Friction stir welding (FSW) is a relatively new joining process that has exhibited many advantages over traditional arc welding processes, including greatly reducing distortion and eliminating solidification defects. Because melting does not occur and joining takes place below the melting temperature of the material, a very-high-quality weld can be created with low heat input, minimal distortion, no filler material, and no fumes. Friction stir welding is also highly efficient and more environmentally friendly than traditional welding methods.

For the pipeline industry in particular, FSW is advantageous because, compared to conventional fusion welding processes such as arc and laser beam welding, FSW is highly energy efficient, with reduction in energy usage of 60 to 80% not uncommon. Friction stir welding offers better weld quality because it is immune to the welding defects caused by solidification in fusion welding. It offers high weld joint strength, is a highly productive method of welding, and can join dissimilar materials and composites.

Until recently, applications for FSW have been limited mostly to aluminum and other low-melting alloys, and because FSW equipment is not inherently portable, it was not applicable for on-site construction of large and complex structures such as pipelines, bridges, and refinery vessels. Recent technology breakthroughs in tool composition and technology, however, have increased FSW’s joining capability to include high-strength steels and other high-melting-temperature materials. Also, portable equipment

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The process offers tremendous advantages in productivity and cost savings for the pipeline industry
Friction stir welding of ferrous alloys is particularly useful in production environments where welding repair and direct costs are high. From a mechanical capability standpoint, FSW of up to ½ in. (12.7 mm) maximum on steels is very repeatable, and development is currently underway to expand this capability up to ¾ in. (19 mm). The world currently has an estimated 6,200 miles (10,000 km) of onshore pipelines used to transport oil and gas, with capital expenditure estimated as exceeding $16 billion. More than half of the world’s undeveloped hydrocarbon reserves are remote from potential users, and very large pipelines, up to 56 in. (1.42 m) diameter are required to transport the fuel to market. The welding process used to make the site girth welds has a significant bearing on the total cost of the pipeline. FSW offers significant cost improvements over the current practice of using mechanized or automated gas metal arc welding (GMAW) processes.

The FSW process is relatively easy to control in the presence of adverse environmental conditions, and the weld parameters are robust. Because it is capable of single-pass welds, FSW saves time and reduces the pipeline welding logistics considerably. This equipment can also be operated by a nonwelder, which can save labor cost but, more importantly, addresses the current shortage of qualified welders.

**The Friction Stir Weld Process**

The FSW process was patented in 1991 by The Welding Institute (TWI) for use with low-melting-temperature materials such as aluminum, brass, and copper. FSW is a solid-state welding process in which a nonconsuming tool is rotated along the interface between two materials to be joined. The tool consists of a protruding pin, which is plunged into the workpieces, and a larger concentric “shoulder” that is maintained on the surface of the joint. The concave surface of the shoulder produces a mixture of frictional heating and forging pressure. Frictional heating created by the shoulder and pin rotation in contact with the base material produces a local plasticized region around the tool. As the tool moves along the weld joint, the plasticized material is displaced. Under the heat and forging pressure of the tool, a fully consolidated metalurgical bond is produced — Figs. 1, 2.

Welding parameters for FSW consist of the travel speed of the tool with respect to the base material, the rotational speed of the tool, and the forging pressure applied by the tool. These parameters are governed by the tool geometry (i.e., shoulder and pin diameter), mechanical properties of the material to be joined (i.e., flow stress), and material thickness.

The process was originally limited to low-melting-temperature materials because initial tool materials could not hold up to the stress of “stirring” higher temperature materials such as steels, stainless steels, and nickel-based alloys. This problem was recently solved with the introduction of new tool material technology using very hard materials such as polycrystalline cubic boron nitride (PCBN), tungsten rhenium, and ceramics. The use of a liquid-cooled tool holder and telemetry system has further refined the process and capability — Fig. 3.

Tool materials required for FSW of high-melting-temperature materials require high “hot” hardness for abrasion resistance, along with chemical stability and adequate toughness at temperature. Material developments are advancing rapidly in different tool materials, each material having specific advantages for different applications. Shown in Fig. 4 are tool profiles of a 6-mm pin tool before and after more than 100 ft of friction stir welding in A36 steel. Little tool wear is present, without tool fracture or cracking.

During the FSW process, microstructurally distinct regions are characterized much like those found in arc welds. These include the following (Fig. 5): A) the unaffected base material, B) heat-affected zone (HAZ), C) thermal mechanically affected zone (TMAZ), and D) the stir zone (SZ) or weld nugget. The SZ consists of fine equiaxed grains. Recrystallization has occurred in order to relieve the high amount of plastic strain introduced by the FSW process. Adjacent to the SZ are the TMAZ and HAZ regions. The TMAZ is distinguished by an elongated plastically deformed grain structure. The HAZ, just as in an arc weld, is the region that has experienced an elevated thermal cycle but has not undergone any deformation.

An advancing and retreating side of the weld occurs with FSW. The side of the weld in which the tool rotation and the travel direction is in the same direction is considered the advancing side. The side of the weld in which the tool rotation is opposite to the travel direction is considered the retreating side. Distinct microstructural features are present in these
areas depending upon the material being joined, FSW tool geometries, and the welding parameters. Also, because of impinging heat and mechanical variations between the advancing and retreating sides, different alloys can be joined together.

**Advantages of High-Melting-Temperature FSW**

The low heat input and lack of solidification defects in the weld provide friction stir welding with a number of important advantages over fusion welding. These include the following:

1. No filler metal is used, providing significant cost savings in materials
2. The process can be fully automated
3. The energy input is efficient as all heating occurs at the tool/workpiece interface
4. Minimum postweld inspection is required due to the solid-state nature and extreme repeatability of FSW
5. Depending on the target alloy, FSW is tolerant to interface gaps and requires little preweld preparation
6. No weld spatter needs to be removed
7. The postweld surface finish can be exceptionally smooth with very little to no flash
8. No solidification-related cracking, porosity, or oxygen contamination occurs
9. Little or no distortion is found in the base metal
10. No operator protection is required as there are no harmful emissions
11. Weld mechanical and fatigue properties are improved
12. The joint can be joined in a single pass

In addition, FSW offers these advantages over traditional welding methods in pipelines:

1. Single-pass welds reduce time and money related to weld schedules, consumables, and propensity of weld failures.
2. Lower consumable costs. New FSW tool material and geometry designs promise even longer tool life than currently promised.
3. Friction stir welding is a reproducible, machine tool welding process
where wire chemistry and power supply variances are not issues.

4. Does not require direct involvement/supervision, nor does the operator need to be a skilled welder.

5. Very low degrees of distortion, leading to greater precision in assembly and reduced rectification.

6. Reduce number of welding stations due to faster completion rates.

7. Fewer weld parameters to monitor, making it less cumbersome in the field.

8. All-position welding facilitating orbital or other out-of-position scenarios.

9. Has been used on many associative grades of steel up to API 5L-X100.

10. Significant economic advantages over current GMAW practices.

11. Able to perform full circumferential welds without stopping. Start and stop overlap quality is very high quality as the process will weld over itself.

12. Able to operate in the wide temperature swings inherent to global field operation without special modifications to the equipment.

13. Very low energy consumption, mostly related to driving the welding spindle.

14. Promises to greatly reduce weld-related rework by further reducing field defects.

**Beyond the Linear Weld**

Until recently, FSW has been typically utilized in linear butt and lap joint configurations. To make this technology applicable for on-site applications, such as pipeline welding, a portable, rotating machine needed to be developed. In addition to the advantages mentioned earlier, FSW on pipe can be completed in a single out-of-position pass that is not affected by gravity. Load data and process parameters developed on flat plate were used to facilitate the design of rotary pipe welding fixtures and operation parameters.

This portable pipe welding machine was designed to be a field-ready, stand-alone machine that was capable of friction stir welding stationary pipe typical of that found in the assembly of a pipeline. This machine was designed to produce single-pass, complete joint penetration welds on 12 in. (305 mm) ID pipe with a wall thickness up to 0.5 in. (13 mm). The machine is designed to weld butt joints in pipe segments using a spindle head that traverses the joint with the FSW tool on the outside while an expandable mandrel supports the backside of the weld on the inside of the pipe.

In a typical linear weld, as welding occurs, specific loads act on the FSW tool. These consist of the force that opposes the travel direction of the weld (X axis load) and the force acting against the tool should...
The tool depth into the plate is controlled through the Z axis load, which can be set to a specific value depending upon the tool design and material thickness. The X axis loads were monitored at various welding parameters on typical horizontal welds to establish important design criteria such as load capacities, tool holder concentricity requirements, tool offset parameters, and rigidity requirements of the system. This information was then extrapolated to suit a rotary application.

As one would expect, the portable orbital welding machine adds a W-axis to drive the spindle and FSW head assemblies circumferentially around the pipe. A clamping fixture clamps and holds the two segments of pipe together for butt-joint welding — Fig. 7. To provide the internal pipe support to prevent wall collapse due to the high pressures exerted by the FSW process, an internal, expandable anvil was designed.

An inherent problem with FSW is the presence of an extract hole after the weld is completed. On linear joints such as in plate, a run-off tab is often used. This tab is removed after the weld is completed. The same solution was used for removing the exit hole for pipe welding. For a full circumferential weld, a run-off tab was fixture over a joined portion of the pipe near the starting point of the weld after the weld had begun. The joint consists of the weld overlapping at the beginning and then moving off-axis on a run-off tab to complete the weld. After the weld is completed, the entire assembly unclamps for removal from the finished weld joint.

The FSW pipe machine is designed to function in a field environment and requires only one operator — Fig. 7. Additional people may be required to attach, detach, and move the machine to the next joint. This basic machine design can also be configured to weld pipe in a vertical position and for a variety of diameters. It can also be used for bead welds. Large-diameter pipes can also be retrofitted for multiple welding heads for increased productivity.

Technology Development

Friction stir welding is a technology in constant development. This technology becomes more and more attractive as the tool design allows for thicker section welding. Currently the thickness is limited, but single-pass welding of API grades of steel is being developed for thicknesses up to 1 in. Tool designs needed for welding tubular geometries are more complex than those used for linear welding and the control systems needed require a higher level of sophistication, such as control algorithms that vary parameters to maintain a specific tool temperature.

Trends in pipe development have moved toward the development of higher-strength steels for use in pipelines. These new high-strength grades provide cost savings; however, they also introduce difficulties in welding while using conventional welding methods. Although FSW has many advantages over its fusion welding counterparts, careful parameter development is needed to understand the essential variables that are required for friction stir welding in these special grades of steel.

Summary

Friction stir welding of out-of-position welds such as that involved for pipe welding offers tremendous advantages in productivity and cost savings for the pipeline industry. This disruptive technology has the potential to significantly alter the way this industry does business in the coming decades.◆

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