

A Decade of Friction Stir Welding R&D
At NASA's
Marshall Space Flight Center
And
a Glance into the Future
by

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Welding at NASA's Marshall Space Flight Center (MSFC), Huntsville, Alabama, has taken a new direction through the last 10 years. Fusion welding processes, namely variable polarity plasma arc (VPPA) and tungsten inert gas (TIG) were once the corner stone of welding development in the Space Flight Center's welding laboratories, located in the part of MSFC know as National Center for Advanced Manufacturing (NCAM). Developed specifically to support the Shuttle Program's External Tank and later International Space Station manufacturing programs, VPPA was viewed as the paragon of welding processes for joining aluminum alloys. Much has changed since 1994, however, when NASA's Jeff Ding brought the FSW process to the NASA agency. Although, at that time, FSW was little more than a "lab curiosity", NASA researchers started investigating where the FSW process would best fit NASA manufacturing programs. A laboratory FSW system was procured and the first welds were made in fall of 1995. The small initial investment NASA made into the first FSW system has certainly paid off for the NASA agency in terms of cost savings, hardware quality and notoriety. FSW is now a part of Shuttle External Tank (ET) production and the preferred weld process for the manufacturing of components for the new Crew Launch Vehicle (CLV) and Heavy Lift Launch Vehicle (HLLV) that will take this country back to the moon. It is one of the solid state welding processes being considered for on-orbit space welding and repair, and is of considerable interest for Department of Defense (DoD) manufacturing programs. MSFC involvement in these and other programs makes NASA a driving force in this country's development of FSW and other solid state welding technologies. Now, a decade later, almost the entire on-going welding R&D at MSFC now focuses on FSW and other more advanced solid state welding processes.

EARLY FSW DEVELOPMENT

FSW development at MSFC began using a Kearney and Trecker 200 5-axis CNC horizontal boring mill. The 14 ton, 25 horse power machining center was totally dedicated to FSW process development at MSFC. Traditional FSW, originally conceived at The Welding Institute (TWI), Cambridge, U.K., was first performed using a single piece pin tool comprised of a shoulder and smaller pin. The rotating pin tool, with a pin length less than the weld depth required, plunges into a weld joint of two workpieces until the tool shoulder is in contact with the surface where it frictionally heats the

workpieces. The rotating pin within the workpiece "stirs" the metal and produces a plasticized plug region around the pin. As the rotating pintool is moved in the direction of welding the leading face of the pin, assisted by a special pin profile, crushes and forces plasticized material to the back of the pin while applying a substantial mechanical forging force which consolidates the weld metal. This process produces a high strength, high quality weld as compared to a weld made with a fusion weld process. Magnified metallurgical examination will reveal a fine, dynamically recrystallized grain structure instead of the large dendritic grain structure typical of fusion welds.

Welding metals in the solid state temperature range (also referred to as the solid phase or plastic state) is a significant advancement for man-rated hardware manufacturing. Welding metals without melting precludes the risk of traditional weld defects found in fusion welds such as liquation cracking, solidification cracking, oxide formation, and further minimizes the potential of other undesirable weld anomalies such as thermal distortion and high residual stresses. The FSW process is very forgiving. Keeping materials in the solid-phase during FSW results in greater retention of metallurgical properties in the weld metal, thus, in many cases, enabling mechanical and fatigue properties near to those of the parent metal. In addition to the superior mechanical properties realized from the weld process, the overall cost of using the process is significantly lower than fusion weld processes. There are no consumables required for the process and the careful removal of oxide from the joint area immediately prior to welding is unnecessary. The FSW machine is ideally suited to automation and integration with other machine tool operations and equipment maintenance is minimal. In addition, extensive operator training is not necessary.

Early weld trials at MSFC were conducted using various aluminum alloys (2219, 2195, 7075, 5XXX and 6XXX series). Development expanded to include metal matrix composites and high melting temperature alloys including steel, narloy-z, GRCop-84 and titanium alloys. A tremendous amount of data collected during the early development of FSW demonstrated the high degree of process repeatability. The FSW process requires the control of only three process variables; shoulder plunge depth, tool rotational speed and welding travel speed. Once optimized, the computer controlled process variables are highly repeatable, thus, resulting in the same quality of weld time and time again. FSW allows the removal of the human element (the welder) from the process. This minimizes risk of weld defects. These process attributes, along with expected cost savings influenced the NASA agency's decision to begin studying the feasibility of implementing FSW into Shuttle External Tank production.

IMPLEMENTATION INTO THE SPACE SHUTTLE EXTERNAL TANK MANUFACTURING PROGRAM

The FSW implementation process into the ET manufacturing program began in 1998 by first demonstrating the welding process on simulated ET hydrogen barrel welds. The FSW weld demonstration was completed through a Special Developmental Study (SDS) between the ET Project Office and the prime contractor, Lockheed-Martin. NASA and Lockheed-Martin engineers fabricated a 27.5 foot diameter simulated hydrogen tank

barrel section comprised of 6 barrel panels measuring 15 feet tall. Marshalls Vertical Weld Tool (VWT) (FIGURE 1) was used for the welding. The test article included 15 foot constant thickness weld joints as well as weld joints tapering in thickness from .320" to .650". The tapered welds demonstrated, for the first time, the use of a FSW retractable pin tool for manufacturing purposes. Two subsequent SDS's were completed between 1999 and 2001 which further characterized the FSW process for ET welding. NASA's Circumferential Weld Tool (CWT) (FIG 2) was modified to demonstrate circumferential welding and fixturing techniques. FSW was implemented into production in 2001. FIG 3 shows the two FSW production tools located at the Michoud Assembly Facility, New Orleans, LA where the Shuttle External Tank is manufactured. Eight longitudinal weld joints on the liquid hydrogen barrel and four longitudinal welds on the liquid oxygen barrel are welded using FSW. There is approximately one-half mile of weldments on each ET. Approximately 700 feet is done using FSW with VPPA welding used for the remainder of the weldments.

Fabrication of man-rated hardware for NASA's manned space programs requires manufacturing processes with a high degree of reliability and repeatability. Qualifying a welding process for manufacturing, for example, requires precise statistical evaluation of weld mechanical property data generated using optimal welding parameters for a given material, weld joint design and thickness. Once optimal weld parameters are established, they are used to generate a large population of weld test samples which are used for subsequent mechanical testing. The test data is used to evaluate weld strength and quality and assists in defining critical flaw size and margins of safety. Statistically speaking, the fracture and structural analysis of the weld mechanical test data results require a 95% confidence level that 90% of the weld strength values fall within structural design criteria. This statistical evaluation process, which NASA refers to as the "A Allowables Program", establishes margins of safety required to safely support and protect human life in space. The A Allowables Program was put into place soon after the ET manufacturing program began. At this time, VPPA was used as the primary weld process, and the margins of safety for the ET were partly determined using the standard deviation of VPPA weld test data. Today, the ET has a greater margin of safety using the FSW process because the standard deviation of test data is more closely distributed. The FSW process has favorably affected the safety factor of welded hardware.

CONTINUED FSW DEVELOPMENT

FSW development efforts continue at MSFC in support of the Shuttle and other programs. The self-reacting pin tool for friction stir welding (SR-FSW) is one of the latest advancements in FSW technology (FIG 4). NASA is focusing on the development of SR-FSW for circumferential welds in ET and the CLV upper stage hardware. The SR-FSW pin tool has two shoulders. One is positioned on the top surface of the weld piece and the other on the bottom side. A threaded pin, captured by each shoulder, protrudes through the material thickness. During a weld, the two shoulders are tightened against the top and bottom sides of the weldpiece, thus, "pinching" it while applying required forging loads. The dual shouldered/pin assembly rotates as a single unit while traversing the weld joint. The primary advantage in using the SR-FSW pin tool (instead of the

traditional single piece pin tool) is that it removes the requirement for expensive tooling which is needed to react the mechanical forging forces generated during the FSW process. The SR-FSW could not be employed, however, without new NASA design features incorporated into the shoulders. The "scroll shoulder" and "tapered scrolled shoulder" are the most important features developed at MSFC which enables the SR-FSW to operate perpendicular to the surface instead of a slight angle as required of the single piece pin tool. The SR-FSW has been used successfully to weld 27.5 foot diameter ring test sections located between barrel sections in the Shuttle ET. The Horizontal Weld Tool (HWT) (FIG 5) was used for the demonstration.

NEW NON-DESTRUCTIVE TEST (NDT) TECHNIQUES

NDT engineers at MSFC have played a significant role in developing new NDT techniques required for FSW implementation into the Shuttle Program. Conventional NDT techniques used for fusion welds, such as film radiography, dye penetrant, and ultrasonics are not adequate processes for the FSW inspection of man-rated hardware. NASA engineers recognized deficiencies in these processes and assisted in the development of newer inspection technologies including eddy current arrays, digital x-ray and phased array ultrasonics. These advancements in NDT have enabled the effective life cycle management of structures and pressure vessels incorporating FSW joining techniques. Phased Array ultrasound uses multi-element piezoelectric and composite transducer technology with sophisticated software timing routines to generate tightly controlled elastic waves in materials being tested. The resulting transmitted and received signals produce much higher resolution and provide much more detection sensitivity with lower noise, than with conventional transducers. For the Space Shuttle's External Tank, an RD Tech Tomoview with 128 element transducers are used to detect possible critical embedded and near-surface flaws such as lack of adequate forging (similar to lack of fusion in conventional welds), lack of penetration (LOP, considered embedded when root side is in compression and undetectable by penetrant methods), wormholes, surface galling, tears and residual oxides. The advancing fields of flexible circuit board and microstrips have enabled the use of multi-element eddy current sensors, which have also improved the resolution, detection and coverage of metallic material, near-surface defects and allowed for the more accurate measurements of electrical characteristics. Multi-element eddy current has allowed for the replacement of fluorescent dye penetrant in many FSW applications for the detection of surface galling, LOP, and tears. For FSW technology, many of the flaws are planar and do not have much volume, but film radiography is still utilized for wormholes and larger, thru-thickness, lack of forging flaws. NASA has begun to incorporate the use of digital x-rays using fiber optic coupled scintillator detectors and flexible phosphor plates with conventional x-ray tubes. As the resolution and detectability of such techniques increase in the future the more they will be incorporated as an effective complimentary technique to ultrasonics. The baseline inspections will be phased array ultrasonics incorporating sophisticated TOFD techniques for the detection of embedded flaws and eddy current arrays for the detection of near-surface and surface flaws.

MODELING THE FSW PROCESS

In parallel with implementing this process into the fabrication of launch vehicles, NASA has also implemented mathematical modeling efforts to better understand the physics of the metal flow in the FSW process. During a FSW weld, the pin portion of the FSW pin tool rotates and "stirs" inside the weld point as the shoulder rotates on the surface generating frictional heat. As the pin rotates it forces the plastic material to move, or, flow in the vicinity of the pin. The path that the material flows is critical to the quality of the weld. Unfortunately, the understanding of the material flow path is very difficult because it cannot be seen realtime during the weld. However, by using analytical "tools" based upon the principles of mathematics and physics, investigators can create an interactive weld model for the computer. Heat data, pin tool geometry, travel rate data, etc., can be entered into the model and the resulting computer generated weld can be evaluated to determine if proper material flow paths evolved during the "weld". Researchers can use the weld model to look, intuitively, inside the weld without physically doing a weld. They can predict with greater accuracy, the FSW process parameters that will produce quality welds and gain an understanding of the material flow paths. The weld modeling process saves significant development costs because it reduces costly trial and error approaches to obtain quality welds.

GOING TO THE MOON

On January 4, 2004, the Vision for Space Exploration was released giving the directive to NASA to pursue human exploration to the Moon and beyond. The current schedule calls for a 2010 launch of a test vehicle. This short preparation time presents a tremendous challenge to the Marshall Space Flight Center engineers as they are responsible for the overall design and manufacture of the new lunar space vehicles. Although the design is not yet complete, the approach is to launch two vehicles called the Crew Launch Vehicle (CLV) and the Heavy Lift Launch Vehicle (HLLV). (FIG 6). The Crew Exploration Vehicle (CEV) sits on top of the CLV. During the actual mission, the CLV is launched and places the CEV into earth's orbit. A subsequent launch of the HLLV places the HLLV in earth's orbit. The CEV then mates with the second stage (and cargo hold) of the HLLV to form the Earth Departure Vehicle (EDV). The EDV then proceeds to the moon. Marshall welding engineers are already planning for their role in the fabrication of the CLV upper stage components where FSW is the baseline weld process. Recognizing that the manufacturability of the final design must be conducive to welding, welding engineers are working as part of an Integrated Product Team (IPT) from a welding view point. The final design of the CEV and HLLV will follow. Engineers at MSFC are preparing to fabricate full scale hardware test articles and possibly flight hardware articles. There is already a new Robotic Friction Stir Welding (RFSW) system in the planning (FIG 7). This system will be the largest FSW system in the country. It will be capable of welding full scale man-rated space vehicle hardware comprised of complex geometries such as domes and ogive sections.

IN-SPACE WELDING AND WELD REPAIR

Long duration space travel requires unique capabilities that can be realized only through the development of new leading-edge technologies. Human existence during long range space travel will rely, to a large extent, on the ability to react to unexpected scenarios, such as micrometeoroid impact and mechanical failure. There will be the routine maintenance and repair activities. There must be capabilities to generate original space light hardware, spare parts, and consumables. Welding technologies must be developed to support the many roles required for long duration space travel.

Welding in space is not new to NASA. Important lessons were learned from the In Space Weld Experiment (ISWE) conducted at MSFC in the late 1980's and 1990's. ISWE was intended to address the high risk and unknowns associated with welding operations in the vacuum and microgravity of space. The primary lessons learned from the electron beam space weld experiment were concerns and potential dangers of high-energy beams, molten metal and sparks. Solid state joining techniques eliminates these safety concerns. In addition, experimental data generated in microgravity experiments indicates a propensity for porosity defects when a material is solidified in a microgravity environment.

Several new solid state welding concepts have been initiated over the past several years for the purpose of welding and weld repair in space. Two solid state welding apparatus will be required for in-space welding; a small, manual hand held unit for thin materials and a larger portable unit for thicker materials. Two concepts are being pursued for a solid state hand held manual welding apparatus. The high speed friction stir welding (HS-FSW) concept is based on the premise that high spindle speeds (tens or hundreds of thousands of revolutions per minute) in FSW reduce the forces necessary to produce sound welds while at the same time allowing higher travel speeds. Reducing the forces will hopefully lead to manual hand-held devices. MSFC engineers have already begun studying the affects of high speed revolution pin tools using the high speed machine tool for FSW (FIG 8) located at MSFC. The machine is capable of 30,000 RPM, with a travel speed up to 200 IPM. It has been used to weld .060" GRCop-84, a copper alloy being investigated for thrust chambers. Further research is planned to investigate high speed phenomena relative to forces, feed rates, pin-tool designs and robotic applications. A parallel development effort is currently in place between MSFC and the University of Wisconsin to study the feasibility of integrating robotic operation with a manual hand held solid state apparatus. It is believed that robot integration will be required to effectively operate a solid state welding device in space. Dr. Weija Zhou, Director of the Wisconsin Center for Space Automation and Robotics (WCSAR), Madison, Wisconsin, is currently working on the design and fabrication of the first robotically assisted hand held high speed FSW prototype. Delivery is expected late 2006. Another solid state welding process developed at MSFC called Ultrasonic Stir Welding (USW) (patent pending) is also being investigated for hand held welding applications. The USW concept utilizes ultrasonic energy as the medium to bring material into the plastic state. Unlike FSW, there are no rotating shoulders producing frictional heat. This concept may

be more practical as an on-orbit welding and repair process because high rotational speed stability issues will be minimized. Solidica, Inc., Ann Arbor, Michigan, has completed initial assessment of integrating ultrasonic technology with a hand held solid state weld apparatus. "The feasibility of integrating ultrasonic heating into a weld tool looks promising", comments Dawn White, president of Solidica, Inc. Solidica is a recognized leader in the application of ultrasonics for solid-state bonding systems. "This technology should leverage into a hand held manual device for both space based and land based applications", continues Ms. White. FIG 9 shows a conceptual prototype of a hand held solid state welding device for in-space applications. Thermal Stir Welding (TSW) (patent pending) is yet another weld process being developed at MSFC for in-space welding of thicker members. (FIG 10). TSW is different from FSW in that the heating, stirring, and forging process elements found in FSW are controlled independently. There is no frictional heating which means no high speed rotating shoulders. Like the USW concept, stability issues associated with high speed rotational parts will be kept to a minimum.

MSFC has unique facilities to test prototype welding hardware for space application. Fig 11 and 12 shows Marshall's vacuum chamber complete with viewing ports and space suit gloves. The 4 foot by 4 foot chamber can be pumped down to 10^{-6} torr to simulate the vacuum of space.

MILITARY AND PRIVATE SECTOR APPLICATIONS

"NASA's Marshall Space Flight Center has perhaps the most concentrated resources and expertise in the country for FSW and other solid state welding development", comments John Vickers, director of Marshall Space Flight Center's National Center for Advanced Manufacturing. "Our VWT, CWT and HWT weld systems are sizable weld tools capable of supporting prototype development of large structures. We also have smaller systems for standard weld test pieces. Our welding expertise is represented by both civil service and contractor engineers and technicians. Through the Space Act Agreement (SAA) process, companies, large and small, can gain access to our facilities and engineering expertise to pursue welding R&D".

The SAA process has been used by numerous companies pursuing FSW capabilities at MSFC including Hayes Wheels, Williams International, and more recently, the U.S. Army, Lockheed-Martin and Keystone Synergistic Enterprises, Inc. In order to qualify for a SAA, the proposed R&D must benefit NASA programs and interests. "There are several types of SAA's available to industry", says Sammy Nabors of the Technology Transfer Office. "The type of SAA depends on the proposed statement of work and the relevance to the overall NASA mission. The important thing about the SAA is that all data generated from the effort is proprietary to the company who is doing the work."

Work done at MSFC through the SAA program provides engineers the opportunity to expand NASA technology applications beyond the applications of specific NASA projects and "return" the tax-payer's technology development investment to the commercial sector. "We call this technology spin-off", says Mr. Nabors. "The "spin-off" process is an important part of the civil service worker. We, the government, are

obligated to take the technology developed with the tax-payer dollars, and return it back into the private sector. This is done through the licensing of NASA owned technology. The SAA process", continues Mr. Nabors, "allows NASA to work closely with U.S. companies willing to invest in technology and develop the technology for specific industry segments". An example of such an effort is ongoing with a Florida company call Keystone Synergistic Enterprises, Inc. Keystone's intent is to develop and commercialize technologies for both defense and commercial applications and offer other companies licenses for the use of thermal stir joining. Keystone works closely with DOD primary contractors to develop technologies closely aligned with the needs of defense systems while looking for near-term commercial spin-offs to establish a commercialization foundation. An example of a potential commercial spin-off is while the Navy is interested in effective titanium alloy joining technologies for shipbuilding, an emerging market for high-performance personal yachts made from titanium also has interest in the TSW process.