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Seam-Tracking for Friction Stir Welded Lap Joints

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This article presents a method for automatic seam-tracking in friction stir welding (FSW) of lap joints. In this method, tracking is accomplished by weaving the FSW tool back-and-forth perpendicular to the direction of travel during welding and monitoring force and torque signals. Research demonstrates the ability of this method to automatically track weld seam positions. Additionally, tensile and S-bend test result comparisons demonstrate that weaving most likely does not reduce weld quality. Finally, benefits of this weave-based method to FSW of lap joints are discussed and methods for incorporating it into existing friction stir welding control algorithms (such as axial load control) are examined.

Keywords automation, friction stir welding, robotics, seam-tracking

1. Introduction

1.1 Friction Stir Lap Welding

Friction stir welding (FSW) is a relatively new solid-state welding process. It was patented in 1991 by TWI, and is finding an increasing range of industrial applications (Ref 1). In FSW, a rotating tool is plunged into the material to be joined and then traverses the joint line. The FSW tool typically consists of a shoulder which rides along the surface of the weld applying heat and pressure, and a probe which is plunged into the material and accomplishes stirring.

Friction stir welding has shown to be applicable to a number of joint types, including butt-, lap-, and T-joints. Lap (or overlap) joints are joint types where the material is laid one on top of the other creating an overlap region. The FSW probe plunges completely through the upper material, and slightly into the lower sample and traverses through the overlap region. An illustration of friction stir welding of lap joints is shown in Fig. 1.

Figure 1 points out some important nomenclature used in this article and the literature. The advancing side of the weld is the side in which the direction of tool rotation and tool travel direction relative to the material to be joined are the same, and the retreating is the opposite. Additionally, a right-handed lap weld is one in which the top member is on the right when viewed from the start of the weld. The seam of a lap joint is defined to lie between the edges of the overlapping parts of the joint. The seam is typically centered between the edges, although this is not a requirement. The seam does not normally consist of the entire overlapped region, although it may do so.

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Friction stir welding of lap joints is currently used in a number of applications and has potential for wider application. Ericsson et al. point out for example that "high-strength aluminum structures in airplanes (often of lap- or t-joint type), traditionally viewed upon as unweldable and fastened by rivets, can be friction stir welded" (Ref 2). An advantage of using FSW for lap joints is that the shear tensile strength of FSW was found to be "2.4 times that of single row riveted joints" (Ref 2).

1.2 Seam-Tracking and Robotic Welding

Robotic FSW represents an opportunity for a more flexible welding process, and the increased applicability of FSW. Smith et al. demonstrate that by robotizing the FSW process, time and money can be saved due to a robot's ability to perform numerous weld passes on a single fixturing (Ref 3). Smith et al. conclude that FSW is "following in the footsteps of several other welding processes with regard to the need for flexibility," for instance Gas Metal Arc Welding (GMAW).

A common feature of arc welding robotics today is the seam-tracking ability of the robot. This enables the robot to follow the joint-seam automatically, and reduces the need for precision fixturing. A typical instantiation of seam-tracking for arc welding robots is called through-the-arc sensing. As discussed by Cook, through-the-arc sensing follows the joint-seam during welding by adjusting position according to signals which are intrinsic to the welding process: arc current and voltage (Ref 4). Seam-tracking may enable robotic arc-welding to cope with variations in joint positioning and therefore may reduce the need for precise fixturing and path-planning.

In this article, a method for the implementation of seam-tracking for FSW is presented. In this method, weld forces and torques are monitored while the FSW tool is weaved back-and-forth perpendicular to weld travel. This system mirrors what is used in through-the-arc sensing, both in the employment of weaving, and also in the selection of feedback signals intrinsic to the welding process: forces and torque in FSW, voltage and current in arc welding.

An important advantage of this seam-tracking system is its use of a feedback signal which is likely already monitored in most existing robotic FSW systems. Smith et al. in their discussion of robotic FSW, state the need for force feedback in

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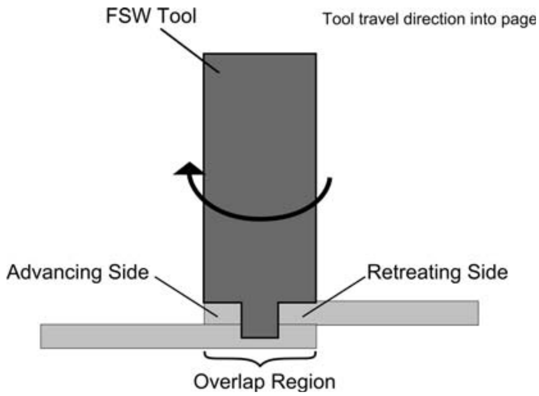

Fig. 1 Diagram of FSW of a lap joint

robotic FSW in order to monitor and control the axial load and penetration depth (Ref 3). Therefore, a system which uses axial force signals to maintain joint position in the vertical direction can require but may allow for no additional sensing equipment. This can reduce the time and cost of adding a seam-tracking system. However, even in cases where new sensing equipment is required, seam-tracking may still be helpful, such as processes in which part variability is significant. Additionally, for lap joints it will be shown that tracking can be accomplished simultaneously with load-control during welding.

Prior research has documented the existence of useful force relationships existing between certain weld forces and torque and tool position relative to the weld seam. Fleming et al. trained a neural network to predict lateral position of the tool with respect to the joint line for T-joint FSW (Ref 5). The authors also documented the differing ways in which the weld forces correlated with tool-seam alignment. For this research in lap joints, it was discovered that both axial force and torque correlate very well with tool-seam alignment and both were explored as the feedback signal in the seam-tracking control system.

In this article, weave-based seam-tracking for FSW of lap joints is presented. Experiments demonstrate the ability of the system to track both overlap regions which are parallel to travel direction as well as overlaps which are linear, but at an angular offset from travel direction. The described system can be utilized in an FSW process, robotic or non-robotic, which has the ability to move perpendicular to the direction of travel during welding and can sense load or torque. Additionally, the effect of weaving on the mechanical properties of lap welds is evaluated, and test results indicate that using weaving for seam-tracking does not reduce weld quality. Finally, recommendations for the continued development and implementation of the system and its use to industry are presented.

2. The Seam-Tracking Control System

As discussed earlier, in this weave-based seam-tracking system the FSW tool traverses back-and-forth perpendicular to weld travel during welding, while a controller monitors a force or torque signal at the limits of weave travel and compares them to determine the direction of the center of the weld with respect to the current position. This mirrors mechanically what is done electrically in through-the-arc sensing (with force and torque

while *Weaving* **do**
    Move $Weave_{Adv}$ mm at $WeaveRate$ cm min^{-1} toward advancing side
    Store $\Sigma_{current} \rightarrow \Sigma_{Adv}$
    Move $Weave_{Ret}$ mm at $WeaveRate$ cm min^{-1} toward retreating side
    if $\Sigma_{current} > \Sigma_{Adv}$ **then**
        $WeaveWidth \rightarrow Weave_{Adv}$
        $WeaveWidth + StepSize \rightarrow Weave_{Ret}$
    else
        $WeaveWidth + StepSize \rightarrow Weave_{Adv}$
        $WeaveWidth \rightarrow Step_{Ret}$
    end
end

Fig. 2 Weave-based seam-tracking algorithm

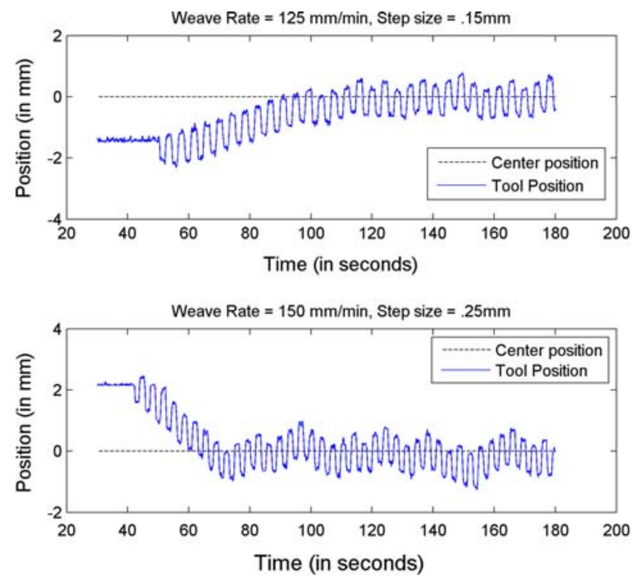

Fig. 3 Results of applying seam-tracking with initial offset

replacing voltage and current). Figure 2 illustrates the process algorithmically.

In the above algorithm, Σ_{current} is the current force (either x, y, or z) or torque signal—or some function of these signals—value while Σ_{Adv} represents the force or torque signal recorded on the advancing side of the weave. In the basic version of the algorithm, *WeaveRate*, *WeaveWidth*, and *StepSize* are constant values. The algorithm uses Σ to determine in which direction is the center of the overlap region. The tool weaves back-and-forth where the width of the weave, measured between extremes of motion is approximately *WeaveWidth*. However, the tool travels slightly farther in the direction in which the center is determined to be (*WeaveWidth* + *StepSize* rather than just *WeaveWidth*) and therefore is moved toward the center with each weave. The lateral position of a tool versus time of a weaved weld is presented in Fig. 3.

There are three free parameters in the above algorithm, they are:

(1) *WeaveRate*: The speed of the weaving motion in cm$\cdot$min^{-1}
(2) *WeaveWidth*: The width of the weave in mm
(3) *StepSize*: The length, in mm, of the adjustment made to the center of the weave when moving based on indicating signals.

$Weave_{Adv}$ and $Weave_{Ret}$ then are the distances to move toward the advancing side or retreating side in the current weave motion.

As can be seen from the above algorithm, the process assumes that some signal (a force, torque, or functions of force and torque) indicates position in that when the weave is centered about a position offset to one side of the center of the seam, said signal is larger on the side closer to the center, and on the other side, the reverse is true. Both the axial force and torque were observed to have this property for lap welds. However, the torque signal proved more reliable and accurate and was ultimately selected as the sole feedback signal.

3. Experimental Setup

A series of experiments were performed, both to test the ability of the system to automatically follow a lap joint, and also to examine the effects of weaving on the mechanical properties of an FSW lap weld.

The material used in these tests was 3.175 mm thick 6061 aluminum, and the lap welds were arranged in a right-handed configuration. The width of the overlapped area of the weld was 15.875 mm. The FSW tool used in the experiments was a Flared TriFlute™ with a 15.875 mm shoulder diameter, and a probe which was 6.35 mm wide by 5 mm long. The rotation speed of the tool was 1000 RPM and the welding speed was 5 $cm \cdot min^{-1}$. The friction stir welding system employed was a converted milling machine, adapted for friction stir welding and upgraded to complete computer control of the welding process. The welding process is position controlled, although the discussion section presents possibilities for incorporating seam-tracking with axial load control.

4. Results

4.1 Tracking a Non-changing Lap Joint Position

In the first experiment, the lap joint was fixtured normally; however, the tool started the weld run with some offset with respect to the center of the overlap. The results for two of these welds are shown in Fig. 3.

In the upper result plot, the tool is started offset to the advancing side of the center. When seam-tracking is engaged at 50 s, the system moves directly to the center and then holds this position. In the lower figure, the tool is started offset to the retreating side, and the system again moves the tool to the center and holds the position. In the lower experiment, both the *WeaveRate* and *StepSize* have been increased with respect to the upper experiment and this results in a quicker convergence to the center. The optimization of these parameters, and also the inclusion of more advanced control techniques is the subject of future work.

4.2 Tracking a Linearly Changing Center Position

In a second experiment, the aluminum was machined at an angle, so that when clamped, the overlapped region would remain constant in width and follow a linear path, but this path has an angular offset from the travel path.

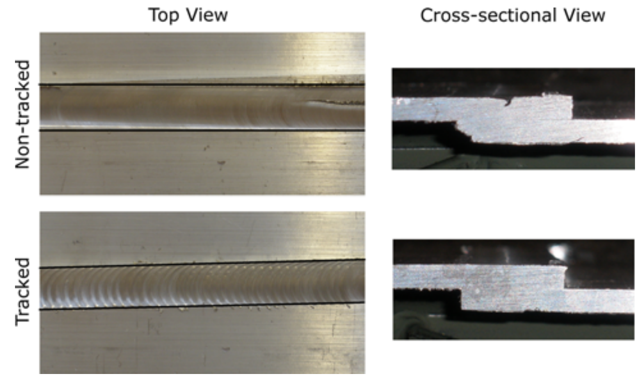

Fig. 4 Comparing tracked and non-tracked welds given changing center position

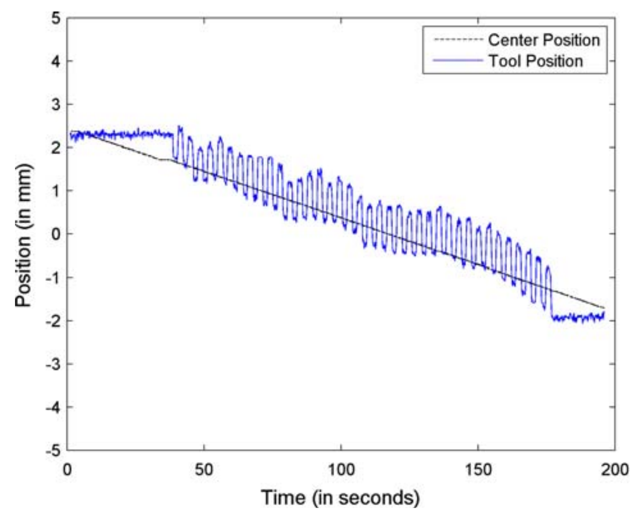

Fig. 5 Tracking a changing center position with seam-tracking

In Fig. 4 the effects of welding this changing lap joint with and without seam-tracking are shown.

In Fig. 4, the top view of the lap welds is shown on the left, with black lines drawn in on the outline of the weld surface to assist clarity. Notice that because the normal weld does not adjust to the changing position, it gradually becomes offset to the point where large surface defects appear. The tracked weld however, follows the seam, and therefore does not exhibit this flaw. Looking at the cross sections of the two welds on the right, one can see that the non-tracked weld was also extruding material. Figure 5 shows the position of the tool and the position of the center of the overlap region over time for the tracked weld.

4.3 Mechanistic Results

Weave-based seam-tracking is a method for tracking the weld seam; however, it is important to consider the impact of weaving on the quality of lap welds and to ensure that the process of weaving does not reduce weld quality. Additionally, in some variations of weaving, portions of the shoulder may by design go out of the overlapped region of the weld, this also might introduce changes to the resultant weld quality.

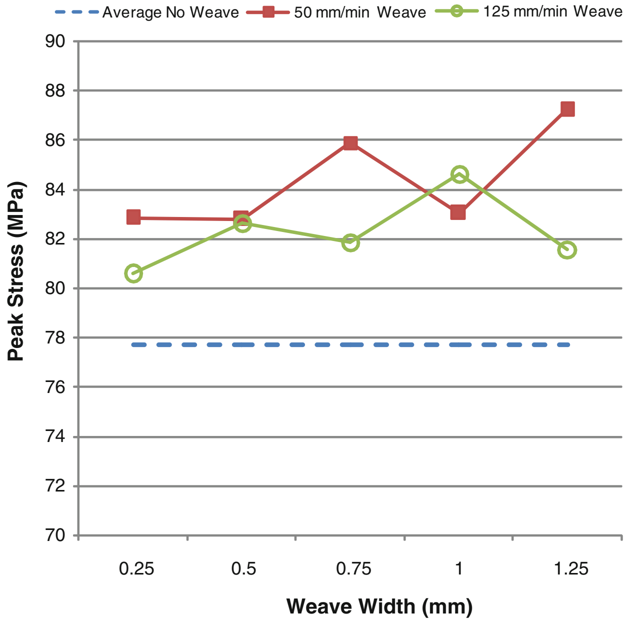

Fig. 6 Tensile test results for weaved and non-weaved welds

In weaving, the tool is moved back-and-forth perpendicularly to the weld seam during traversal. This action is similar to some methods described for the improvement of lap welds in the literature. Cantin et al. describe skew-stir, in which the probe is at an angle to the axis of rotation, thereby sweeping a larger area than the volume of the probe (Ref 6). The Com-Stir™ system, described in Thomas et al., combines orbital and rotary motion of the tool (Ref 7). This produces both a wider weld and should give more "efficient surface fragmentation" than conventional FSW, both of these results implicating a higher quality lap weld.

Weaving is similar in nature to these two processes; it also causes the probe to sweep through a larger volume than the probe itself and thereby producing a wider weld. However, it is not identical, and to date is performed at a lower frequency (weaves $\cdot$ min^{-1} compared with orbits $\cdot$ min^{-1} in Com-Stir™ or the rotation speed of skew-stir). Nevertheless, experiments indicate that weaving currently does, like the above techniques, yield an improvement in weld quality.

Tensile tests were performed to compare the peak stress of weaved and non-weaved welds and the results can be seen in Fig. 6. In all cases the welds were run with proper alignment. Two values of *WeaveRate* were considered, and five values of *WeaveWidth*. In all cases considered, the weaved lap welds achieved a higher peak stress than the non-weaved welds. The 50 mm $\cdot$ min^{-1} weaved welds performed slightly better than the 125 mm $\cdot$ min^{-1} welds. Overall, there was a 7% increase in tensile strength between the average of the 50 and 125 mm $\cdot$ min^{-1} weave results and non-weave results.

In addition to tensile testing, the welds were also bend-tested according to the Hammer S-Bend procedure described in Colegrove et al. as "a rudimentary experiment where the weld is bent into an S-shape which places the joint area in tension and opens any cracks that may have been produced by the welding process" (Ref 8). Further, Thomas et al. suggest that bend test results give good correlation with fatigue test results for FSW lap welds (Ref 9). The results of bend testing a non-weaved and weaved weld are shown in Fig. 7.

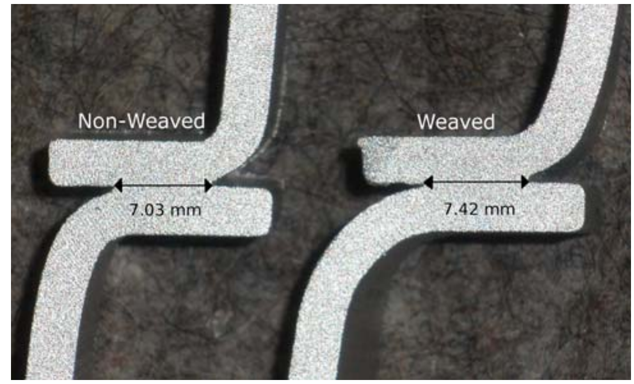

Fig. 7 Results of S-bend test for non-weaved and weaved welds

In Fig. 7, the weaved weld has a *WeaveWidth* of .75 mm and a *WeaveRate* of 125 mm $\cdot$ min^{-1}. One result of bend testing was the demonstration that all weaved and non-weaved welds "passed" the bend test, in that no cracks were opened up at the ends of the unwelded notches. This further indicates that weaving at minimum does no harm to weld quality. However, an additional result is the confirmation that weaving is widening the weld region, as shown in Fig. 7, which is an explanation for the increase in tensile strength.

Weave-based seam-tracking is intended as a technology for the implementation of automatic seam-tracking. The results of tensile testing and bend testing indicate that the process of weaving can be employed for automatic seam-tracking without reducing weld quality.

5. Discussion

The above tests demonstrate the ability of weave-based seam-tracking to effectively track a lap joint. Additionally, mechanical testing and comparisons with related literature indicate that weaving does not reduce weld quality. The methods described can be applied by any FS welding system (conventional, CNC or robotic) that have a servo-controlled axis perpendicular to the direction of travel and the ability to measure the forces/torque experienced by the tool.

As can be seen from the history of welding robots, seam-tracking technologies often serve to improve the robustness and flexibility of automated welders and therefore can decrease the amount of time and money which needs to be invested for a given weld run. Using seam-tracking when performing lap welds implies that the robot can be relied upon to find and track the center of the overlap and can therefore handle variations in fixturing, thereby reducing the burden of precision positioning. However, in considering the possible time savings given by added robustness, it is also possible that weaving might somewhat lower allowable traversal rates by requiring added motion perpendicular to travel. In this article, the traverse rates and weld times for weaved and non-weaved welds were the same, because traverse motion and weaving motion were controlled by separate servos. However, this may be different for robotic welders, and additionally, it may lower maximum traverse rates by raising the effective rate of travel for the tool with respect to the material.

Weave-based seam-tracking has a number of useful features which should facilitate its adoption in industry. The first is that it uses the forces intrinsic to the welding process as its feedback. Forces are very typically measured and monitored in FSW, and especially so in robotic FSW where load control is considered essential. Therefore, for most robotic welding systems, seam-tracking would not require additional sensors. Further, it can be shown that weave-based seam-tracking can incorporate axial load control. Because the system compares only the relative difference between the forces or torque observed at the limits of weaving, correcting the vertical height or spindle speed or traverse rate between weave cycles would not be a problem, doing so should effect the absolute levels of both readings, while their relative difference remains. It is also probable, that other force-based sensing techniques, such as the one described in Boldsaikhan et al., which uses a neural network to identify metallurgical defects, could also be incorporated (Ref 10).

Finally, weaving can very likely be employed without impairing weld quality. It is also possible that weaving can improve weld quality, just as weaving has proven beneficial in arc welding, and processes such as Com-Stir™ and skew-stir have yielded quality improvements in FSW. Future research may address the possible weld quality benefits of weaving.

5.1 Future Work

Future progress on seam-tracking should focus on the refinement of the system, both in terms of sophistication of the control algorithm, and with respect to its mechanical effects.

In terms of control, currently the algorithm has three fixed parameters: the *WeaveWidth*, the *StepSize*, and the *WeaveRate*. One improvement could be to allow one or more of these values to vary dynamically in response to the relation of signals obtained on the sides of the weave. From here, it is conceivable to imagine this proportional style control leading to PID (proportional-integral-derivative) type control settings and from there to more advanced control laws. This initial system should serve as a proof of concept, with a later system achieving improved bandwidth and stability through refined control techniques.

Future research should further investigate the effects of weaving on weld quality. While the results of this article indicate that weaving can be used to implement tracking without harming weld quality, research should be performed to investigate whether weaving may also be employed as a method for improving weld quality in some applications. The initial results provided in this article indicate that this is a possibility, but further research is necessary to confirm whether weaving is truly worthwhile outside of its enabling of seam-tracking.

6. Conclusions

- A weave-based seam-tracking enables seam-tracking of lap joints for FSW. Seam-tracking greatly improved the flexibility and applicability of other robotic welding technologies and could do the same for FSW.
- The system uses the forces and torque intrinsic to the welding process, which may be already sensed in many existing robotic FSW technologies.
- The system could incorporate existing force-based sensing techniques such as load-control, and quality monitoring.
- Tensile results indicate weaving does not harm weld quality, and future research may demonstrate that weaving can be employed to improve weld quality.

Acknowledgments

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References

1. W.M. Thomas, E.D. Nicholas, J.C. Needham, M.G. Murch, P. Temple-Smith, and C.J. Dawes, G.B. Patent 9125978.8, 1991
2. M. Ericsson, L. Jin, and R. Sandstrom, Fatigue Properties of Friction Stir Overlap Welds, *Int. J. Fatigue*, 2007, **29**, p 57–68
3. C.B. Smith, J.F. Hinrichs, and W.A. Crusan, Robotic Friction Stir Welding: The State-of-the-Art, *Proceedings of the 4th International Friction Stir Welding Symposium* (Salt Lake City, UT), The Welding Institute, 2003
4. G.E. Cook, Robotic Arc Welding: Research in Sensory Feedback Control, *IEEE Trans. Ind. Electron.*, 1983, **IE-30**(3), p 252–268
5. P.A. Fleming, D.H. Lammlein, D.M. Wilkes, G.E. Cook, A.M. Strauss, D.R. DeLapp, and D.A. Hartman, Misalignment Detection and Enabling of Seam Tracking for Friction Stir Welding, *Sci. Technol. Weld. Joint*, 2009, **14**(1), p 93–96
6. G.M.D. Cantin, S.A. David, W.M. Thomas, E. Lara-Curzio, and S.S. Babu, Friction Skew-Stir Welding of Lap Joints in 5083-O Aluminum, *Sci. Technol. Weld. Joint*, 2005, **10**(3), p 268–280
7. W.M. Thomas, D.G. Staines, K.I. Johnson, and P. Evans, *Com-stir*™—Compound Motion for Friction Stir Welding and Machining, The Welding Institute, Cambridge, UK, 2003
8. P.A. Colegrove, H.R. Shercliff, and T. Hyoe, Development of the Trivex Friction Stir Welding Tool for Making Lap Welds, *Proceedings of 5th International Symposium on Friction Stir Welding* (Metz, France), The Welding Institute, 2004
9. W.M. Thomas, D.G. Staines, I.M. Norris, and R. de Frias, Friction Stir Welding—Tools and Developments, *FSW Seminar* (Porto, Portugal), 2002
10. E. Boldsaikhan, E. Corwin, A. Logar, and W. Arbegast, Neural Network Evaluation of Weld Quality Using FSW Feedback Data, *Proceedings of Friction Stir Welding, 6th International Symposium* (Saint-Sauver, Nr Montreal, Canada), The Welding Institute, 2006