ABSTRACT

In many applications it has been difficult to justify the use of friction stir welding (FSW), mainly due to the high capital cost requirements of FSW and the relatively poor productivity that results from the use of standard FSW machines. To solve these issues, robotic FSW solutions have been proposed. However, until recently the viability of using an industrial robot to perform FSW for production applications would have been limited to relatively small number of applications, due to limited force capability and stiffness of industrial robots. The recent introduction of relatively low cost robots with higher payloads has made production robotic FSW viable in numerous applications. Additionally these new robots also have much improved control systems, which allow for much more flexibility in developing software and control systems required to perform robotic FSW in a production environment. Using one of the new robots, a production capable stir welding system has been developed. The capabilities of a robotic FSW system, and its force control system will be reviewed. A robotic welding application will be reviewed, with an emphasis on how the improved flexibility of the robotic system can be used in applications where FSW was previously considered too costly.

INTRODUCTION

Early in the development of friction stir welding, it was recognized that FSW had many advantages over other joining processes for aluminum in numerous applications. However, it was often concluded that FSW was uncompetitive in many of these applications for a couple reasons. First, the high forces that FSW requires, caused the need for expensive custom-built machinery. These custom built machines also created relatively high productivity losses in many applications, due to the inability to achieve high duty cycles (‘on time’). These two factors made FSW uncompetitive, especially where robotics are currently employed.

To overcome this issue, the development of robotic FSW solutions were required. Starting in 1996, there were multiple efforts to develop robotic based FSW solutions. One solution was developed at Tower Automotive (Figure 1) and another at GKSS (Figure 2)\textsuperscript{1,2,3}. Each solution was successful and demonstrated that robotic FSW was indeed a possibility. Critical to the success of the programs, was the development of force control systems that were used to overcome any lack of stiffness the robot may possess. These force control systems were also deemed a requirement for any robotic FSW system, to help overcome variation seen in production processes.
These robotic systems showed definite promise for the future use of robotic FSW systems. However, the use of these particular systems would be limited to laboratory or prototype applications for relatively thin material (4 mm or less), due to limitations of the robots. Their capability in a production environment was questionable.

The Tower Automotive system was implemented on an ABB IRB 6400 robot, seen in Figure 1. Although this robot has the open architecture that is required for any robotic FSW system, the early 1990’s computer technology inherent in the system proved to be limiting in the performance of the force control system. This resulted in slow response of the control system. The forces that the robot was producing at any point in time were calculated from torque feedback of the robot’s six motors. This resulted in significant computation overhead to calculate the actual force the robot was generating, resulting in poor sample rates and slow response. It was shown that the force control could correct and maintain a commanded force, but for production applications it was deemed that the response was too slow. It was also determined that success was limited to material 3 mm or thinner, but travel speeds up to 2 m / min were possible in certain applications.

More recently improvements have been made with the use of an ABB IRB 6400 robot due to improved computer controls and elimination of the calculation of the force from the motor torques. Instead, spindles have been developed that have integral force measurement. With these improvements and the development of special force control software, significant improvements in the force control system have been realized.

This robot system has been used to make thousand’s of parts, but its applicability in production applications is still questionable, for several reasons. First, the high duty cycles seen in production applications tend to overheat the robot’s motors. Secondly, the response time of the force control is still slower than would be required for production application. And, lastly, the relative lack of stiffness of the robot, can make development
of weld paths challenging and require a highly skilled robot programmer. Thus, this robot system is relegated to prototype applications.

The GKSS solutions have involved the use of Neos Tricept type robots. These robots have a parallel kinematic structure, which yields a significantly stiffer structure than the serial structures typically used with other industrial robots. This parallel kinematic structure has definite advantages when attempting to develop robotic FSW systems. However, these type of robots have rather limited working envelopes when compared to serial kinematic structures. Additionally their cost has been significantly higher than standard serial kinematic robots. In FSW studies, similar laboratory and prototype successes have been reported with the use of this family of robots.

**RECENT DEVELOPMENTS**

Since the development of the first robotic FSW systems, there have been several important advancements in robot technology that provide significant improvements to robotic FSW technology. The most significant advancement is the advent of serial kinematic robots with much higher payloads. There are several industrial robot companies (e.g. ABB Robotics, Kuka Robotics) that now provide robots with payloads up to 500 kg. One such robot is an ABB Robotics IRB7600, which has up to a 500 kg payload, shown in Figure 3. This payload is approximately 2.5 times greater than what was previously available. Furthermore, these robots are somewhat stiffer than the previous serial kinematic robots. Another important advancement with these new robots is the modern, more powerful control systems, that allow for significant improvements in the force control system capability.

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**Figure 3:** IRB7600 Serial Robot  
**Figure 4:** IRB940 Parallel Robot
Another change is the availability of the parallel kinematic robots from ABB Robotics (IRB 940), shown in Figure 4. This has significantly lowered the cost of these parallel kinematic robots, where they are much more competitive with the serial kinematic structures. In applications where a relatively small work envelope is required or where more force capability is required, the use of this type of robot will be competitive with other robotic joining technologies. This type of robot would also be helpful in applications where machining of the part is also required. A further benefit of this new solution is that this robot now has a common architecture with the serial kinematic robot, making integration of other FSW hardware and software relatively seamless.

**ABB IRB 7600 ROBOT FRICTION STIR WELDING SYSTEM**

Using the new robot technology, a FSW system has been developed and integrated to an ABB IRB7600 robot. The system consists of several components and is shown in Figure 5. The system consists of spindle, a motor, a mechanism to drive the motor, and software to control the system. The spindle and motor are attached to the robot’s wrist, while the motor drive mechanism is either external to the robot cabinet or within the cabinet. The software resides on the robot controller and is developed in the robot’s native high level programming language.

![Figure 5: FSW Robot System](image)

The motor is mounted atop the spindle and can either be an electric servo-motor or a hydraulic motor, depending on the requirements of the specific application. If a servo-motor is employed, then an external drive (included with the robot) can be used to drive the motor and control its speed. The external drive is mounted within the robot’s control cabinet. If a hydraulic motor is selected, then a servo-controlled hydraulic pump is used to drive the motor. A servo-control pump is required because the system experiences highly variable loads (torques) from a free rotating state to welding. The hydraulic pump
is located near the base of the robot. When a hydraulic motor is used, a rotation speed sensor is required. The sensor’s output is connected to the robot control cabinet. The motor’s rotation speed is controlled via a PID control loop in the friction stir welding software.

To accommodate the forces of FSW, the motor is mounted to a spindle. This spindle is specially designed for FSW, in that it accepts the forces (thrust and radial) generated by FSW and additionally contains force sensing capability. The output of the force sensor is connected to the robot controller. The friction stir welding software uses the output of the force sensor in a PID control loop to maintain constant force during welding.

The most important component of the system is the software that has been developed specifically for the friction stir welding application. This software is embedded into the robot controller. The software has been designed such that, to the robot operator, the robot programming appears similar to other welding software packages. This software has several critical features that are essential to performing FSW with a robot. These features have been developed to manage several characteristics that are particular to the FSW process, including

1) The need to be able to operate in a force-controlled mode during welding. It has been widely accepted that operating FSW in a force-controlled mode as opposed to position control produces improved FSW quality and robustness.
2) The additional need to be able to operate the process in a position controlled mode during initial teaching of the process.
3) The inability to program the actual path during initial teaching, because the FSW tool must be ‘in’ the material during welding. Thus the actual path during welding must be controlled using the taught positions as reference positions.
4) The orientation of the robot (work and travel angle) during friction stir welding is more critical with FSW than with other welding processes. Thus, there must be some means of more accurately teaching the FSW tool orientation than the standard means of teaching the robot.
5) A need to interact with the robot during initial welding, so as to optimize the teaching process. There needs to be some means of increasing or decreasing the welding force in real-time.
6) The need for weld parameter records which are specific to FSW. Traditional welding processes (gas metal arc welding, resistance spot welding) have parameters that are specific to these applications. To control the robot’s welding, the robot has built-in records or data structures to accommodate the specific welding process. To accommodate FSW, special records or data structures needed to be developed.
7) A need to gracefully halt the welding process, during welding. Simply halting robot movement and tool rotation during welding will cause the FSW tool to lodge into the material that is being welded. Removal of the tool is very difficult once it is lodged into the material.
8) A need to be able to dry cycle the welding path. That is, there needs to be a method of having the robot follow the welding path, without welding, to check
the programmed path. Since no welding (no tool rotation) is performed during a
dry cycle, the actual path of the dry cycle cannot be the desired welding path,
otherwise the FSW tool will crash into the material that is to be welded.

All of these requisite features and others have been developed into the stir welding
software package (StirWare™), along with other optional features. These optional
features are now feasible, with the advent of more powerful computer systems,
networkability, increased data storage, and improved programming languages. These
options include:

1) The ability to store and download welding data, while the robot is welding. The
software is capable of storing and downloading, force, torque, and rotation speed.
This is a helpful tool during initial process engineering. Additionally, in
production situations it is used to periodically review welding data.

2) The ability to monitor various data during welding. Various limits are set on
welding data (force, torque, position, temperature) to warn the operators or halt
the welding process. This feature can be used as an error-proofing tool. A good
example, is the need to error proof an FSW tool failure, such as a pin breaking.
This can be detected as unusually low torques or forces during the plunge process
or as spikes (high or low) of torque and force during welding. Another example is
monitoring of spindle temperature or cooling water temperature. This can be used
to indicate failure of various components and indicate to the user that the system
needs attention before serious damage is done to the system.

3) The ability to monitor the tool life. This can be done in several ways. The first
method is tracking the total linear distance of welding that a specific tool has
performed. The operator can be notified to replace the tool after this certain
distance of welding has been achieved. The second method is to periodically
change a tool based on time. The last method is to use the monitored variables to
indicate when a tool is worn. It may be possible to detect changes in torque as the
tool wears. A threshold could be set to replace the tool based on changes in
required torque.

The results of the force control and data storage capabilities are shown in Figure 6. This
particular chart shows the actual thrust force, the commanded thrust force, the robot
position, and actual torque. The plunging and traversing areas are noted in the graph. In
this particular example, the user was developing a weld path. For testing purposes, the
user had programmed the end position of the weld 2 mm deeper than the start (see change
in plunge depth). The robot’s force control algorithm reduces the plunge depth (depth
with respect to programmed position) along the weld. The commanded force profile was
6.1 kN for the first half of the weld and then increased to 6.3 kN. At this point, the user
was still in the process of teaching the plunge depth. The robot can be seen plunging
slowly (extended time for plunge) as the user was commanding the robot to commence
the traverse in real-time, to determine the appropriate plunge depth at the weld start.
With the improved mechanical and computer technology in these robots, the development of a production capable robotic FSW package has become a possibility. All of these system components (spindle, motor, motor drive mechanism, and software) are integrated to external equipment to generate a complete production capable friction stir welding system. This external equipment includes positioners, platforms, fixtures, electrical controls (programmable logic controllers, sensors, etc.), and safety equipment (fencing, light curtains, safety mats, etc.)

**ROBOT FSW APPLICATION STUDY**

To demonstrate the applicability of robotic FSW, an actual application will be reviewed, that has features of numerous applications where FSW can be employed. These types of applications highlight the need for a robotic FSW solution, where currently, robotic systems are typically used for fabrication. This particular application is an automotive chassis component that was redesigned for FSW\textsuperscript{5}. The part is a replaceable crush assembly that mounts to a chassis.

The redesigned component replaces a gas tungsten-arc welded (GTAW) aluminum component that had several steel reinforcements. These steel reinforcements were riveted and adhesively bonded to the aluminum structure. Given these added operations, the old component was costly. It was felt that FSW could be used, with its improved weld quality, to eliminate the need for all of the steel reinforcements. The redesigned component was required to eliminate the need for all reinforcements, meet or exceed all destructive testing specifications, and have a lower welding cost than the GTAW’ed component. It was also important to minimize detail part tooling costs.
Given these considerations, it was determined that the new component must be fabricated entirely of extrusions. The FSW design essentially consists of a tube, with mounting flanges on either end. The flanges on each end are created from five separate components, which are all extrusions. Two of the components are identical. Extrusions were selected due to minimize cost in this relatively low volume product. To minimize cost, maximize strength, and maintain energy absorbing characteristics of the product 6063-T4 Al was selected for the tube material and stronger 6061-T6 Al was selected for the flanges. The final design is shown in Figure 7.

![Figure 7: FSW’ed Automotive Chassis Component](image)

The design of the extrusions and weld joints are shown in Figure 8 below. The welding locations are shown for each of the joints, as indicated by the red. There are several important characteristics of each extrusion.

The extrusions at the right end are attached with a partial penetration butt weld and a lap penetration weld. It can be seen that the flange for the lap penetration weld has a contour that minimizes stress concentrations at the corners. This is very important to the strength of the component, but also causes the need to weld on an angle, something that a robot has the capability of doing. The extrusion thickness is 4.5 millimeters in the area of the weld and requires a tool with 7 mm of penetration depth. The partial penetration butt joint is also important for robotic type applications. Since full penetration butt welds are sensitive to penetration depth, they should be avoided in high volume applications, given material variations that are often present. Partial penetration butt welds do not have this feature. The penetration depth for this weld is 3 to 4 millimeters.
The large extrusion (left end) is the most complex. It can be seen that it requires two lap penetration welds to be joined to the end of the tube. These lap penetration welds have the same contour as the welds at the other end, allowing for the use of a common FSW tool. Of importance is the fact that the extrusion is designed to be self supporting. This is required to avoid having to insert a long mandrel inside the part during production; something that is undesirable.

The last two parts are reinforcements that are attached to the right end of the tube and to the complex extrusion. This particular area of the component sees the highest loads (bending stresses) during side-impact testing and required additional reinforcement in this area. Again, these components are designed with a contoured lap penetration joint and require the same FSW tool as the other lap penetration joints.

Now, we will consider the production system and welding costs for fabricating this component. This particular example is hypothetical since high production volumes are assumed, whereas this particular component is low volume in reality. However, it has features of many high production volume applications that are found throughout industry. We will consider various solutions that are plausible for this application, including gas metal arc welding (GMAW) robot system, FSW robot system, single axis FSW machine, and a multi-axis FSW machine.

Before calculating the cost, a production system concept must be determined. It is requisite to maximize the duty cycle of the equipment (welding time versus non-welding time), in order to minimize welding cost. Thus, for many applications such as this one, an external positioner is considered, so that the non-value added material handling (loading and unloading) will be performed while the machine is welding. As part of the concept stage, a simulation of the system is often created, to confirm cycle time, robot reach, and perform interference analysis. A simulation of a typical FSW robot solution applicable to this component is shown in Figure 9.
A similar conceptualization exercise is performed for each of the other potential production solutions. Once the concept is completed, the capital cost and other input costs are calculated for each potential solution. For each solution, the following items are considered as input costs to determine the relative direct costs for each solution:

**GMAW Robot**
1) 2-Axis external positioner is used to facilitate loading and unloading during welding. The 2\textsuperscript{nd} axis is required to avoid out-of-position welding.
2) 3 Fixtures are required
3) Shielding gas, filler wire, and contact tips are assumed as consumable costs.

**FSW Robot & Multi-Axis FSW Machine**
1) Single axis positioner is used to facilitate loading and unloading during welding. Welding can be performed out of position, so only a single axis dial feed table is required.
2) 3 Fixtures are required
3) FSW Tools are assumed to have a life of 2000 meters of welding
4) FSW License is assumed as an operating cost.

Single FSW Machine
1) No positioner is used, due to need for numerous positions.
2) 10 Fixtures required (one for each weld)
3) FSW Tools are assumed to have a life of 2000 meters of welding.
4) FSW License is assumed as an operating cost.

The following are included in the costs and are assumed to be constant for each solution:

1) One operator
2) Travel speed of 1 meter / min.
3) Electricity costs (Cost / kwh)
4) Floor space and cost
5) Repair, rework, scrap, and warranty costs. Note, FSW is typically much more robust and has significantly lower costs in this area. However, these costs are assumed to be constant in initial cost studies, due to the unknown true cost.
6) Machine efficiency of 78%. Includes machine downtime for maintenance, breakdowns, and operator breaks. Again, this is assumed to be constant, due to the unknown nature of actual FSW operations.
7) Costs for maintenance and technical services during breakdowns.
8) Life cycle, number of shifts per day (assumed to be 2), and yearly production is assumed to be the same.

Figure 10: Relative Welding Costs for Various Production Solutions

Figure 10 shows the relative welding costs per meter of weld. For this application, it is seen that the FSW robot has approximately 20% less cost than a GMAW robot solution. Additionally it is seen that employing a custom built FSW machinery is much more costly than the GMAW robot solution. However, it is important to note, that the multi-axis FSW machine (approximately 2 times more expensive than a single axis FSW
machine) is less costly per part than a single axis FSW machine. This is because the machine utilization (duty cycle) is much improved for the multi-axis machine. This characteristic is also present with robotic solutions with their multi-axis capability. Not only do they have lower capital cost, but a robot’s multi-axis capability allows for much improved machine utilizations and results in significantly more productivity. This is primarily because multiple welds can be made in the same setup, eliminating the non-value added material handling that detrimentally affects the final welding cost using single axis FSW solutions.

These results are not indicative of all applications, as other FSW solutions (custom built machines) have proven to be cost effective in certain applications, as has been demonstrated by their use in production applications. However, these results are indicative of many applications where robotic solutions are currently being used. This comparison is meant to demonstrate why FSW requires a robot solution to be cost effective in many applications.

CONCLUSIONS

Friction stir welding is following in the footsteps of several other welding processes with respect to the need for flexibility. Two prime examples are the Gas Metal Arc and Resistance Welding processes, which together account for 95% of the robotic welding systems in the industry. Both of these processes started off being performed manually and then progressed to being performed with automatic machines. The advent of robotics in the 1980’s opened a whole new opportunity for these processes. Nowadays automatic welding with these processes is only a small percentage of the market. FSW has grown up in the robotics era and thus will reap the benefits of robotics early in its history. The future is bright because more powerful robots combined with intelligent software will open many more cost effective opportunities for FSW in many industries.

REFERENCES