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Final Technical Report: Flexible Friction Stir Joining Technology

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Advanced Manufacturing Office

FINAL TECHNICAL REPORT: FLEXIBLE FRICTION STIR JOINING TECHNOLOGY

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ACRONYMS

AMO	Advanced Manufacturing Office
API	American Petroleum Institute
DOD	Department of Defense
DOE	Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
FSW	Friction Stir Welding
GMAW	Gas Metal Arc Welding
HAZ	Heat Affected Zone
LNG	Liquid Natural Gas
NASA	National Aeronautics and Space Administration
NDE	Non-Destructive Evaluation
OEM	Original Equipment Manufacturer
ODS	Oxide Dispersion Strengthened
ORNL	Oak Ridge National Laboratory
PCBN	Polycrystalline Cubic Boron Nitride
TWI	The Welding Institute

ACKNOWLEDGEMENTS

This project was funded by the US Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE) Advanced Manufacturing Office (AMO), with industry cost-sharing. This project was managed as CPS Agreement Number: 17877. The lead organization was the Oak Ridge National Laboratory (ORNL). The project duration was from October, 2008 through September, 2013.

Other project partners included MegaStir Technologies and ExxonMobil Upstream Research Company.

EXECUTIVE SUMMARY

Reported herein is the final report on a U.S. Department of Energy (DOE) Advanced Manufacturing Office (AMO) project with industry cost-share that was jointly carried out by Oak Ridge National Laboratory (ORNL), ExxonMobil Upstream Research Company (ExxonMobil), and MegaStir Technologies (MegaStir). The project was aimed to advance the state of the art of friction stir welding (FSW) technology, a highly energy-efficient solid-state joining process, for field deployable, on-site fabrications of large, complex and thick-sectioned structures of high-performance and high-temperature materials. The technology innovations developed herein attempted to address two fundamental shortcomings of FSW: 1) the inability for on-site welding and 2) the inability to weld thick section steels, both of which have impeded widespread use of FSW in manufacturing. Through this work, major advance has been made toward transforming FSW technology from a "specialty" process to a mainstream materials joining technology to realize its pervasive energy, environmental, and economic benefits across industry.

The technology development in this project primarily focused on its first targeted application: construction of steel pipelines for energy transmissions (natural gas, oil, hydrogen, etc.). It also benefited potential near future applications for construction of wind towers, pressure vessels, refinery vessels, shipbuilding, bridges, and nuclear power reactors.

The project comprised the following major technology development activities.

- Process innovations. They included the development of tool materials with the durability and strength necessary for joining of steels and other high-temperature materials; the concept of auxiliary heating to reduce process load and increase welding speed & productivity; and the patented multi-pass multi-layer FSW that fundamentally overcomes the thickness limitations of today's FSW approach.
- Development of the field-deployable FSW prototype systems to provide flexibility and affordability for on-site construction.
- Technology validation and demonstration fabrications. The project included the demonstration on different steel pipe diameters and wall-thicknesses based on market needs and technology progression; the validation of field fabrication capability and robustness of the developed FSW system to handle variations in materials, pipe dimensions and pipe alignment etc., and the patented pipe welding without internal support.
- Generation of weld property data to support codes & standards acceptance
- Business case and market analysis to guide the specifics of technology development. It also formed the basis for commercialization plan.

The concept of field deployable FSW was realized and demonstrated by means of the construction and use of a prototype FSW welding system capable of joining large diameter steel pipelines, on-site. All individual program goals were met including the ultimate goal of demonstrating the ability to friction stir weld 76 cm (30 inch) diameter, 15.9 mm (0.625 thick inch) wall, X70 linepipe steel without using internal support. This is a very important demonstration of the merits and feasibility of the innovative approach invented by the project partner, ExxonMobil, for onshore pipeline applications.

In addition, a similarly important goal for offshore pipeline fabrication was to demonstrate the ability to friction stir weld 32 cm (12.75 inch) diameter, 12 mm (0.5 inch) wall thickness, X52 and X65 linepipe steels using a sacrificial anvil to achieve consistent full penetration. The mechanical properties and Charpy toughness (at temperatures from -80 to 25°C) of the weld zone, from both

approaches, are superior to parent metal properties. Further, welds were inspected per API 1104 guidelines including visual, radiography, bend tests, nick break tests, and once the appropriate weld procedures were established, the welds were deemed to be acceptable by independent test facilities.

FSW is highly energy efficient. For the steel welding applications studied in this project, FSW only uses 20-40% of the arc welding energy. Additional energy saving from reduced materials usage accounts for another 20-25% energy and materials cost reduction. Furthermore, due to reduced welding passes for pipeline welding, our research shows that the "effective" fabrication productivity (welding speed) of FSW for welding ½ to 5/8" thickness steel pipeline was about 2.2 to 4.5 times of the reference arc welding processes commonly used in the industry.

Finally, according to a companion study by ExxonMobil, the FSW technology specifically developed in this project can potentially reduce the cost of pipeline construction by 5-10% for onshore applications, and 20-30% for offshore applications.

The technology development in this project has built a strong foundation for near future commercialization of FSW for on-site constructions. Pipeline construction for natural gas transmission, hydrogen pipelines, nuclear reactor pipeline system, layered steel pressure vessel including high-pressure hydrogen storage vessel, and certain defense related applications have been identified by the industry partners to pursue in the next 3 to 5 years.

Figure 1 Successful on-site fabrication demonstration and validation of the field-deployable FSW system in welding steel pipelines in this project.

1. INTRODUCTION

1.1 FRICTION STIR WELDING TECHNOLOGY

Friction stir welding (FSW) is an innovative solid-state joining process invented in the 1990s by The Welding Institute in the United Kingdom (UK) [1-4]. It is considered as one of the most significant welding process inventions in the last two decades. Compared to other solid-state joining processes such as rotary friction welding and inertial welding, the FSW process is unique in that it enables the advantages of solid-state joining for fabrication of continuous linear welds, the most common form of weld joint configurations that are predominately made by the arc welding processes in today's industry.

The basic principles of FSW process are illustrated in Figure 2. The specially designed tool has two essential parts. The first part is the profiled pin extending along the rotating axis. The second part is the shoulder. Rotating at high angular speeds, the pin plunges into the workpiece until the shoulder makes full contact with workpiece surfaces. The rotating tool then moves along the joint line with the shoulder fully in contact with the workpiece surface under a relatively high axial forging force. Owning to largely the frictional heating between the rotating tool and the workpiece, the temperature in a column of workpiece material under the tool is increased substantially, but remains below the melting point of the material. The increase in temperature softens the material, and allows the rotating tool to mechanically stir the softened material flowing to the backside of the pin where it is consolidated to form a metallurgical bond.

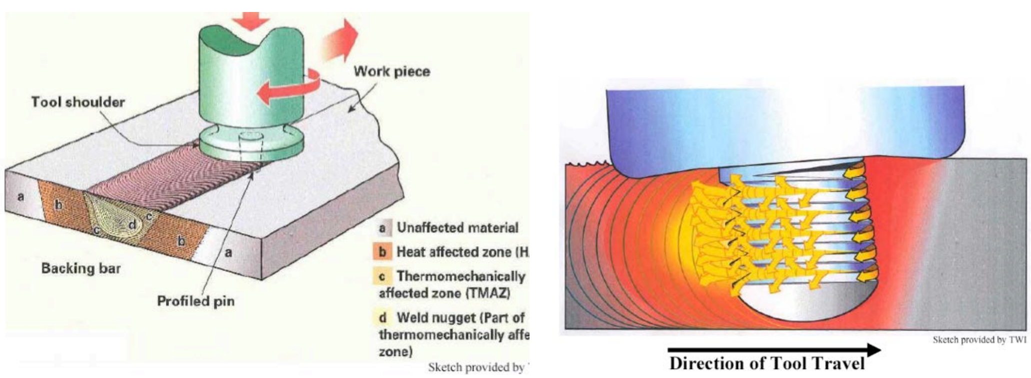


Figure 2. Friction Stir Welding Process.

FSW creates a weld joint without bulk melting. Compared to the widely used fusion welding processes (e.g. arc welding, laser welding), an inherent advantage of FSW is that it is immune to the defects and property deteriorations associated with solidification. Solidification cracking, porosity, and melting and coarsening of strengthening phases are eliminated in FSW. In addition, the extensive thermomechanical deformation of FSW refines the microstructure of the weld region [5]. Hence, whereas fusion welding generally results in weld property degradation, FSW can produce a weld with mechanical properties *similar to* or even *better than* those of the base metal [6,7]. For example, as shown in Figure 3, the impact energy absorption of a friction stir weld is much higher than the base metal of a commercial pipeline steel. The improved mechanical properties are a very important aspect of FSW, as the weld region made by the fusion welding processes are often the weakest region of a welded structure for a variety of high-performance engineering materials. The friction stir process has also been utilized to refine or modify microstructures for superplasticity forming, casting property improvement, and to produce ultra-fine microstructures or even nano-structures [8].

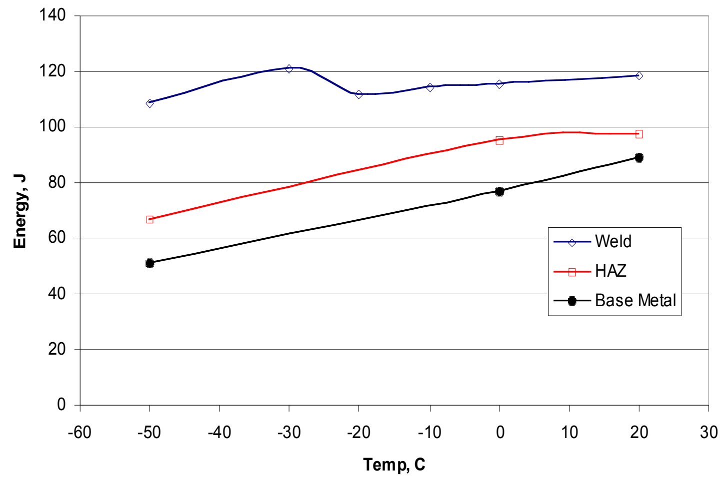


Figure 3. Drastic increase in Charpy impact energy absorption of X65 pipeline steel as result of friction stir welding (after Feng et al [6]).

Today, the FSW process is primarily being used to join low-melting temperature materials, mostly various aluminum alloys that are difficult to fusion-weld. Well-known applications include the Delta rocket booster for the Space Shuttle, the light-weight advanced amphibious assault vehicles for the US Marine Corps, high-speed express trains in Japan and China, cruise liner superstructures in Europe, and nuclear waste copper alloy containers in Europe [9-11]. The auto industry is also actively pursuing the application of FSW in light-weight body structures [12]. The economic and technological benefits of FSW have been well documented for Al alloys and other low-melting temperature materials. For example, the automotive industry [12] reported over *90% energy related cost-savings* when friction stir spot welding (a variant of the linear FSW process) is used to replace the resistance spot welding process (the conventional assembling welding process) for aluminum auto-body structures. The capital investment of a FSW system is only *60%* of an equivalent conventional resistance spot welding system.

The above-mentioned applications of FSW technology are considered specialty markets in the grand scheme of the welding industry, representing a small fraction of the overall welding market. FSW has yet to reach the status of a mainstream welding process (such as gas metal arc welding) thus unlocking its energy and cost benefit potential, due in large part to the fundamental shortcomings described in the next section.

FSW is a "green" technology due to its energy efficiency, environment friendliness, and versatility. As compared to the conventional welding methods, FSW consumes considerably less energy. Also, because it is solid state, no harmful emissions are created, thereby making the process environmentally friendly. **Table 1** lists some of the metallurgical, environmental and energy benefits associated with FSW.

Table 1 Key benefits of friction stir welding

Metallurgical benefits	Environmental benefits	Energy benefits
Solid phase process, i.e., no melting. Low distortion. Good dimensional stability and repeatability. No loss of alloying elements. Excellent mechanical, fatigue, toughness and corrosion properties in the joint area. Fine recrystallized microstructure. Absence of cracking. Replace multiple parts joined by fasteners.	Minimal shielding gas required. Minimal surface cleaning required. Eliminate grinding wastes. Eliminate solvents required for degreasing. Consumable materials saving, such as rugs, wire or any other gases. No harmful emissions. No slag.	Improved materials use (e.g., joining different thickness) allows reduction in weight. Only 2.5% of the energy needed for a laser weld. Decreased fuel consumption in light weight aircraft, automotive, and ship applications. Reduced joint preparation. Single pass weld.

1.2 TECHNICAL BARRIERS PREVENTING PERVASIVE APPLICATION OF FSW

Several fundamental shortcomings of current FSW technology hinder its pervasive adoption for commercial and defense applications. One shortcoming is that today's FSW manufacturing systems are predominately gantry type machines that are limited to geometrically simple structures. For example, the US Army recently considered applying FSW for Bradley Fighting Vehicle battle-field damage repair. Despite significant labor cost-savings and reduction of repair time estimated by an original equipment manufacturer (OEM), it was found that the gantry-type FSW systems were unable to deal with the complex structural geometry of armored vehicles. This OEM abandoned FSW process and resumed conventional repair using the gas metal arc welding process. Furthermore, the gantry-type FSW machines cannot be used for *on-site welding* – a vast market including pipeline construction, shipbuilding, and large-scale structural steel erection (such as reactor vessels for nuclear power plant and refinery vessels in the petrochemical industry). Indeed, many energy companies including ExxonMobil are interested in applying FSW to energy infrastructure construction and maintenance. However, field-deployable FSW technology does not exist. Although robotic FSW systems have been available for some time, they are still limited to thin gage (typically less than 5-mm thick) Al alloy structures. These limits are due to the high forging and other processing loads required to join thick section Al alloys and high-temperature materials such as steel. *Technology innovations are needed to make the FSW process more agile for complex components and capable of on-site welding construction.*

A second shortcoming is that current FSW technology is essentially a "single" pass welding process and thereby limited to joining thin-section structures. As shown in Figure 4, for single-sided welding, the pin length in principle needs to be equivalent to the plate thickness, because FSW relies on the pin to completely penetrate the workpieces. For double-sided welding where one weld pass is applied to each side of the workpieces, the pin length must be slightly longer than half of the workpiece thickness. As workpiece thickness increases, the requisite increase in tool geometry results in large process loads and this complicates FSW system design and limits the availability of tool materials. Practically speaking, thick-section FSW using current technology is essentially impossible. Today, FSW is practically limited to 2-in thick Al alloy structures, and the thickness limitation for steel structures and other high-temperature materials are even more severe (less than 1 inch). As a reference, the wall thickness of pressure vessels of nuclear power plant ranges from 5 to 20-in thick, and vessels in chemical industry and oil & gas refineries are even thicker. *Technology innovations are needed for FSW of thick-section structures common in many industries such as oil & gas, nuclear energy, and shipbuilding.*

Figure 4. Appearance of a double-sided FSW joint made by TWI on a 10-mm thick 12Cr steel plate.

Another shortcoming in current FSW technology is tool durability for joining high-melting temperature materials such as structural steels (the most widely used structural material), titanium alloys, and nickel base alloys. The high-temperature strength of these materials drastically increases the processing loads (axial load, bending load, and frictional load) as compared with the Al alloys and other low temperature materials. For example, the typical axial force for ¼" thick aluminum alloys is in the range of 1,000 to 3,000 lbs. In comparison, the axial force for the same thickness superalloy IN738 exceeds 20,000 lbs. The extremely high processing loads associated with applying FSW to high-temperature materials causes extensive wear and/or fracture of the tool. *Technology breakthroughs in tool material development and in reducing the process loads are critical to extend the FSW process to high-temperature material applications.*

1.3 TECHNICAL OBJECTIVES OF TECHNOLOGY DEVELOPMENT

The goal of this project is to advance the FSW process as a manufacturing technology that can be deployed for on-site construction of large, complex and typically thick-sectioned structures made of high-performance and high-temperature materials (such as high-strength steels, Titanium alloys and superalloys). This would transform FSW from a specialty joining process into one with pervasive application potential across a number of industrial sectors where the payoff of energy reduction, environmental and economic benefits would be significant.

Achieving the project goal required both innovative process concepts and due-diligent engineering efforts to overcome the fundamental shortcomings of current FSW technology. To this end, we proposed to develop a field-deployable friction stir welding system with the flexibility and affordability for complex structural components. This field-deployable FSW system served as the platform for a concerted effort in this project, to integrate relevant innovative process concepts to enhance field-welding capabilities.

A primary demonstration of the project goal was the construction and use of prototype FSW welding systems capable of joining large diameter steel pipelines for energy transportation (natural gas, oil, or hydrogen). The development of such systems leveraged recent developments by MegaStir. It also addressed our industry partner ExxonMobil's primary application interest.

The R&D and FSW technology development was organized into the following three phases in this project:

<u>Phase I:</u>

- Baseline process development
- Thin-wall steel pipeline demonstration (12” diameter, ¼” wall thickness)
- Weld properties and welding productivity per codes/standards requirements
- Business and economic analyses and identification of application and commercialization opportunities

<u>Phase II:</u>

- ***Off-shore applications*** (12” diameter, 0.5” wall thickness, in single pass without auxiliary heating, with improved internal support)
- FSW system and tooling for such applications, incorporating lessons learned from the baseline development in Phase I

<u>Phase III:</u>

- ***Onshore applications*** (30” diameter, 0.625” thick, high-strength pipeline steels, with arc weld root pass to eliminate the internal support)
- Code/standard acceptable weld properties & quality to specific metrics
- Construction-site demonstration
- Commercialization and technology transfer per business interests of team members

2. RESULTS AND DISCUSSION

The major results and outcome achieved in this project are described below, organized according to the aforementioned phased approach.

2.1 PHASE I BASELINE FSW TECHNOLOGY DEVELOPMENT

2.1.1 Tool Material Development

The tool material development was carried out by MegaStir. The activities were directed to two major goals: (1) a new material formulation to increase the durability and with adequate abrasion strength, and (2) tool material synthesis technology scale-up to produce tools capable of welding 20 mm thick steels (from the current 4-6 mm thick tool). Both goals have been successfully achieved in this project.

New composite tool materials were intended to overcome the low temperature brittleness of the polycrystalline cubic boron nitride (PCBN) tool material patented by MegaStir. The new composite tool material was a blend of PCBN with a W-Re matrix binder. Figure 5 shows typical microstructure of a composite tool material developed in this project by MegaStir. The compositions and the fabrication processes for the new composite tool material are proprietary information of MegaStir. Extensive tool life experiments were performed in this project. It is shown that the new tool material was capable of producing over 114 foot long welds with a single tool, on ¼” thick carbon steel, using typical welding process conditions for such thick steel.

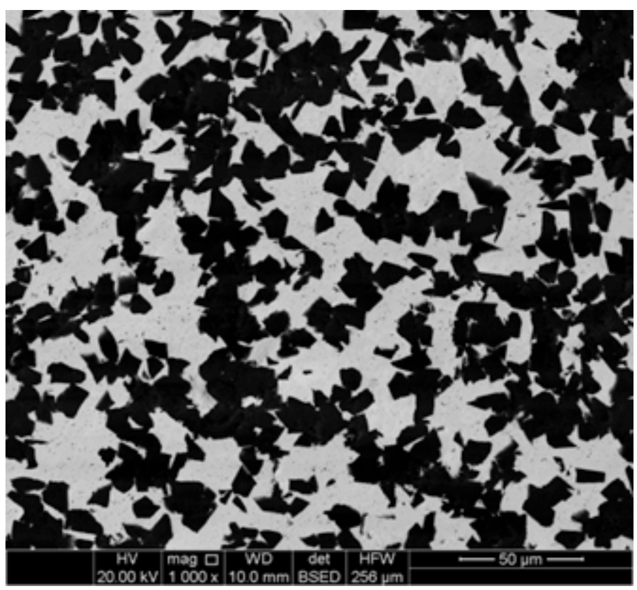


Figure 5. Typical microstructure of the composite tool material showing fully reacted PCBN in W-Re-alloyed matrix.

The capability of making large tool for thick-section steel welding was also developed in this project (Figure 6). Tools capable of welding 20 mm thick steels with the new composite tool materials were produced, and successfully demonstrated to make defect free welds in a single pass (Figure 7).

Figure 6. Comparison of tool size for welding of 6mm, 9mm and 20mm thick steel.

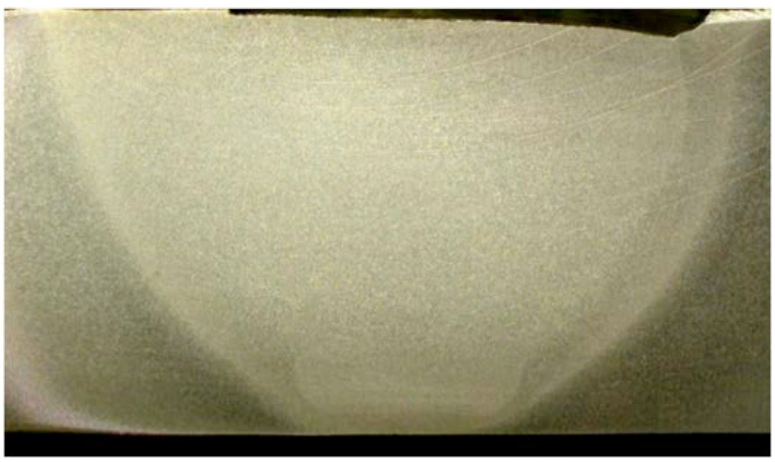


Figure 7. Fully consolidated weld in 20mm thick steel plate made in single pass.

New tool designs were also developed for friction stir welding (FSW) of high temperature metals. A number of significant design changes (compared to the conventional PCBN tool design used previously for steel welding) were proposed and evaluated. In certain designs, the tool pin diameter was increased both at the pin base and pin tip for strength and 3-flats have been added to the pin to enhance metal flow. In others, the tool shoulder is flat (as opposed to convex) to increase contact area with a curved surface and increase heat input. Finally, flow cavities were added to the shoulder to replace the scroll pattern used in the conventional tool design. These new tool designs were evaluated for the potential to 1) significantly reduce tool fabrication costs for deep penetration tools, 2) improve wear resistance by eliminating small features on the tool shoulder, and 3) weld with lower loads and lower torque thus increasing tool life and also simplifying the FSW system itself. Figure 8 and Figure 9 show two tool designs used in this project.

Figure 8. Tool design capable of producing 12 mm deep friction stir weld in steel.

Figure 9. Tool design used to weld the large diameter heavy wall linepipe in Phase III.

2.1.2 Field Fabrication Study and Demonstration on Thin-Wall Steel Pipeline

One of the major requirements of field-deployable FSW system is its robustness in handling the unavoidable dimensional variations or mismatches of pipes in pipeline construction. The mismatches included the wall thickness variations of a pipe and those between different pipes, the ovality of pipe, and pipe misalignments. The ability to weld steels with different chemistries (such as from different vendors for a given API grade) must also be developed. To this end, this task involved two major activities: (1) to develop the welding process operation window to successfully handle such diversity, and (2) to validate the performance of the FSW system developed in this project in field welding tests. The project team decided to investigate this critical requirement early on in the project – the first year of the project on 12-in diameter and ¼-in thick steel pipes, so that the lessons learned from this early on investigation would be used to assist the design and engineering of the second-generation prototype machine in later part of this project.

The field-deployable FSW system was evaluated against a rather strict dimensional mismatch matrix that mimics dimensional mismatches of steel pipes expected under real-world pipeline construction conditions. Detailed testing matrix and schedule are shown in Figure 10. Steel pipes were purchased from two different steel vendors to increase the dimensional mismatches and were used to evaluate the FSW system's ability to join steels with different strengths. The evaluation matrix consisted of two sets of welds. The first set included evaluating the "as-received" pipe dimensional variations from two steel vendors. For the second set, local thinning of wall was created through grinning and machining to reach the maximum allowable dimensional mismatch specified by the API specification.

Total 6' long pieces from steel A= 6 (Pipe ends are marked as A1, A2, A3,..., A12)
Total 6' long pieces from steel B= 12 (Pipe ends are marked as B1, B2, B3, ..., B24)

Table #1: Welds with natural misalignment

Welding #	Pipe Sections	Dye penetrant	API 1104	Weld Splitting*	Radiography	Charpy tests	Run-off Tab Macro	Weld macro	Hardness	Steels	Comments
1	A11 + A8	X		X		X	X	X	X	A	
2	B10 + B22			X		X	X	X	X	B	
3	B18 + B20	X	X		X					B	
4	A4 + A10	X	X		X					A	
5	B2 + B3	X	X		X					B	
6	B5 + B24			X		X	X			B	
7	B7 + B12			X		X	X			B	
8	A5 + A2	X	X		X					A	
9	B14 + B15	X	X		X					B	

*Use magnetic particle tests from weld ID after splitting the weld

Table #2: Welds with local thin areas

Welding #	Pipe Sections	Dye penetrant	API 1104	Weld Splitting*	Radiography	Charpy tests	Run-off Tab Macro	Weld macro	Hardness	Steels	Comments
10	B16 + A3	X		X		X	X	X	X	Mixed	
11	B1 + B9			X		X	X			B	Locally thinned pieces
12	B23 + B17	X	X		X					B	Locally thinned pieces
13	A6 + A12	X	X		X					A	Locally thinned pieces
14	B6 + A9	X	X		X					Mixed	
15	B21 + B11			X		X	X			B	Locally thinned pieces
16	B4 + A1			X		X	X			Mixed	
17	B19 + B8	X	X		X					B	Locally thinned pieces
18	B13 + A7	X	X		X					Mixed	

*Use magnetic particle tests from weld ID after splitting the weld

Weld #	4		8		1		5		3		6		7		2		9	
Pipes	#A4	#A10	#A5	#A2	#A11	#A8	#B2	#B3	#B18	#B20	#B5	#B24	#B7	#B12	#B10	#B22	#B14	#B15
Angular Position	12	5	12	5	12	3	12	7	12	11	12	12	12	8	12	12	12	6

Weld #	14		18		16		10	
Pipes (Mixed)	#B6	#A9	#B13	#A7	#B4	#A1	#B16	#A3
Angular Position	12	4	12	1	12	10	12	5

Weld #	13		12		15		17		11	
Pipes (Thinned)	#A6	#A12	#B23	#B17	#B21	#B11	#B19	#B8	#B1	#B9
Angular Position	12	7	12	7	12	12	12	11	12	1

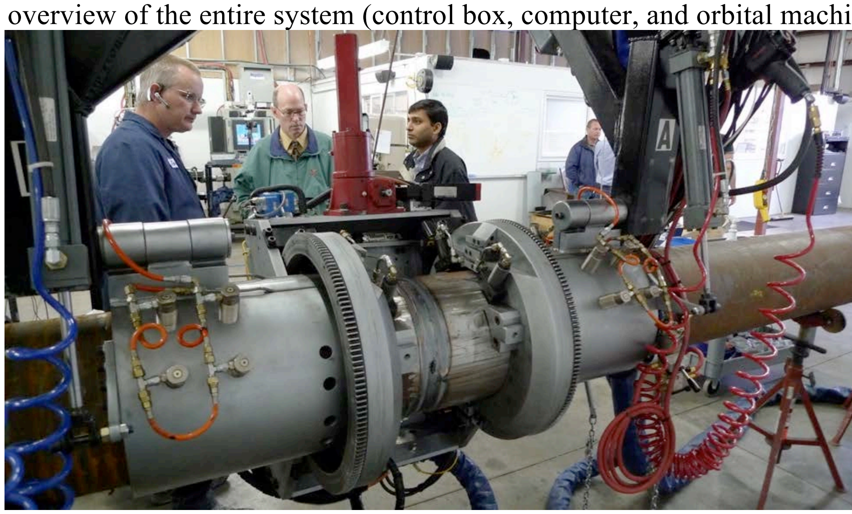
Figure 10. Field welding evaluation matrix for thin-wall FSW development and demonstration.

Figure 11 shows the field-deployable FSW system used this task (GEN 1 FSW system). It included automated seam tracking and inside anvil technology for heating and cooling. The laser based seam tracking system was designed and integrated with the portable FSW system to provide the capability to track the joint line during welding – an essential feature for on-site construction. The tracking system is shown in Figure 12. This tracking system was tested during the field welding evaluations.

Figure 13 shows the process window developed in welding ¼" thick steel pipes. Defect-free welds can be produced in a relatively wide range of welding conditions, including achieving a welding speed of 10 in/min. In addition, the process load was kept at 7000 – 8000 lb range, which was essential for minimizing tool wear and premature failure. Figure 14 shows the operation of the portable FSW system in joining the steel pipes.

Figure 15 shows examples of welds produced at 6, 7, and 8 in/min welding speeds. All welds were full penetration without the lack of bonding root defects observed before. All welds also passed the root bend test, a special weld quality test specifically designed to determine the lack-of-bonding defect in friction stir weld, as shown in Figure 16. Figure 17 shows the appearance of the weld made at 7 in/min welding speed. There was very little flash and surface indentation that reduces the thickness of the weld region, a concern that may reduce the strength of the weld.

(a) overview of the entire system (control box, computer, and orbital machine).



(b) Close view of tracking system

(c) Close view of welding head (d) Computer interface

Figure 11. First GEN orbital FSW system for thin-wall steel pipes.

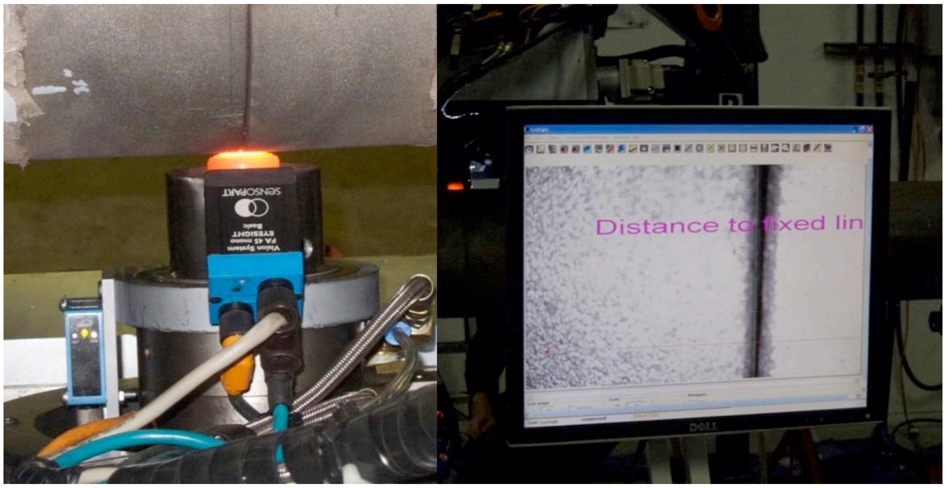


Figure 12. Laser based vision weld seam tracking system.

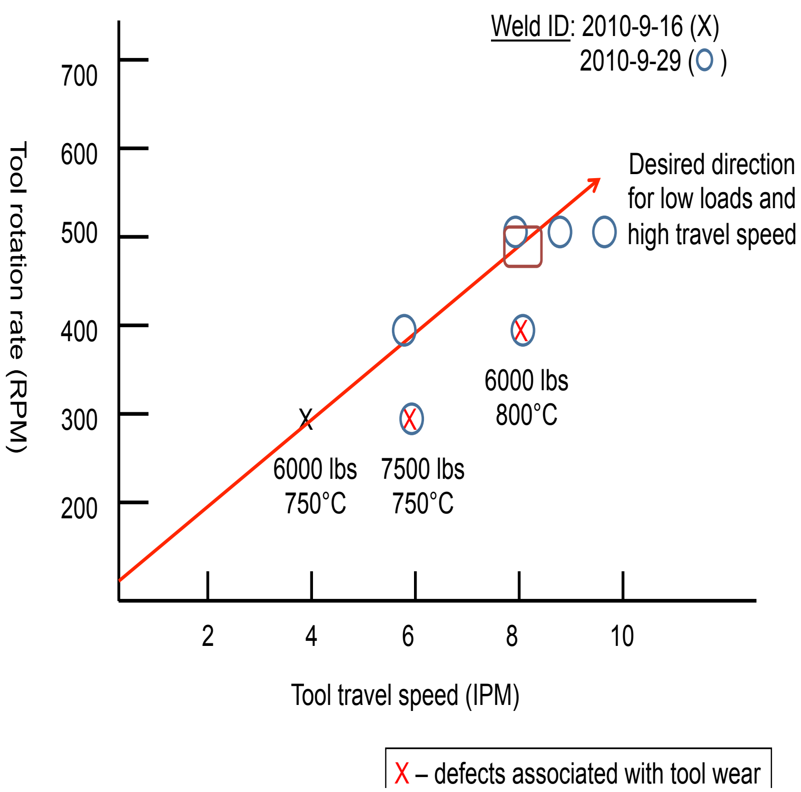


Figure 13. Process windows developed for ¼" thick steel pipes.

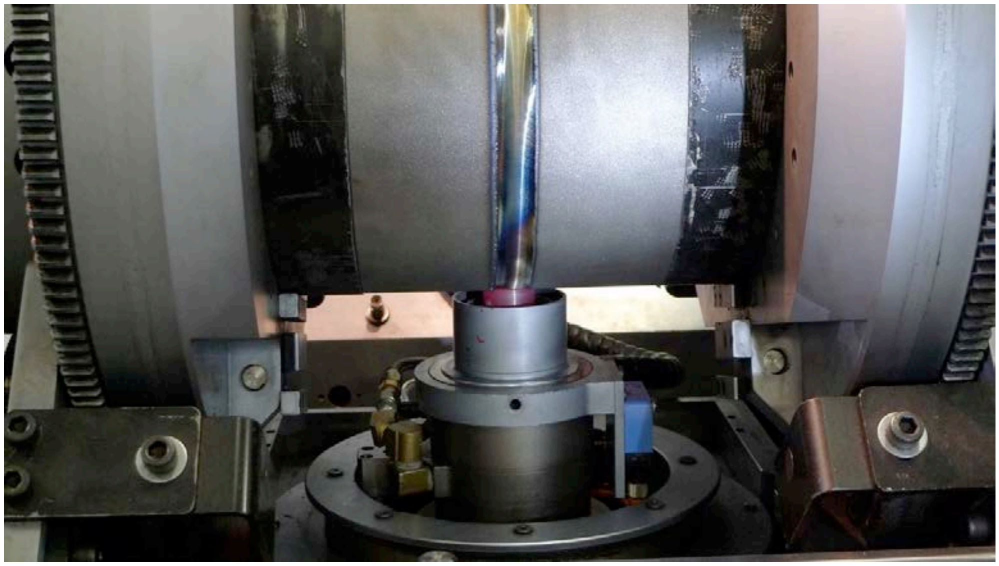


Figure 14. Friction stir welding of steel pipes with the first generation portable FSW system.

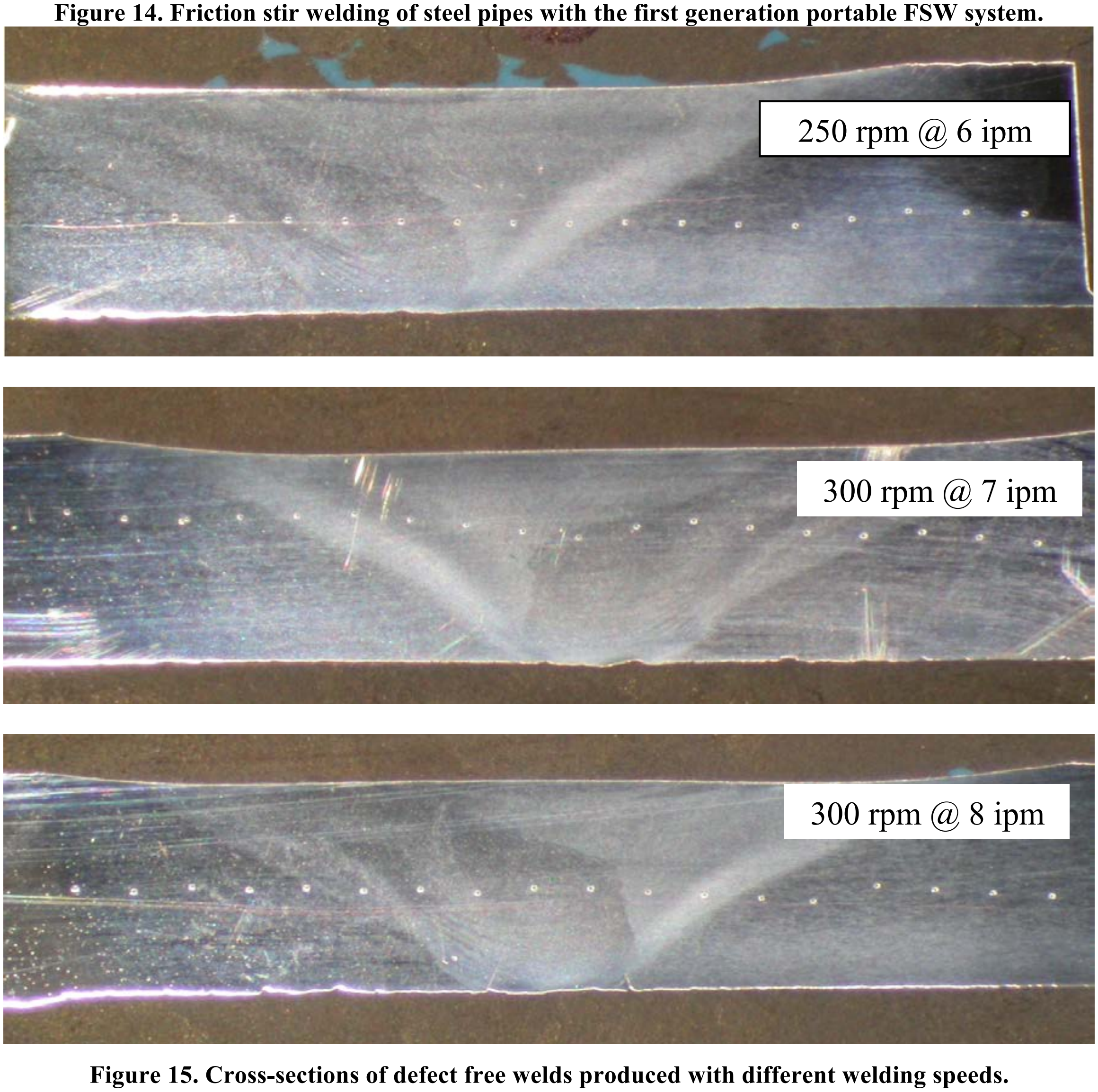


Figure 15. Cross-sections of defect free welds produced with different welding speeds.

Figure 16. Root bend test of friction stir welds.

Figure 17. Appearance of weld surface. 7 in/min welding speed.

In conducting the first set of welding evaluation on pipes with the "as-received" mismatches, it was found that the inadequate internal supports could cause lack of complete bonding in some of the welds. The internal supports were further refined and adjusted before the second set of welding evaluation on pipes with artificial local thinning (i.e. more severe mismatches). All welds made after the final internal support improvements showed no apparent weld defects. Figure 18 through Figure 19 show some of the welds made during the field welding demonstration.

Figure 18. Project team during field welding evaluation.

Figure 19. Welds cut from welded pipes made during field evaluation for further quality inspection and mechanical property testing.

The final validation of the field-deployable FSW system developed in this project was the field demonstration of a completely self-contained field construction station that consisted of a diesel power generator, a lift crane, the portable FSW system, and the internal supporting system, as shown Figure 20. This on-site fabrication test showed that three 12-in diameter steel pipes could be field-welded in about 30 minutes, meeting or exceeding the productivity requirement of on-site fabrication of steel pipelines for energy transportation. Figure 21 and Figure 22 provide examples of this off-the-field welding demonstration.

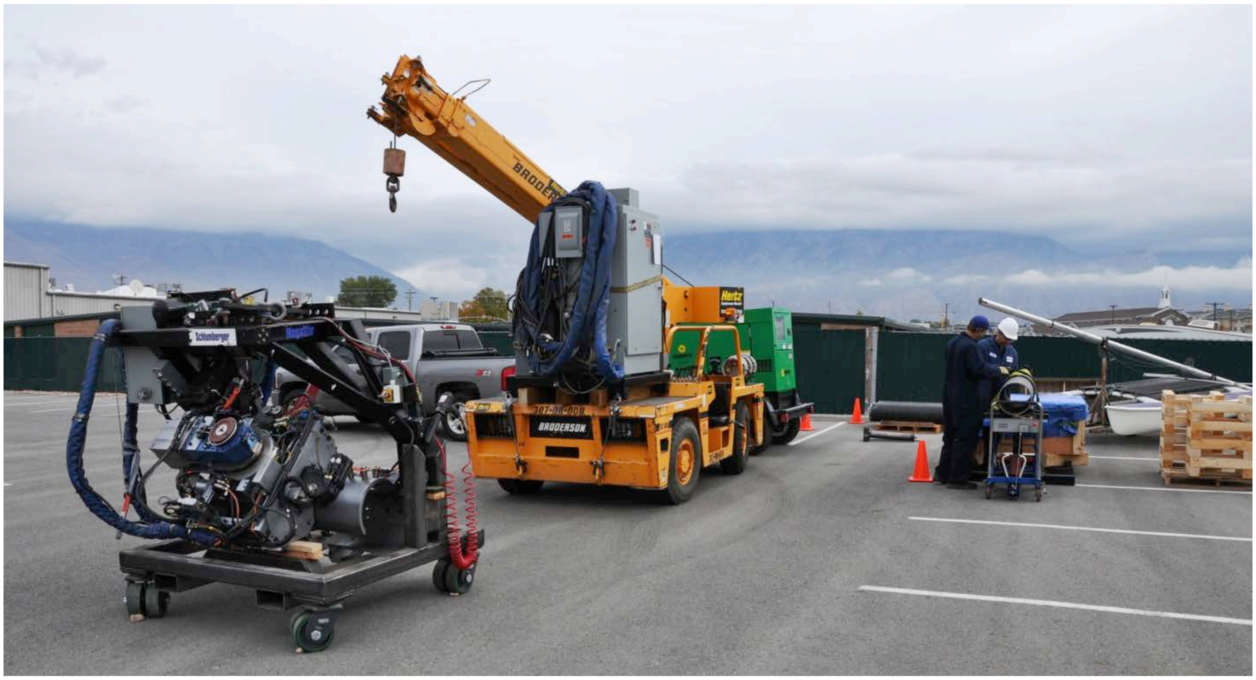


Figure 20. An FSW station for on-site pipeline construction.

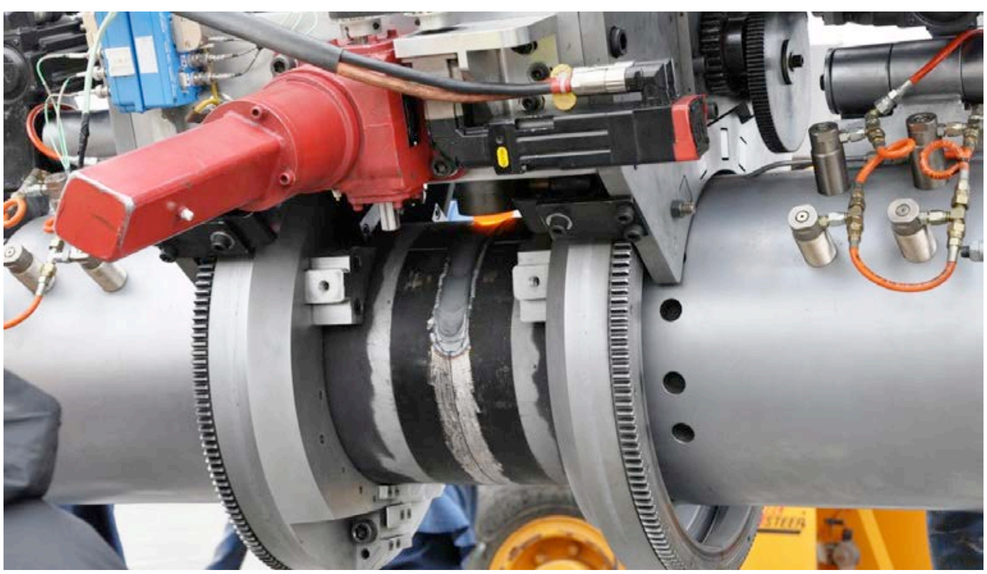


Figure 21. On-site FSW of a 12" diameter and 3/8" wall steel pipe.

Figure 22. Demonstration of on-site FSW with a mobile FSW station.

Most welds produced in this validation and demonstration task, when deemed appropriate, were further evaluated through non-destructive evaluation (NDE), destructive evaluation, and mechanical property testing, based on the API specifications widely accepted by the industry for natural gas pipelines.

The non-destructive evaluations included, visual inspection, radiography and dye penetrant tests of the *entire length* of the welds. The destructive evaluation included nick-break, face bend and root bend. The mechanical property testing included the transverse weld tensile test at the ambient temperature, and the Charpy V-notch test between -80 to 25°C. All tests were performed by an independent API certified testing house.

The cross-weld tensile test revealed that the tensile strength of all welds tested ranged from 60.5 to 89.3 ksi for the combination of X52 and X60 steel pipes. The strengths were relatively high for the steel grades, and all samples failed in a ductile manner. The Charpy impact energy varied considerably depending on the material combination and testing temperature. At -60°C, it ranged from 90 to 200 ft-lb for X52-X60 bi-metal welds. At -40°C, it ranged from 110-130 ft-lb for mono X60 welds, and 140-190 ft-lb (with exception of one data point at 20 ft-lb) for X52-X60 bi-metal welds. *Nevertheless, the Charpy impact energy values of the welds far exceeded the API specified minimum value at minimum service temperature (29 ft-lb average or 22 ft-lb individual).*

For non-destructive testing, all welds passed the visual inspection and the dye penetrant examination. They also passed the radiography examination except one at the run-off ramp and one at the advancing side due to lack of bonding.

For other destructive tests (face bend, root bend and nick-break), some welds did not pass the root bend test, although they passed the non-destructive test. Further examination of the failed samples and metallographic examination of the weld cross-section revealed that a lack of bonding at root side of the weld, although too small to be detected by the non-destructive test (typically in the range of 0.3 to 0.5mm deep), was the cause of the root bend test failure. The issue of the occasional lack of root side bonding was successfully solved with two innovative approaches in Phase II and Phase III of the project

In summary, we successfully developed and demonstrated the field deployability of FSW technology to weld ¼" thick steel pipes with various dimensional mismatches for real-world on-site pipeline construction conditions. Overall, the weld nugget was free of volumetric flaws, there is little surface flash with a corresponding defect free surface finish, the tensile strength is high, and Charpy impact results over a large temperature range (-80 to 23°C) indicate ductile and fracture resistant weld metal. However, a lack of penetration weld root flaw (root side bonding) occurs intermittently but persistently. Lack of penetration flaws are due to both incomplete FSW tool penetration and at times poor FSW tool/joint line alignment. Thus, the dominant impediment to achieve defect free welds, i.e., welds that can pass root bend and nick-break tests, is the inability to consistently achieve full penetration. This issue was solved in Phase II and Phase III.

2.1.3 Hybrid Process

In hybrid process, the heating generated by the friction stir process is augmented with auxiliary heating. The induction heating technique was chosen for integration with the GEN II large diameter FSW system. An electro-magnetic-thermal finite element model was developed to refine the induction heating technique and apparatus for FSW of pipe. Detailed modeling studies were carried out to determine the induction heating device configurations for the intended use for pipeline heating. Due to the progress in tool materials and other process developments (such as root pass arc welds), the project team considered that it was possible to achieve the targeted offshore and onshore applications without the use of auxiliary heating. Thus, it was decided to stop this activity in this project, to concentrate the project resources and effort to other areas of the project. Without the auxiliary heating, the FSW system would be simpler to operate and commercialize.

2.1.4 Multipass FSW

In this project, we have successfully demonstrated the multipass FSW on three-layer steel plates. The process conditions were refined such that all the failure locations during the cross-weld tensile were in the base metal region, far away from the weld and the heat affected zone (HAZ). In addition, the Charpy impact values in the weld and HAZ are considerably higher than that of the base metal, for the entire temperature range typical of API code requirement for the gas transmission pipeline. Details of this activity have been published and available in public [13].

The multi-pass layered FSW concept is illustrated in the schematic of a cross-section of the sequence of weld, 4, for a three-layer, five pass weld assembly (Figure 23). Initially, a root weld is made to join the two machined plates, Figure 23(a), location (1). Second, a plate (shown in blue) is inserted above the root pass and butt welded at the edges, Figure 23(b), weld locations (2). Third, a final plate (shown in yellow) is inserted above the first plate and butt welded at the edges, Figure 23(c), weld locations (3). The final welded structure is shown schematically in Figure 23(d) where the weld nuggets are shown in red. It is noted that, in order to produce high-integrity weld, it is necessary that the FSW tool should penetrate to the material underneath for all weld passes except the first pass, as shown in Figure 23(d).

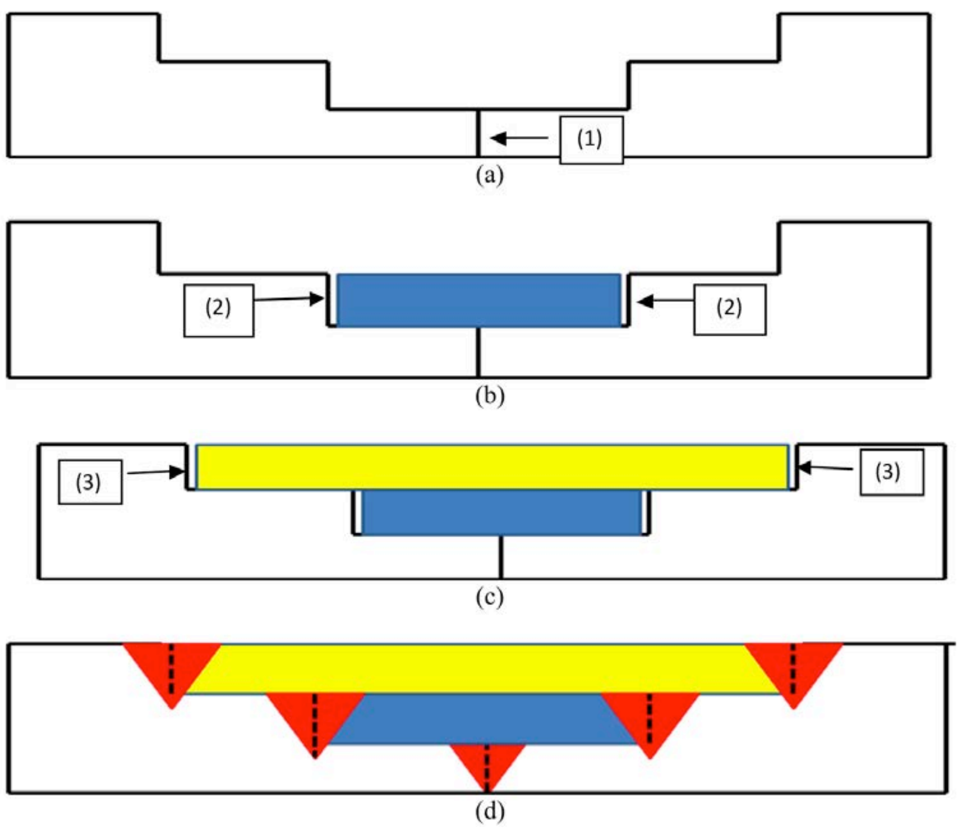
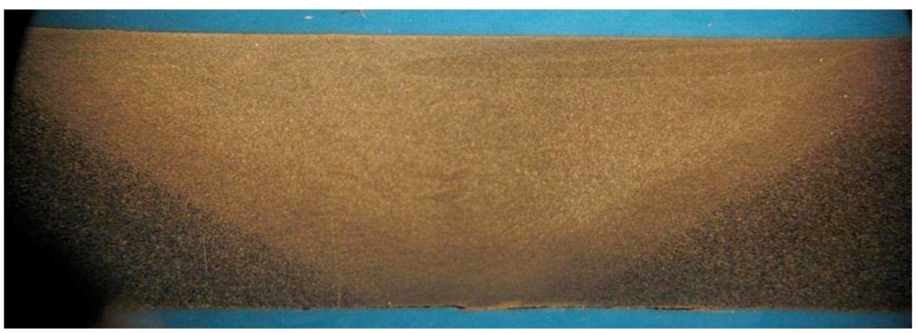


Figure 23. Multi-pass, multi-layered FSW approach for welding thick-sectioned materials.

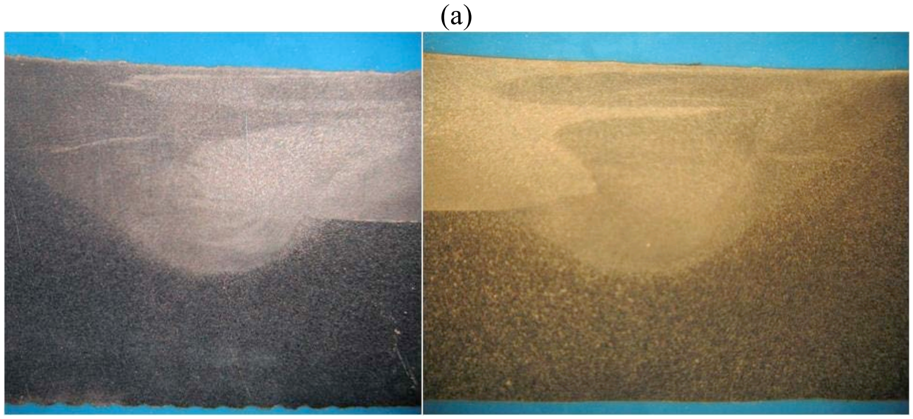
Two different tools were used in the study (Figure 24) to evaluate the effect of tool geometry on the process load: the "standard" tool used previously to weld ¼" thick steel pipes (Figure 24(a)), and the modified tool with a larger pin diameter (Figure 24(b)).

Figure 24. Two different tool geometries used in multi-pass FSW study. (a) "standard" tool used previously (b) modified tool with large pin diameter.

Fully consolidated, defect-free, and full penetration welds were consistently produced. Figure 25 shows examples of the different weld passes made with the multi-pass FSW. The weld zone shows refined grain size (Figure 26), relative to that of the base metal. With the finer grain size in the weld nugget, the weld nugget strength was greater than the parent metal strength.

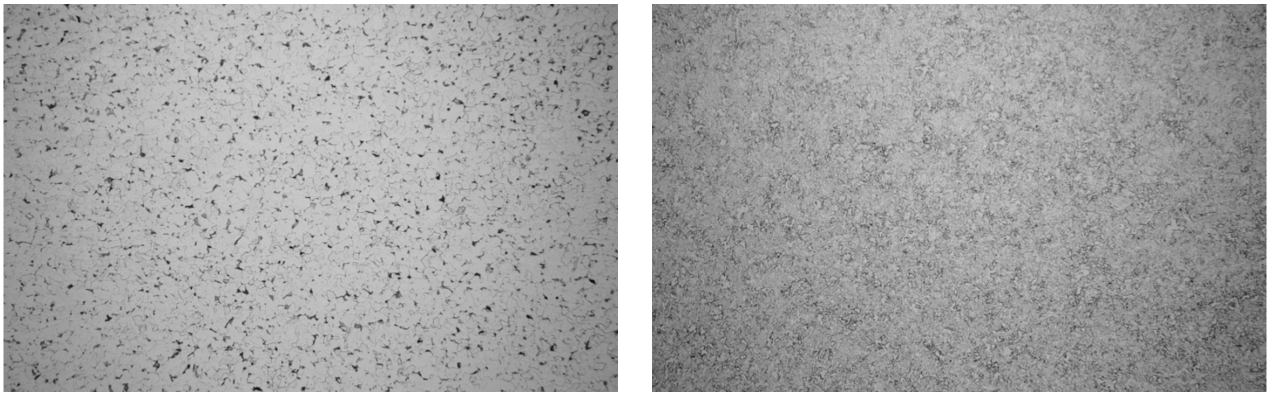


(a)



(b)

Figure 25. Macro cross-sections of defect-free weld passes. (a) full-penetration root pass, (b) subsequent passes



(a) (b)

Figure 26. a) Parent metal microstructure and b) finer grain weld nugget microstructure.

2.1.5 Business and Economic Analyses and Identification of Application and Commercialization Opportunities

During the course of the project, the project team performed extensive business, economic and market analyses to identify the industry's general needs and specific business interest of industry partners of the project. These analyses identified several applications as near-term market and technology commercialization opportunities. The second part of the project was directed to develop technically viable solutions to meet these potentially significant business opportunities.

ExxonMobil conducted a detailed independent analysis of economic incentives for welding steel pipelines using FSW. In this study, the FSW technology was compared to the baseline mechanized gas metal arc welding (GMAW) most commonly used for on-site steel pipeline construction. The analysis included both onshore and offshore construction scenarios. Significant economic incentives for FSW technology were revealed for both onshore and offshore situations. For onshore construction, about a 7% cost savings could be realized when FSW is applied to weld 42" diameter pipes. For offshore construction, the potential cost savings are in the range of 25% for 12" diameter pipes. The findings of the ExxonMobil study are summarized in a recent publication [14].

Further, our FSW technology development has attracted strong interests in nuclear power plant applications. The first likely application is the repair welding and construction welding of nuclear reactor piping systems that are made of steel and other high-temperature alloys such as nickel based super alloys. The basic technology requirement for this potential application was similar to the pipeline construction identified by ExxonMobil in the oil and gas industry.

Another potential application was construction of high-pressure hydrogen storage vessels for the upcoming hydrogen fuel-cell energy infrastructure. A particular application is the layered steel vessels designed to mitigate the hydrogen embrittlement issues of steel vessels [15]. FSW would be a potential fabrication technology for construction of hydrogen embrittlement free hydrogen storage vessels.

Based on the business and market analysis and the technical viability demonstrated through the on-site steel pipeline FSW R&D described in this section, the second part of the project was divided into two phases (Phase II and Phase III). Each of the phases was focused on technology development for a specific targeted application in oil/gas pipeline applications. Phase II was focused on the offshore application that was characterized by small diameter and relatively high wall thickness to diameter ratio. Phase III was on the onshore applications of large diameter steel pipelines. Each phase had a different set of technical challenges and specific requirements that would need to be solved in this project, to lead to the estimated cost reduction in the ExxonMobil economic analysis.

2.2 PHASE II OFFSHORE PIPELINE APPLICATIONS

The onshore large diameter pipeline constructions were originally considered as the primary application target for the flexible FSW technology development during the planning stage of the project. However, ExxonMobil's economic analysis during the first phase of the project suggested that there are even greater potential economic benefits of the FSW technology for offshore applications. Therefore, the project R&D plan and activities were adjusted to support both onshore and offshore applications.

The offshore pipeline is generally characterized by relatively small diameter and high wall thickens of diameter ratio. In this project, 12" diameter steel pipes with 0.5" wall thickness were chosen as the basis for FSW technology development. This was a scale-up in wall thickness from the Phase I baseline studies.

The following key technology developments in Phase II were identified, based on the offshore pipeline construction scenarios outlined in the ExxonMobil economic analysis [14]. They included (1) tool material development suitable for ½" thick steels, and (2) application specific solution (sacrificial anvil) to solve the intermittent root side lack of bonding encountered in the Phase I of the project, as discussed in Section 2.2.1 of this report, (3) upgrading the FSW system used in Phase I to increase the system load bearing capability for ½" steel pipes, and (4) modification of internal mandrel support to accommodate the sacrificial anvil to ensure root side bonding.

The tool material development and the tool design for thick-section FSW was covered in Section 2.1.1.

2.2.1 Improving Root Side Bonding by Use of Sacrificial Anvil

In our Phase I demonstration study on ¼" thick steel pipes, occasional lack of bonding on the root side of a simple pass weld was found. A number of different approaches were investigated in this project for the purpose of consistently producing full a penetration weld to solve the root-side bonding problem. We down-selected the sacrificial anvil approach due to its simplicity for implementation in field welding environment.

A sacrificial anvil concept for flat plate is schematically illustrated in Figure 27. Figure 27a illustrates the workpiece (green) positioned on top of a structural anvil (red) with a thin sacrificial anvil (yellow) inserted into the structural anvil beneath the weld joint. Figure 27b illustrates the FSW tool penetrating through the thickness of the workpiece and into the sacrificial anvil. Following weld completion, Figure 27c shows the workpiece welded to the sacrificial anvil and the structural anvil removed. The dimensions of the sacrificial anvil can be small and different shapes can be used. In this study, 0.889 mm (0.035 inch) thick rectangular steel shim stock was used. It would be preferable to use the same material chemistry as the workpiece. With the sacrificial anvil approach, the potential for a lack of penetration defect is significantly reduced. That is, with the conventional anvil approach, tool positioning must be relatively precise to achieve consistent full penetration without contacting the structural anvil. Conversely, if the tool is allowed to penetrate beyond the pipe wall thickness into a sacrificial anvil, the dimensional tolerance for consistent full penetration depends only on the sacrificial anvil thickness and this tolerance can be large.

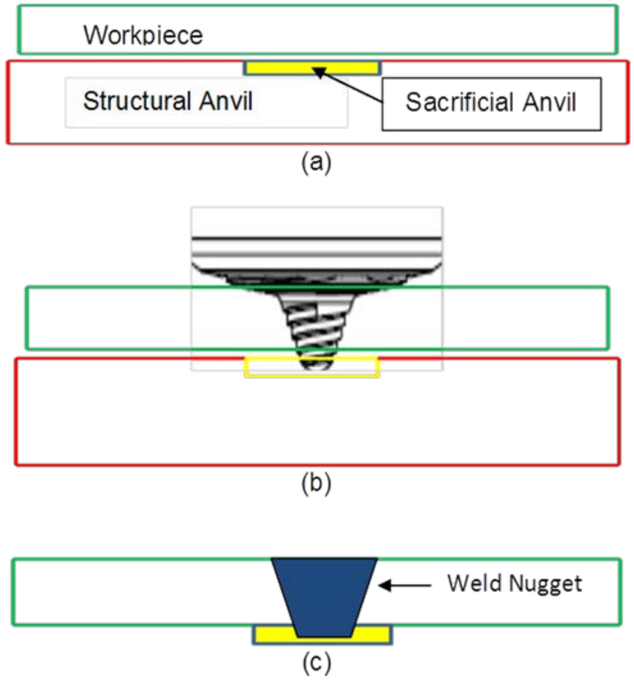


Figure 27. Schematic illustration of FSW with a sacrificial anvil.

Figure 28 illustrates the weld approach whereby a sacrificial anvil is secured into a cavity in the structural anvil and the workpiece positioned such that the weld joint is centered on the sacrificial anvil. This test setup is designed for pipe geometry. For machining convenience, a relatively wide sacrificial anvil was used. This is not the approach proposed for production but is sufficient to illustrate merits and/or deficiencies of the approach. Welding was performed using force control at a load of 14,000 lbs for the large FSW tool used to weld the 12 mm (0.5 inch) wall thickness pipe. When using the sacrificial anvil approach, the sacrificial anvil remains attached to the inner diameter of the pipe following FSW. The use of the sacrificial anvil necessitates the modification of the internal mandrel (the structural anvil). With the new internal support design, clamping was achieved with wedge movement in the horizontal direction. In addition, a groove was machined into the structural anvil portion of the new internal mandrel to accommodate the sacrificial anvil.

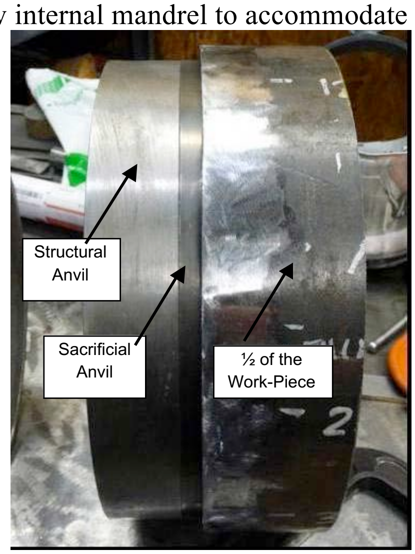


Figure 28. Illustration of the sacrificial anvil weld setup

2.2.2 Demonstration for Offshore Pipeline Welding

The pipeline steels used included both X52 and X65 carbon steel with dimensions ~32 cm (12.75 inch) outer diameter and 12.7 mm (0.5 inch) thick wall pipe.

Examples of welding in operation are shown in-progress in Figure 29 and Figure 30. Figure 30 shows the excellent surface finish on the weld crown, i.e., no undercut, very little flash, and a very smooth surface finish. Once welding is initiated, the welds were performed in load control (14,000 to 15,000 lbs). These high loads are due to the large shoulder diameter of this tool design. Weld parameters included a weld travel speed of 1.4 mm/s (4 ipm) at a tool rotation rate of 250 rpm. However, slight manual adjustments were made during the weld.

Figure 29. Friction stir weld in-progress with sacrificial anvil approach.

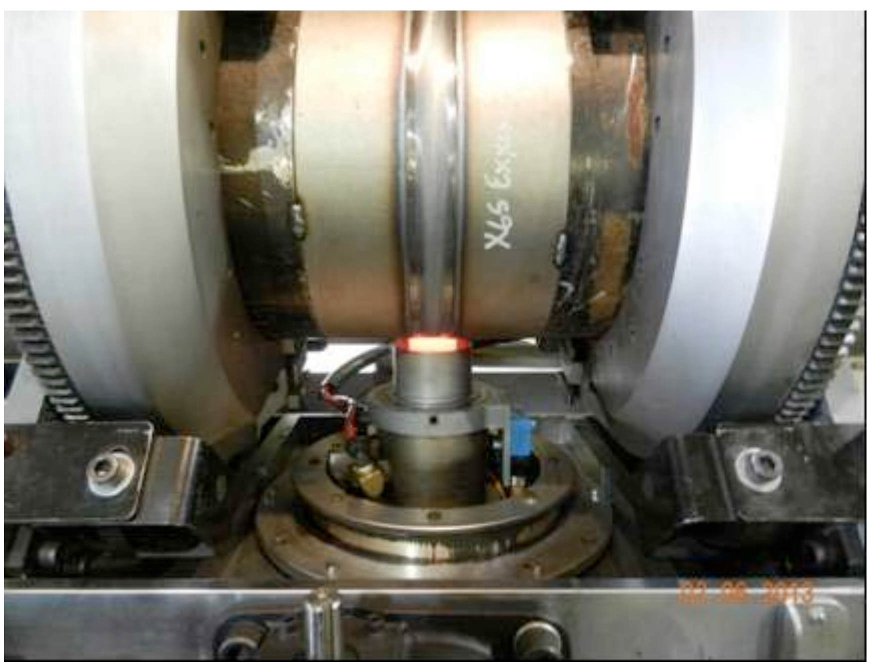


Figure 30. Friction stir weld in-progress showing the excellent surface finish.

Figure 31 is a macrograph of a weld cross-section with the sacrificial anvil attached. As shown, i) the weld nugget is defect free, ii) a full penetration weld is achieved, and iii) the sacrificial anvil is "welded" to the weld root. It is possible the sacrificial anvil can be easily removed manually.

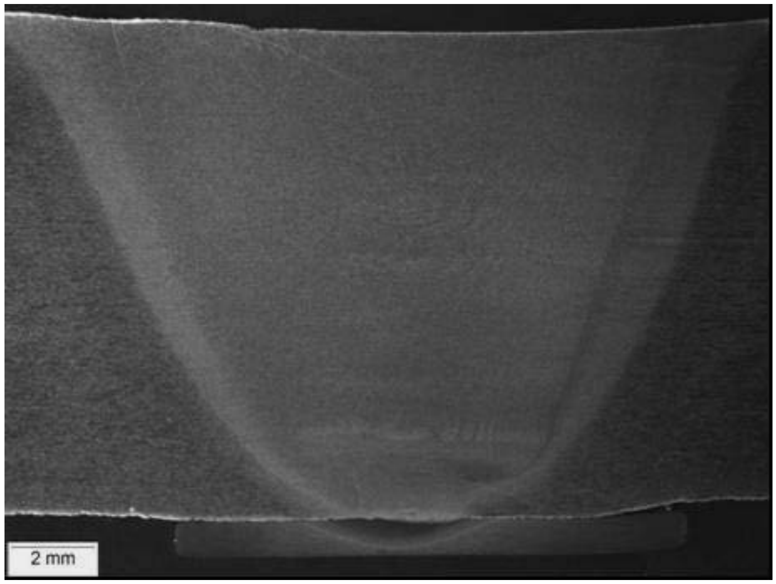


Figure 31. Macrograph of friction stir weld using sacrificial anvil approach.

Radiography, metallography, and root-bend tests illustrated the integrity of the welds. When performed properly, consistent full penetration welds were achieved. Limited mechanical testing was performed to provide mechanical properties based on API 1104 testing guidelines. These results demonstrated that the sacrificial anvil approach has the potential to achieve *consistent* full penetration. However, additional improvements could be considered in the future including: 1) a better approach to secure the sacrificial anvil, 2) reduce the size of the sacrificial anvil, 3) change the shape of the sacrificial anvil, 4) alter the FSW tool design to improve heat transfer across the lap interface, and 5) use the same material for the sacrificial anvil as that of the pipe.

2.3 PHASE III ONSHORE PIPELINE APPLICATIONS

In Phase III, the flexible friction stir welding technology was further developed and demonstrated for onshore steel pipeline applications. The following key developments were carried out, which were necessary to realize the potential cost savings for onshore pipeline construction outlined in the ExxonMobil economic analysis [14].

- Eliminate the internal mandrel support, which is a productivity bottleneck for onshore pipeline welding construction.
- Scale-up the field-deployable FSW system for welding large-diameter with corresponding increase in wall thickness of steel pipelines. This includes additional control modes, and the system redesigns for mandrel-less operation.
- Develop tool (material and geometry) capable of welding up to 20mm thick steels.
- Develop welding fabrication process window to produce defect free, full penetration welds per API 1104 standard guidelines.

The tool material development and the tool design for thick-section FSW was covered in Section 2.1.1.

2.3.1 Arc Root Pass Weld to Eliminate Internal Mandrel Support

In a recent study on pipe girth welding, friction stir welding (FSW) was shown to significantly reduce pipeline construction costs compared to gas metal arc welding [14]. Approximately 5-10% savings in pipeline construction costs were estimated for onshore, large diameter pipelines. However, for onshore construction, use of an internal mandrel as shown in Phase I and Phase II of this project does not appear to be an economic construction scenario.

Alternatively, a single pass root weld by means of arc welding on the inner side of the pipe was proposed by the ExxonMobil team to replace the use of the internal mandrel during welding. The concept is shown in Figure 32. The primary function of the arc root pass weld was to provide the structural integrity to sustain the plunge force of the friction stir weld, a function of the internal mandrel was designed for. In fact, the use of a back anvil support to counter the high plunge force was in the original FSW patent and widely followed in butt welding situations in the invention of FSW. In this regard, the concept by the ExxonMobil team of using an arc root pass weld was an ingenious innovation that received an US patent [16].

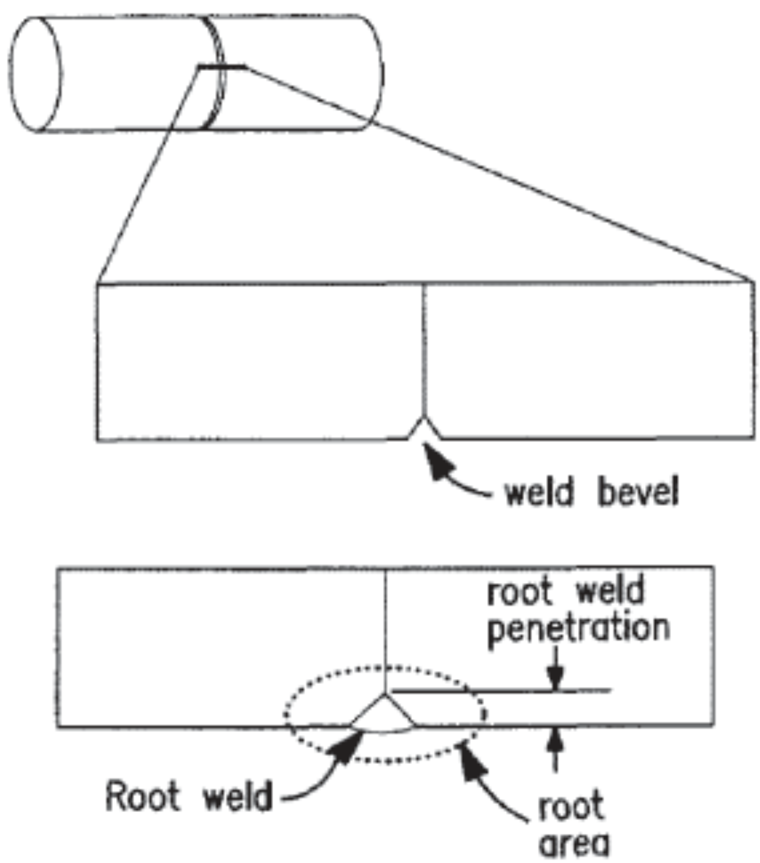


Figure 32. Arc root weld pass with friction stir welding (the arc root weld pass typically has 3-5 mm penetration).

Furthermore, the arc root pass weld would also eliminate the lack of root side bonding issue that have been the most common weld flaw associated with friction stir welding, as experienced during the Phase I of the project and reported in literature.

One of the main objectives in Phase III was to develop the specific technical know-hows and the FSW hardware system to implement the arc root pass weld approach to eliminate the use of the internal mandrel. *Most importantly, the ability of the root arc weld to support and prevent collapse of the weld zone during FSW needs to be developed and demonstrate.* The relatively large diameter of the onshore pipelines made it possible to use commercially available gas metal arc welding equipment to make the arc root pass weld.

The development and demonstration of the field-deployable friction stir welding system were based on welding 30 in (76mm) diameter and 0.625 in (15.9mm) thick-wall steel linepipes, at the suggestion of ExxonMobil.

2.3.1.1 Making internal arc root pass weld

An image of the internal root welding taking place is shown in Figure 33. The welder is controlling the arc on the video screen while a boom holds the welding torch inside the rotating pipe. 1G welding would not be how the welding would be conducted in the field. In the field, an internal root weld would be made in the 5G position (a weld torch would travel around the inside of the pipe instead of the pipe being rotated).

Figure 33. Photograph showing the internal arc weld in-progress.

Through a number of experiments, the gas metal arc weld procedure was developed to process the root pass weld with sufficient penetration necessary to resist loads at elevated temperature during FSW. The root pass penetration was at 5 to 6 mm for the 30 in diameter and 0.625 in thick steel pipe.

2.3.1.2 Field deployable FSW system for onshore pipeline construction

In Phase III, the field-deployable FSW system underwent major modifications to accommodate large diameter (76 cm [30 inch]) linepipe. This scale-up for larger diameter linepipe required design and fabrication of major components. A number of these components are illustrated in Figure 34 and their position in the FSW system identified. In addition, a new frame and other supporting system was designed and fabricated to accommodate the increased pipeline size and to support the increased weight. The new orbital FSW system fully assembled is shown in Figure 35.

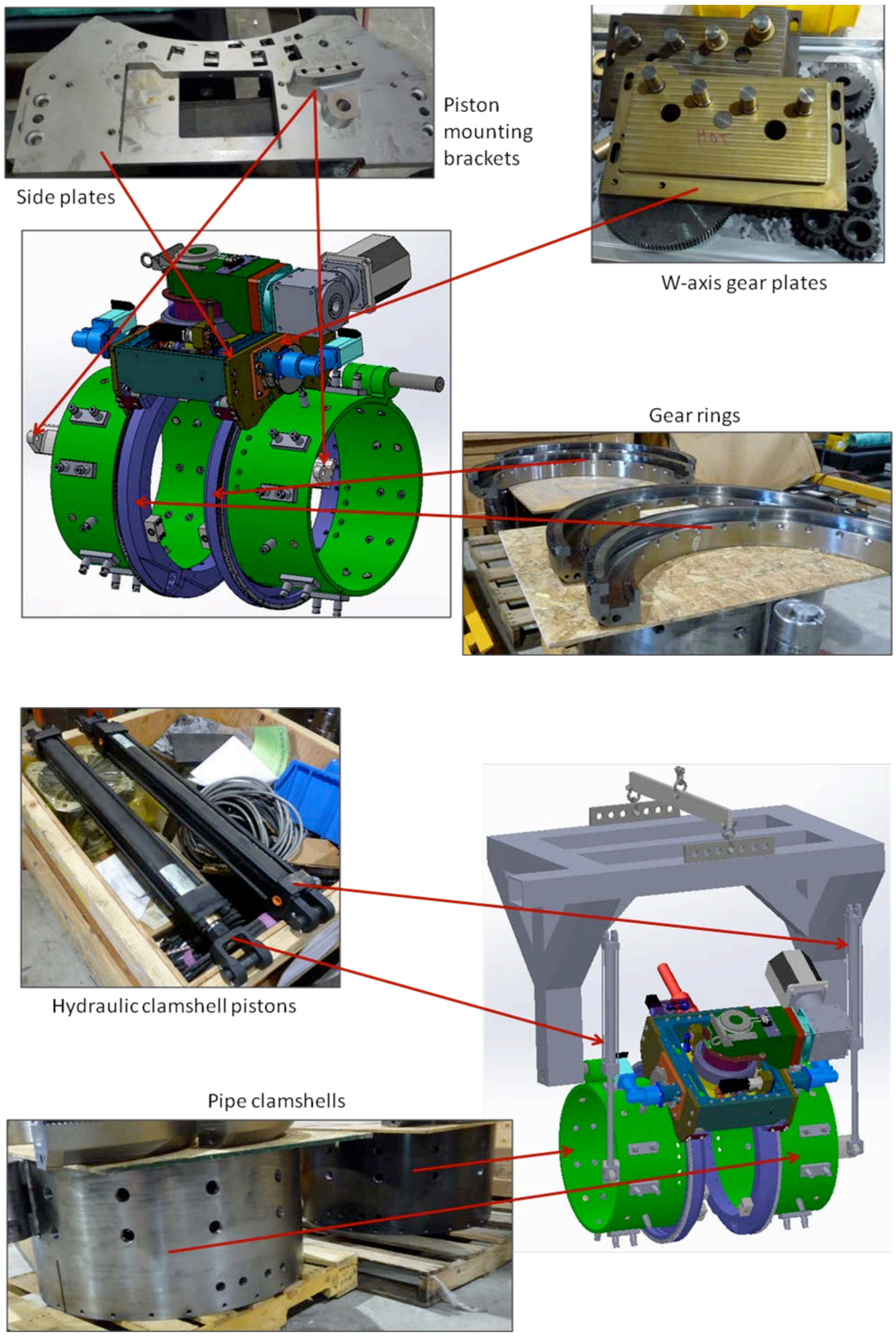


Figure 34. Design and fabrication of the FSW system for 30-inch diameter onshore steel pipeline construction.

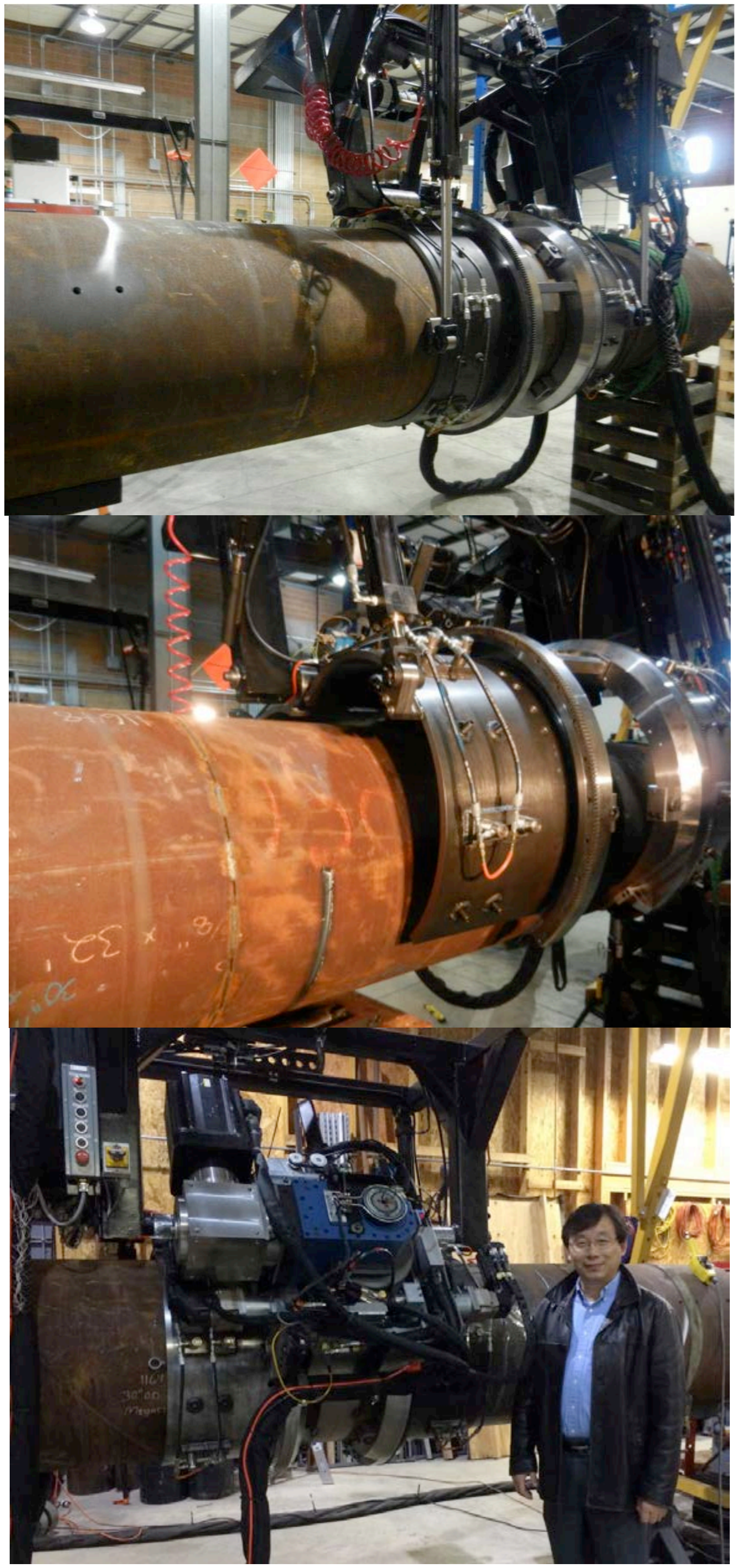


Figure 35. Views of full assembled field-deployable FSW system for welding 30 inch diameter steel pipes.

2.3.1.3 FSW demonstration on 30 inch diameter steel linepipes

Using the FSW system fabricated in Section 2.3.1.2, and lessons learned from previous studies (optimum tool designs and tool materials, weld parameters, plunge procedure, anvil materials, root arc weld procedure, etc.,) friction stir welding experiments were carried out on 30-in diameter, 0.625 in thick X70 line-pipe steel. Weld parameters included a weld travel speed of 1.3 to 1.7 mm/sec (3-4 ipm) at tool rotation rates of 175 to 250 rpm. Appropriate tool offset was determined, which required on a curved surface to achieve the optimum contact between the tool shoulder and the pipe surface. Manual adjustments to these parameters were made during welding based on the weld crown surface appearance. Welds were completed using force control at loads ranging from 7,938 to 8,164 kg-f (17,500 to 18,000 lbs).

Figure 36 shows the friction stir welding in-progress on the 30 inch diameter X70 steel linepipe. For much of the weld length, the crown surface is excellent, i.e., a smooth surface topography, no undercut and no weld flash (Figure 37).

Figure 36. FSW in-progress on large diameter heavy wall X70 steel linepipe.

Figure 37. Surface topography on the crown surface following FSW.

Figure 38 is another view from the inside of the pipe showing the inner surface of the pipe and the arc weld root pass during FSW. The glow from the friction stir weld can be seen on the inner surface of the pipe. Although the inner surface is hot, the root arc weld provided sufficient support such that the weld zone did not collapse under the FSW loads. This result is significant and validates the arc root pass weld approach as a viable method to perform FSW without the use of an internal mandrel. There can be modest or drop-through on the inner diameter surface during the tool plunge. Modifications to the plunge procedure should be considered to minimize this inner surface deformation.

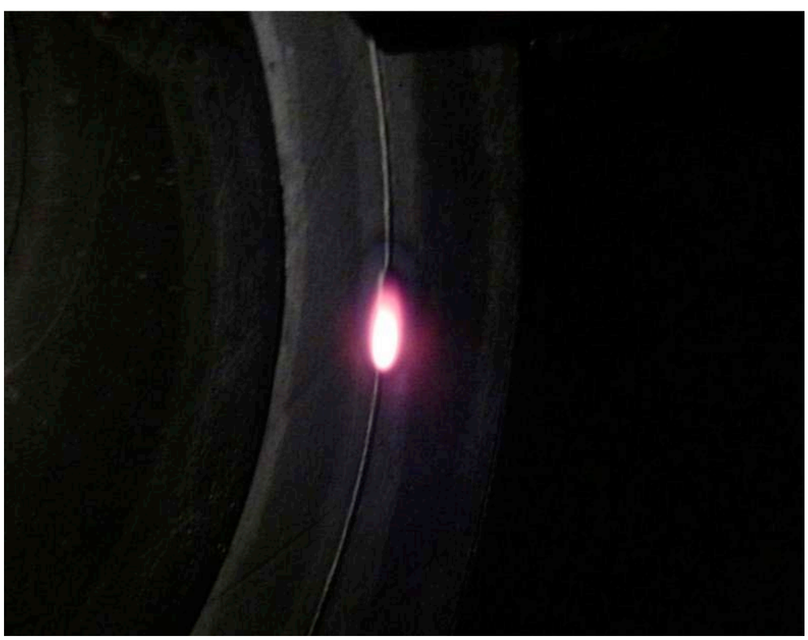


Figure 38. Welding in progress viewed from inside the 30” diameter steel pipe.

2.3.1.4 Weld property and quality assessment

Friction stir welds completed in the demonstration welding trials in Section 2.3.1.3 were evaluated per the guidelines of the API 1104 standard. Nondestructive tests included visual and radiography inspections. Destructive tests included metallography, cross-weld tensile properties, side bend, root bend, and Charpy impact as a function of temperature from -112°F to 73°F (-80°C to 23°C).

Radiography

Radiography was completed by an API certified third party, Fugro, Houston TX, using API 1104 guidelines and acceptance criteria. For two welds inspected, no indications were identified. All welds were acceptable per API 1104 acceptance criteria.

The exit hole appeared to be defect free and radiography failed to locate defects. Thus, volumetric tunnel defects were not expected. Albeit some samples were free of flaws and defects, occasionally, there were small flaws located at the intersection of the arc weld and friction stir weld. These flaws became visible following side bend tests.

Side Bend Tests

Eight side bend tests were completed by an API certified third part testing house, Exova, per API 1104 guidelines. Six were acceptable and two tests were unacceptable. Figure 39 illustrates a typical macrograph and a micrograph of a side bend test that passed. A small flaw opens at the intersection between the arc weld and friction stir weld. This is considered to be a flaw and not a defect because the sample passed the side bend test per API 1104 requirements. However, two samples did fail the side bend test and it appeared the cause for failure was a defect similar to but larger than that shown in Figure 39.

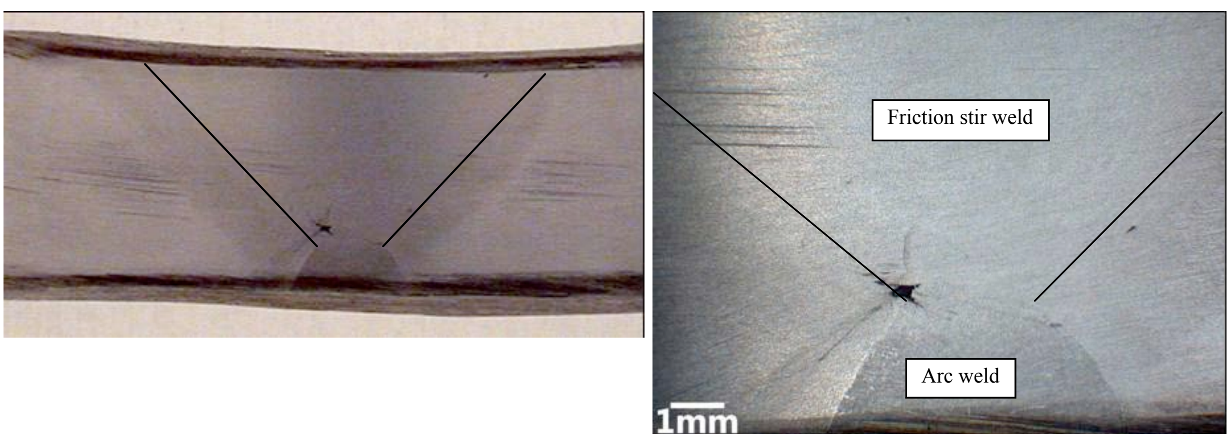


Figure 39. Macrograph and micrograph of a side bend test sample illustrating a small flaw located at the intersection between the arc weld and friction stir weld that opens in tension. This sample passed the side bend test.

Further examination of the failed welds revealed that the failure were related to the abnormal softening of the arc root pass weld when it was intersected with the original spiral weld in making the steel linepipe. The details of this investigation are given in [17].

Root Bend Tests

For a wall thickness >12 mm (0.5 inch), root bend tests are not specified by API 1104 but instead side bend tests are required. However, because one of the objectives of this project was to assure consistent full penetration, root bend tests were performed to demonstrate the completion of this objective. 6 root bend tests were performed. In all cases, there was no indication of a lack-of-penetration defect on the tensile surface.

Cross-Weld Tensile Test

The average tensile strength from a total of five cross-weld tensile specimens was 652.5 MPa, respectively. For comparison, the tensile strength of the base metal is 677 MPa based on the mill certification. It was also found that excessive thinning of the crown surface of the FSW, which would be visible upon examination of the weld surface, would reduce the tensile strength by as much as 70MPa, or about 10% of the base metal strength, representing a under matched weld region. This suggests that the thinning of the weld zone would be minimized during FSW. It should be noted that under-matched welds are not uncommon in high-strength pipeline steels.

Charpy Toughness

The average Charpy toughness results are presented in **Table 2** as a function of temperature. Steels show a ductile to brittle transition with decreasing temperature and a Charpy test is a reasonable method to identify the transition temperature and the notch toughness. The test sample had a 2 mm deep notch with a 0.25 mm radius on the side opposite the impact. In general, the Charpy toughness results for the friction stir welded linepipe were relatively consistent and demonstrated a weld zone with considerable toughness maintaining good toughness from 23 to -20°C before the toughness begins to decrease. Excellent toughness is maintained even at -60°C with the ductile to brittle transition temperature between -60 and -80°C.

The high energy absorbed values are substantiated by high levels of percent shear on the fracture surface as well as high levels of lateral expansion. Lateral expansion is a measure of the ductility of the specimen. When a ductile metal is broken, the test-piece deforms before breaking and material is deformed out on the sides of the compression face. The amount by which the specimen deforms in this way is measured and expressed as millimeters of lateral expansion. As shown, the weld nugget samples were ductile at all temperatures down to -60°C and even at -80°C there was some ductility.

Table 2 Charpy toughness results as a function of temperature

Temperature (C°)	Energy Absorbed (J)*	Percent Shear	Lateral Expansion (mm)
23	165	90	76
0	180	100	78
-20	187	70-80	74
-40	144	60-90	61
-60	125	60-80	60
-80	48	10-30	23

*Average of three tests

3. BENEFITS ASSESSMENT

3.1 TECHNOLOGY IMPACTS ASSESSMENT

The full energy savings potential and economic benefits of friction stir welding can only be realized if this process can be readily applied to a variety of engineering materials without limitations in structural complexity and dimensions – the flexible FSW technology developed in this project offers such possibility.

Current FSW applications are limited to Al alloys and other low-temperature materials. Advancing the use of FSW to higher temperature materials will bring about significant economic and energy benefits. Perhaps the most significant benefits relates to the elimination of certain inherent difficulties posed by fusion welding the most common structural materials. The majority of industry structures are primarily made of high-strength steels or other high-performance structural materials. The fusion welding of these materials involves such problems as hydrogen cracking and solidification cracking; therefore, large resources are expended for inspection and repair to ensure adequate quality. FSW has the potential to eliminate these types of fusion welding defects and the associated remedial measures. Another reason that advancing FSW to high-temperature materials will provide significant benefit relates to applications involving advanced materials such as intermetallic alloys, Ni-based superalloys, titanium alloys, oxide dispersion strengthened (ODS) alloys, and metal matrix composites. These high-performance alloys are very difficult, if not impossible, to fusion weld. FSW, a solid-state joining process, is ideally suited for joining these materials. The development of high-temperature FSW system in this project offers advantages to eliminate conventional fusion welding limitations.

A comparison of the survey statistics of the aluminum and steel consumptions in the U.S can illustrate the market and economic scale that the flexible FSW technology could potentially access. In 2006, the consumption of finished steel products in the U.S. was 120 million metric tons [18,19], about 10% of the worldwide production. For the same period, the use of aluminum was about 6.5 million metric tons, about 17% of the worldwide production [20]. The business interests and the market potential for advancing FSW technology for steel structure construction are clear from this comparison. Indeed, *steel structures were the primary focus of the technology development*. This is consistent with the interests of the project industrial partners.

The ability for on-site welding and the ability to join thick section materials are another area of application where the field-deployable FSW technology can excel. These joining features are applicable across a number of industry sectors: aerospace, automotive, shipbuilding, power generation – nuclear and fossil, oil & gas, and chemical, as well as being useful for government agencies such as DOE, the Department of Defense (DOD) and the National Aeronautics and Space Administration (NASA). In the US, potential applications of FSW identified by the commercial and military users include: (1) construction of high strength steel pipelines for various energy-related applications (hydrogen, natural gas, and liquid petroleum products), (2) repair of irradiation-damaged stainless steel structures in nuclear power plants (nuclear industry), (3) joining high creep-resistant ODS steels, vanadium alloys and dissimilar materials for fusion reactors and other high-temperature applications (power generation, petrochemical industry), (4) fabrication and repair of aero engine components made of Ni-based superalloys and mechanically alloyed materials (aerospace, DOD/Air Force), (5) titanium-alloy intensive aircraft, spacecraft, and Navy ship superstructures (Air Force, NASA, Navy), (6) super austenite alloy (such as Al-6XN) for Navy ship structures (Navy), and (7) ultra-high-strength steels for light weight, high performance auto vehicle body-structures (automotive industry).

It is the aspect of on-site welding fabrication that has brought the industrial partners to this project. ExxonMobil are keen on joining structural steels for oil and gas pipelines, as well as for other large steel structures such as deep-water risers and liquid natural gas ships. MegaStir, as FSW equipment manufacturers and tool makers, are attracted by the tremendous potential of this new market. The market potential will be further illustrated with the example of pipeline construction.

3.1.1 Example: Pipeline Welding

The example pertains to the construction of natural gas transmission steel pipelines to satisfy the increasing energy needs of the country. Natural gas is one of the fastest growing energy sources in the United States. Nearly all natural gas is transported by a network of 2,000,000 miles of pipelines [21]. The consumption of natural gas is projected to increase to 29-33 tcf/year (trillion cubic feet per year) in 2015 from 22 tcf/year in 1997 under a business-as-usual scenario [22]. The demand for natural gas in electric utilities and non-utility generators could double or triple in next 20 years. One of the reasons for the appeal of gas is related to its capabilities as a clean energy source. When compared to other technologies such as coal based energy, the carbon emission advantage of gas is notable. The rapidly increasing demand for gas will require the construction of new transmission pipelines and because gas reserves are increasingly located in remote locations (e.g. arctic and deepwater), many of these pipelines will be large diameter and extend over long distances. Long distance, large diameter pipelines consume tonnages of steel unparalleled in engineering endeavors and require the mobilization of large work forces. New energy efficient and cost effective construction technologies will be necessary to produce economic solutions for future pipeline projects. According to the DOE Federal Energy Regulatory Commission [23], major pipeline projects on the horizon account for over 7200 miles pipeline new or expansion constructions.

Adjusted to today's dollars, the construction cost of the 800-mile long trans-Alaska oil pipeline is approximately 10 billion US. The proposed Alaska Gas Pipeline Project, a 3,600-mile structure, has an estimated cost on the order of 20-30 billion US. Welding is extensively used for construction of onshore pipelines (Figure 40). It accounts for about 10 to 15% of overall project cost and remote construction places ever increasing pressures on project economics. In general, the cost of major oil and gas projects range from a few billion to tens of billions of dollars, therefore even small advances in construction efficiency can potentially have large impacts. Advancements in FSW technology have the potential for such impacts with respect to the delivery of oil and gas to the US energy market.

Figure 40. On-site construction of natural gas pipelines in an ExxonMobil pipeline project.

Extensive arc welding and labor intensive nature of construction are evident in figure 40. From top left clockwise: Overview of the construction site; pre-heating of pipe to prevent hydrogen induced cracking during arc welding; manual arc welding; welded pipe rolling in terrain before buried underground.

As is done currently with natural gas, an extensive pipeline infrastructure would also be considered as the most cost-effective and energy-efficient means to deliver hydrogen in the future hydrogen energy economy [24]. In this regard, advanced FSW technology would be an important enabling manufacturing technology in the construction and conversion to the hydrogen based energy infrastructure.

However, today's FSW technology is generally applied inside a welding shop, on a gantry type of systems. These systems are not suitable for on-site construction of energy transmission pipelines showing in Figure 40. This example clearly illustrates the need for field deployable FSW technology, and its huge economic benefits to the nation's energy industry. If FSW can be transformed into a portable joining technique applicable to high temperature materials, it has the potential to enter markets currently not serviced.

3.2 POTENTIAL ENERGY, CARBON, ECONOMIC AND ENVIRONMENTAL BENEFITS

Welding is one of the most important and widely used fabrication technologies in modern industry.

Currently, in the United States, over 50% of the gross national product depends on welding. Durable goods manufacturing industries in which welding is a critical enabling technology accounts for 90% of total U.S. durable goods production [25]. Many industries that employ welding processes provide the backbone for our nation's defense, infrastructure, and economic well-being. Advances in welding efficiency have the potential to provide very large energy savings and environmental benefits.
In this section, some broad characterization is provided to describe the energy, economic and environmental benefits that would be impacted by the successful development and commercial implementation of the flexible hybrid FSW technology. In addition, specific examples will be given to further demonstrate the potential benefits of the technology.

3.2.1 Basis for Benefit Analysis

The baseline welding technology used for energy consumption, environment and economic benefits analysis is the arc welding processes which include gas metal arc welding, submerged arc welding, shielded gas arc welding, gas tungsten arc welding. The arc welding processes are the most widely used welding processes in the industry. The flexible FSW technology developed in this project would be expected to displace the arc welding processes in a variety of applications. They include steel pipeline construction, fabrication and repair of military vehicles as well as other example applications given in previous sections.

In general, energy input can vary considerably for a given welding application. A weld can be made either "hot" with more energy input, or "cold" with less energy input, depending on a number of practical considerations. This is true for both baseline arc welding as well as FSW. In addition, the welding conditions (therefore the energy input per unit volume of weld) can vary considerably from one end of the welding fabrication spectrum to the other (such as pipeline construction verses shipbuilding verses gas turbine welding). Therefore, the energy analysis of welding fabrication can be complicated.

For simplicity, a "bottom-up" and unified approach is adopted here to compare the energy consumption in FSW and arc welding process. Such an approach provides reasonably accurate comparison while avoiding the complicity and ambiguity in the energy analysis associated with specific welding cases.

The energy analysis adopted here consists of two major steps. The first step is to determine the unit energy consumption for both the baseline welding technology and the new welding technology. This included determination of the theoretical minimum energy requirements for both current and new process, the actual average energy usage by U.S. industry for the current technology, and the estimated energy usage for the new technology. In the second step, representative U.S. domestic market figures are used, together with the unit energy usage data from the first step, to demonstrate the energy of the new technology.

Similar approaches are also adopted in the analysis of the economic and environmental benefits.

3.2.2 Energy Benefits

The energy benefit analysis consists of three parts: the energy usage during welding, other energy usage as part of welding construction, and the energy savings as result of reduced material usages due to improved weld properties.

3.2.2.1 Energy requirement during welding

The theoretical minimum energy requirement for welding fabrication can be estimated from the temperature changes in the weld region and the process efficiency.

The theoretical minimum energy required for arc welding is:

$$E = \int_{T_1}^{T_2} C_p dT + \Delta H$$

where Cp is the heat capacity of the material, T_1 is the ambient temperature, and T_2 is the welding temperature of the molten weld pool which typically ranges from 500 to 3000°C above the melting temperature of the material. ΔH is the latent heat of fusion required to melt the material.
The theoretical minimum energy required for the solid-state FSW welding can be similarly estimated as:

$$E = \int_{T_1}^{T_2} C_p dT$$

The welding temperature in FSW is typically about 75% of the melting temperature of the material. Note also that the latent heat of fusion is not required in the solid-state joining process.

Table 3 shows that comparison of the theoretical minimum energy requirement between the FSW process and the baseline arc welding process. The energy saving potentials are very significant in the range of 60 – 70% for the common structural materials (steel, Al, Mg and Cu alloys), as the solid-state FSW process eliminates the need to melt the material and reduces the welding temperature. While these energy reduction numbers are surprising at first glance, similar energy savings figures have been reported recently by the automotive industry. Mazda reported over 99% energy savings when friction stir welding of Al alloys is compared with the conventional electrical resistance spot welding (a process involving melting of the material being welded) [12].

Table 3 Comparison of Theoretical Minimum Energy Consumption for 1kg of Weld Metal

Material	Specific Heat (kJ/kg-C)	Latent Heat of Fusion (kJ/kg)	Melting Temp (C)	Arc Welding Temp (C)	FSW Temp (K)	Arc Welding Energy (kJ/kg)	FSW Energy (kJ/kg)	Energy Saving
Al	0.9	397	660	1160	495	1418	423	70%
Fe	0.45	247	1538	2538	1154	1378	508	63%
Cu	0.4	206	1085	1885	814	950	316	67%
Mg	1	358	650	1150	488	1483	463	69%

** The superheating in the weld pool in arc welding varies from material, and typical values are used.*

It is important to note that the above estimates only consider the energy required to bring the weld metal to the welding temperature. In reality, much more energy than the above theoretical minimal is required to maintain the welding temperature, as the heat will be lost to the surrounding metal through heat conduction in the metal (the major portion) and to the surrounding environment (a small fraction). For the same material, the energy loss to the surrounding materials is a function of the temperature difference between the welding zone and the base metal according to the physics of heat transfer. Therefore, it is expected that the percentage of energy loss of the FSW process would be similar to, if not less than, that of arc welding processes as the temperature difference in a FSW process is less than that in the arc welding process (**Table 3**). This is consistent with the experience in friction stir spot welding by the industry [12].
To illustrate the energy savings during weld operations, the survey results from a major U.S. heavy equipment manufacturer (name withheld for business reasons) are used. This company uses approximately 15 million pounds of weld wire and electrodes annually in its arc welding fabrication.

Assuming that 20% of the arc welding operation will be replaced by FSW in five years, 3 million pounds of weld wire will be saved. Typically, the average energy required to deposit one-millimeter of linear weld is 1.5 kJ (typical arc welding condition: 20 volts, 300amps and 10 in/min travel speed) for a weld wire of 1.3 mm diameter. Three million pounds of weld wire would require use of 261 million Btu. *A 50% energy savings due to the use of the solid-state FSW process would result in energy saving of 130 million Btu for one major U.S. manufacturing company.*

According to a study sponsored by DOE Advanced Manufacturing Office [26], the annual energy usage by the welding industry was 129 trillion Btu in year 2000, the 2nd highest among the supporting industry after the heat-treating industry. A 25% reduction of energy consumption would result in 32 trillion Btu savings annually. Such energy savings would be highly achievable based on the above single company analysis, if FSW can be commercialized and fully utilized in construction of steel and other high-temperature materials.

3.2.2.2 Other energy consumptions as part of welding fabrication

The energy used to melt weld metal (or to heat the weld in the case of FSW) is not the only energy used during welding fabrication. For high-strength steel structures such as pipelines and pressure vessels, pre-weld heating and post weld heat treatment are part of mandatory requirements to prevent hydrogen induced cracking. Other materials (such as nickel alloys) also require pre-weld heating and post-weld heat treatment to prevent other types of solidification related quality problems (such as solidification cracking) during fusion welding. In arc welding, hydrogen enters the molten weld pool and become supersaturated at room temperature which causes hydrogen cracking in steel welds. For the solid-state FSW process, the molten weld pool does not exist and hydrogen entering the metal is no longer a concern. Expensive heating operations can be eliminated through use of FSW. The energy savings, as well as cost and productivity, from such efficiencies can be very significant by considering a typical heat treatment procedure for hydrogen induced cracking prevention in steel:

- Preheat the weld and surrounding area to 100°C before welding
- Maintain interpass temperature of the weld metal above 100 - 200°C between weld passes.
- Post-weld heat treatment: 230°C for 1hour per inch of thickness.

Although the pre-heating and post-weld heat treatment temperatures are relatively low compared to the welding temperature, the area of material to be heated are much greater than the weld pool region (see Figure 40 for an illustration of pre-heating of pipeline before welding). In some cases, the entire structure will be heated and maintained at temperature for several hours. Therefore, the energy usages by pre-heating and post-weld heat treatment are generally several times higher, and up to an order of magnitude higher than the energy used during welding.

Since the majority of industrial structures are constructed with high-strength steels, energy savings by eliminating the need for pre-heating and post-weld heat treatment in FSW process will be tremendous.

3.2.2.3 Energy savings from reduced material usage

Welding thermal cycles generally result in a weld joint with microstructures and material properties that are different from the parent metal. Because the parent metal microstructure and properties are optimized for the intended application, the inferior properties in the weld region can be a limiting factor in designing a structure for demanding services. The weld metal degradation is especially an issue for high-performance engineering materials. For structural steels, the strength reduction in the weld region depends on the steel chemistry and strength, with higher strength steels suffering higher degrees of strength reduction. The strength in the weld region of some ultra high strength steels can be as low as 60% of the parent metal [27]. For this reason, the wall thickness of a structure may be increased simply to reduce the service stresses.

The improved weld properties by FSW as shown in Figure 3 suggest the feasibility to avoid or reduce the design penalties due to weld property degradation. Furthermore, it also allows higher strength steels being used without greater design penalties. This will result in less tonnage of steels used for the same design load. It is estimated that for certain nuclear power generation reactors, up to 20% of structural steel can be saved if weld property degradation can be eliminated.

In the oil and gas industry, typical steel grades for use in pipeline construction range in strength from about 52 to 70 ksi. The API grades X60 and X65 represent "workhorse" materials. The Alliance pipeline project is perhaps the most notable long distance pipeline constructed recently (late 1990's) and it used X70 pipe steel. The Cheyenne Plans project (a 380 mile pipeline constructed in 2004) used X80 while future mega-projects like those necessary to deliver Alaska gas are considering X100 and X120 grades. For the same design pressure, the required pipe wall thickness is in inverse relation to the pipe grade. Using a 48-inch diameter 0.75-inch wall X100 linepipe for a 1500-mile pipeline versus a 1-inch wall X70 pipe would save 44,870 tons of steel. Assuming 18 million Btu energy usage for each ton of steel produced [28,29], the total energy savings in this one project alone is about 0.8 TBtu (trillion Btu). The increasing demand for natural gas is likely to necessitate the construction of several major pipelines in the coming decades. The use of X120 steels would save 71,795 metric tons of steel or 1.3 TBtu of energy.

According to DOE Federal Energy Regulatory Commission, over 7,200 miles pipelines have been applied for permit or were close to apply for permit for construction as major new or expansion pipeline projects [23]. Most of these projects are expected to complete in 10 years. The steel strength upgrade due to the use of FSW over the baseline arc welding process would be in several trillion Btu range.

Clearly, the flexible FSW technology, once successfully developed and commercialized, can readily meet the 20% reduction goal of the manufacturing energy consumption. It can also meet the 15% of increase in material yield by using less amount materials in pipeline and other structural constructions. Considering the broad market that its can apply in, the adoption of the energy-efficiency FSW technology will result in very large amount of energy savings in welding steel structures. With the concerted efforts in this project and future follow-on development and commercialization work by vested parties, one can expect that the FSW will begin to be used in steel structure constructions in five years.

3.2.3 Environment Benefits

The environmental benefits associated with the FSW technology over the conventional arc welding processes can be evaluated in two aspects: the elimination of harmful welding fumes, and the reduction of greenhouse gas emission from reduced material usage.

3.2.3.1 Environmental benefits during welding

The primary environmental concern for fusion welding operations (arc welding, laser welding) is emission of weld fumes [23]. Welding fumes are formed by the vaporization and subsequent recondensation of metallic elements upon cooling in ambient air. The U.S. Environmental Protection Agency published a comprehensive report summarizing the development of particulate and hazardous emission factors for electric arc welding [30]. It was stated that particulate emissions may reach up to

23 grams per kilogram of deposited weld metal for flux cored arc welding (FCAW) and 8 grams per kilogram of deposited weld metal. The fumes contain hazardous particulates of Fe, Cr, Mn, Cu and other metal oxides, metallic elements, and gas (CO_2, CO, NCOx, and O_3). Welding fumes are particularly harmful to the health and safety of the welders.

As a solid-state joining process, the hybrid FSW technology will completely eliminate the emission of particulate and hazardous fumes into the atmosphere. This will be a very important environmental benefit for the welding industry.

3.2.3.2 Environmental benefits from reduced material usage

In the pipeline example given in previous section, FSW would reduce material usage as a result of improved weld properties. This will result in reduction of greenhouse gases and other particulates during steel making.

Taking the 1,500 miles X120 steel pipeline project as an example, the reduction in greenhouse emission gas (carbon dioxide) by using less energy in steel making along is 107×10^3 tons using the published data on steel making industry [31]. The reduction of CO_2 from the use of different energy sources are given below:

- From use of natural gas: 18×10^3 tons
- From use of coal: 32×10^3 tons
- From use of electricity: 32×10^3 tons
- From use of oil: 25×10^3 tons

3.2.4 Economic Benefits

The economic benefits will be demonstrated with the following specific example of pipeline construction.

3.2.4.1 Economic benefits related to pipeline construction

FSW for use in pipeline construction has a number of potential advantages ranging from pure economic to increased integrity. One practical advantage regards recent trends in American work force. Welding, a somewhat dirty and dangerous job, has fallen out of favor over the past two decades, as young skilled laborers pursue cleaner, safer and less physically demanding work. This trend has received attention from the Wall Street Journal [32] and is a focus of the American Welding Society. The implications for mega-projects like a natural gas pipeline from Alaska are that not enough welders will be available from the US workforce. Importing foreign welders may be necessary. On the other hand, automated systems as envisioned for FSW have the potential to eliminate the need for large numbers of manual welders.

With respect to economic factors, FSW can provide higher welding productivity compared to typical arc welding processes. The primary gain comes from being able to weld thicker material with fewer "passes". For example, typical pipeline steels range in thickness from about 0.5 to 0.8 in. requiring anywhere from about 6 to 20 welding passes, depending on joint design. An advanced FSW system can join these wall thicknesses in a single pass [33,34]. Significant reductions in construction expenditures can be expected for steel pipeline construction by use of FSW process, as shown in the ExxonMobil's economic analysis [ ] – where about 5-15% cost saving is expected for onshore pipeline application, and 20-30% for offshore pipeline constructions. For a $25 billion onshore pipeline project, the cost savings can be on the order of one billion dollars US. Additional savings are expected, but hard to quantify, for reduction in repair rates and increased pipeline integrity. Perhaps the greatest economic benefit for high efficiency joining processes may come if the cost impact can be accounted for in early project planning and it is realized that the efficiencies are actually enabling. The Alaska gas resource has been identified for decades, but currently remains stranded primarily for economic reasons.

4. COMMERCIALIZATION

During the course of the project, the project team performed extensive business, economic and market analysis to identify the industry's general needs and specific business interest of industry partners of the project. These analyses identified the following applications as near-term (next 3-5 years) market and technology commercialization opportunities.

The first near term technology commercialization opportunities would be for the construction of the steel pipeline for gas/oil transmissions. The ExxonMobil economic analysis revealed significant economic incentives for FSW technology for both onshore and offshore situations. Therefore, our research plan and activities were adjusted to support both onshore and offshore application. Specifically, the technology development in the second part of the project was directed to develop technically viable solutions to meet these potentially significant business opportunities.

Further, our FSW technology development has attracted a strong interest in the nuclear power plant applications. The likely near term application is repair welding and construction welding of piping systems. This potential application was in line with the pipeline construction identified above in oil and gas industry.

Another potential application was construction of high-pressure hydrogen storage vessels for the hydrogen fuel-cell energy infrastructure. FSW would be a key fabrication technology for construction of hydrogen embrittlement free hydrogen storage vessels.

The FSW technology developed in this project has already received interest and applications. MegaStir has developed several business opportunities/applications in the oil/gas industry and nuclear industry. Specifics of such applications are not disclosed in this report due to business sensitivity. Also, we have received several inquiries of the technology development from companies in the Middle East and Asia. These new opportunities are being evaluated and strategy being developed to follow-up these opportunities.

The industry participants include the world's largest publicly traded energy company ExxonMobil which has vested interest in commercializing FSW. The oil and gas industry, in terms of yearly project construction, represents a multi-billion dollar/year energy entity. FSW has the potential to provide significant economic efficiencies into this industry. ExxonMobil has developed some of the world's most advanced high-strength steels for energy transmission pipelines and other energy storage applications [35, 36]. The flexible FSW process will be a significant joining technology to help realize the full property advantage of these high-strength steels.

5. ACCOMPLISHMENTS

The tasks making up this project had several successful outcomes.

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6. CONCLUSIONS

In this work, we have successfully developed the field-deployable FSW system and technology, and demonstrated the technical viability for field construction of steel pipelines for both onshore and offshore oil/gas transportation applications. The following specific project milestones have been achieved.

FSW Process Innovations:

- Demonstrated the patented arc root pass weld to eliminate the internal mandrel support to reduce the cost of onshore pipeline construction
- Developed the sacrificial anvil approach to effectively solve the lack of root side bonding issue for offshore pipeline construction.
- Developed the patented multi-pass multi-layer FSW that fundamentally overcomes the thickness limitations of today's FSW approach.

FSW Tool Development:

- Developed more durable composite tool materials and successfully demonstrated their durability and abrasion strength for steel welding.
- Upgraded tool material synthesis and manufacturing processes to produce tools capable of welding 20 mm thick steels (compared to previously 4-6 mm thick steels) with complex features.

Prototype Field-Deployable FSW Machine System:

- Demonstrated scalability of the field-deployable FSW system for steel pipeline welding. Several prototype FSW machines were designed, fabricated, and successfully applied to weld up to 30" diameter, 5/8" thick steel pipelines.
- Demonstrated the machine's capability to handle the dimensional variations of steel pipelines expected in field construction

Property and Quality of Welds:

- Performed extensive weld property and quality testing per API 1104.
- Overall, the mechanical properties and Charpy toughness (at temperatures from -80 to 25°C) of the weld zone, are superior to parent metal properties. Further, welds were inspected per API 1104 guidelines including visual, radiography, bend tests, nick break tests. Once the appropriate weld procedures were established, the welds were deemed to be acceptable by independent test facilities.

Economics Benefits and Identification of Near Future Business Opportunities:

- Identified significant cost reduction for both onshore and offshore pipeline constructions using FSW by the independent economic analysis of ExxonMobil. Under the scenarios in ExxonMobil analysis, about 5-10% of cost reduction could be realized by FSW for onshore applications, and about 20-30% cost reduction for offshore applications.
- Used the results of economic and marketing analysis to guide the targeted FSW technology development for both the onshore and offshore pipeline applications.

Significant Energy Benefits:

- FSW is highly energy efficient. Detailed energy consumption analysis revealed that, for the steel welding applications studied in this project, FSW only uses 20-40% of the arc welding energy. Additional energy saving from reduced materials usage accounts for another 20-25% energy and materials cost reduction.

Productivity Improvement

- Due to reduced welding passes for pipeline welding, the "effective" fabrication productivity (welding speed) of FSW for welding ½ to 5/8" thickness steel pipeline was about 2.2 to 4.5 times of the reference arc welding processes commonly used in the industry.

In summary, all individual program goals were met including the ultimate goal of demonstrating the ability to friction stir weld 76 cm (30 inch) diameter, 15.9 mm (0.625 inch) wall, X70 linepipe steel without using a removable internal mandrel. That is, an arc weld on the inner diameter surface (~5.6 mm deep) was sufficient to support the loads associated with FSW. This is a very important demonstration of the merits and feasibility of the innovative approach for onshore pipeline applications. This accomplishment is unique. In addition, the project achieved a similarly important goal for offshore pipeline fabrication – to demonstrate the ability to friction stir weld 32 cm (12.75 inch) diameter, 12 mm (0.5 inch) wall thickness, X52 and X65 linepipe steels using a sacrificial anvil to achieve consistent full penetration.

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