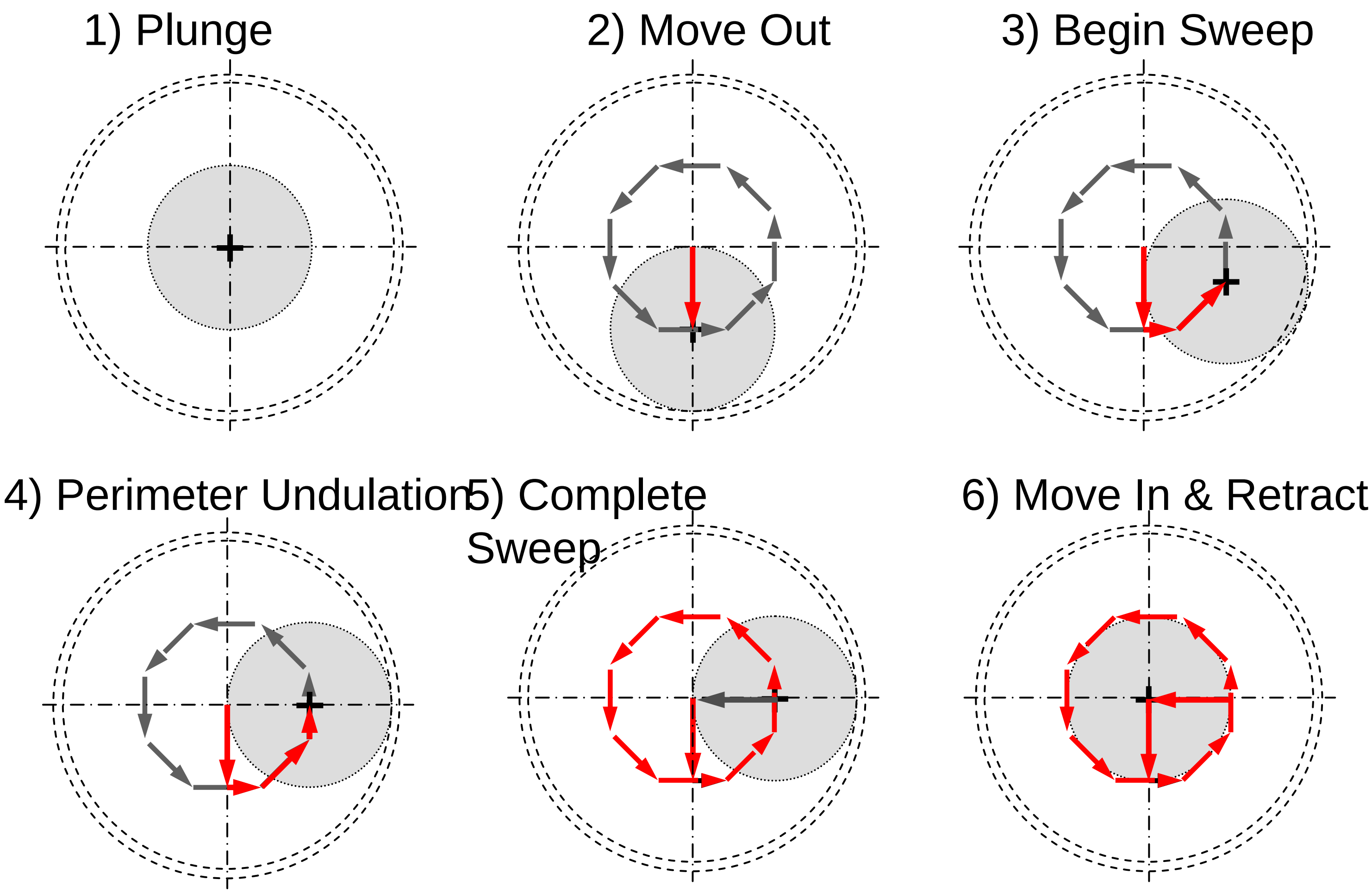
Plunge (Poke) Spot



Swept Spot

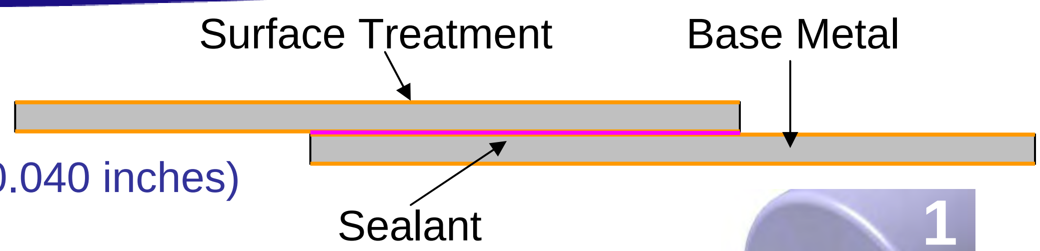


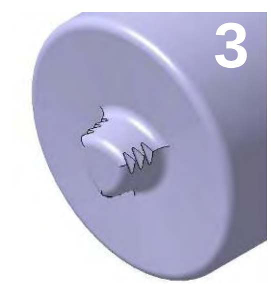
Background – Octaspot™ Tool Path



Procedure

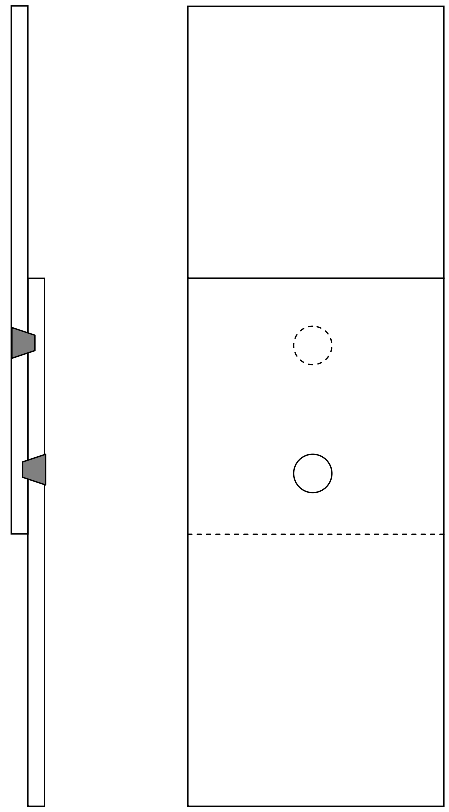
- Materials
  - Alloys
    - 2024-T3 - 1.0 mm thick (0.040 inches)
  - Surface Treatments
    - Bare (untreated)
    - Clad
    - Chromic Acid Anodized (CAA)
    - AlodineMaterials (cont.)
  - Sealants
    - PRC-DeSoto PR-1432 GP
    - Pelseal PLV 6032
  - Tool Options
    - Psi
    - Counterflow
    - Modified Trivex





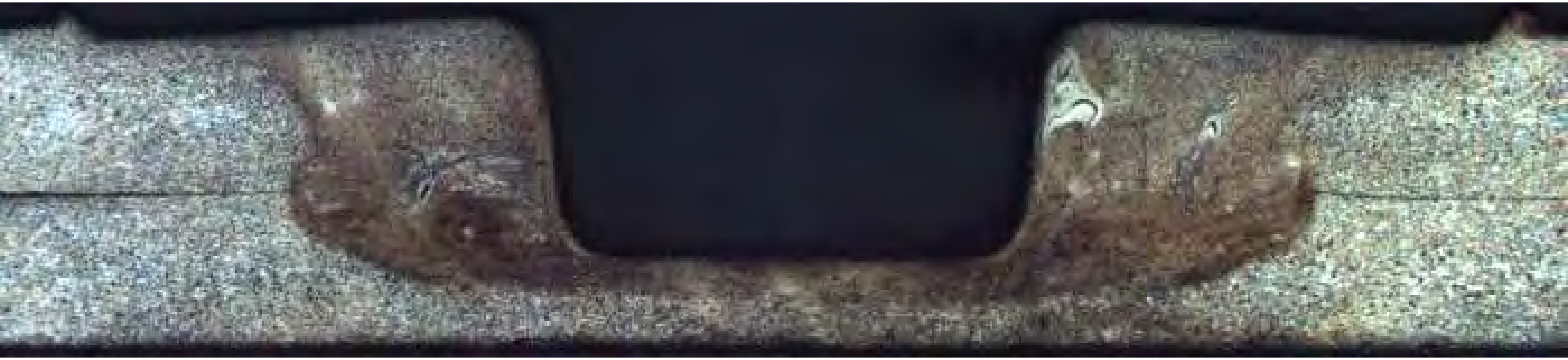
Procedure

- Tool and Parameter Selection
  - 3rd DOE – NASM 1312-4 Dual Opposing Spot Configuration
    - CAA Material
    - PR-1432 GP Sealant
    - Refined from 2nd DOE
    - Variables
      - Rotation Speed
      - Travel Speed
      - Lead Angle
      - Forge Load (Load Control)
    - Response
      - Ultimate Tensile Load
      - Failure Mode



FSSW Through Surface Sealant Results

- **Surface treated material with the PR-1432 GP sealant have strength equivalent to that of Bare with no sealant.**
  - Sealants can increase the strength of the coupon
  - Surface treatments and sealants appear to increase scatter
- **Calculated S-basis strengths**
  - S-basis ultimate load per spot = 1113 lbs
  - 30 coupons, 3 parameter sets, 6 batches



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	508	673	732	[c] 806	...	...	
0.063	536	781	1045	1135	[c] 1200	1285	
0.071	554	803	1110	1365	1445	1530	[c]
0.080	558	827	1140	1565	1735	1835	
0.090	...	854	1175	1605	1990	2200	
0.100	...	...	1205	1645	2030	2525	
0.125	...	...	1230	1740	2140	2650	
0.160	...	...	...	1755	2230	2820	
0.190	...	...	...	...	...	2840	
Rivet shear strength[d]	558	854	1230	1755	2230	2840	

Pin tool (part # and description)	WSU-07-0055-0400-06 - Counterflow Pin Tool								
Sheet material	2024-T3								
FSSW Diameter, in. (nominal swept diameter of pin tool)	1/8 (0.125)	5/32 (0.15625)	3/16 (0.1875)	7/32 (0.21875)	1/4 (0.250)	9/32 (0.28125)	2/7 (0.295)	5/16 (0.3125)	1/3 (0.333)
	Ultimate Strength, lbs								
Sheet thickness, in.									
0.025									
0.032									
0.040					1003		1164		1315
0.050									
0.063									
0.071									
0.080									
0.090									
0.100									
0.125									

Pin tool (part # and description)	WSU-07-0055-0400-01 - Concave Trivex Pin Tool								
Sheet material	2024-T3								
FSSW Diameter, in. (nominal swept diameter of pin tool)	1/8 (0.125)	5/32 (0.15625)	3/16 (0.1875)	7/32 (0.21875)	1/4 (0.250)	9/32 (0.28125)	2/7 (0.295)	5/16 (0.3125)	1/3 (0.333)
	Ultimate Strength, lbs								
Sheet thickness, in.									
0.025									
0.032									
0.040					801		827		950
0.050									
0.063									
0.071									
0.080									
0.090									
0.100									
0.125									

Wichita State University

A Look Forward

- Expected Outcomes & Benefit to Aviation
  - Verified qualification methodology & procedure
    - Testing & certification
    - Controls & acceptance criteria
    - Consistent & safe designs
  - Organized & certified design data
    - MMPDS (Mil HDBK 5) type data
    - S, A, & B basis
  - Design Parameters and Process Guides
    - Process & performance Specifications
    - Comparative data
  - 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 towards implementation