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

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Abstract

A powerful new friction stir welding e-NDE technique, which is based on process monitoring, shows promise for increasing the accuracy and precision of probability of detection (POD) analyses when compared to conventional inspection techniques. The technique is based primarily on monitoring the F_y (transverse) force feedback signal, which has previously been correlated with defect formation. As an e-NDE near real-time inspection technique, force feedback process monitoring adds a second layer of "greenness" to an already extremely "green" process by reducing and potentially eliminating the need for secondary inspection operations like X-ray, and ultrasonic inspection steps. 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.

Introduction

Successful implementation of friction stir welding (FSW) is reliant upon basic metal-working principles applied and controlled at a local level.[1] The thermal and mechanical mechanisms involved in FSW are similar to those found in other metal working processes such as rolling, extruding, and forging. However, unlike these bulk thermo-mechanical (TM) processing operations, the highly localized nature of FSW introduces steep thermal and deformation gradients into the material adjacent to and along the joint line. Therefore, standards and specifications for friction stir technologies must of necessity address and account for the localized metal working nature of friction stir technologies.

e-NDE for FSW: In FSW the side of the weld tool is pressed against the workpiece in a manner similar to that of machining with the side of an end mill. However, unlike end mill machining, in FSW the tool design and process parameters are selected such that the displaced material is captured and reconstituted into the original material – as opposed to removing it from the work zone in the form of "chips" as is done in machining. Consequently, there are both similarities as well as dramatic differences in the dynamic response of the respective tools used in end milling and FSW.

In machining, it is important to clear the cut metal (chips) from the tool at a sufficient rate to prevent clogging of tool features, namely the flutes, etc. In FSW the opposite is true. The features of a FSW tool, such as threads, grooves, etc., are expected to become impacted with metal – and thereby maintain a full frontal engagement between the tool and the material of the workpiece – while in machining only the tool cutting

edges are expected to be in contact with the workpiece. This full engagement between the FSW tool and workpiece leads to unique dynamic behavior not typically experienced in machining.

In machining, advanced control techniques have been investigated for reducing chatter. For example, Zhang and Sims assessed the ability of "piezoelectric active vibration damping" to arrest chaotic tool behavior.[2] To reduce defect formation in FSW associated with chaotic tool motion, Boldsaikhan,[3] and Jene et al.,[4] have studied machine tool-material interactions by monitoring force feedback signals. As these studies demonstrate, in both machining and FSW, process monitoring may serve as the basis for reducing chaotic tool behavior and, thereby, provides a means for improving part quality in both machining and FSW.

In FSW, the tool tends to vibrate or oscillate side-to-side (nominally transverse to applied loading vector) while under the local dynamic side loading conditions imposed on the tool at the tool-workpiece interface. In machining, when the tool oscillates in a chaotic manner, a self-excited vibration phenomenon called "chatter" tends to form, leaving erratic markings on the newly cut surface. Similar chaotic oscillations in FSW tend to be associated with the formation of voids within the joint (resulting from the lack of consistency in the reconsolidation of material along the joint line).

The advancing, rotating FSW tool presses against the material directly ahead of it, creating a shearing action that extends around the tool front. In a generalized manner, 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, thin layers of material are

transported from the advancing side of the tool to the retreating side of the tool.[a] This

action is then repeated, with cooler material again being exposed to the leading face of
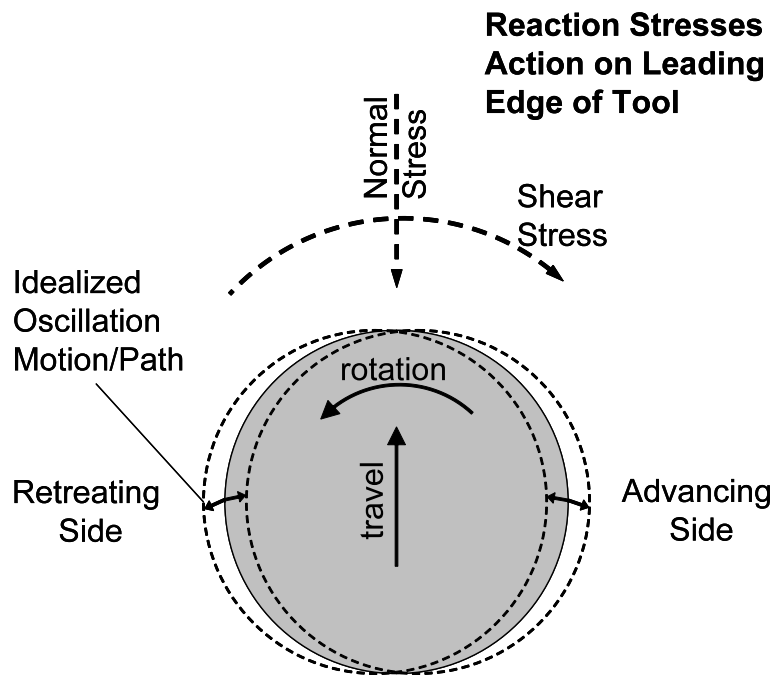
the rotating, advancing tool.

**Reaction Stresses
Action on Leading
Edge of Tool**

Normal Stress

Shear Stress

Idealized Oscillation Motion/Path

rotation

travel

Retreating Side

Advancing Side

Figure 1: Schematic cross-section of a generic FSW tool probe located

midway below the tool shoulder and the end of the probe to depict the ide-

alized oscillation of the tool as it advances. Tool rotation is counter-

clockwise and the direction of travel is toward the top of the page. The re-

action forces act on the tool in opposition to the tool motion. A periodic

shearing and movement of metal along the leading edge of the tool – from

the advancing side to the retreating side – results and the tool oscillates

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[a] The advancing side of the tool is the side of the tool where the rotation direction is the same as the travel direction of the tool. The retreating side of the tool is the opposite side where the rotational direction of the tool is opposite the travel direction.

side-to-side (nominally) in response the primary reaction forces acting on

the leading edge of the FSW tool probe.

This 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. This 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, which in turn causes the tool to move in a periodic motion, nominally side-to-side, as the tool is advanced. This process is schematically depicted in Figure 1 (depicting only simplified, idealized frontal force conditions).

Material flow and the associated resultant forces acting upon the tool are actually much more complex than idealized in the model shown in Figure 1.[5] 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.[6] The full engagement of the rotating, advancing FSW tool further aggravates 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.

Uniformity in FSW tool oscillations is dependent upon the periodicity (or lack thereof) in the material flow behavior around the tool front. It is anticipated that the lower the abruptness in the material heating and shearing cycle, the less likely the process will

become chaotic in its behavior (action). Selection of tool features and process parameters are expected to contribute to the overall stability of the tool control process.

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 such as X-ray, ultrasonic phased array (UPA), or penetrant inspections. By simply analyzing the force feedback signal of each weld, this lean and effective e-NDE technique can be utilized to improve production and quality based directly on recorded weld information. It further 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.

Thermal Components of FSW: The thermal process elements or components of FSW are typically controlled indirectly (i.e. passively) through the process variables that most strongly influence them, namely mechanical factors such as spindle speed, travel speed, and the applied weld tool axial force. Through the influence of these indirect means, thermal energy is generated during FSW by forcing a rotating, non-consumable metalworking tool into the joint line between components to be joined. Once stable processing conditions are established locally, the weld tool is then forcibly translated or advanced along the joint line to form a consolidated unit.

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 as applied to the workpiece through the specialized, non-consumable metalworking 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. This heat, which is generated in a local but traveling work zone, 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.).

Ideally, the distribution of heat flow away from the localized work zone will remain stable without either a substantial build-up of heat or a substantial loss of energy as the weld progresses. The level of heat build-up or loss may shift due to, for example, a local change in the thermal mass of the part and/or fixture (e.g. at a stiffener or with an increase or decrease in section thickness). Or it may result from traveling at a rate faster than heat can be dissipated along these three paths collectively.

In practice, the proportion of heat that flows along each of these heat sink paths at any given time can vary widely. Many factors influence the relative heat flux along each path. For example, in Path 2, the workpiece path, the flux of heat away from the local work zone is first regulated by the thermal conductivity and heat capacity of the workpiece and is then regulated by these same properties of the fixturing and supporting components (e.g. the backing bar). For regularly shaped parts, where the effective

thermal mass cross-section does not vary over the length of the part, a greater probability exists that the process will remain stable throughout the duration of the FSW process. In contrast, in irregularly shaped parts or setups, which vary in thermal mass along the direction of the weld (e.g. variations in the joint cross-section), joint properties can vary substantially as a result of the changing thermal environment (heat sink) in and around the local work zone if not properly accounted for and addressed.

Edge effects also have the potential for contributing to joint property variation. As the FSW process progresses toward the end of a workpiece, for example, the heat generated in the part tends to build up near the end of the part where there is a decreasing amount of material available to contain the heat generated by the advancing tool. Potential approaches for maintaining a consistent thermal environment as the local work zone nears the end of a part may include changing process parameters to lessen the heat input into the joint line in the closeout region of the joint.

Rather than attempting to precisely regulate heat flow during FSW, application development work is typically based on a phenomenological approach in which process parameters are developed for each unique setup and welding system.[7] Bounding welds are usually conducted first to identify a suitable process window limit. Then experimental design techniques (SPC and DOE) are employed to refine the process window for optimizing selected joint properties. If changes are made to any of the three general thermal conduits in the system, the process output (e.g. joint material properties) should be checked to determine what impact, if any, there may have been as a result of the change. With such an approach, thermal management may be viewed as more of an art than a science. However, this approach is often justified where a thorough analysis

of the setup is not warranted or deemed tractable given the available program resources.

The actual thermal efficiency of a given FSW process, and the gradients associated with it, may never be well understood or directly controllable. As such, attempting to establish repeatable processes through a single rigid process specification (e.g. fixing the setup, tool, process parameters, weld system, etc.) for all applications is not deemed necessary or even appropriate. Notwithstanding the complexities involved, performance specifications, along with the appropriate controlling documents (e.g. welding performance specifications), provide sufficient control to achieve the ultimate process goal of fabricating structure that meets engineering requirements.

Mechanical Components of FSW: Unlike the thermal components of the FSW process, the mechanical components are typically controlled directly through the FSW machine capabilities and controls, the selection of the metalworking tool and fixture designs, setting processing speeds and feeds, etc. Because process controls can be set directly through machine settings and tool designs, defining a process specification around machine controls may seem to be a straightforward approach to establishing handbook quality data for FSW. However, the steep gradients introduced by FSW mean that small variations in input (independent) variables (speed, feed, load, tool design, etc.) can lead to relatively large variations in local response variables (e.g. thermal gradients, residual stresses, transverse tensile properties).

Therefore, in order to establish usable databases for FSW design data, an understanding of potential sources of variation is required and robust methods for managing

these inherent variations must be developed. For example, once the basic FSW machine is selected, an unlimited number of metalworking (weld) tools may be used with it. Literally hundreds of combinations of geometric features on weld tools are in use today throughout the various industries utilizing FSW. Shoulder design considerations alone include a multitude of factors to be established, such as its basic shape (concave, convex, flat, etc.) and the optimum ratio between the shoulder diameter and the probe. Should the shoulder have scrolls? If so, how many should it have and in what configuration? How deep or wide should they be? Should they be tapered or irregularly staggered?

The answer to such questions is that there is not one single tooling solution for all joints, not even for a specific joint. In general, many different tools may be used to produce the required engineering properties for a given application as long as an optimized process window is established for each tool on a tool-by-tool basis.[9] Further, 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 determined how tool design affects joint properties, ultimately, it is more important to determine what level of control for a given tool is needed to ensure consistent joint properties over the life of the tool, as well as between setups, part configurations, suppliers, etc.

Alloy and workpiece dimensions all come into play when selecting appropriate tool features and combinations of features. While it may be straightforward to control processing parameters such as spindle and travel speeds, attempting to control all of the factors that go into the process is not so straightforward. Different alloys react differ-

ently to the possible combinations of features as well. Consider further the fact that there are numerous patents covering weld tool features. In other words, attempting to establish process specifications by fixing tool designs, etc., will not lead to the desired outcome of a controlled process. Specifications must be data and results driven. The e-NDE technique featured in this paper will greatly facilitate the establishment of performance based specifications for FSW and will ultimately become the basis of developing design data for FSW joints in multiple structures made from multiple alloys and product forms.

Bridging the Gap

Industry Standards	Material / Joint Performance Specs (Sets)	Supplier Internal Process Controls/Procedures
AWS	Performance Requirements	Command Media
ISO	Property Minimums	Internal Process(es)
SAE	Acceptance Criteria	WPS
ASTM		PQR 1
…	Deliverables	PQR 2
		PQR …
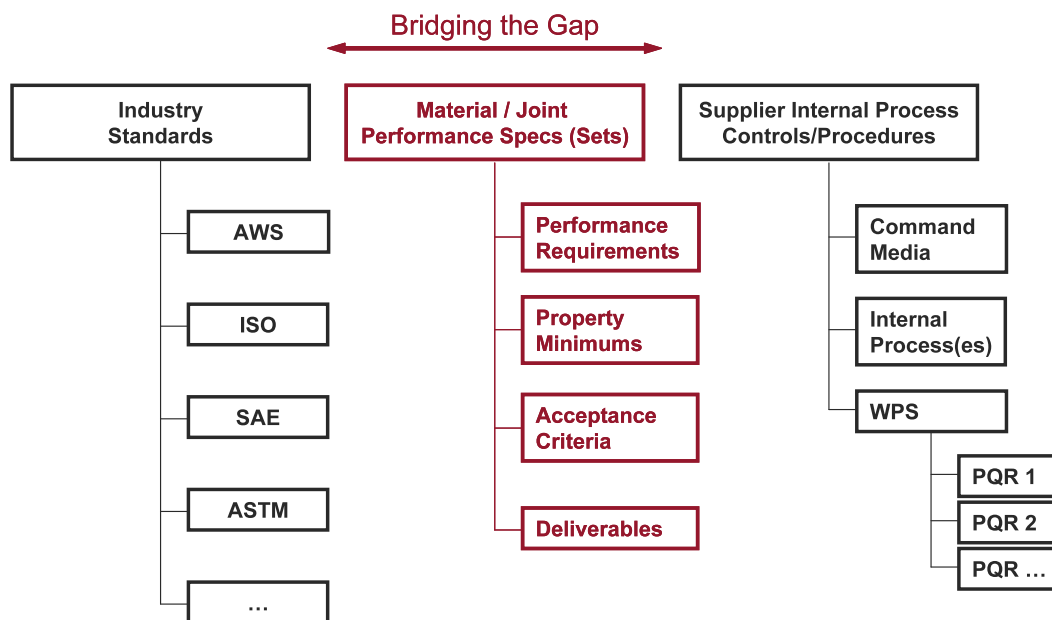
Figure 2: Illustration of a new initiative to bridge the gap between industry standards and internal specifications currently in place by developing material and joint specifications for friction stir material.[9]

Industry Performance Specification: In December 2009 the American Welding Society (AWS) published AWS D17.3/D17.3M:2010, *Specification for Friction Stir Welding of*

Aluminum Alloys for Aerospace Applications.[8] While this document provides process controls and specifications, it does not provide guidance or information regarding expected joint properties produced by FSW. Specifically, in 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.

An initiative to establish performance specifications independent of weld tool design and process parameters was formerly introduced.[9] Through this initiative, coordination of material and joint standards was begun through the SAE AMEC committee. As illustrated from Figure 2, the objective in establishing SAE sponsored material and joint specifications is to bridge the gap between industry standards and the internal command media of individual organizations.

Justification for establishing performance specifications is based on the observation that FSW has a sufficiently flexible process window that allows all aluminum alloys to be joined with a wide variety of weld tool designs operated within independently developed process windows.[10,11] Therefore, it was concluded that 1) an unspecified number of tool designs can be used to make equally sound joints with independently developed process windows, 2) any advantage one tool may have over another is expected to be evident primarily in terms of productivity, i.e. welding and processing speeds, and 3) the process can be effectively controlled via performance specifications.

Additional observations support the tractability of the path-independence approach. For example, FSW does not change bulk chemistry (no filler typically added), and it

does not involve recasting the alloy (no bulk solid/liquid phase transformation). Joint properties are observed to be related to parent material mechanical properties (e.g. strength). They are typically increased in work hardened, non-heat treatable alloys (e.g. AA5xxx) via grain refinement in the dynamically recrystallized zone (DXZ), i.e. the weld nugget. They are typically decreased in precipitation-strengthened Al alloys, for example, by over-aging in the heat affected zone (HAZ) adjacent to the joint.

Consider aircraft aluminum alloy AA2024-T3 for an example. It may be produced in one of many ways, including on a continuous rolling line or in a batch facility. Both product forms may be sold to the same industry specification because the specification does not explicitly call out the type of rolling stands or the other mechanical equipment used to process the material thermomechanically. Likewise, extruded and forged materials come in a variety of shapes and sizes, each requiring its own processing schedule, but they are still sold to the same material specifications. Even though each piece does not get exactly the same thermomechanical treatment in production, it may be sold to common minimum property specifications. Similarly, FSW, developed as a thermomechanical process can be expected to produce common minimum property values independent of the processing steps involved.

Experimental Approach

A Nondestructive Evaluation (NDE) inspection round robin was conducted on a set of 30 friction stir welded plates.[12] The plates tested were selected based on the results of a "path independence" FSW study previously reported on at the 2009 JAMS conference.[9] 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). Force feedback data sets from the MTS system were analyzed with a computer software program written 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. The tools selected for this study are shown in Figure 3. They represent a wide variation in probe and shoulder features. A schematic, showing different processing parameters developed for each of these five tools from the prior study, is shown in Figure 4.[9]

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]

Previously, Boldsaikhan demonstrated that the amplitude of the F_y signal for three welds revealed how increased low frequency oscillations (relative to spindle frequency) are directly correlated with continuous void, or wormhole, defects; see Figure 5. This same approach formed the basis of this study.
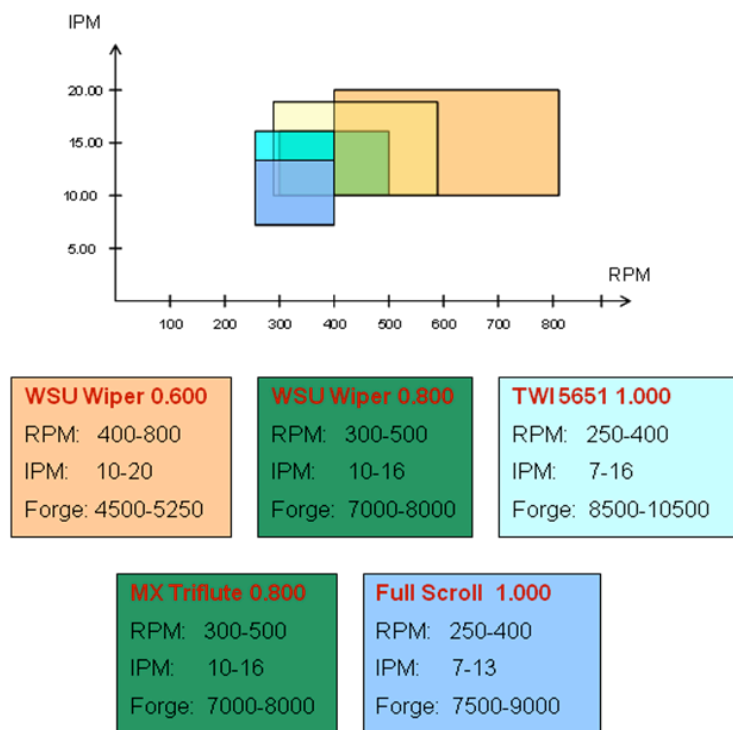
Figure 4. Welding process window and process parameters for the five different tools shown in Figure 3.[1,12]

The F_y feedback force data was analyzed using the Discrete Fourier Transformation (DFT) – Neural Network (NN) training and a classification program prepared by Bold-saikhan. For comparison, the plates were tested using X-ray analysis by Cessna Aircraft, Spirit Aerosystems, Hawker Beechcraft, and Bombardier Aerospace Short Brothers. Each company tested the panels per their own internal specifications. One

company also provided ultrasonic phased array (UPA) results for 28 of the plates. "Probability of detection" (POD) curves were then constructed based on the inspection report submitted by each company. The results were compared against metallographic inspection and mechanical tensile test results performed in the AJP lab.
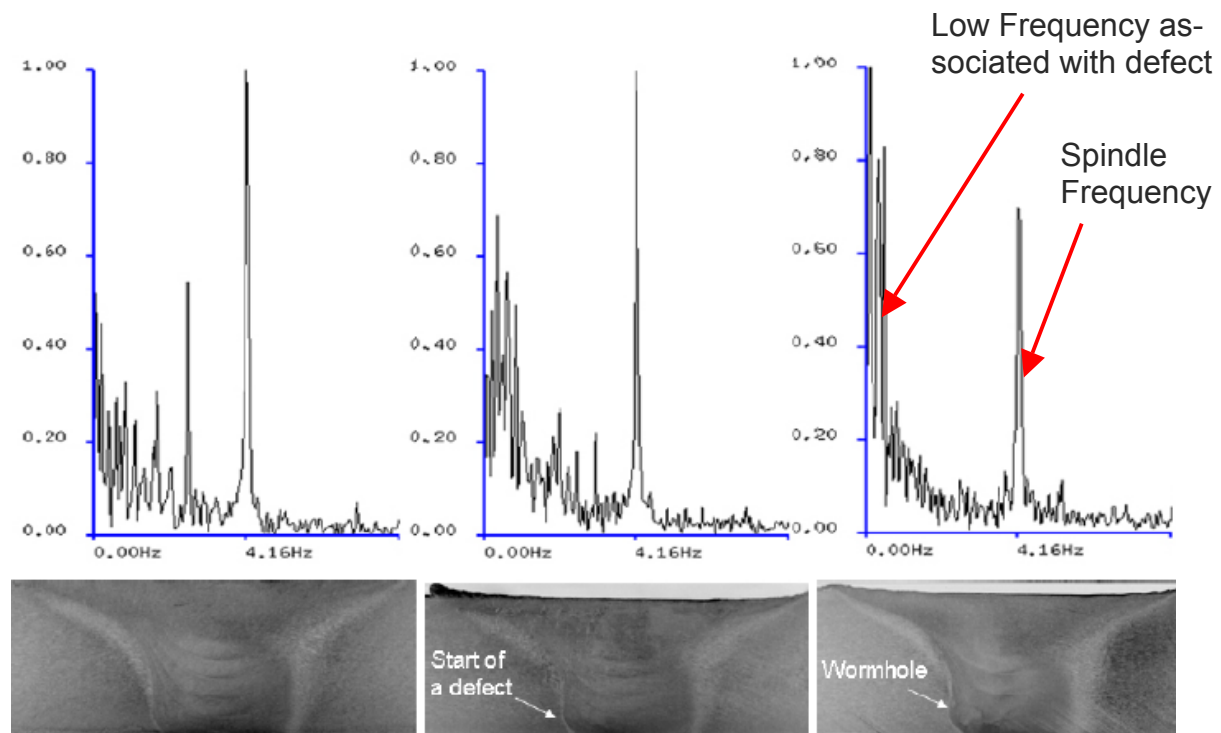
Figure 5. Frequency spectra of Y force with the corresponding metallographic images. The vertical axis is the amplitude normalized by the maximum amplitude. The spindle peak is located at 4.16 Hz (250 rpm). Amplitude of low frequency oscillations tend to increase while a wormhole defect starts forming.[3]

All 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. An example plate marked and ready for excising metallographic and tensile coupons is shown in Figure 6.
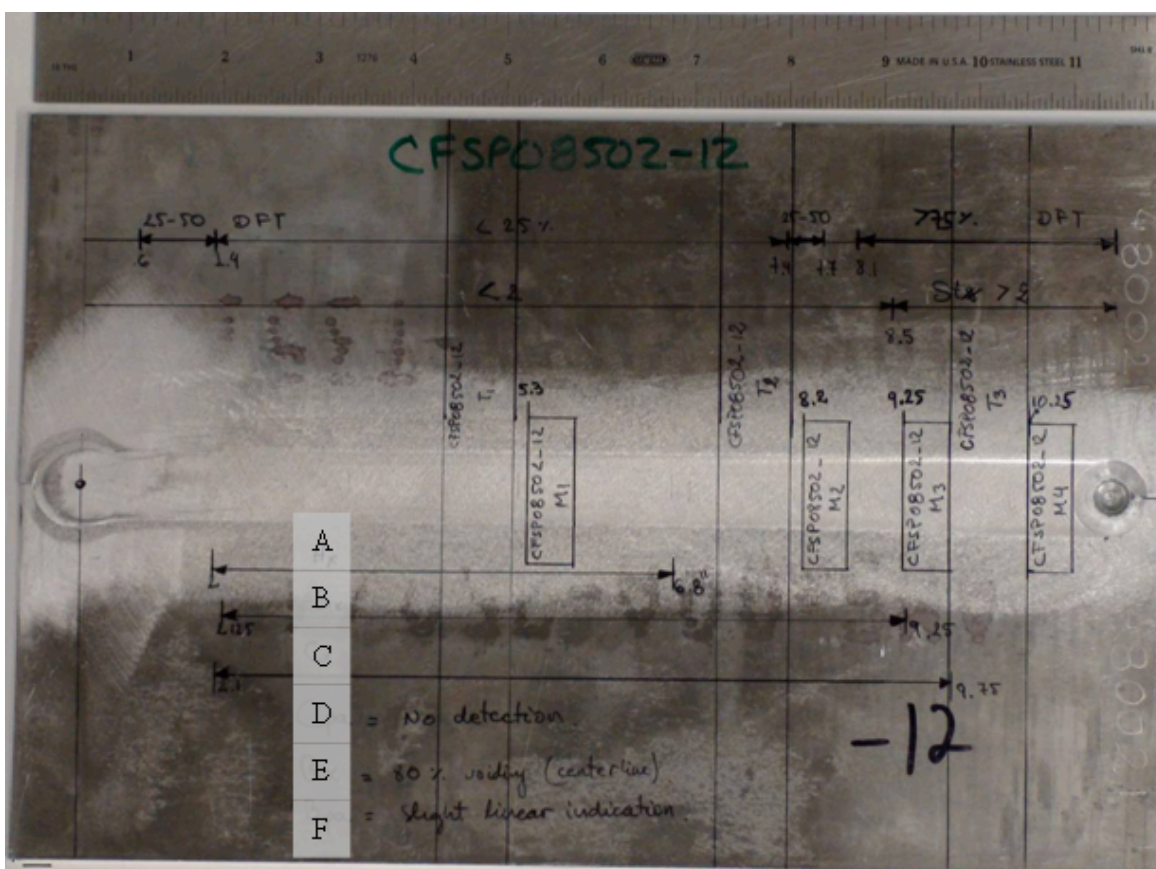
Figure 6. Cut plan on CFSP08502_12. A, B, C, and E correspond to X-ray analysis. D and F correspond to UPA analysis.[12]

Every macro section was inspected at the lab to identify and document the presence of voids. The longest dimension of each void in any direction was the recorded size of

the void. In the situation of multiple voids in the same macro section, the dimension of the largest void was used. Each void associated with a cluster of voids was recorded separately. Although a cluster of voids may affect the overall tensile properties, the primary concern in this study was the ability to detect the size each void.

The neural network (NN) algorithm provided by Boldsaikhan, described elsewhere,[13,14] was trained using three feature vectors per each point of interest obtained from the F_y feedback force signal. Two 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

The mean POD curve computed from the three X-ray analysis reports are plotted together in Figure 7. The lower 95% confidence bound is also plotted for reference.
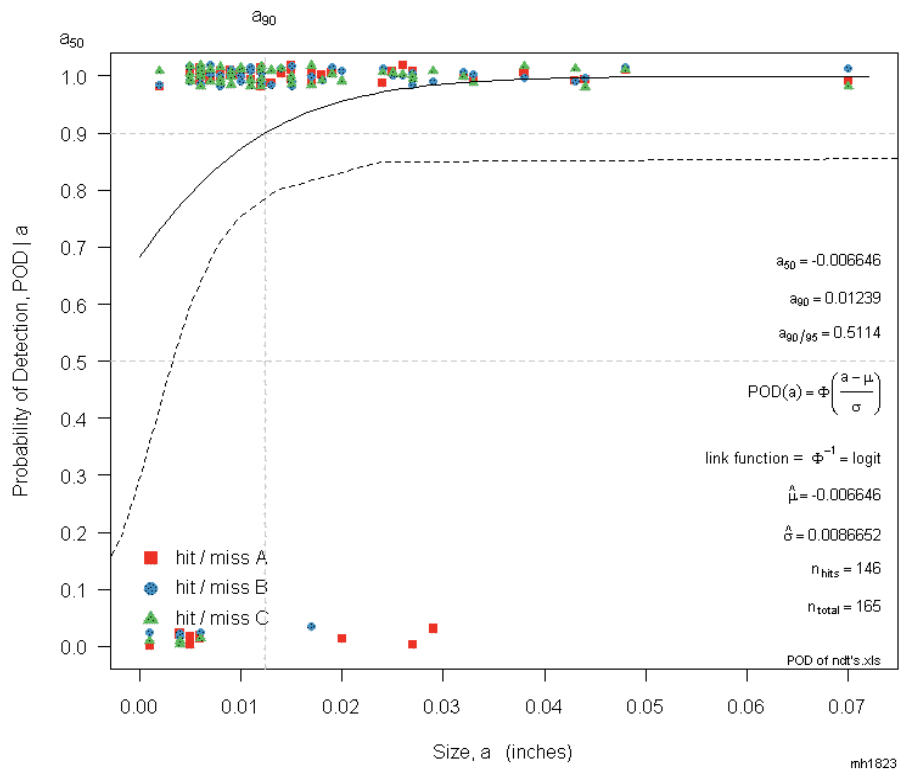
Figure 7: Mean POD curve versus void size computed from the three reported X-ray analyses.[12]

The mean POD versus void size of the neural network (NN) classification is shown in Figure 8. Note that the X-ray method detected voids with a length greater than 0.30 mm (0.012 in) with a 90% mean POD but it cannot guarantee detection at a 95% confidence level for 90% POD (see Figure 7). In contrast, the NN – DFT based method identified voids with a length greater than 0.13 mm (0.005 in) at a 90% mean POD, and a length of 0.48 mm (0.019 in) with a 90% POD at a 95% confidence level (Figure 8).
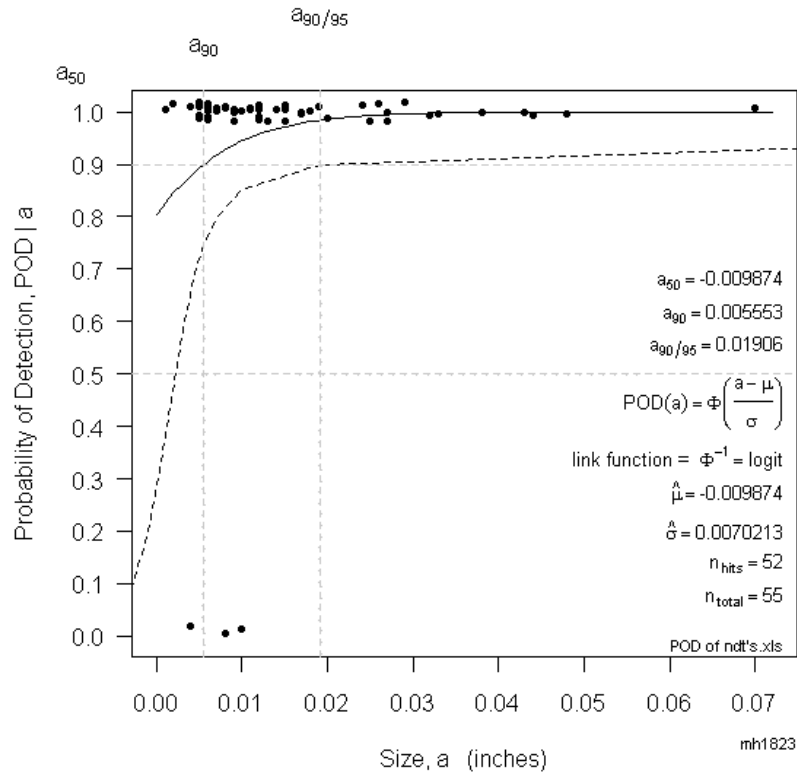
Figure 8: Mean POD versus void size for the NN analysis results.[12]

To evaluate the effects of defects, a POD curve was constructed for transverse tensile strength values as a function of wormhole or void size. The same binary regression analysis based on a maximum-likelihood method was applied to the tensile binary result obtained in this test program. Figure 9 shows the probability of detection of low tensile strength due to wormhole size. As shown, a wormhole larger than 0.38 mm (0.015 in) has 90% POD of causing low tensile strength.
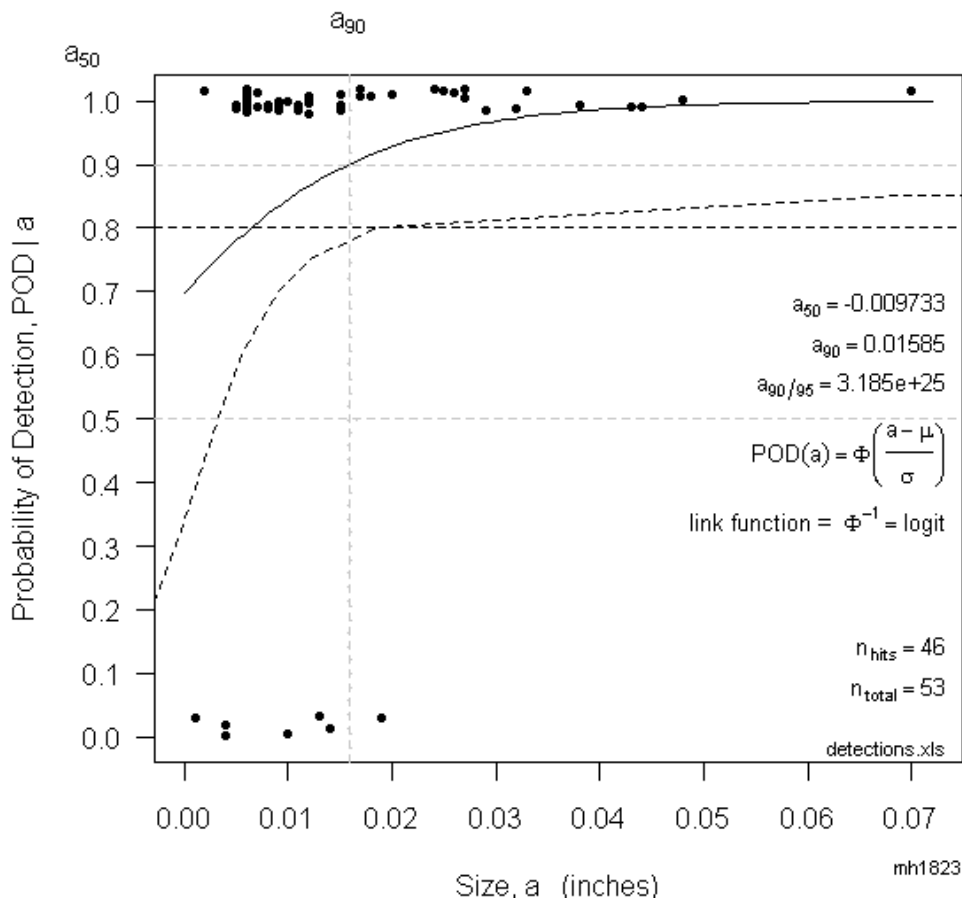
Figure 9: Effect of Defect - Mean POD versus void size for the Tensile Test analysis results.[12]

To summarize, the trained neural network (NN) system evaluated in this study was found to provide better detection capability than either X-ray, a non-destructive method, or tensile testing, a destructive test method.

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 will form the basis of a

powerful e-NDE technique that will greatly reduce 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. 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. 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.

Future Work

The basic principles outlined for force feedback process monitoring have potential applications in other processes and materials systems. For example, drilling holes in composites for mechanical fasteners 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.[15] 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.

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