JAMS

Evaluation of Friction Stir Weld Process and Properties for Aerospace Application: e-NDE for Friction Stir Processes

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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 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
  - Establish FSW & FSSW design allowables data
    - Based on a performance and procedure specification methodology
    - Supported by developing industry standards (e.g. AWS, ISO, SAE, etc.)
- Approach
  - Develop & demonstrate protocols for developing FSW & FSSW design data
    - Demonstrate process path independence approach for butt & lap joints
    - Develop FSSW as integral fasteners & qualify them as installed fasteners

FAA Sponsored Project Information

- Principal Investigators & Researchers
  - Dwight Burford, PI, Researcher
  - Enkhsaikhan Boldsaikhan, Researcher
  - Pedro Gimenez Britos, Researcher
  - Jeremy Brown, Researcher
- FAA Technical Monitor
  - Lynn Pham
- Other FAA Personnel Involved
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- Industry Participation
  - Boeing IDS: *John Baumann (St. Louis)*
  - Bombardier Aerospace: *Ken Poston (Ireland), Leo Kok (Toronto), & Krish Patni (Wichita)*
  - Cessna Aircraft: *Ali Eftekhari & Jason Scheuring*
  - Hawker Beechcraft: *Byron Colcher, Phil Douglas & Ron Preston*
  - Spirit AeroSystems: *Mike Cumming, Mark Ofsthun & Gil Sylva*

Outline

- *Introduction*
  - *e-NDE for FSW*
  - *Industry Performance Specification*
- *Experimental Approach*
- *Discussion of Results*
- *Conclusions*
- *A Look Forward*
- *Acknowledgements*

e-NDE for FSW

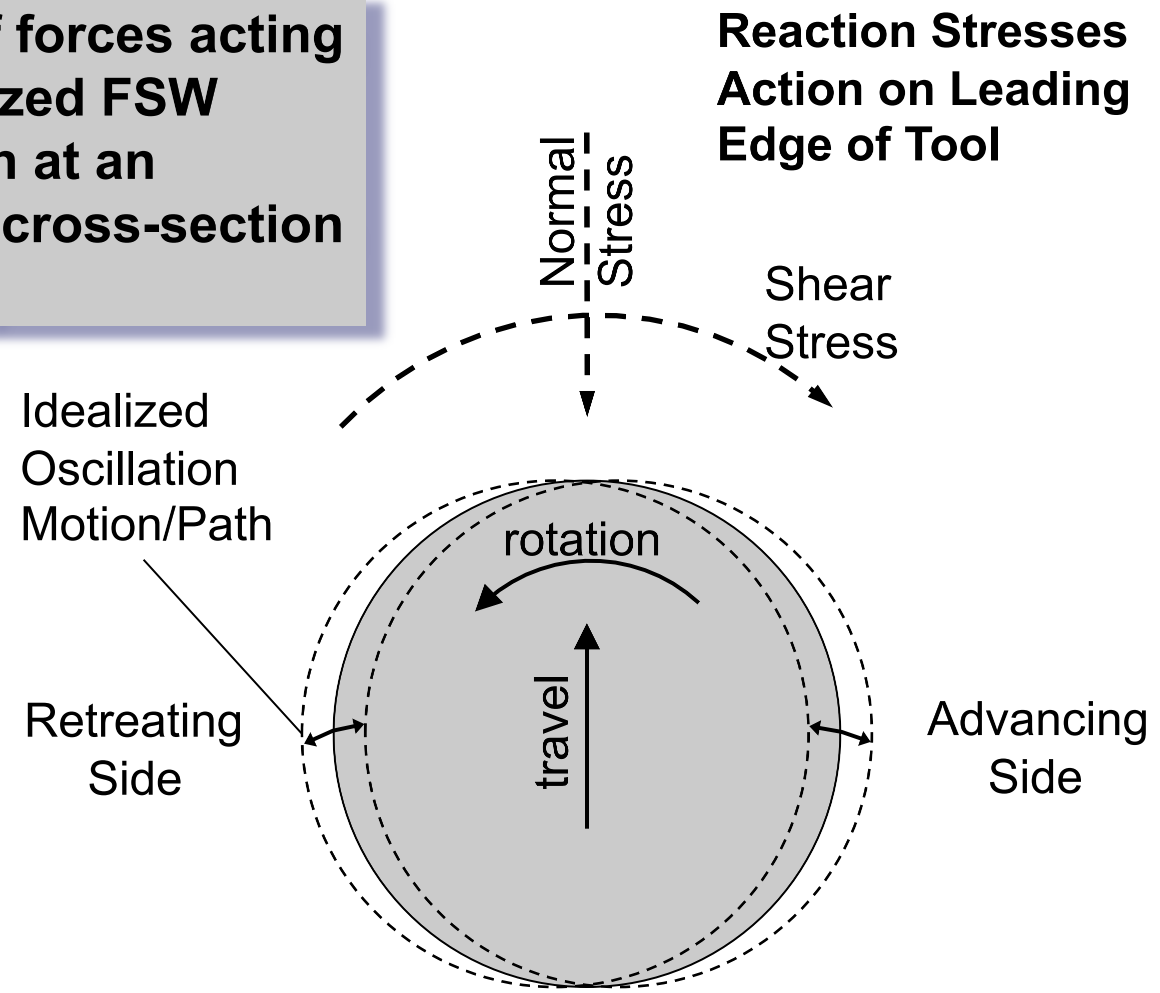
- Compare & Contrast FSW & End Milling
  - Dynamic response of the respective tools used in end milling and FSW
    - End Milling
      - Side of milling tool is pressed against the workpiece
      - Chips are cleared from tool flutes to ensure good flow of material away from work piece
    - FSW
      - Side of welding tool is pressed against the workpiece
      - Displaced material is captured and reconstituted back into the original material

e-NDE for FSW

- Chaotic Tool Behavior
  - End milling
    - “Chatter,” resulting in roughened marks on machined surface
  - FSW
    - Partial consolidation of material (voids called wormholes)
- Strategies to prevent chaotic tool behavior include process monitoring & analysis

e-NDE for FSW

Schematic of forces acting on a generalized FSW probe (shown at an intermediate cross-section of the probe)



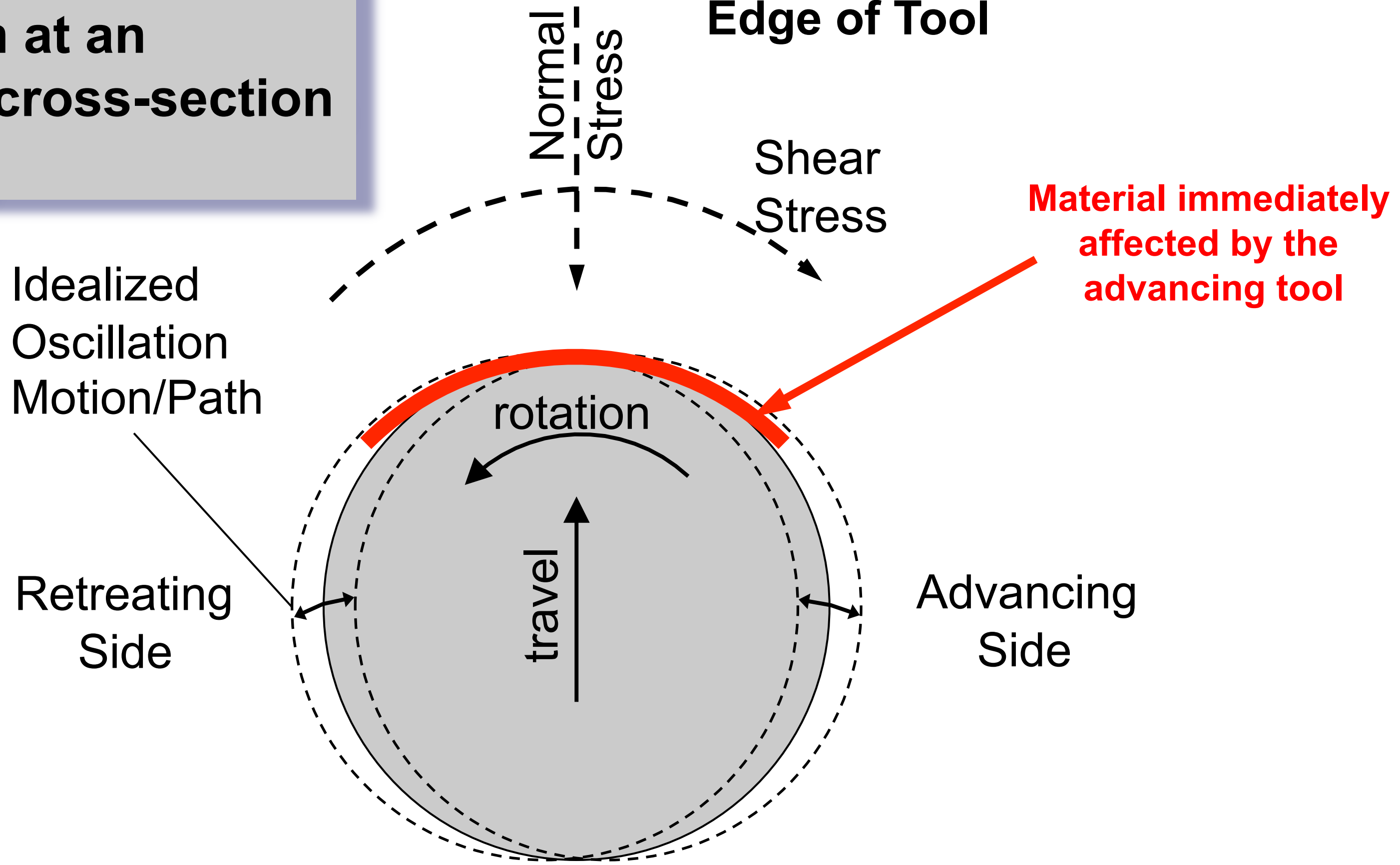
e-NDE for FSW

- The advancing, rotating FSW tool presses against the material directly ahead of it, creating a shearing action that extends around the tool front.
- Generalized, when the material directly in front of the tool is sufficiently heated under the pressure and shearing action imposed on it by the advancing FSW tool, a thin layer of the material is transported from the advancing side of the tool to the retreating side of the tool.

e-NDE for FSW

Schematic of forces acting on a generalized FSW probe (shown at an intermediate cross-section of the probe)

Reaction Stresses Action on Leading Edge of Tool



Material immediately affected by the advancing tool

e-NDE for FSW

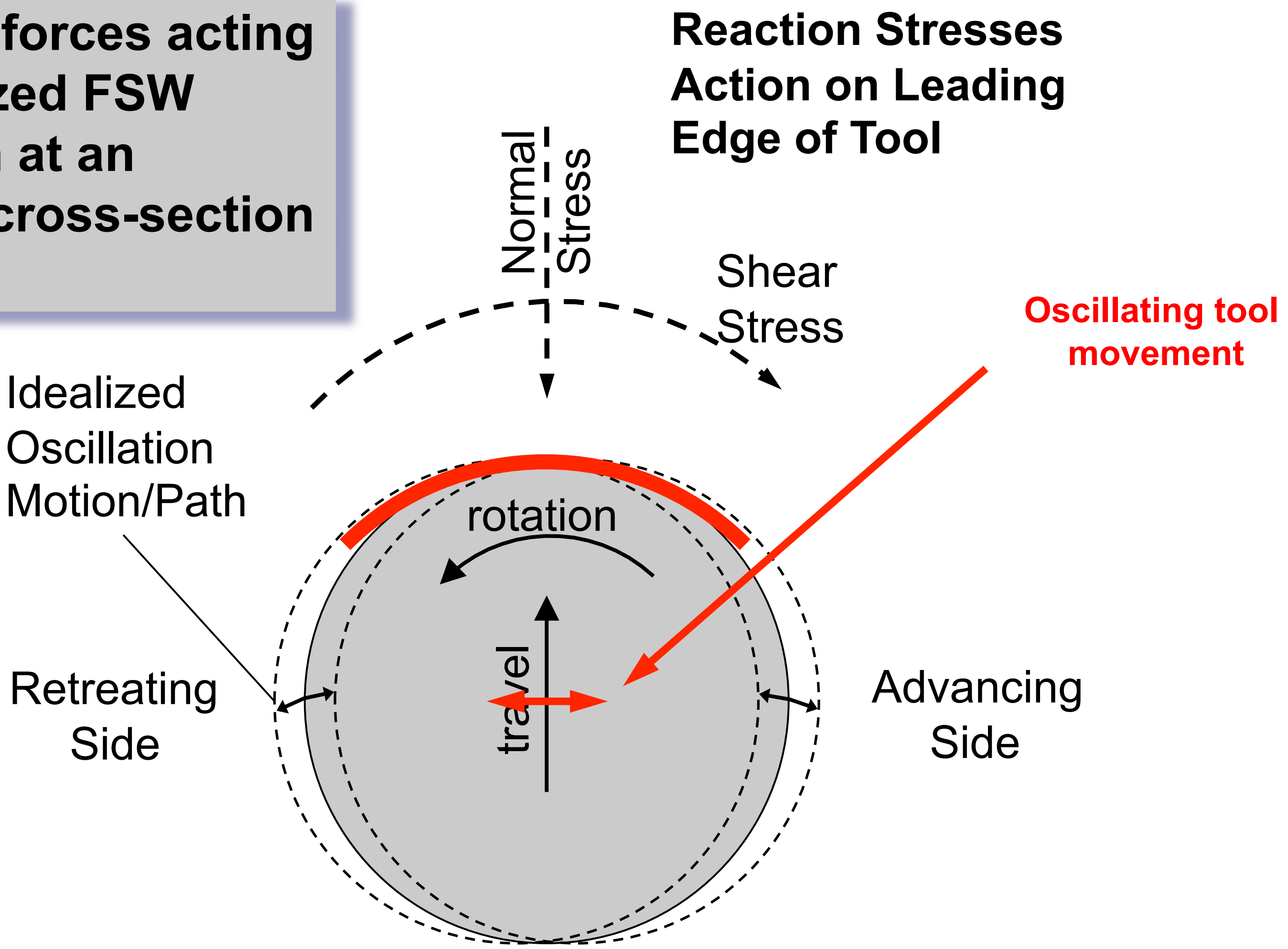
- This action is then repeated, with cooler material again being exposed to the leading face of the rotating, advancing tool.
- A new interface or band of material is again pressed upon until it is sufficiently heated to be moved along the tool front from the advancing side to the retreating side.

e-NDE for FSW

- The undulation in metal movement along the leading edge of the tool promotes an oscillatory or alternating pattern in both normal and shear forces acting on the tool surface.
- The alternating patterns in turn cause the tool to move in a periodic motion, nominally side-to-side, as the tool is advanced.

e-NDE for FSW

Schematic of forces acting on a generalized FSW probe (shown at an intermediate cross-section of the probe)



e-NDE for FSW

Qualifications

- Material flow and the associated resultant forces acting upon the tool are actually much more complex than idealized in the schematic shown in this presentation.
- With the tool probe completely submerged in workpiece, forces act on the probe from all directions in response to its dynamic loading environment (the resultant of which may be measured experimentally).

e-NDE for FSW

Qualifications (cont'd)

- The full engagement of the rotating, advancing FSW tool further aggravates and/or dampens its tendency to oscillate in a chaotic manner.
- Adding to the complexity of FSW tool oscillatory motion is the spinning motion of the tool shoulder face on the surface of the workpiece.
  - This tends to cause a walking motion of the end of the tool, which even further promotes chaotic tool behavior as the tool seeks (or seeks to establish) a center of rotation on the workpiece surface.

e-NDE for FSW

Benefits:

- The ability to analyze force feedback signals of welds provides a lean e-NDE technique for improving efficiency as well as quality.
  - It is based directly on recorded weld information.
  - It offers the potential ability to actively and adaptively control FSW operations in production.
  - It can also conceivably be developed to monitor tool wear, optimize design and performance of FSW tools, and compete different tooling design concepts, etc.

e-NDE for FSW

Benefits (cont'd):

- The ability to monitor the dynamic behavior of FSW tools through force feedback signals provides an effective way to dramatically reduce or eliminate the inspection costs associated with secondary inspection techniques, e.g.
  - X-ray
  - ultrasonic phased array (UPA)
  - etc.

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- *Introduction*
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Industry Performance Specification

- American Welding Society (AWS) published FSW process specification in December 2009
  - AWS D17.3 /D17.3M:2010
  - *"Specification for Friction Stir Welding of Aluminum Alloys for Aerospace Applications"*
- While this document provides guidance for process controls, it does not provide guidance for developing joint properties produced by FSW.
  - Section 5.1, *Weldment Design Data*, the following statement is made: "The Engineering Authority shall develop or obtain appropriate material property data to support the weldment design."
- Therefore, each organization relying upon this specification must produce its own material property data for design.

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Experimental Approach

- Nondestructive Evaluation (NDE) inspection round robin
  - A set of friction stir welded plates were selected from the “path independence” FSW study previously reported on at the 2009 JAMS conference.[12]
  - The plates were produced on a MTS® ISTIR™ PDS welding machine located at Wichita State University in the Advanced Joining and Processing Lab (AJP) of the National Institute for Aviation Research (NIAR).[9]
  - The F_y feedback force data was analyzed using the Discrete Fourier Transformation (DFT) – Neural Network (NN) training and a classification program prepared by Boldsaikhan.[3]
  - Ten different combinations of process parameters and weld tools were used to prepare three sets of 10 plates made from 6.3 mm. (0.25 in.) thick aluminum alloys 2024-T351.[12]

Experimental Approach

Classic TWI 5651 tool

Tri-flute^{TM}

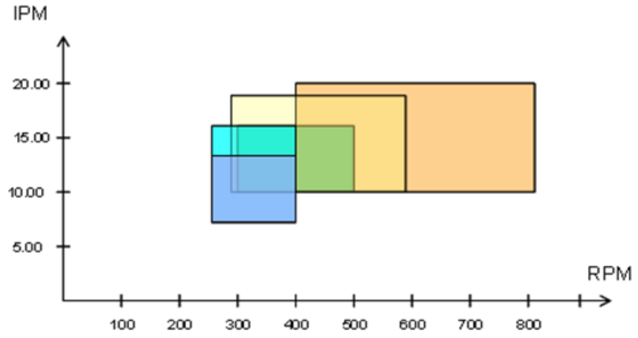
Scroll

Small Wiper^{TM}

Wiper^{TM}

Figure 3. Tool designs include the classic TWI 5651, Tri-flute™, Scrolled shoulder with threaded pin and straight flats, Small (shoulder) Wiper™ with threaded pin and twisted flats, and a Wiper™ (large diameter shoulder) with threaded pin and twisted flats. [1,12]

Experimental Approach



WSU Wiper 0.600
RPM: 400-800
IPM: 10-20
Forge: 4500-5250

WSU Wiper 0.800
RPM: 300-500
IPM: 10-16
Forge: 7000-8000

TWI 5651 1.000
RPM: 250-400
IPM: 7-16
Forge: 8500-10500

MX Triflute 0.800
RPM: 300-500
IPM: 10-16
Forge: 7000-8000

Full Scroll 1.000
RPM: 250-400
IPM: 7-13
Forge: 7500-9000

Figure 4. Welding process window and process parameters for the five different tools shown in Figure 3. [1,12]

Experimental Approach

- The plates were tested using X-ray analysis by:
  - Bombardier Aerospace Short Brothers
  - Cessna Aircraft
  - Hawker Beechcraft
  - Spirit Aerosystems
- Each company tested the panels per their own internal specifications.
- “Probability of detection” (POD) curves were then constructed based on the inspection reports submitted by each company.
- The results were compared against metallographic inspection and mechanical tensile test results performed in the NIAR AJ&P lab.

Experimental Approach

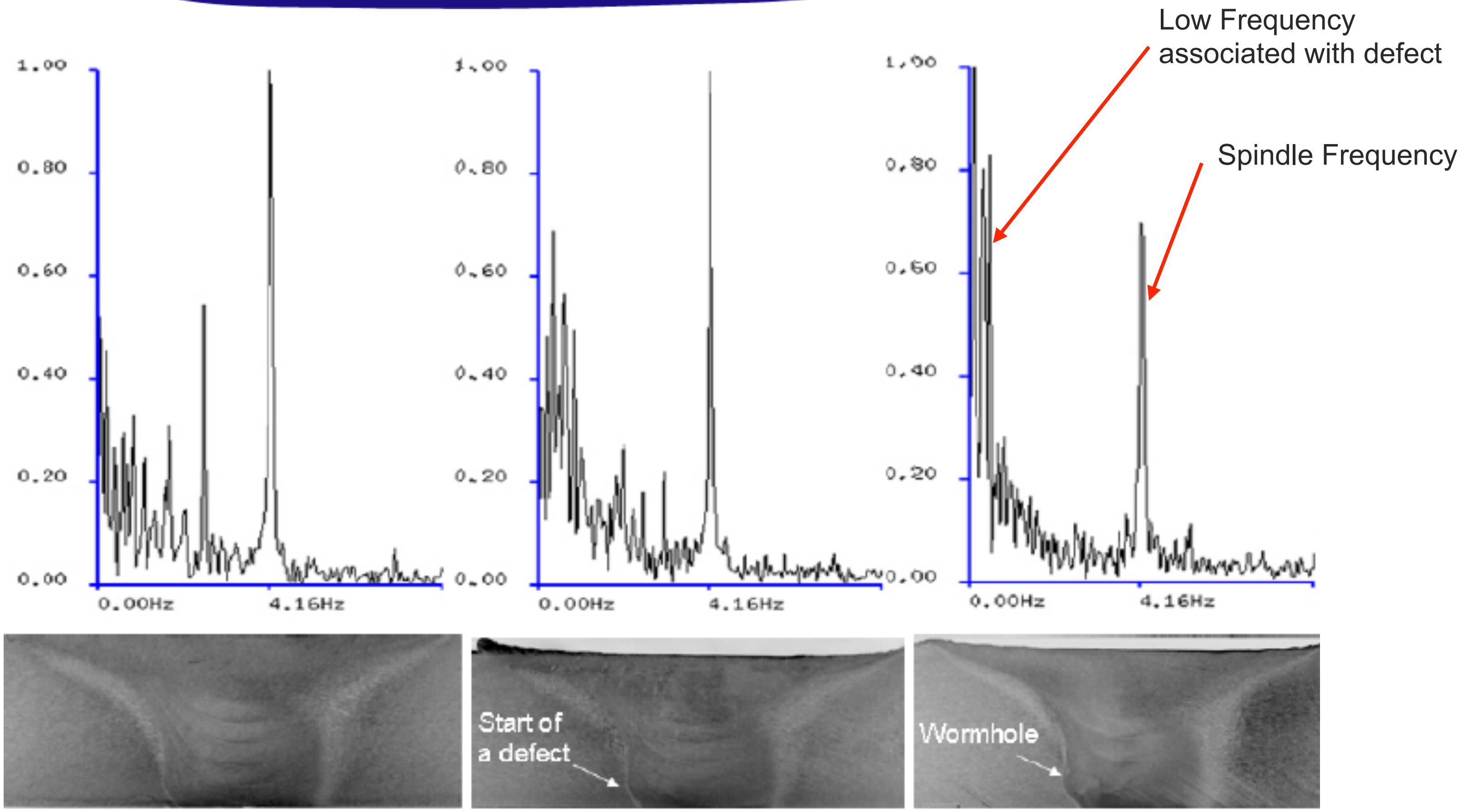


Figure 5. Frequency spectra of Y force with the corresponding metallographic images. The vertical axis is the amplitude normalized by the maximum amplitude. The spindle peak is located at 4.16 Hz (250 rpm). Amplitude of low frequency oscillations tend to increase while a wormhole defect starts forming. [3]

Experimental Approach

- All NDE indications were marked on the plates based on the inspection reports of the round robin participants.
- Metallographic inspection and mechanical test coupons were excised from each welded plate based upon the collective NDE findings.
- A total of 83 macro sections and 82 tensile coupons were cut from the 30 welded plates.

Experimental Approach

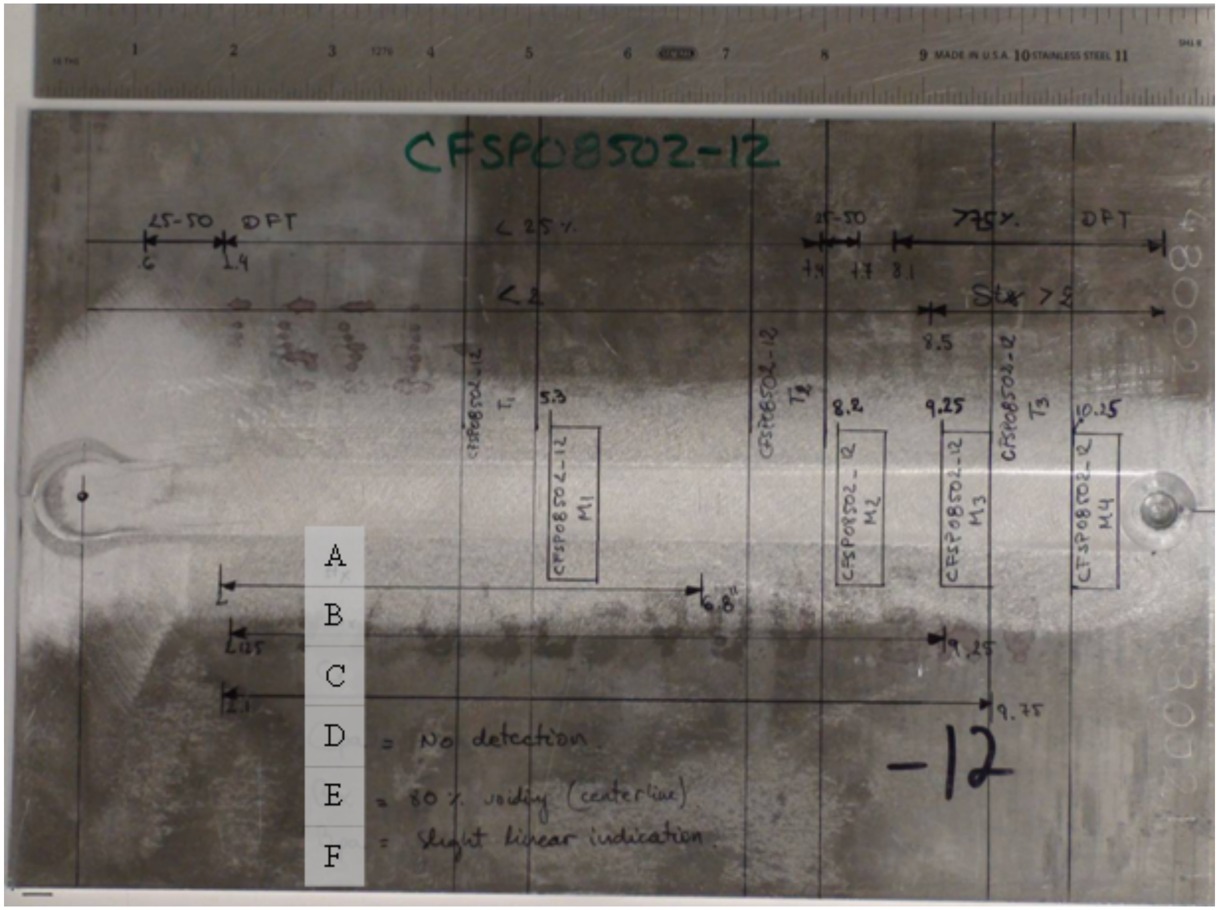


Figure 6. Example cut plan (sample CFSP08502_12). Markings A, B, C, and E correspond to X-ray analysis. D and F correspond to UPA analysis. [12]

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  - *e-NDE for FSW*
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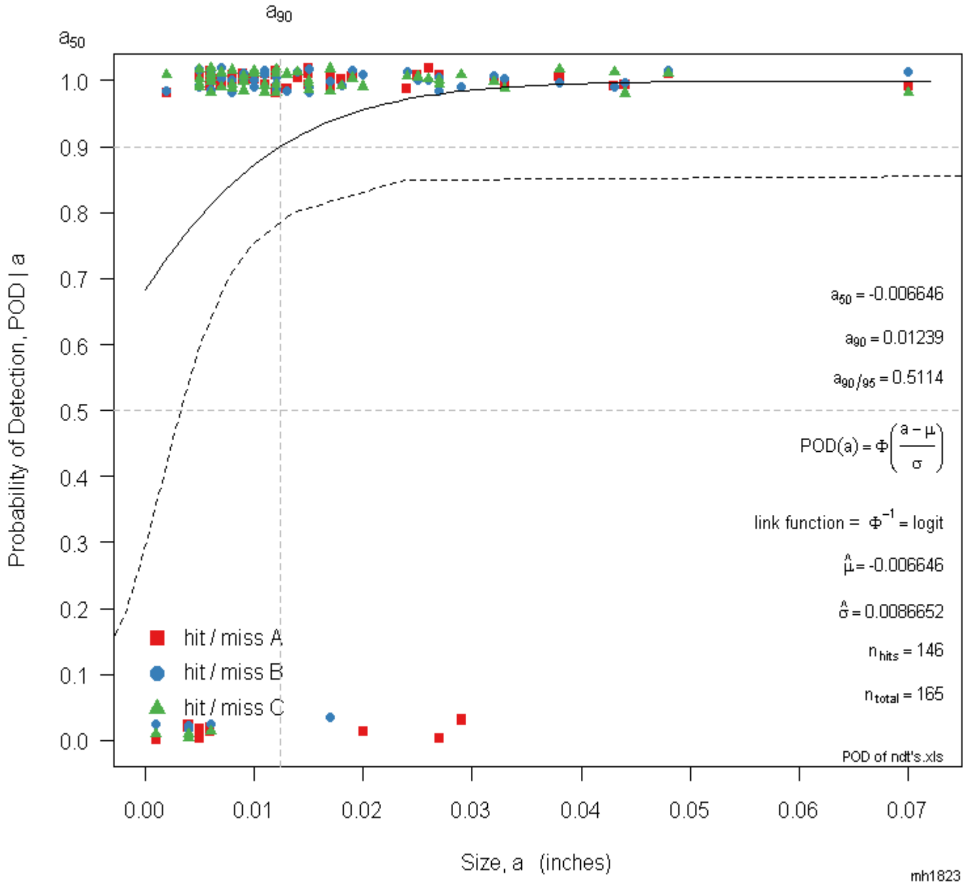
Discussion of Results

- The neural network (NN) algorithm was trained using three feature vectors per each point of interest obtained from the F_y feedback force signal.
  - Two feature vectors were used to train the NN, and
  - The third point was used to test the classification computed by the NN based on the other two.
  - It was possible to train the NN with 100% of the feature vectors, and the NN was able to correctly classify 92.7% of the samples.
  - Only 3 samples of a total of 28 were false classifications and only 3 samples with voids were not detected.

Discussion of Results



Mean POD curve vs. void size detected by X-ray

- Based on 3 independent X-ray analysis reports.
- The lower 95% confidence bound is also plotted for reference.
- The X-ray method detected voids with a length greater than 0.30 mm (0.012 in) with a 90% mean POD
- Note: It is not able to guarantee detection at a 95% confidence level for 90% POD.

Figure 7: Mean POD curve versus void size computed from the three reported X-ray analyses. [12]

Discussion of Results

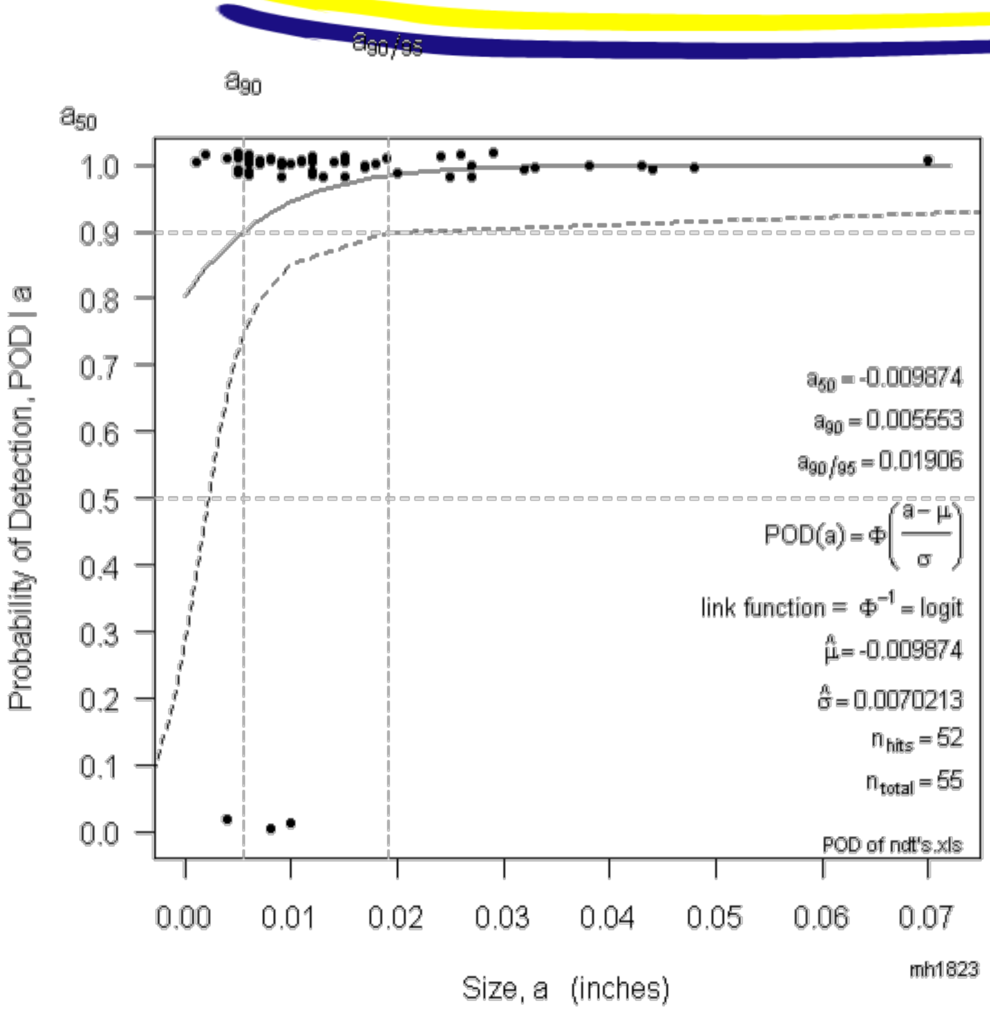
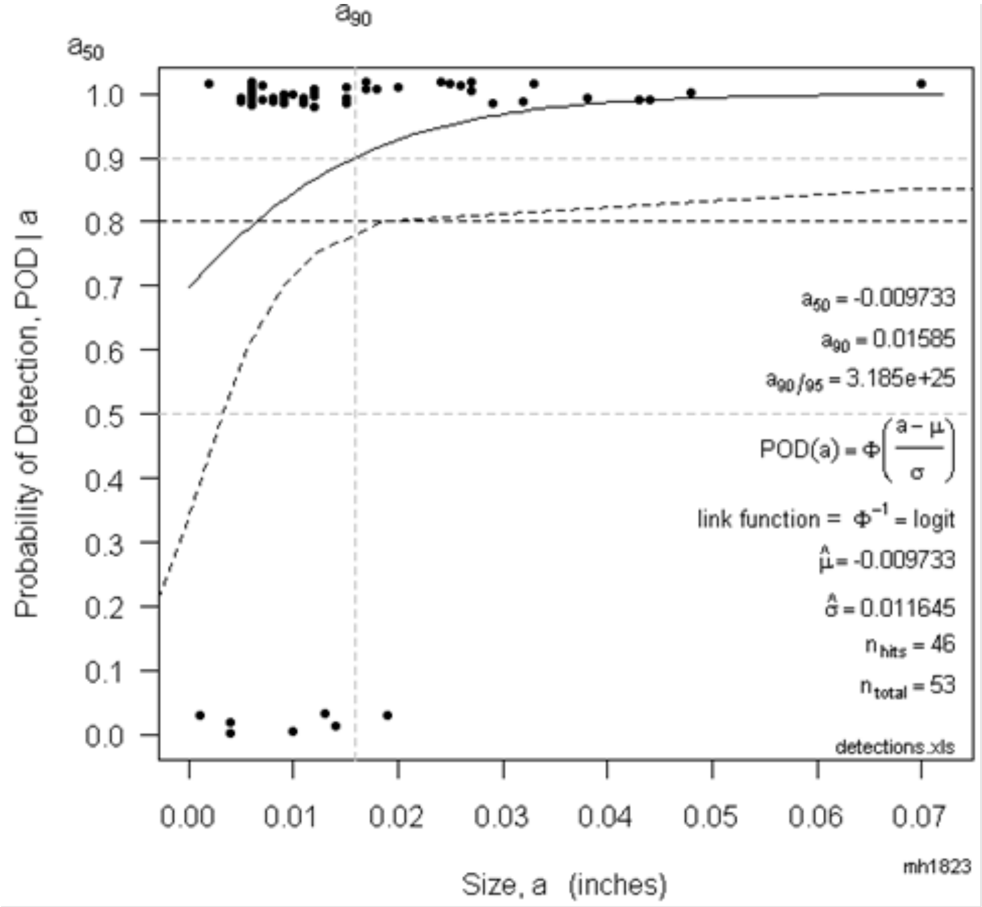


Figure 8: Mean POD versus void size for the NN analysis results. [12]

Mean POD curve vs. void size detected by NN

- Voids with a length greater than 0.13 mm (0.005 in) at a 90% mean POD detected
- Voids with a max length of 0.48 mm (0.019 in) can be detected with a 90% POD at a 95% confidence level.
  - Compare with Figure 7

Discussion of Results



Effects of defects:

- POD curve were prepared for transverse tensile strength as a function of wormhole or void size.
- The curves were based on the same binary regression analysis used for NDE results.
- A wormhole larger than 0.38 mm (0.015 in) has 90% POD of causing low tensile strength.

Figure 9: Effect of Defect - Mean POD versus void size for the Tensile Test analysis results. [12]

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- *Experimental Approach*
- *Discussion of Results*
- *Conclusions*
- *A Look Forward*
- *Acknowledgements & References*

Conclusions

- The ability to both monitor and correlate F_y force feedback signals to the occurrence of defect formation provides a major opportunity to actively and adaptively control FSW operations in production.
- This unique process monitoring tool forms the basis of a powerful e-NDE technique that greatly reduces inspection costs, both in terms of time and resources, as well as in terms of accuracy and quality.
- Because of its evaluation capability, process monitoring of F_y (transverse) feedback forces provides a viable alternative or complement to conventional NDE techniques.

Conclusions

- As an e-NDE near real-time inspection technique, process monitoring for force feed back signals adds a second layer of “greenness” to an already extremely green process by reducing and potentially eliminating the need for secondary inspection operations like penetrant, X-ray, and ultrasonic inspections.
- It can also conceivably be developed to monitor tool wear, optimize design and performance of FSW tools, and compete different tooling design concepts, etc.

Conclusions

- In terms of establishing standards and specifications for friction stir technologies, the e-NDE technique featured in this paper will greatly facilitate the establishment of performance based specifications for FSW that will ultimately become the basis of developing design data for FSW joints in multiple structures made from multiple alloys and product forms.

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  - ***e-NDE for FSW***
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- ***Experimental Approach***
- ***Discussion of Results***
- ***Conclusions***
- ***A Look Forward***
- ***Acknowledgements & References***

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 design data
    - S, A, & B basis values
  - 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

A Look Forward (cont'd)

- The basic principles outlined for force feedback process monitoring have potential applications in other processes and materials systems.
- Example: Drilling of holes in composites for mechanical fasteners:
  - Drilling introduces a point load on these highly laminar materials.
  - If the drilling process is not performed properly, cracks and thermal stresses may be introduced into the material during the drilling process, significantly degrading the mechanical performance of the joint.
  - Monitoring and controlling the thrust force (axial feedback force) when drilling is crucial to maintaining quality holes.
  - The axial force is a function of the feed rate and drill performance and, therefore, can be used as an indicator of the quality and efficiency of the process.
  - So far, no significant studies have been reported on controlling the drilling process for composites using the feedback signals.
  - Hence, one of the important objectives of potential future work would be to advance the state of drilling practice by introducing an intelligent process monitoring analysis technique.

Outline

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  - *Industry Performance Specification*
- *Experimental Approach*
- *Discussion of Results*
- *Conclusions*
- *A Look Forward*
- *Acknowledgements & References*

Acknowledgements

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- FSW, metallographic preparations, and mechanical testing were performed by the staff and students of the Advanced Joining & Processing (AJ&P) Lab of the National Institute for Aviation Research (NIAR) located at Wichita State University, 1845 Fairmount, Wichita, Kansas.
- Cessna provided the AA 2024 plate.
- The Welding Institute provided several of the tool designs evaluated in this study.
- The NIAR Research Machine Shop fabricated all of the friction stir welding tools.
- The X-ray analyses were conducted by Cessna Aircraft, Spirit AeroSystems, Hawker Beechcraft, and Bombardier Aerospace Short Brothers.

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Outline

- ***Introduction***
  - ***e-NDE for FSW***
  - ***Thermal Components of FSW***
  - ***Mechanical Components of FSW***
  - ***Industry Performance Specification***
- ***Experimental Approach***
- ***Discussion of Results***
- ***Conclusions***
- ***A Look Forward***
- ***Acknowledgements***

Thermal Components of FSW

- The thermal process elements or components of FSW are typically controlled indirectly (i.e. passively) through mechanical factors
  - spindle speed
  - travel speed
  - applied axial force (axis of spindle)

Thermal Components of FSW

- The energy for conveying material from the advancing to the retreating side of the weld tool is supplied by the torque and compressive forces of the FSW machine.
- It is applied to the workpiece through the specialized, non-consumable metalworking (weld) tool.
- The actual energy imparted to the workpiece by the machine is converted into heat through mechanical stirring and frictional/shearing interaction between the non-consumable tool and workpiece.

Thermal Components of FSW

- This heat is generated in a local but traveling work zone.
- It can be viewed conceptually as flowing away from the work zone along three generalized heat sink paths (or conduits):
  - **Path 1:** The Spindle Path: including the metalworking (welding) tool, tool holder, spindle, machine frame, etc.
  - **Path 2:** The Workpiece Path: the workpiece, fixture, machine bed, machine frame, clamps, connecting structure, etc.
  - **Path 3:** The Surroundings Path: the atmosphere, applied materials (coolants, gases, etc.).

Thermal Components of FSW

- Therefore, to provide an adequate thermal environment for each application of FSW, development is typically based on:
  - – Bounding welds to identify a suitable process window limit.
  - – Experimental design techniques (SPC and DOE) are employed to refine the process window for optimizing selected joint properties.

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- *Introduction*
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  - *Mechanical Components of FSW*
  - *Industry Performance Specification*
- *Experimental Approach*
- *Discussion of Results*
- *Conclusions*
- *A Look Forward*
- *Acknowledgements*

Mechanical Components of FSW

- The mechanical components are typically controlled directly through system elements:
  - FSW machine capabilities and controls
  - Selection of the metalworking tool and fixture designs
  - Setting processing speeds and feeds
  - etc.

Mechanical Components of FSW

- There is no single tooling solution for all joints.
  - In general, many different tools may be used to produce the required engineering properties for a given application.
  - An optimized process window must be established for each tool on a tool-by-tool basis.
- However, some tools may be more sensitive to tool wear and variations in the manufacture of weld tool features in terms of how they affect the data population generated.
  - Therefore, while it may be possible to determine how tool design affects joint properties, ultimately, it is more important to determine what level of control is needed for a given tool to ensure consistent joint properties over the life of the tool, as well as between setups, part configurations, suppliers, etc.