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Friction Stir Welding Development at NASA – Marshall Space Flight Center

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Abstract

This paper presents an overview of friction stir welding (FSW) process development and applications at Marshall Space Flight Center (MSFC). FSW process development started as a laboratory curiosity but soon found support from many users. The FSW process advanced very quickly and has found many applications both within and outside the aerospace industry. It is currently being adapted for joining key elements of the Space Shuttle External Tank for improved producibility and reliability. FSW process modeling is done to better understand and improve the process. Special tools have been developed to weld variable thickness materials including thin and thick materials. FSW is now being applied to higher temperature materials such as copper and to advanced materials such as metal matrix composites. FSW technology is being successfully transferred from MSFC laboratory to shop floors of many commercial companies.

Introduction

In 1994 friction stir welding (FSW) was a mere laboratory curiosity at Marshall Space Flight Center (MSFC). MSFC was very interested in developing an improved joining process for Space Shuttle elements. FSW looked attractive because it was capable of performing linear welds without melting the material, which is frequently the source of defects in welds. It did not require filler material or protective shielding gas/inert atmosphere and was capable of higher joint efficiency than fusion weld processes. Perhaps the most interesting aspect of the process was the prospect of welding without using an electric heat source, but using a mechanical pin-tool instead. Inquiries into this new weld process were directed to The Welding Institute (TWI), Cambridge, U.K., owners of FSW intellectual property rights. TWI was then collaborating in a group sponsored project entitled, "Development of the New Friction Stir Technique for Welding Aluminum". The purpose of this initial effort was to transform FSW from a laboratory curiosity to a viable metals joining process suitable for manufacturing hardware. MSFC joined this project and at the same time began its own FSW research and development effort to investigate possible aerospace applications for the FSW process. The work involved nearly all aspects of FSW development, including development of tooling to use FSW for welding components of the Space Shuttle, process modeling, scale up, and applications to advanced materials. This paper presents an overview of the FSW development activities at MSFC, including technology transfer.

Chronology of FSW development at MSFC

The MSFC Materials, Processes and Manufacturing Department started FSW development work with a Kearney and Trecker (K&T) 14-ton horizontal boring mill. Initial efforts focused on welding, mechanical property evaluation and metallurgical analysis for various aluminum alloys including the aluminum-lithium alloy 2195 used to fabricate the Space Shuttle Super Lightweight External Tank (SLWT). Superior FSW mechanical property data gathered on aluminum 2195 soon sparked intense interest in developing the new weld process for ET manufacture. Clearly, the FSW solid-state weld process produced welds of higher strength, and more reliably than the Variable Polarity Plasma Arc (VPPA) Welding Process currently used to fabricate the ET. However, the FSW process (shown schematically in Figure 1) needed modifications before it could be successfully applied to ET manufacturing. The one-piece pin-tool (Figure 1) could not be used to weld variable thicknesses, nor close out the characteristic keyhole left upon termination of a circumferential weld. For use in ET manufacturing, the welding of tapered thicknesses and the closing out of keyholes in circumferential welding would have to be implemented.

FSW process development began on a purely empirical basis. But process development without a theoretical understanding to focus attention on critical process features tends to go off in numerous directions, many of which are expensive blind alleys. In the development of the FSW process it was considered wise to include an effort to understand the fundamental physics of the process through modeling studies. Mathematical modeling was not considered an end in itself, but rather a heuristic tool used to understand the nature of the FSW process so as to be able to select parameters for particular applications or to redesign tooling for better performance on a rational basis.

Since the inception of the ET implementation effort, additional FSW applications have been identified within NASA programs. FSW has been identified as the baseline joining process for 2nd and 3rd Generation Vehicle cryogenic tanks. MSFC's FSW development has broadened to include other advanced materials including aluminum matrix composites and the newly developed GRCop-84 copper alloy developed at Glenn Research Center, Cleveland, Ohio. The details follow.

Development of Tooling for FSW

When the first FSW welds were made using the K&T mill, it was quickly realized that of "z-axis" forces resulting from the tool pushing on the work piece, (Figure 1) were significant (5000-8000 pounds). Deflections between 0.027- and 0.030-inches were measured as a result of these forces. The K&T mill was rigid enough for use as a machining center, for which it had been designed, but not necessarily for the FSW process. Deflection had to be understood and accommodated in order to make the FSW work properly. Deflection issues instigated study of one of the critical process parameters of FSW, – force. Forces exerted upon the K&T during welding were measured with precision equipment. The forces became integral to parametric calculations used for all subsequent welding. Once the deflection issues were resolved, a mechanical property database was generated for 2219, 2195 and 7075 aluminum alloys. These mechanical properties represent some of the first such data obtained in this country. Hundreds of welds were made on similar and dissimilar material combinations of these alloys.

Pin tool design experimentation commenced around 1996. One-piece pin-tools were typical at this time, but it became clear that a pin tool with an adjustable pin length was needed. A NASA-Boeing design resulted in U.S. Patent =6,138,895 entitled, "Manually Adjustable Pin-tool for Friction Stir Welding" (Reference 1). The FSW pin has to be optimally positioned with respect to the backside of the weld test plate. The manually adjustable pin-tool became invaluable when welding test plates varying in thickness by several thousandths of an inch.

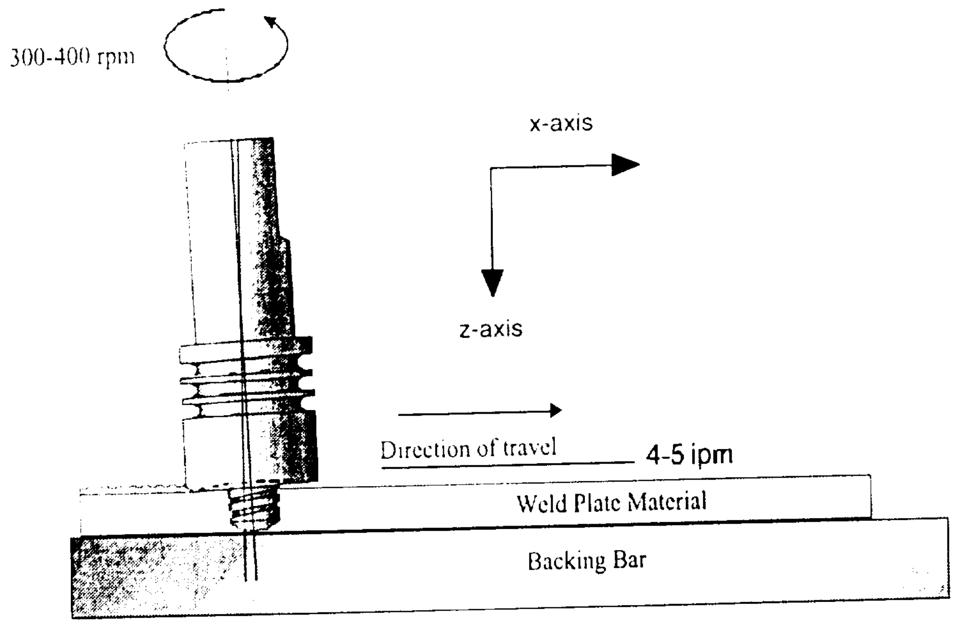

Figure 1. Schematic of FSW Process Using a Single Piece Pin-Tool.

The next major advancement at MSFC was a novel pin-tool design in which the pin could extend and retract automatically during a weld. The Auto-Adjustable Pin Tool for Friction Stir Welding (better known as the Retractable Pin Tool, or, RPT, Figure 2) was successfully demonstrated at MSFC in 1996. The RPT became the first U.S. Patent (#5,893,507, Reference 2) awarded to

NASA in the interest of advancing the FSW technology. (Additional improvements have been submitted in the form of U.S. Patents (Reference 3) and will be addressed in the Technology Transfer section of this paper). The RPT is a critical piece of hardware required for the implementation of FSW into ET manufacturing. It allows weld joints which taper from one thickness to another to be welded. It also closes out the keyhole upon weld termination in circumferential welds planned for future FSW implementation.

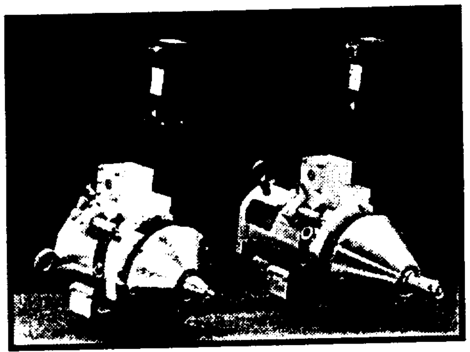

Figure 2: Retractable Pin-Tools for Friction Stir Welding

FSW development continued at MSFC focusing on ET implementation. In support of this effort, two existing weld tools located in MSFC's Productivity Enhancement Complex have been modified for FSW. The Vertical Weld Tool (VWT, Figure 3) was converted to FSW process in 1998. It supported a Special Developmental Study (SDS) conducted jointly with Lockheed-Martin to develop a mechanical property database showing FSW as a viable welding process suitable for man-rated hardware.

Fifteen-foot longitudinal welds were completed using the VWT. The ET development effort continued the following year in 1999-2000 when a second SDS was initiated. The Circumferential Weld Tool (CWT, Figure 4) was converted to FSW for this study. It was used to demonstrate the FSW process for circumferential weld joint applications. Results of these studies have culminated in the current implementation of FSW into ET production at the Michoud Assembly Facility (MAF) located in New Orleans, Louisiana.

Figure 3. Vertical Weld Tool.

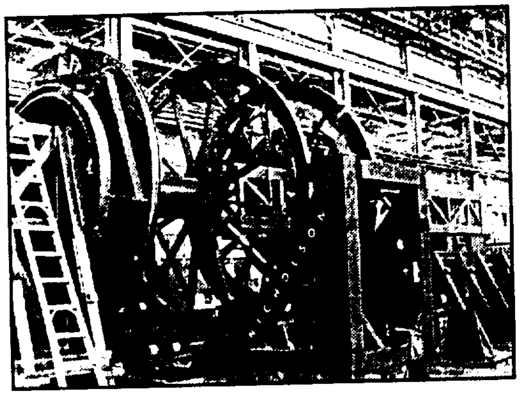

Figure 4. Circumferential Weld Tool.

Advanced Development of FSW

MSFC is developing the FSW process for several projects associated with the major thrust areas at the center. Each project has a unique set of requirements that necessitate expanding the process capabilities in order to be successful. A brief description and status of ongoing friction stir development projects follows.

Space Shuttle External Tank

The External Tank (ET) of the Space Transportation System, an extremely large welded structure, is made of 2195 aluminum-lithium and 2219 aluminum alloys joined by an automatic plasma arc welding process (Figure 5). The weld joints on the external tank taper in thickness through a range of values from 0.125 inch to 1.00 inch. The 2195 alloy is more susceptible to hot cracking during fusion welding than the 2219 alloy. Consequently 2195 alloy needs to be repaired more often and suffers from reduced weld properties associated with repairs. In 1997 (Reference 4) MSFC began investigating FSW as an alternative to fusion welding for 2195 alloy with a view to improving weld producibility and properties.

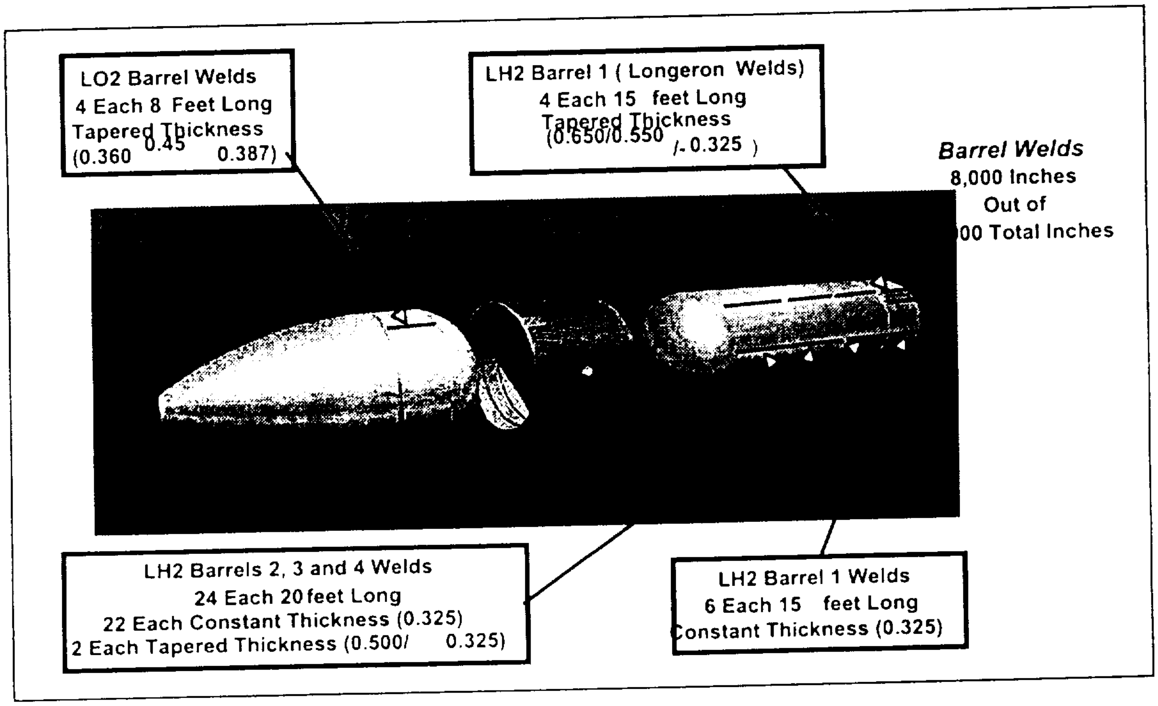

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Figure 5: External Tank Component Breakout with Planned Friction Stir Welding for Barrel Application.

The benefits of FSW on 2195 alloy were immediately evident. In addition to eliminating hot cracking problems, friction stir welds had higher joint efficiency (70% of parent metal), reduced shrinkage, and better ductility than fusion welds. Implementation of FSW on the ET would begin using the simplest weld joint configurations on the tank, - the longitudinal barrel welds. The barrel was welded on the VWT (Figure 3) at MSFC, which had been converted from a plasma welding tool to a FSW tool. In 1998, a 28 foot full scale diameter hydrogen barrel was welded at MSFC, demonstrating tapered welding and bimetallic weld joints (Figure 6). The tapered welds were made both single-sided using the retractable pin tool and dual-sided (an overlapping partial penetration weld made from each side, Reference 5). Unlike fusion welding, the weld parameters developed on the test panels required no modification when scaling up to the 15 ft. full scale barrel length. By first demonstrating the process at MSFC, the tooling specification, process parameter development, and non-destructive inspection development requirements were defined early in the implementation program without impacting current barrel production. FSW longitudinal barrel weld tools are currently scheduled to go on-line in the year 2002 at the Michoud Assembly Facility.

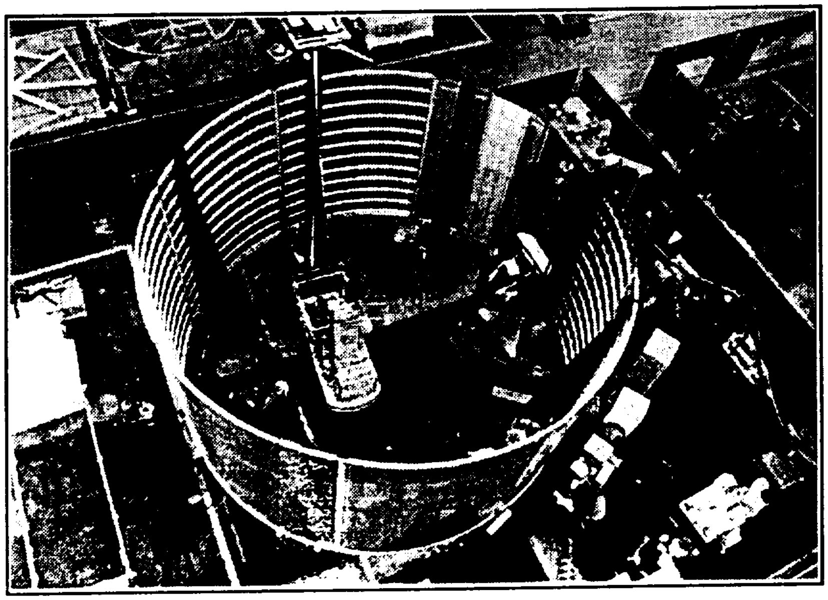

Figure 6: Full Scale Friction Stir Welded Barrel Demonstration.

Space Shuttle: Solid Rocket Booster

2219 aluminum structures attached to the forward end of the Space Shuttle Solid Rocket Booster (SRB) motors house parachutes, electronics, and separation hardware. These structures are intended to be fully reusable, so as to limit the quantity of flight hardware required in the Shuttle inventory. Impact damage from descent into rough seas has, over time, cracked the housings of several SRB forward skirts, making them unusable. A FSW repair scenario where a patch is welded in place of the damaged area has been investigated. For this application a pin tool capable of single-sided welding of thicknesses tapering from 0.500 inch up to 1.5 inch thick was developed.

Space Launch Initiative: GRCop-84 Material Development

Copper alloys are employed to promote heat transfer and prevent temperature buildup in combustion chamber or nozzle ramp applications (Reference 6). A copper alloy designated GRCop-84 developed by the Glenn Research Center, Cleveland, Ohio, exhibits improved life and performance benefits over other alloys. Copper alloy components are economically produced by rolling and forming sheet or plate and friction stir welding the seams. For this application FSW process development for linear welds on thin (0.040 inch) copper alloy sheet and thick copper alloy cylinders of 8.0 feet diameter is under way. FSW of copper alloys is carried out at substantially higher temperatures than is the case for aluminum alloys. Preliminary efforts have made use of tooling designs and modifications to provide inert gas shielding during welding and water cooling of the anvil and pin tool to control heat buildup. Figure 7 shows the friction stir weld setup and a representative weld in 0.250 inch thick GRCop-84 plate.

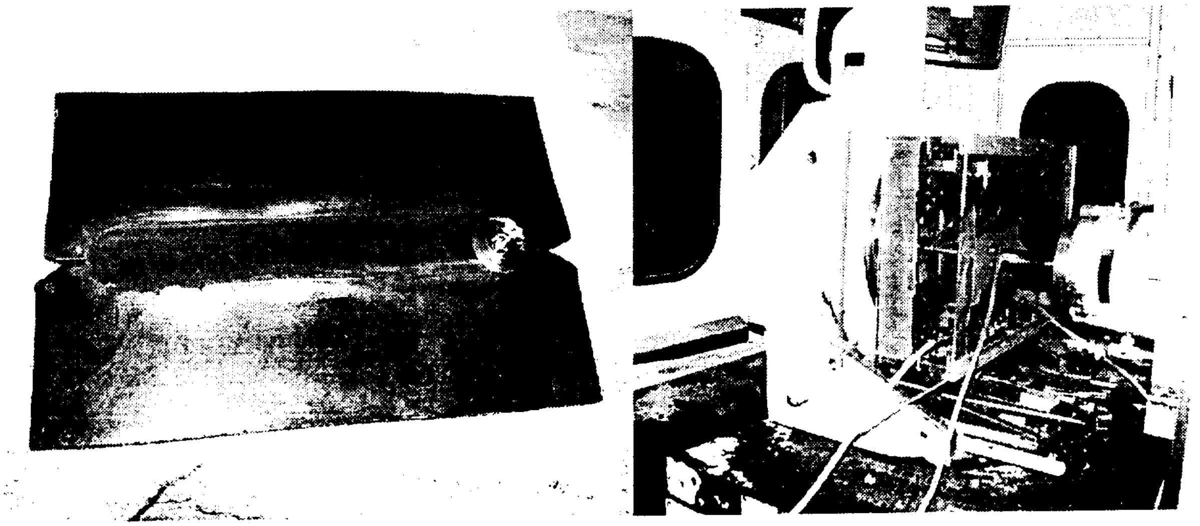

Figure 7: Friction Stir Weld Set up for GRCop-84 welding (right) and resultant weld panel.

Space Launch Initiative: Metallic Cryogenic Tank

Metallic cryogenic tanks are considered the backup solution for the Space Launch Initiative (SLI) program in the event that the baselined composite technology is not ready. Metallic tank manufacturing is relatively mature when compared to composites. Lessons learned from the Space Shuttle SLWT Program apply directly. The SLWT design was driven by the fusion weld properties, which were driven by repair welding. Solid-state FSW joining techniques have demonstrated higher joint efficiencies than fusion joining techniques for aluminum-lithium alloys. Higher efficiencies reduce the weight of a metallic cryotank. FSW is also less likely to induce weld defects requiring repair than fusion welding. Linear FSW of square butt joints has been demonstrated for SLWT and is considered low risk for SLI. FSW of contoured joints, lap fillet joints, and circular joints is needed and is to be developed.

It is also possible that the baselined composite SLI cryotanks will incorporate thin metal liners to guard against leakage. Fabrication of such liners would constitute a likely application of FSW.

Modeling of FSW

As mentioned before, FSW process modeling was attempted to develop a better theoretical understanding of the process so as to be able to select parameters for particular applications or to redesign tooling for better performance on a rational basis. And when problems arise, as they always do, the understanding obtained through process modeling is there to help diagnose and solve problems expediently.

FSW process modeling work began at MSFC in 1995 with an attempt to understand the pattern of metal flow around the FSW pin-tool. By 2000 a flow model that explained the basic features of FSW metal flow was being presented (ref. 7, 8, 9, 10) to the FSW research community. The model is a modified slip-line field model, more akin to a metal cutting model than to earlier extrusion or molten fluid film flow models.

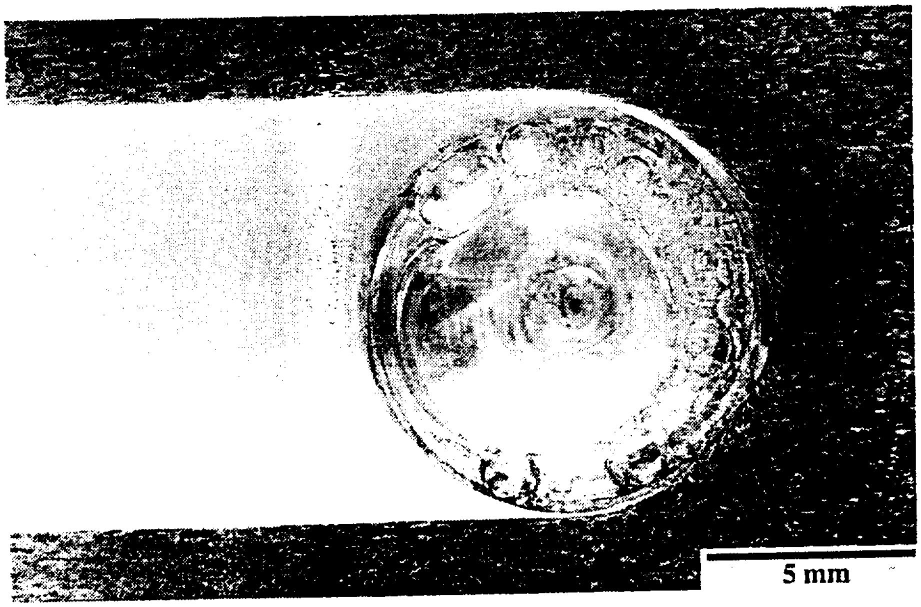

Figure 8. A midsection of a FS weld in 2219-T87 aluminum. Mounting compound with internal bubbles occupies the place of the pin-tool. Notice the sharply defined shear boundary, the greater thickness of the metal plug rotating with the tool on the retreating (top) side of the tool, and the so-called "tool marks" present not just on the work piece surface, but deep inside the work piece.

The basic model has a cylindrical plug of weld metal sticking to the tool and rotating against the surrounding metal over a cylindrical shearing surface of discontinuity. See Figure 8. The weld metal is engulfed by the plug, carried around to the rear of the plug, and abandoned by the plug to the tool wake. A strain increment of approximately $R\omega/V$, typically on the order of 100, is incurred when metal is engulfed or abandoned. R is the radius of the plug; ω, its angular velocity; and V, the weld speed. A relatively slow ring vortex flow surrounding the tool is invoked to explain radial and up-and-down motions in the vicinity of the tool. The tool threads drive the ring vortex flow.

How does the FSW process work? Truly clean metal welds by simple contact. The high strain increment draws out the faying surface so as to juxtapose clean, freshly exposed metal over the order of 99% of the expanded faying surface. When this happens, as the weld seam encounters the rotating plug, the weld seam disappears.

Preliminary models that compute tool loading (torque, plunge force, longitudinal force, lateral force) have been constructed, and studies are underway to assess and develop these models. It is desirable to minimize tool forces to reduce tool breakage and cut the expense of heavy tooling structures. An understanding of tool forces is also needed for the sake of instituting weld control through force sensor feedback.

FSW defects and the conditions under which they are produced is being modeled. For example wormholes open up in welds when the heat-softened metal in the vicinity of the tool extrudes out of the weld cavity. Temperature gradients (via weld parameters) and tool shoulder and anvil contact geometries can control extrusion.

Finer structural details of FS welds are also being modeled. For example the so-called "tool marks" in the wake of the weld (See Figure 8) may be caused by tool asymmetry. (The exit channel for metal flow within the tool threads introduces an asymmetry in the plastic flow down the tool.)

Any aspect of the FSW process that can profit from better understanding is subject to modeling efforts. The emphasis is, of course, on generating useful *concepts*, not on mere computation.

Advanced Development

FSW modeling is now sufficiently advanced so as to be able to lend some support to advanced development. One case in point is root penetration. If a gap exists between the anvil and the bottom of the shear zone, the gap metal may be severely twisted, but lacks the strength of the metal passed through the shear zone. By analogy with fusion welding processes, this is called "lack of penetration," even when extensive shearing deformation in the gap makes it difficult to detect unwelded areas on the residue of the seam. The shear zone extends all the way to the anvil if the torque required to rotate the tool is less for this configuration than for the "partial penetration" configuration. Conditions emerge out of the model for "full penetration."

Furthermore the model suggests a more precise indication of "full penetration" than that obtainable by conventional Non-Destructive Evaluation (NDE) methods used for fusion welds: Look for the kind of structure shown in Figure 8 on the root side of the weld to assess "full penetration" unambiguously. With unambiguous assessment of "full penetration" comes a higher weld strength with reduced variation. (FSW, being more akin to a machining than to a fusion operation ought to exhibit less variation in strength than a fusion weld.)

FSW of Metal Matrix Composites (MMCs)

MMCs are a special class of materials that are of interest to the propulsion community because of potential weight and cost savings resulting from their use in propulsion systems. MMCs are attractive due to their increased specific strength and stiffness, low thermal expansion coefficient, better thermal and electrical conductivity than polymer or ceramic matrix composites, and they derive their ductility from the metal matrix. Their affordability stems from being able to make complex parts by low cost castings. However, as attractive as their properties are, the non-metallic reinforcements in MMCs pose challenges in joining them using conventional methods developed for monolithic alloys. As a result FSW technology is being investigated for MMCs under an internally funded research and development program.

FSW of Al 6092/17.5% SiC/T-6 MMCs:

Al 6092/17.5 SiC/T-6 was selected as parent metal for the first phase of the program. FSW tools were fabricated from H-13 tool steel heat treated to 53-55 HRC, and H-13 tool steel coated with B4C coating with surface hardness of 93-95 HRC. B4C coating was chosen for its outstanding wear resistance, superior lubricity, good corrosion resistance, and low cost.

The FSW crown side surface had a coarse appearance. The B4C coating eliminated the surface roughness while it lasted, but it wore off in a few inches. The SiC particles at the edge of the HAZ were broken up by the pin-tool and became smaller toward the center of the HAZ. The SiC particle volume concentration was reduced at the edge of the HAZ. Joint efficiencies of 61-72% as-welded and 92-100% heat-treated were obtained.

FSW of Functionally Graded Al-MMC to Al-Li 2195:

Functionally graded (FG) Al-MMCs were welded to 2195 alloy in the second phase of the program. The bulk contained about 50% by volume of SiC reinforcement. Welding edges contained 5% to 27% by volume of Al_2O_3 Saffil paper MMC. Each FG plate was 4"x12"x 0.25" thick. Successful welds were made. Further evaluation will include welding edges of 5% to 30% Saffil, and 40% and 55% SiC with bulk composition of 40% SiC.

FSW Technology Transfer

Technological innovation developed at MSFC is disseminated to the private sector through the licensing of NASA intellectual property rights and through cooperative R&D efforts with private sector companies. The vehicle through which private sector companies come to MSFC is the Space Act Agreement (SAA) and administered by the Technology Transfer Office. This agreement allows companies to utilize MSFC engineering expertise and FSW facilities to resolve welding issues. Several SAA's pertaining to FSW have been completed over the past several years:

- MSFC engineers successfully demonstrated FSW closeout welding of aluminum "hoops" for a major supplier of wheel rims to the automotive and trucking industries. The "hoops" were to be formed into wheel rims at the company's wheel rim plant.

- MSFC FSW facilities were used by an aerospace company to establish FSW parameters for an aluminum alloy under consideration by the air frame industry.

- MSFC engineers used FSW to join one-inch thick armor plate aluminum for a Department of Defense contractor. Results of ballistic tests at Aberdeen Proving Grounds were beyond expectations and contributed favorably to the decision to use FSW in the fabrication of the new Advanced Amphibious Vehicle, currently in production for the U.S. Marines.

Two new SAA's are in the approval process:

- MSFC has been requested to assist in developing sounding rocket and launch vehicle technology. This effort entails development of FSW parameters for rocket thrust chamber material.

- MSFC has been requested to use FSW to fabricate a large-scale prototype of a tank to be used to transport compressed gas aboard ships.

Two U.S. companies have licensed the RPT, U.S. Patent #5,893,507 (Reference 2), developed at MSFC for commercialization.

FSW technical innovation has been made available to the marketplace through other patents (References 1 and 3). New patents are in process:

- Precision Control System for the Friction Stir Welding Retractable Pin Tool (provisional patent)

- Orbital Friction Stir Weld System (provisional patent)

And the FSW process has inspired a new solid state welding concept that separates the heating and stirring elements and eliminates the need for a backing anvil. The new process is still in the conceptual stage. It is anticipated that the separation of heating and stirring functions will result in a more flexible welding process.

Summary

MSFC began to develop the FSW process with an eye to Space Shuttle External Tank production in 1994, only a few years after The Welding Institute's 1991 FSW patent. By 1999 MSFC engineers had patented the retractable pin tool that enabled the application of FSW to fabrication of the External Tank. Full scale tools have been developed for the longitudinal and circumferential welds used to fabricate the External Tank. Weld modeling studies have supplied an understanding of the process that is beginning to yield fruit in improved technology. Extension of FSW capability to new materials, e.g. copper alloys and metal matrix composites, is under way. New NASA programs, e.g. Space Launch Initiative, will incorporate FSW. An active Technology Transfer program is in place to transfer the benefits of FSW development at MSFC to the commercial sector.

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List Of Acronyms

CWT	Circumferential Weld Tool
ET	External Tank
FSW	Friction Stir Welding
MMC	Metal Matrix Composite
MSFC	Marshall Space Flight Center
NDE	Non-Destructive Evaluation
RPT	Retractable Pin Tool
SDS	Special Developmental Study
SAA	Space Act Agreement
SLI	Space Launch Initiative
SLWT	Super Light Weight Tank
TWI	The Welding Institute
VPPA	Variable Polarity Plasma Arc
VWT	Vertical Weld Tool