Int J Adv Manuf Technol (2017) 90:81–91
DOI 10.1007/s00170-016-9362-1

ORIGINAL ARTICLE

Development of friction stir welding technologies for in-space manufacturing

William R. Longhurst [1] · Chase D. Cox [2] · Brian T. Gibson [3] · George E. Cook [4] · Alvin M. Strauss [5] · Isaac C. Wilbur [6] · Brandon E. Osborne [6]

Received: 16 June 2016 / Accepted: 15 August 2016 / Published online: 26 August 2016
© Springer-Verlag London 2016

Abstract Friction stir welding (FSW) has emerged as an attractive process for fabricating aerospace vehicles. Current FSW state-of-the-art uses large machines that are not portable. However, there is a growing need for fabrication and repair operations associated with in-space manufacturing. This need stems from a desire for prolonged missions and travel beyond low-earth orbit. To address this need, research and development is presented regarding two enabling technologies. The first is a self-adjusting and aligning (SAA) FSW tool that drastically reduces the axial force that has historically been quite large. The SAA-FSW tool is a bobbin style tool that floats freely, without any external actuators, along its vertical axis to adjust and align with the workpiece's position and orientation. Successful butt welding of 1/8 in. (3.175 mm) thick aluminum 1100 was achieved in conjunction with a drastic reduction and near elimination of the axial process force. Along with the SAA-FSW, an innovative in-process monitor technique is presented in which a magnetoelastic force rate-of-change sensor is employed. The sensor consists of a magnetized FSW tool that is used to induce a voltage in a coil surrounding the tool when changes to the process forces occur. The sensor was able to detect 1/16 in. (1.5875 mm) diameter voids. It is concluded that these technologies could be applied toward the development of a portable FSW machine for use in space.

Keywords Friction stir welding · Process monitoring · Automation and control · In-space manufacturing

✉ William R. Longhurst
longhurstw@apsu.edu

1 Department of Physics and Astronomy, Austin Peay State University, Clarksville, TN 37044, USA

2 Screens and ICDs, Schlumberger, Houston, TX 77039, USA

3 Materials Processing and Joining Group, Materials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, TN 37931-6140, USA

4 Department of Electrical Engineering, Vanderbilt University, Nashville, TN 37240, USA

5 Department of Mechanical Engineering, Vanderbilt University, Nashville, TN 37240, USA

6 Department of Physics and Astronomy, Austin Peay State University, Clarksville, TN 37044, USA

Nomenclature

KN	Kilonewton (force)
MPa	Megapascals (strength)
N	Newton (force)
N-m	Newton-meter (torque)
lb_f	Pound-force (force)
lb_f-ft.	Pound-force-foot (torque)
mm	Millimeters (length)
min	Minutes (time)
psi	Pounds per square inch (strength)

1 Introduction and literature review

The need for in-space assembly, fabrication, and repair (ISAFR) is identified by the United States' National Aeronautics and Space Administration (NASA) in their Space Technology Roadmaps under Technology Area 12—Manufacturing [1]. Having the ability to perform manufacturing operations while in space greatly enhances mission capability. Manufacturing in space will lead to prolong missions beyond low-earth orbit. Crews would be able to become more self-sufficient and no longer need to be supplied with items fabricated prior to launch. One particular area of manufacturing that could greatly enhance in-space operations is material joining via welding. Being able to weld large structures in-space would give a new operational capability. Crews would be able to create load-bearing structures and machines.

Since its patenting in 1995 [2], friction stir welding (FSW) has emerged as an attractive process for fabricating aerospace vehicles. Historically aerospace vehicles have been constructed with a lightweight metal that has high strength such as aluminum. Aluminum has a relatively low meting temperature and has proved to be very difficult to join using fusion welding processes such as arc welding. However, with its low melting point, aluminum can be joined very effectively using the solid-state process of FSW.

As illustrated in Fig. 1, conventional FSW utilizes a rotating tool that consists of a shoulder and pin, to plastically deform the parent materials along their faying surfaces and then forged them together. The addition of heat from plastic deformation and friction between the surface of the tool and the workpiece combine to raise the temperature and soften the material in the welding environment to a point where it easily stirs with the rotation of the tool. For the process, a critical requirement is the proper engagement of the tool with the workpiece. Without the proper engagement of the tool with the workpiece, the necessary amount of forging pressure from the downward force is not achieved and welding flaws such as wormholes emerge. These flaws reduce the structural integrity of the weld or prohibit bonding of the parent materials.

Maintaining proper engagement of the tool with the workpiece (or plunge depth) is challenging because of workpiece variation and machine deflection. Workpiece variations present challenges especially with large and curved components. As the FSW tool traverses along the weld seam, unexpected variations or changes in the curved surface require adaptations of the tool's position to be made during the process. Force control has been demonstrated to be an effective method for maintaining proper tool engagement with work present by Longhurst et al. [4], Soron et al. [5], and Smith [6]. With force control, the tool's vertical position relative to the workpiece is allowed to vary in order to achieve a desired force. This control strategy has proved to be key for robotic applications due to the compliant nature of robots and their flexible structures.

The current FSW state-of-the-art uses large custom-built FSW machines or computer numerical control (CNC) milling machines to perform the process. These types of machines with their strong load-bearing capability are necessary to maintain the proper forging force described above. Hence, the use of FSW has been restricted because of the need to use these types of machines. Recent success has been made with robotic FSW by using articulating arm industrial robots in conjunction with force control. Although use of industrial robots allows for more widespread use of FSW, the process still remains confined to a factory environment. For FSW to be used as prevalently as arc welding, the necessary equipment must be comparable in portability and cost.

Since the forging force is quite large in most FSW processes, prior work has been done to investigate methods to reduce the force. A reduction in force would lead to smaller and more flexible machines that are more easily portable. As noted by Cook et al. [7], as well as by Crawford et al. [8], increasing the tool's rotation speed as well as decreasing the tool's traverse speed leads to a lower force. With a faster spinning tool, or one that is traversing slower, more heat is added in the welding environment. This heat softens the material. Another approach to softening the material is to preheat the material prior to welding. Work by Sinclair et al. [9] showed that preheating the material with an external heat source will lower the welding forces by about 20 %.

A novel approach to maintain the required forging force has been with the development of bobbin tools by Fuller et al. [10], Sued et al. [11], and Colligan et al. [12] and retracting pin tool (RPT) technology by Ding et al. [13]. Bobbin tools utilize two shoulders, one on the top and one on the bottom, to squeeze together the material in the welding environment. The two shoulders are connected through a central pin. Similar to conventional tools, features such as groves and scrolls are often added to the shoulders while threads and flats are added to pin. These features enhance the stirring of the parent materials. The advantage of bobbin tools over

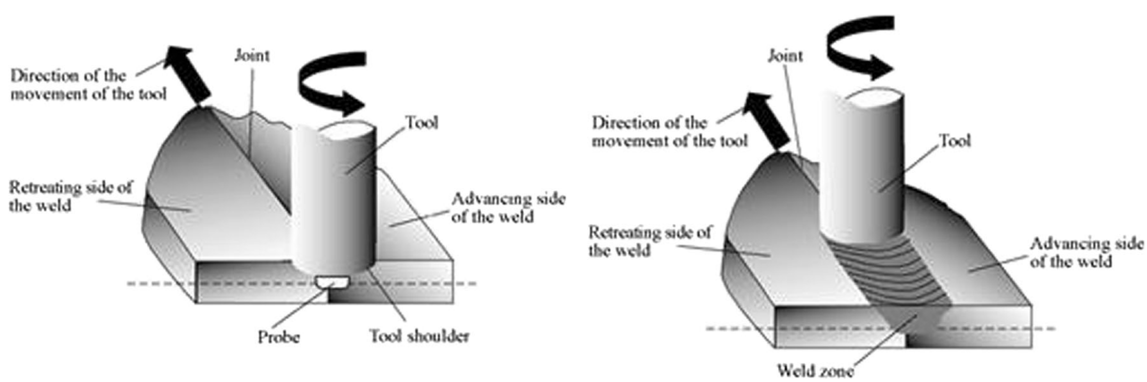

Fig. 1 The FSW process [3]

conventional tools is there is no need for a backing anvil. Because the tool has two shoulders to stir and the material, more heat is generated and the process forces are typically lower as compared to conventional FSW. In addition, if the workpiece is perfectly centered in-between the two shoulders, there will be no external axial force on the tool. All the axial force is contained within the connecting pin and shoulders. This leads to less load-bearing requirements from the frame of the FSW machine.

RPT technology adjusts the bottom shoulder to maintain a desired force on the workpiece. With the bottom shoulder adjustable in position, the workpiece material is squeezed to maintain the proper forging pressure. This type of bobbin tool is also known as a self-reacting tool. It has a great advantage over fixed shoulder-to-shoulder distance bobbin tools because it can adjust to varying thickness in the workpiece. However, actuation and control hardware is needed for adjusting the position of the bottom shoulder. This leads to added complexity of the FSW system.

For in-space FSW to become feasible, the welding machines must become portable. FSW technology must evolve to point where the welding equipment is comparable to the portability and ease-of-use of an arc welder. Along with portability, management of the forces must also me considered when operating in a low gravity environment. Reaction to process forces must be countered and keep internal to the welding machine.

Lastly, we must consider how to perform inspection of the weld to insure its quality. Current state-of-the-art inspection of welds includes the use of X-rays and ultrasonic methods. These are reliable methods; however, they are performed after the welding process and typically offline. When a flaw is detected, the weldment is either scraped or repaired. With limited resources available to a crew in space, a more efficient inspection process is needed. As suggested by Davé et al. [14], the inspection of the welding needs to be in situ and be done simultaneously with the process. If the monitoring is in-process, flaws could be identified before they are fully developed. With this identification, process parameters could be altered immediately to correct the welding. At a minimum, in-process monitoring could identify flaws and replace nondestructive testing methods.

1.1 Presented research

Presented in this paper is work on two technologies that may assist with the development of a portable FSW machine for use in space. The first innovation is a fixed shoulder-to-shoulder distance bobbin tool that has convex shoulders and free-floating motion capability along its vertical axis. The fixed convex shoulders in conjunction with the free-floating motion allow the tool to self-adjust and align with the workpiece thereby eliminating the need for any actuating mechanisms. Along with the self-adjusting and aligning FSW (SAA-FSW) tool, a method for in-process monitoring is presented. The monitoring can be done during the welding process and without the use of an external power source. The method employs the use of a magnetoelastic force rate-of-change sensor to detect voids in the weld seam. The tool is magnetized and changes in process forces acting on the tool cause it to deflect. With the deflection of the tool and the corresponding magnetic field, a voltage is induced in a coil of copper wire surrounding the tool.

The presented technologies are ideal for enabling an in-space FSW machine. The SAA-FSW tool requires no actuation and control devices for aligning and adjusting to the workpiece; thus simplify the machine. In addition, it eliminates the axial force external to the tool and it eliminates the need for a backing anvil. With the in-process monitoring technology, no external power source or traditional nondestructive testing equipment is needed.

2 Self-adjusting and aligning friction stir welding tool

2.1 Experimental setup

The development work was conducted at Vanderbilt University using a Milwaukee model K milling machine that had been retrofitted with servo motors and force-measuring instrumentation for FSW. A force sensing table was constructed as part of the workpiece clamping tooling to accurately measure the traverse, horizontal, and vertical force. Three Futek load cells (model number LRF350) were incorporated into the design of the table. The load cells were capable of measuring both compression and tension forces. The welding torque was measured via the electrical current supplied to the spindle motor [15]. The FSW machine with the force table and clamping hardware is shown in Fig. 2.

The workpiece material selected for development of the SAA-FSW tool was 1/8 in. (3.175 mm) thick aluminum

Fig. 2 FSW machine used for the development of the SAA-FSW tool

1000. Aluminum 1100 is a very lightweight material with a yield strength of approximately 15,000 psi (105 MPa). Due to its light weight, this material was selected because it is more representative of something that would be used to fabricate a structure in space. In addition, aluminum 1000 is a lower strength material that is ideal for research and development of a portable FSW machine for which the SAA-FSW tool is intended.

2.2 Design and development process

The design and development process was very empirical in nature. The design details necessary for a successful bobbin tool were not clearly communicated in the referenced literature discussed in the "Introduction" section [10], [11], [12], [13]. To begin the development process, we focused on producing a fixed shoulder-to-shoulder bobbin tool so we could better understand bobbin tools and their performance characteristics. For each welding trial, 2–10 in. (254 mm) long pieces of aluminum 1000 were butt welded together using prototype bobbin tools. Tool traverse and rotation speeds were varied, and the process forces were measured.

The first prototype bobbin tool we constructed was a very simple design. It was a fixed shoulder-to-shoulder tool with both shoulders flat and featureless. The connecting pin was also featureless. Welding trials were conducted with this tool over a range of traverse speeds and rotation rates for the tool. We were never able to get this tool to successful join the parent metals of the workpiece. However, several key lessons were learned and used on subsequent designs. The most important lesson learned was that the bobbin tool was highly sensitive to the process parameters and not able to adapt as compared to conventional FSW tools. Specifically, the flat shoulder had to be perfectly aligned with the workpiece and the workpiece could have no variation in its thickness. This condition is practically impossible to be obtain in a production environment especially during the welding when transient thermal conditions are present and expansion of the workpiece occurs. In addition, we learned that the material naturally wants to flow away from the pin and not consolidate on the backside. The lack of consolidation was particular problematic at the beginning of the weld. Features must be added to the both the pin and shoulders to enhance this flow.

Another early prototype tool is shown in Fig. 3. The bobbin tool is a fixed shoulder-to-shoulder distance. However, now each shoulder has a 2° slope and six scrolls are present to help move the material inwards toward the pin. In addition, the pin has flats to enhance material flow. A unique aspect of this tool is the construction method. The tool is modular in design meaning that it consists of three individual components: upper shoulder, lower shoulder, and the pin. This modular design allowed us to machine complex design features onto each component. The final assembly was constructed by pressing each shoulder onto the pin. This construction method proved successful and valuable to the development process. However, difficulty was still encountered with getting material to consolidate on the backside of the pin. Once again, it was very difficult to obtain consolidation near the beginning of the weld. We concluded that more aggressive features to both shoulders and the pin needed to be added.

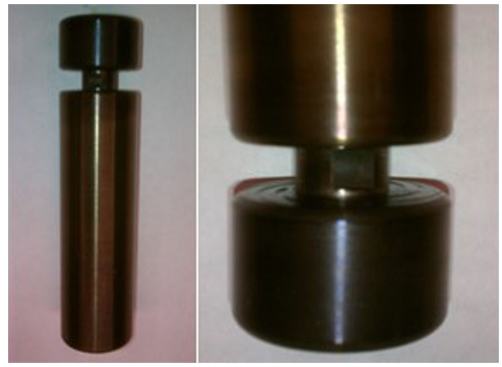

Fig. 3 Prototype bobbin tool

The shoulder and pin features were finalized in the later prototype shown in Figs. 4, 5, and 6. The shoulder-to-shoulder is still a fixed distance but more aggressive scrolls on the upper shoulder are present. In addition, rings along with the existing flats were added to the pin to enhance metal flow. The addition of these items improved the welding quality vastly and their importance cannot be understated.

As can be seen in Fig. 4, very aggressive scrolls were placed on the upper shoulder. These scrolls were approximately twice as deep as they were in previous designs. Each scroll was 3/64 in. (1.901 mm) wide by 0.016 in. deep (0.4064 mm). As a result, a noticeable improvement was evident on the surface of the welds. In addition, the added rings to the pin did a much better job moving the material. This was particular noticeable at the beginning of the welds. As noted above, we had prior difficulty at the beginning of the weld to get the material to consolidate on the backside of the pin. Figure 5 shows the rings and flats on the pin. Once we had the aggressive scrolls and rings added to the tool, the material began to consolidate on the backside of the pin for certain traverse speeds.

We tested the tool for a range of traverse speeds and found that the material began to consolidate at a speed of 6 IPM

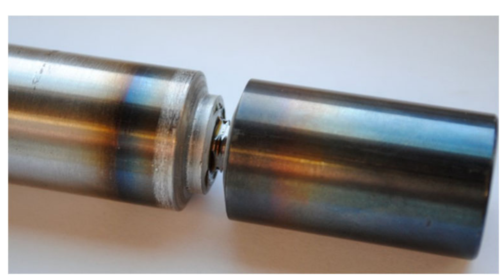

Fig. 4 Picture of the shoulder's features

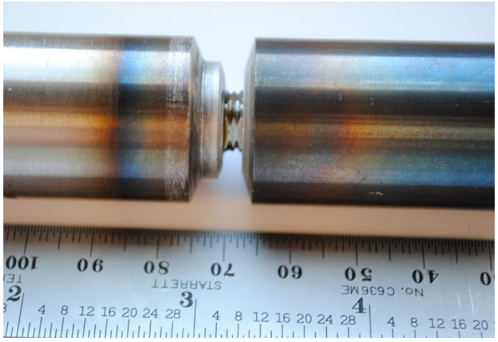

Fig. 5 Picture of the pin's features

Fig. 7 Top side of a sample weld

(152.4 mm/min), while the tool was rotating at 1400 RPM. We also noticed that the best results occurred while the tool was traversing at 9 IPM (228.6 mm/min) and rotating at either 1400 or 1500 RPM. At these speeds, the surface finish on the top and bottom side of the weld was very good.

As can be seen in Figs. 7 and 8, the developed fixed shoulder-to-shoulder bobbin tool produced a high-quality weld. It is worth noting that it took many experimental welding trials to finally achieve the results shown. As previously discussed, the welding environment created with the use of bobbin tools in very sensitive to process parameters and tool features. Evidence of this can be seen in Fig. 7. Notice that the first few inches of the weld were performed using a traverse rate of 3 IPM. The resulting weld surface quality is not esthetically pleasing. However, once the speed was increased to 6 IPM, the resulting quality improved greatly.

With the tool design shown in Figs. 4, 5, and 6, a matrix of welds was produced with varying tool traverse speed and rotation rate. Figures 9, 10, 11, and 12 summarize this data. The purpose for collecting this data was to quantify the process forces so that self-adjusting and aligning (SAA) mechanisms could be added to create the SAA-FSW tool. The process parameters were selected based upon what would be reasonable to expect from a manual welding operation, since the purpose of the SAA-FSW tool is to enable in-space manufacturing.

As can been seen in Fig. 9, the average torque varies from 10 to 12 N-m (7.34 to 8.85 lb_f-ft) when the rotation rate was 1400 rpm. The variation occurs as the traverse speed was varied through 9, 12, and 15 IPM. The lowest torque, 10 N-m (7.34 lb_f-ft), occurred when the tool was traveling at 9 IPM.

Further inspection shows the torque can be reduced by increasing the tool's RPM while welding at 9 IPM. The rotation rate was varied over 1400, 1700, and 2000 RPM. As can be seen in Fig. 9, an average torque of approximately 5 N-m (3.69 lb_f-ft) was experienced when the tool was rotating at 2000 RPM and traversing at 9 IMP. The trending pattern of the data suggests that further reduction of the torque will occur if the traverse rate is reduced further and the rotation rate is increased.

Figure 10 presents the axial force or otherwise known as the vertical force acting through the tool. As can been seen in

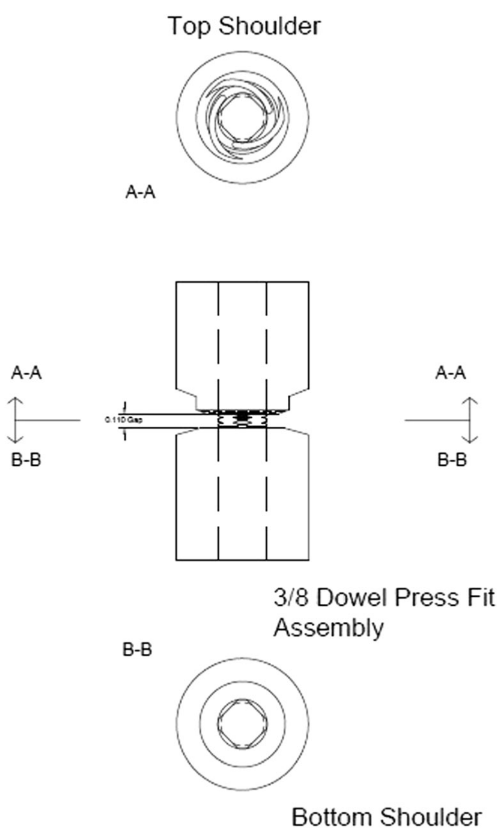

Fig. 6 Assembly drawing of the tool's shoulder and pin

Fig. 8 Bottom side of a sample weld

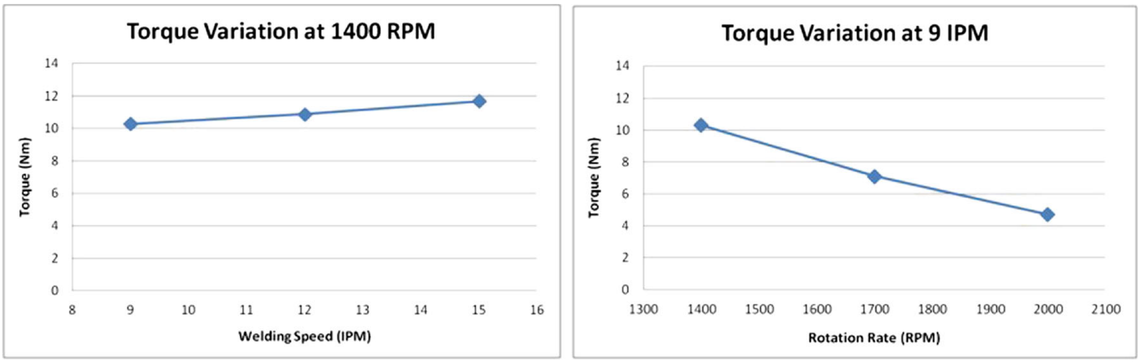

Fig. 9 Summarized torque data collected for SAA-FSW tool development

Fig. 10, it remained fairly consistent when the rotation rate was held at 1400 RPM and the traverse rate varied from 9 to 15 IPM (228.6 to 381 mm/min). As shown, the force is approximately 700 N (157 lb_f). With the traverse rate held at 9 IMP (228.6 mm/min) and the tool rotation rate increased from 1400 to 2000 RPM, a slight decrease occurs in axial force to approximately 500 N (112 lb_f). We believe most of the axial force experienced is due to a very subtle misalignment that occurs between the tool and the workpiece as well as thermal expansion during welding. Tool features such as scrolls on the shoulder and threads on the pin affect the process forces and probably contributed to the nonzero axial force. Theoretically, when the tool is aligned properly, the force acting on the upper shoulder will be countered with the same amount of force on the bottom shoulder. This would result in a net external force of zero. All of the vertical force would remain internal to the tool. However, the experienced force of 500 to 700 N (112 to 157 lb_f) is very small as compared to conventional FSW tools where the force is typically a few thousand Newtons for 1/8 in. (3.175 mm) thick material.

Figure 11 shows the traverse force data. The force experienced is this direction is very low. From Fig. 11, it can be seen that the force varies from a low of 40 N (9 lb_f) to a high of 80 N (18 lb_f) when the tool is traversed at 9 IPM (228.6 mm/min). We also were successful in pulling the workpiece through the tool by hand during one welding trial. This was done to examine the viability of a manual welding operation.

Lastly in Fig. 12, the lateral force (or side force) data is presented. As can been seen at 9 IPM (228.6 mm/min) the force varies from 200 N (45 lb_f) to 350 N (79 lb_f). We believe the reason for this force being higher than the traverse force is because of the forging pressure that is created in the material flow region between the rotating pin and the unaffected region of material outside the weld zone. It is also worth noting that the force was not reduced as the rotation rate was increased. In addition, the force did not increase dramatically as the traverse speed increased either.

With the successful welding of a bobbin tool and collected process data, we incorporated the self-adjusting and aligning features into the design to finalize the SAA-FSW tool. The concept of the SAA-FSW is illustrated in Fig. 13. The convex surface of the shoulders allows for variation in the workpiece thickness while maintaining contact with the workpiece and hence generating forging pressure. For a range of thicknesses, a portion of the shoulders will always be in contact with the workpiece. The curved surface of the shoulder allows for a relatively large range of positions with respect to the workpiece. In contrast, the vertical position of a flat shoulder with respect to the workpiece is more restrictive. As the surface of the workpiece changes, the free-floating capability of the tool in the vertical direction will allow the tool to adjust. In summary, the fixed convex shoulders in conjunction with the free-floating motion allow the tool to self-adjust and align with the workpiece thereby eliminating the need for any actuating mechanisms.

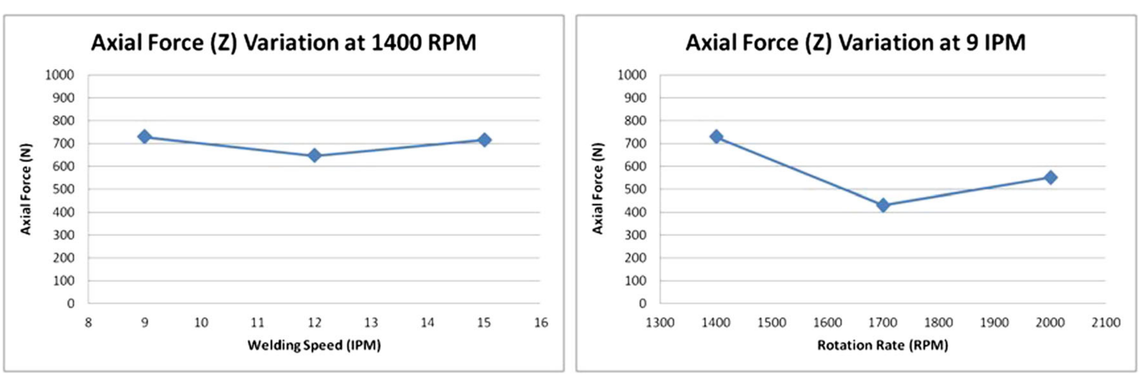

Fig. 10 Summarized axial force data collected for SAA-FSW tool development

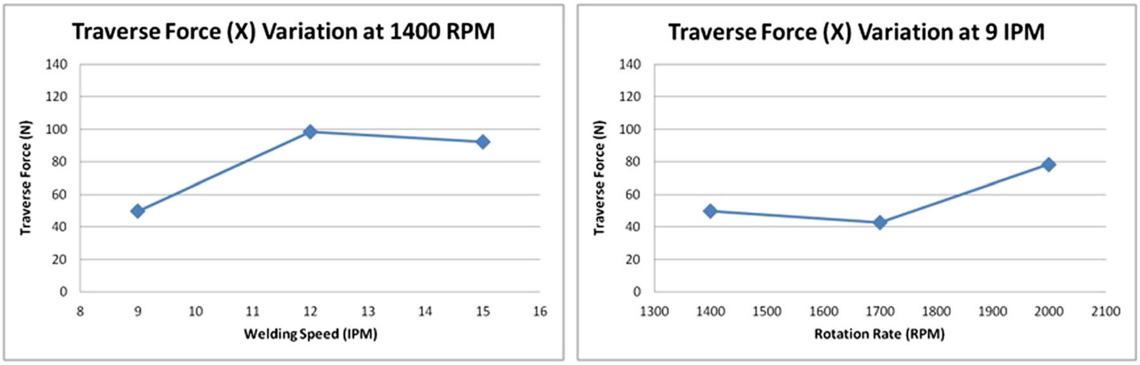

Fig. 11 Summarized traverse force data collected for SAA-FSW tool development

To add the SAA capability to our tool design, we placed a series of linear guide rails surrounding the circumference of the tool. These guide rails allowed the tool to float freely up and down while also allowing torque to be transmitted from the machine's spindle to the tool. The rails are positioned on two collars with the upper collar serving as a stationary base for the rails. The guide rails run through bushings that are pressed into the lower collar. The bushings and rails that run through them allow the lower collar, which is attached to the bobbin tool, to freely move in the vertical direction. The convex shoulders were already incorporated into the tool design shown in Figs. 4, 5, and 6. The completed SAA-FSW tool is shown in Fig. 14, while a cross-sectional drawing is shown in Fig. 15.

2.3 Experimental results of the SAA-FSW tool

Welding trials were conducted with the completed SAA-FSW tool. In particular, focus was given to the tool's ability to eliminate the axial force. The process parameters selected were 1500 RPM for the rotation rate and 9 IPM (228.6 mm/min) for the traverse speed. Once again, we used 1/8 in. (3.175 mm) thick aluminum 1100. Initially, the workpiece was oriented parallel with respect to the work table and orthogonal with respect to the welding tool. The summarized results are as follows:

- Average torque, 11 N-m (8 lb_f-ft)
- Average axial (vertical) Z force, 0 N (0 lb_f)
- Average traverse force, 100 N (22 lb_f)
- Average lateral (side) force, 300 N (67 lb_f)

The axial force was drastically reduced and averaged 0 N (0 lb_f) for the welds. As shown in Fig. 9, the axial force with the prior bobbin tool design, which did not have the SAA features, was averaging several hundred Newtons of force. With the added SAA features, the axial force was drastically reduced and averaged 0 N (0 lb_f). The axial force data collected for a typical weld is shown in Fig. 16. Notice that once the SAA-FSW tool had fully entered the workpiece, the axial force was eliminated. However, during the tool run-in period, a non-zero force was experienced. This transient response was characterized by vibration as evident in Fig. 16. But once fully entered into the workpiece, steady-state conditions emerged. Similar force patterns were observed for the other process forces.

To test the ability of the SAA-FSW to adapt to changing workpiece positions, we placed the workpiece on an inclined surface. The workpiece was 8-in. long with one end of it raised 1/16 in. (1.5875 mm) higher. The end where the tool entered was the lower end while the exiting end was elevated. For this trial, the tool rotation rate was 1400 RPM and the traverse speed was 9 IPM (228.6 mm/min).

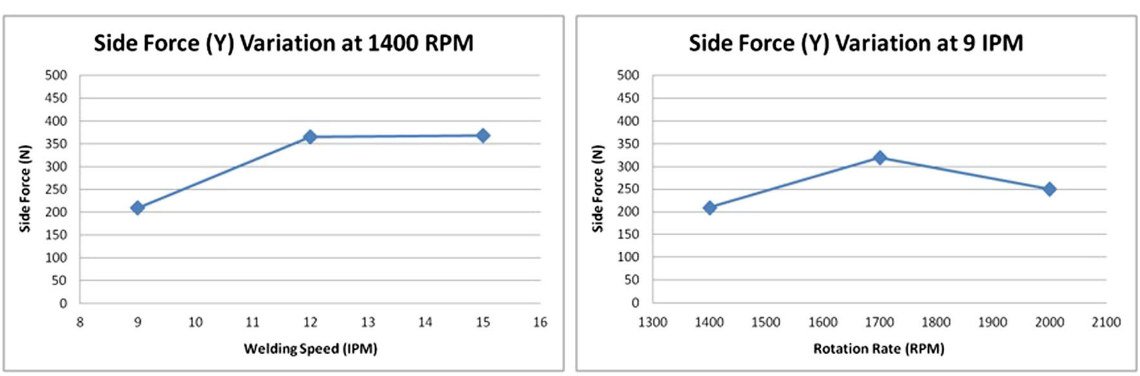

Fig. 12 Summarized lateral force data collected for SAA-FSW tool development

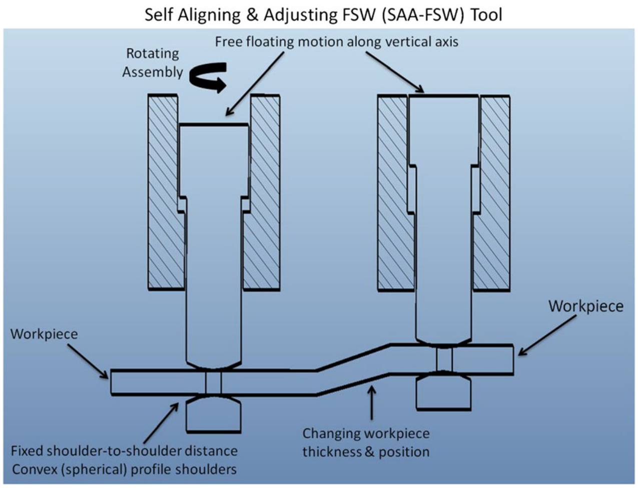

Fig. 13 Concept illustration of SAA-FSW tool

The resulting axial force when the workpiece was placed on the incline is shown in Fig. 17. Once again, tool vibration was encountered during the run-in of the tool but quickly dissipated once the tool was fully engaged. The axial force remained less than 200 N (45 lb_f) during the welding. The reason the force never achieved a value of 0 N was because the position of the workpiece relative to the tool was continually changing. Therefore, there was always a non-zero force being applied to the tool to adjust its position into alignment with the workpiece. Perhaps, this force was also the result of a slight binding between the guide rails and bushings. Regardless, the force was drastically reduced as compared to conventional FSW tooling and bobbin tools with no SAA features.

3 In-process monitoring of FSW via a magnetoelastic force rate-of-change sensor

3.1 Experimental setup

The developmental work for the in-process monitoring method was done at Austin Peay State University using a three-axis

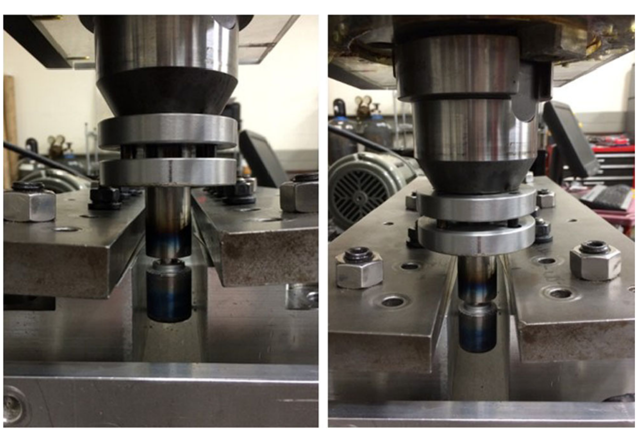

Fig. 14 SAA-FSW tool

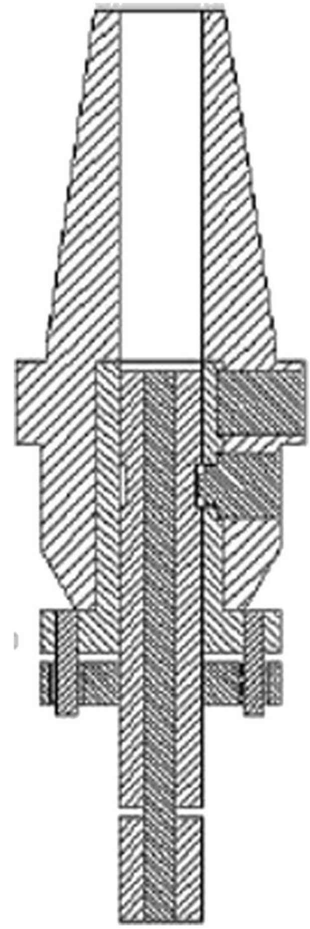

Fig. 15 Cross-sectional drawing of the SAA-FSW tool. All components shown rotate together

GMC milling machine with a 3-hp (2237 W) spindle motor. The worktable had a power feed in the direction of welding. For the welding trials, aluminum 6061 was butt welded together using a conventional FSW tool. The workpiece consisted of 2–8 in. (203.2 mm) long by 2 in. (50.8 mm) wide by 1/8 in. (3.175 mm) thick pieces.

To create voids in the weld seam, 1/16 in. (1.5875 mm) diameter holes by 1/16 in. (1.5875 mm) deep were drilled into the faying surface of each piece of aluminum. The first void was located 3 in. (76.2 mm) from the starting end of the workpiece, and the second void was 2 in. (50.8 mm) past the first void. These voids, when encountered by the tool, created

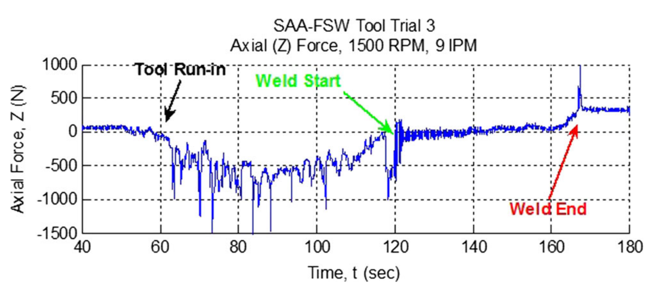

Fig. 16 Axial force with SAA-FSW tool

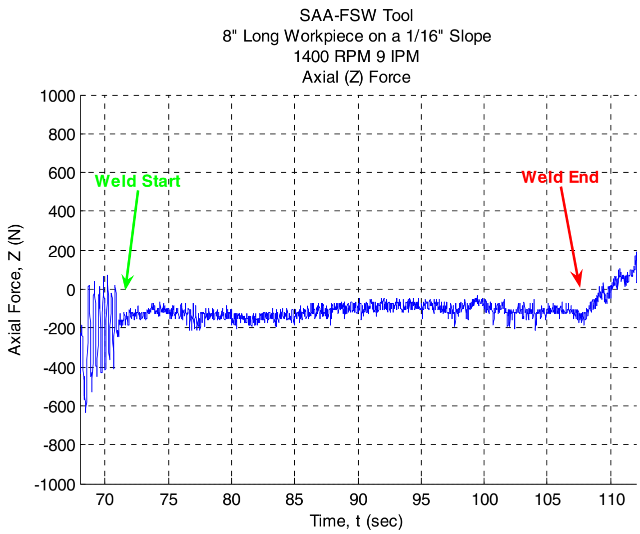

Fig. 17 Axial force with the workpiece on an incline

process disturbances for which we wanted to detect. Figure 17 shows the welding operation with the tool traversing along the weld seam and leaving a butt welded joint in its path. For each weld, the traverse speed of the tool was 2 IPM (50.8 mm/min) while the rotation rate was 1400 RPM.

To detect these voids, a coil of insulated copper wire was wrapped around a plastic spool that was placed around the FSW tool. The plastic spool was 3D printed and mounted such that it did not touch the rotating tool. The coil consisted of 500 turns of 26 American Wire Gauge (AWG) wire. The two ends of the wire were connected to a National Instruments USB-6008 data acquisition device. The hardware setup is shown in Fig. 18. The induced signal was recorded using LabVIEW Signal Express software.

Lastly, a hole was drilled in the topside of the FSW tool and two cylindrical-shaped magnets were placed inside. Each magnet was 1/4 in. (6.35 mm) in diameter by 1 in. (25.4 mm) long. The magnets were N52 grade neodymium and axially magnetized with a surface field strength of 7343 G. Once inserted the ferrous tool became magnetized.

The working principle behind this in-process monitoring approach is Faraday's law of induction. The law states that

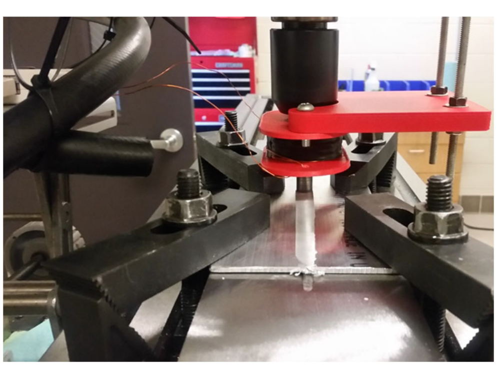

Fig. 18 Experimental setup for in-process monitoring

an electromotive force (emf), or more commonly referred to as voltage, is induced in a coil of wire when the magnetic flux acting through the coil changes with respect to time. The induced voltage is proportional to the number of turns in the wire and proportional to the rate-of-change of the magnetic flux. Thus, the more turns of wire in the coil and the greater the rate-of-change of the magnetic flux, the larger the induced voltage will be. For our experimental setup, the change in magnetic flux occurs when the tool bends and twists due to the process forces. When a void is present in the welding environment beneath the shoulder of the tool, the combined process forces (axial force, traverse force, lateral force, and torque) cause deflection of the tool which in turns changes the direction of the magnetic field acting through the center of the coil. This change in direction results in a change in magnetic flux which then induces a voltage.

A similar approach to process monitoring for machining (milling) operations has been reported prior [16]. The sharpness of the rotating end mill used for cutting was successfully monitored through the application of a magnetoelastic torque rate-of-change sensor. The rotating end mill was magnetized. When each flute cut into the workpiece, a change in torque was detected with the sensor. The signature pattern for the measured rate-of-change of torque changed as the end mill dulled. To the authors' knowledge, this presented work is the first reported use of a magnetoelastic force rate-of-change sensor to monitor FSW.

3.2 Experimental results of the in-process monitoring

With a sample size of about a dozen welds, each with two voids present, the in-process monitoring system was able to detect the voids 100 % of the time. The recorded voltage produces a pattern that characterizes each weld. The root mean square (RMS) of the induced voltage provided a very clear picture of significant changes in process forces. A typical sample of the induced RMS voltage is shown in Fig. 19. As noted above, many trial welds were made, but each one had very identical results to what is illustrated in Fig. 19.

The initial spike in voltage is due to the tool entering the workpiece and a dramatic increase in the process forces. The voids were encountered near the 160- and 230-s marks on the graph. At these points in time, a noticeable spike in induced voltage was detected. These voltage spikes indicate a change in the process forces in the welding environment and hence would identify to an operator that a flaw is likely present in the weld seam.

Further validity can be given to this in-process monitoring method by examining prior work by Longhurst et al. [17]. They were able to successfully detect FSW voids in the weld seam by monitoring the welding torque via strain gauges mounted to the tool and by monitoring the supply current to the spindle motor. Changes in the frequency content of the

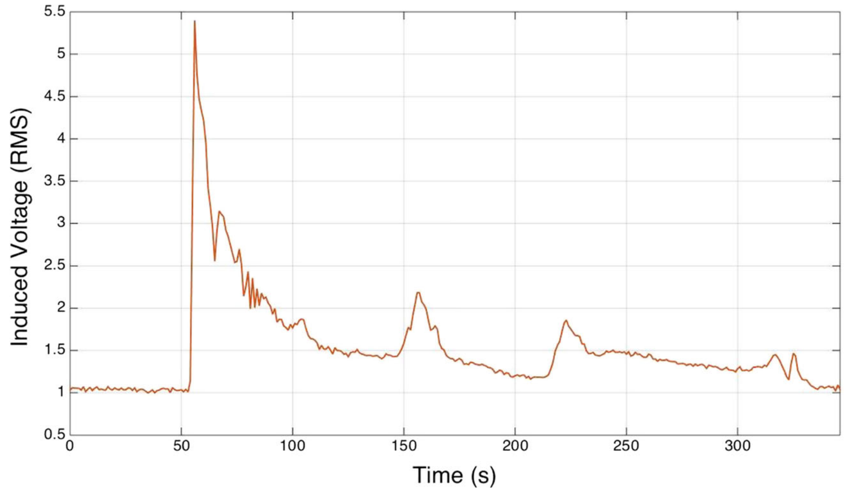

Fig. 19 Induced voltage during welding process. Results typical of all trials

collected torque and current measurements aligned well with the presence of voids in the weld seam. Our presented method of using a magnetoelastic force rate-of-change sensor produced similar results but with a much simpler setup and approach.

4 Conclusions

The presented technologies can support the development of portable FSW machines that could be used in space for manufacturing. The SAA-FSW drastically reduced, and almost eliminated, the axial force. In addition, the simplicity of the design does not require any actuators or control hardware. This purely mechanical design can help increase the reliability of a portable FSW machine system. With a goal of manufacturing in space, and knowing there will most likely be limited resources available in space, reliability of any machine is critical for mission success. In addition, the mechanical only design will help to keep the cost of a portable FSW machine low.

The results show that the presented SAA-FSW tool can successfully butt weld 1/8 in. (3.175 mm) thick aluminum 1100. The forces present during the welding were relatively low as compared to conventional FSW. With the SAA-FSW tool, a portable FSW machine could be designed. However, the design of the portable FSW machine will need to address the transient forces when the tool enters the workpiece as well as the larger lateral force. These forces are large enough to challenge the development of a handheld welder that is comparable to the portability of an existing arc welder.

The presented in-process monitoring using a magnetoelastic force rate-of-change sensor shows promise as an innovative method. Voids created by drilling 1/16 in. (1.5875 mm) diameter holes by 1/16 in. (1.5875 mm) deep into the faying surface could be sensed. Being able to detect welding flaws during the welding process greatly increases manufacturing efficiency. The simplicity of the magnetoelastic force rate-of-change sensor, coupled with the lack of sophisticated equipment, makes this in-process monitoring technique attractive for in-space manufacturing. Further research will need to focus on determining and enhancing the resolution capability of void detection.

References

1. Materials, Structures, Mechanical Systems, and Manufacturing Roadmap, Technology Area 12, NASA 2010. http:www.nasa.gov (accessed 2016)
2. Thomas W, Nicolas E, Needham J, et al. Friction stir butt welding. Patent 5,460,317, USA, 24 October 1995
3. Wikipedia. http://en.wikipedia.org/wiki/Friction_stir_welding (accessed 2013).
4. Longhurst WR, Strauss AM, Cook GE (2011) The identification of the key enablers for force control of robotic friction stir welding. Journal of Manufacturing Science and Engineering: AMSE 133(3): 31008–31019
5. Soron M. and Kalaykov I., A robot prototype for friction stir welding, Proceedings of the 2006 I.E. Conference on Robotics, Automation and Mechatronics, Bangkok, Thailand, 7–9 June 2006, pp. 1–5. New York: IEEE.
6. Smith C., Robotic friction stir welding using a standard industrial robot. Proceedings of the 2nd Friction Stir Welding International Symposium, Gothenburg June 27–29, 2000. Cambridge: The Welding Institute, 2000.
7. Cook G, Crawford R, Clark D, Strauss A (2004) Robotic friction stir welding, industrial. Robot 31(1):55–63
8. Crawford R, Cook G, Strauss A, Hartman D (2006) Modelling of friction stir welding for robotic implementation. Int J Model Identif Control 1(2):101–106
9. Sinclair P, Longhurst WR, Cox CD, Lammlein DH, Strauss AM, Cook GE (2010) Heated friction stir welding: an experimental and theoretical investigation into how preheating influences process forces. Mater Manuf Process 25(11):1283–1291
10. Fuller, C. B., Friction stir tooling: tool materials and design. In: Mishra, R. S., Mahoney, M. W. (Eds.) Friction stir welding and processing, chapter 2. Materials Park, OH: Editors: ASM International, 2007, pages 7–35.

11. Sued M, Pons D, Lavroff J, Wong E (2014) Design features for bobbin friction stir welding tools: development of a conceptual model linking the underlying physics to the production process. Mater Des 54:632–643
12. Colligan, K. J., O'Donnell, A. K., Shevock, J. W., Smitherman, M. T., Friction stir welding of thin aluminum using fixed gap bobbin tools. 9th International FSW Symposium, Huntsville Alabama, May 15–17, 2012.
13. Ding, R. J., Oelgoetz, P. A., Autoadjustable pin tool for friction stir welding. U.S. Patent 5893501, April 13, 1999.
14. Davé, V. R., Hartman, D. A., King, W. H., Cola, M. J., & Vaidya, R. U., Strategy for small-lot manufacturing. Los Alamos Science, Number 28, 2003.
15. Longhurst WR, Cox CD, Gibson BT, Cook GE, Strauss AM (2014) Applied torque control of friction stir welding using motor current as feedback. Proceedings of the Institution of Mechanical Engineers, Part B. Journal of Engineering Manufacturing 228(8): 947–958
16. Garshelis, I. J., Kari, R. J., Tollens, S. P. L., Cuseo, J. M., Monitoring cutting tool operation and condition with a magnetoelastic rate of change of torque sensor. Journal of Applied Physics, Volume 103, Issue 07E908, 2008.
17. Longhurst, W. R., Wilbur, I. C., Osborne, B. E., Gaither, B. W., Process monitoring of friction stir welding via the frequency of the spindle motor current. Proceedings of the Institution of Mechanical Engineers, Part B, Journal of Engineering Manufacturing, Accepted May 19, 2016, Available Online DOI: 10.1177/0954405416654089.