Challenges and State of the Art in Industrial FSW – Pushing the Limits by High Speed Welding of Complex 3D Contours

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Abstract

Over the last 25 years, Friction Stir Welding (FSW) has been gradually moving from research over first applications into mass production. Today, requirements for consistently high-quality welds occur in parallel with a demand for high throughput as well as production flexibility. This paper gives an insight to the state of the art of industrial FSW mass production, current trends, challenges and market demands as well as the potential of high speed complex contour welding on modern multi-axis FSW machinery with respect to process parameters, material properties, machinery requirements and control algorithms, and methods. The design strategy of complex 3D contours as a chance to maximize efficiency is introduced; challenges of its implementation with respect to the state of the art in FSW are described. This includes the importance of advanced force control methods, fixture design, clamping forces and methodology for sustaining high-quality welds as well as the management of distortions and residual stresses by thermal management and optimization of process parameters. Examples of successful weld performance are described. Steps to be taken that result in high-quality welds, as well as situations to be avoided, are discussed.

A short overview over the development of FSW and its machinery

Over the course of the last 25 years, Friction Stir Welding has been gradually moving from basic research over first applications into mass production. Starting in the mid-90s with early commercial applications in ship building, aerospace, and railway [1-5], FSW disseminated and broadened its base in aluminum applications especially during the last 10 years, moved on into new mass markets like automotive and computers and opened up new fields with materials such as copper, steel or dissimilar joining [6-12].
With the maturing of the technology, better awareness of (potential) users and making the move from special application into named mass markets, FSW has started competing more and more with other established joining processes. Today, it has to face about the same requirements regarding quality, certification, robustness, ease of programming, setup and operation but also machinery and tooling, overall equipment efficiency, service and spare parts availability; – or simply spoken from a customer standpoint: regarding overall costs. No longer does friction stir welding deserve or gets a “special treatment” as a niche or special technology from customers, users or third parties such as certification bodies. At the present time, especially the uprising electro mobility, where FSW is widely used for aluminum battery boxes, forcefully supports and speeds up those tendencies.

State of the Art in FSW machinery and industrial application

With this development, FSW machines had to evolve as well following the described customer demands and – in the best case – offering advantageous new possibilities to customers and users such as force or temperature control, better programming possibilities and user interfaces, or different possibilities for quality control. While first applications like panels or tubes were often linear welds on specialized single purpose machines or position-controlled welds on converted milling machines respectively, customers, especially contract manufacturers, started demanding more flexibility, better possibilities of process control, integration and adaption already in early stages of the industrialization of FSW. Today, mainly three FSW machine concepts are found in industry (and research) that offer different kinds of flexibility, specialization, and limitations:

- **Machines specialized on FSW**, commonly C-shapes or Gantry designs

  Purpose-built FSW machines and their spindle systems are usually designed for high normal forces with lower deflection, high force capability (> 20 kN), and multi-channel data acquisition.
- **Robots**, usually industrial robots, rarely other concepts such as hexa- or pentapods

  Robots are a versatile and flexible possibility to implement and integrate FSW on equipment well-known by many customers. While industrial robots usually are by far not as stiff as C-shapes etc. and their force capabilities are limited, they benefit from their flexibility, the possibility of welding of complex geometry parts without self-collision, and therefore are often a suitable possibility for lighter FSW tasks at slower or moderate welding speed.
- **Converted milling machines**, usually C-shapes

  Milling machines can be a readily available and are a low cost alternative to purpose built machines or robots especially for FSW starters, but often lack essential FSW features such as force control. Since mostly built for milling or turning tasks, a high degree of process integration is usually directly possible for FSW applications. Especially older machines for heavy machining can often get a “second life” in FSW when upgraded by process experts with a special focus on force capabilities and bearings, vibration and spindle systems.

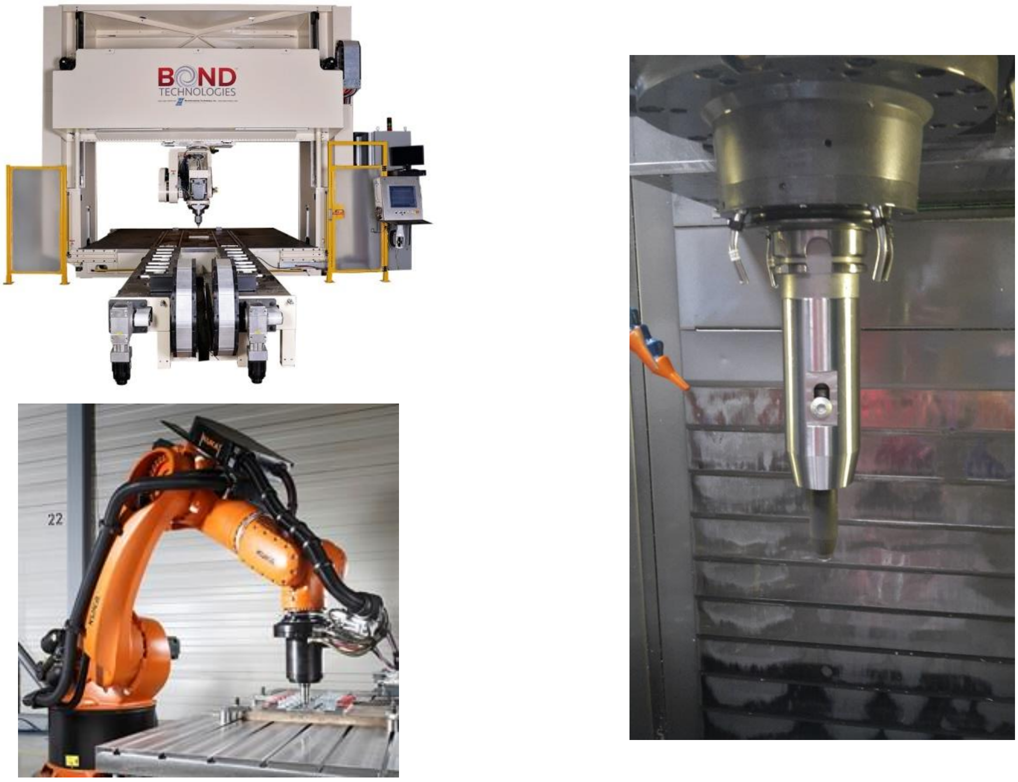

Figure 1: Ball screw driven multi-axis gantry machine for consumer products, industrial FSW robot with spindle system, plug-in force control spindle system with encapsuled telemetric system of a converted and upgraded milling machine for a high degree of process integration, pictures: courtesy of Bond Tech. / TWI / Rapid Technic Switzerland

Today, the “typical” industrial FSW application is a flat 2D weld between 2 and 7 mm depth, carried out on a C-shape FSW machine welding a 5000 or 6000 aluminum alloy, Figure 2. While the plunging phase is quasi always position-controlled, the machine is switched to force-controlled for the welding phase for the majority of industrial welds. With respect to the total number of FSW applications, bobbin tools or even double or more spindle systems are exceptionally rare; – the vast majority of applications in real life use one spindle. The spindle speed typically ranges from 700 to 1500 rpm while the traverse speed of the machine is between 600 and 800 mm/min. Interestingly, the typical welding speed in every-day industrial FSW applications does only rarely exceed 1000 mm/min despite the fact that for more than one decade most FSW machines have been able to weld at least three times as fast. Furthermore to emphasize this aspect, successful industrial implementations of the FSW process with more than 4000mm/min are known to and have been done by the authors. In the authors’ opinion being too conservative regarding reachable welding speeds and so throughput and cost potentials from a supplier side – both parts and machines – is often the reason why FSW does not make the race and customers decide against an FSW solution.

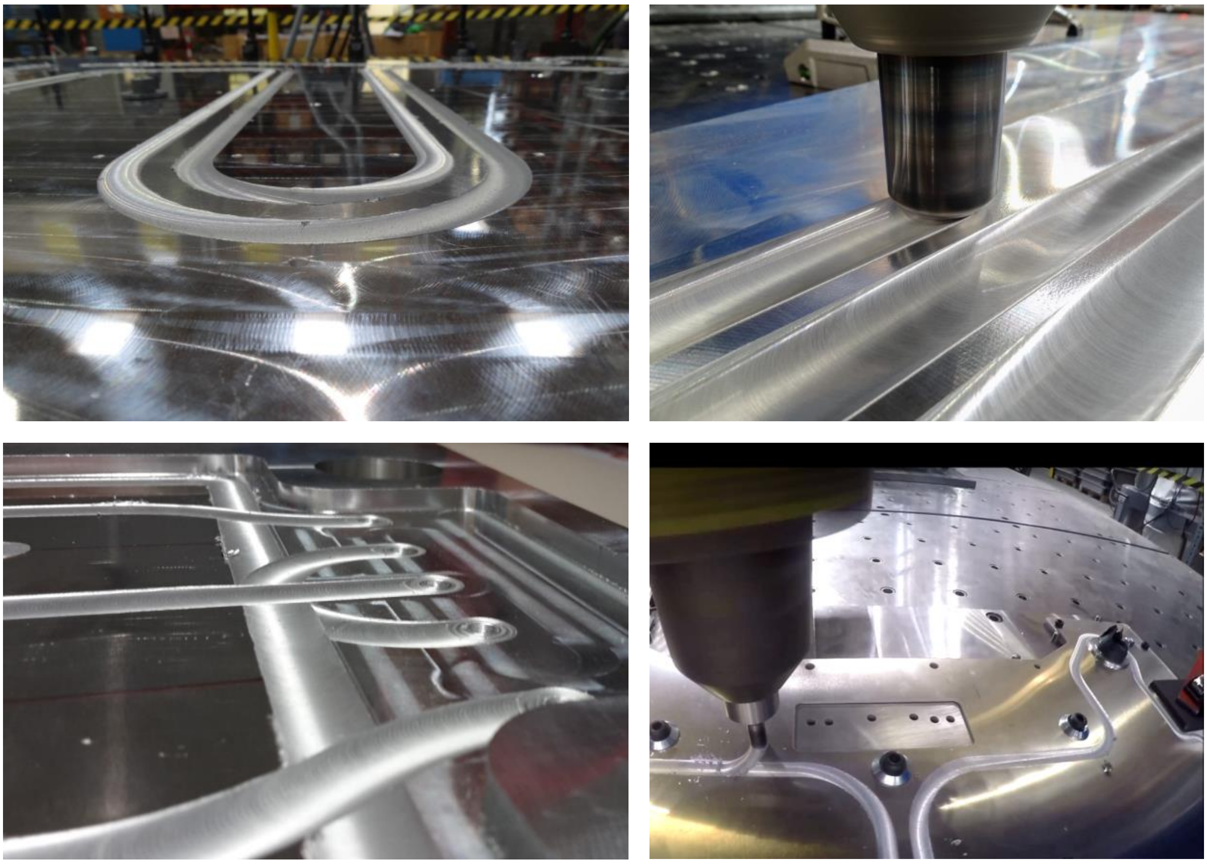

Figure 2: Typical FSW applications – welds laying in the same horizontal welding plane, all pictures: courtesy of Rapid Technic Switzerland

Complex 3D contours as a design strategy and as a chance to maximize efficiency – Challenges and Comparison to the state of the art in FSW

Increasing the welding speed is usually the most obviously and directly realizable efficiency and cost improvement in FSW and usually only requires an optimization of parameters and possibly the tool geometry. In addition, there are other less obvious possibilities such as a higher degree of process integration or the elimination of additional downstream processes, for example through ready-to-use component geometries after welding, improved material utilization and weld quality, lower distortion or burr-free and so directly usable surface quality.

One possibility to combine those features and to extend them by functional integration is the (high speed) welding of complex three-dimensional contours. The design concept uses the capabilities especially of five and six axis FSW machinery to produce parts with 3D features that are already at or very close to the final geometry. Ideally, the weld itself becomes a design element for the component.

Complex 3D contours are usually based on the welding of inexpensive easy-to-source basic materials such as drawn or stamped, cold rolled aluminum sheets that are welded together forming the target component geometry (compare next section). To avoid costly narrow tolerances and material specifications the joining of the parts is usually carried out as a force-controlled overlap weld. By this, target speeds between 3000 and 5000 mm/min become possible and the machinery throughput is maximized while the simple joining concept avoids downtimes, scrap parts, rework, error sources, and complexity and so maximizes the Overall Equipment Effectiveness (OEE). It has to be mentioned in this context, that for reaching those welding speeds on multi-purpose FSW machinery – i.e. for limiting the reaction forces and for establishing a good material flow in the lower sheet – the welding depth is kept usually below 5 mm for overlap welds while using special material and heat flow enhancing tool designs.

Incorporating complex contour welding into the design process of high volume products gives designers flexibility and cost-saving options they would not necessarily realize when thinking about the complex multi-axis FSW machinery and process control involved. While still much work is yet to be done to spread only the basic benefits of FSW to design engineers regarding the unique capabilities offered by and the design requirements of FSW, long time FSW users such as Rapid Technic Switzerland started using 3D contours as a design strategy to provide high quality products at reasonable cost several years ago.
In this context it is noteworthy that Rapid Technic overcomes the programming efforts that usually come with complex 3D contours by using a consistent CAM system. This system not only includes geometrical machine models and is able to simulate the whole process offline but includes all FSW functionalities of the machinery as well. Furthermore, the high speed data acquisition of the machine recommended for higher welding speeds is used for automated part documentation with a SQL database and SAP.

Example application: snow mobile heat exchanger

Figure 3: Snow mobile and aluminum chassis with integrated engine chiller, pictures: Bombardier Recreational Products (BRP)

For snowmobiles, light weight design and high performance are essential characteristics of the product. Despite the usually cold ambient air during operating hours, especially motors of high-performance snowmobiles often have to be actively cooled by a coolant fluid. The fluid runs through the engine absorbing the generated heat by the engine. Then, before the coolant can be recirculated, it needs to be cooled down by running through a heat exchanger.

One snowmobile manufacturer, BRP, has recently chosen FSW to produce a heat exchanger assembly for their SkiDoo [13, 14]. To form named heat exchanger, a top part is welded to a bottom part where at least one of them has a recess and so forms a passage for the coolant, Figure 4. By its “hockey stick” geometry the heat exchanger fits to the geometry and fulfills the application related requirements of the adjacent chassis.
Since the recess geometry to the tunnel has a complex geometry it requires a multi axis weld, Figure 4 bottom left. This weld in turn not only joins the two sheets, but is– as described above – itself a functional part of the component.

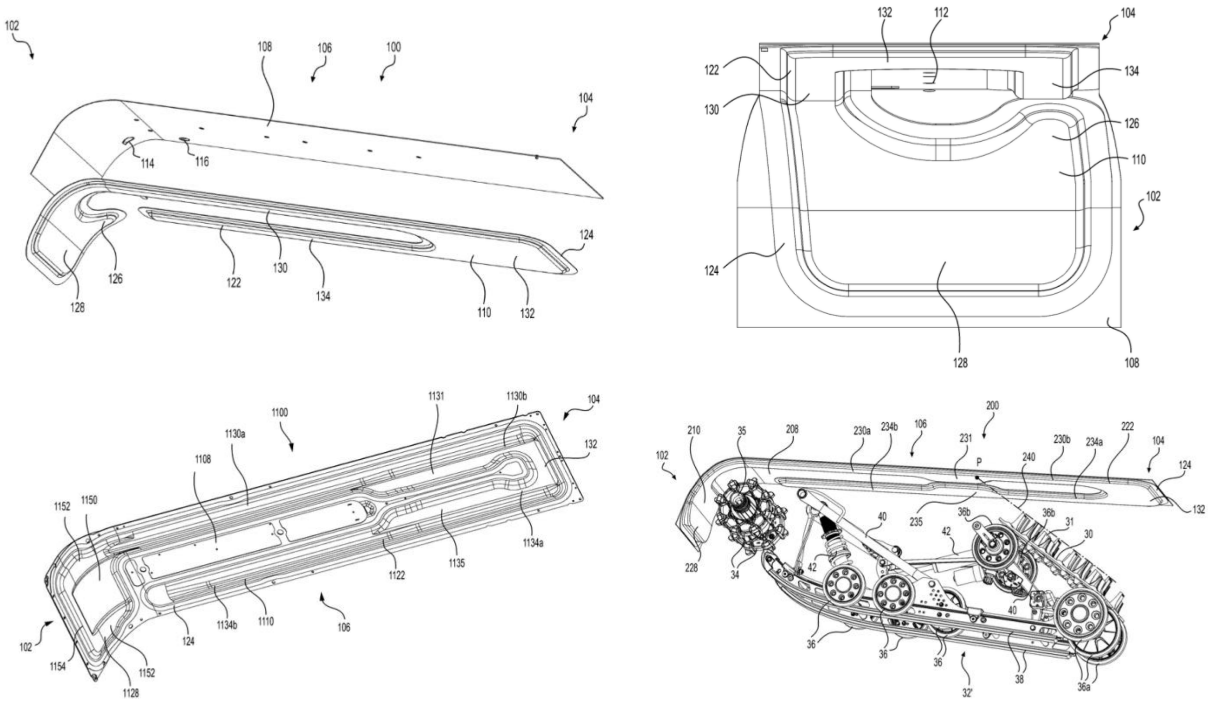

Figure 4: Upper and lower sheet forming the heat exchanger assembly with passage for the coolant, detail of collector area and geometry, joined heat exchanger, and installation position with undercarriage, all pictures taken from US20170158046A1

Requirements of high speed welding of 3D contours

Different requirements and challenges arise when 3D contours shall be friction stir welded with higher welding speeds that have already been implied during the last sections. In the following some of them are described and discussed in detail.

Force control

One very well-known feature of FSW is the possibility to control the process directly via its force feedback. This not only enables online compensation for part tolerances and so a more robust and cheaper process but even more some applications especially on industrial robots can only be implemented because of force control due their reduced stiffness. Furthermore, by limiting the forces during plunging and also traversing tool failure as well as wear can be prevented.

When the welding conditions change, the reaction forces in FSW change almost immediately due to the thermo-mechanical working principle. This opens up the possibility to control even very fast welding processes based solely on the force feedback. For high speed complex contour welding, weld conditions can change very rapidly as the tool moves from one region of the part to the next, which could have very different parameter requirements. Parts produced in high volumes can have geometric variations that cause forge force to change suddenly, especially when feed rates are high and transitions between welding planes are welded. The ability to respond quickly to a changing of all forces is very important, so response time must be very small. For example, when welding with 4500 mm/min even if a force feedback signal is processed

by the machine's control system within 0.2 seconds and the machine could perform a compensation movement within that time, the tool would have traveled about 15 mm what is about one shoulder diameter.
Therefore, a permanent observing of the process forces with a high frequency is required to identify tendencies early. In addition, sometimes it can be recommended that a pre-production weld development includes experiments to adjust the force control algorithm to ensure that it has a sufficient response characteristic tailored to the parts geometry or the weld path respectively. Key aspects of the force control algorithm are step response time, overshoot, and settling time.

The ability to gather force data at a high sample rate can help achieve a by fare more accurate analysis. Nevertheless, actual high frequency measurements of weld forces appear to contain much noise, but in fact, most of this "noise" is real and caused by physical variations in the forces during the welding process such as parts of the discontinuous material flow [15]. Various methods of measuring weld forces exist, with varying amounts of mechanical dampening. One method of measuring force, for example, is by placing load cells beneath the fixture. The mass of the fixture, clamping system and part being welded tend to dampen out the higher frequencies, but it is possible to measure forge, traverse and cross seam forces using this method. Using hydraulics to control and monitor force can have a low-pass filtering effect, yet this method is generally limited to the forge force only. By suspending the spindle assembly using load cells, the spindle and motor also serve to dampen the higher frequencies, but benefit from being directly in the load path and the ability to measure all three forces. When using converted milling machine, spindle systems or a tool holder with an encapsuled telemetric system can be recommended for closed loop force control, Fig. 1.

Machine Rigidity

Machine stiffness can affect the weld performance very strongly for example by deflection or deviations from the planned path. This circumstance increases even more when welding complex 3D contours, since the machine moves in several axes simultaneously, accelerates and brakes abruptly especially when entering or leaving 90 degree transitions, compare Figure 4. In this context, elastic energies stored in the machinery must also be taken into account, as must the effect of mass inertia on the machinery's own structure. For example, when high speed welding (>3000 mm/min) the transition radius between two 90 degree planes, a machine that is braced against the part might plunge too deep suddenly because of the mass inertia of the machine which brakes abruptly and starts transitioning into the other welding plane.

For complex contour welding, multi-axis machines are required, which immanently have less rigidity than three axis concepts, Table 1. The actual amount of deflection depends in addition on the angle of the joints and the direction of the net force vector. Complex contour welding can also be done by industrial robots, but the deflection usually is significantly higher than that of purpose-built gantry machines. Because of the mentioned requirements welding speeds are usually by far lower than those of multi-axis FSW machines while the smaller stiffness up to two powers may affect the process' stability and quality significantly if no active path tracking and compensation is used.

Table 1: Average static system stiffness of different machine concepts without tool against anvil. Own survey and measurement

Concept	N / µm	m/N
Gantry machine	38	$2.6 \cdot 10^{-8}$
C-shape	50	$2 \cdot 10^{-8}$
Industrial robot	0.5…2	$0.6\ldots2 \cdot 10^{-6}$

Machine kinematics

As stated in the last section high speed welding of complex 3D contours includes abrupt changes in direction and forces. Therefore it is important to understand the kinematic limitations of machinery and its axis motors during fast and complex maneuvers in order to ensure that the feed rate remains high and constant, and to implement complex contour welding.

Complex contour welding can encounter singularity points on robots as well as multi-axis gantry machines. A singularity point in the context of a multi-axis friction stir welder is a situation where the motor velocity is commanded to approach infinity in order to achieve a certain radius of a curvature. For example, assume a weld is being done in the X-Y plane with the weld path changing direction from +X to +Y. Assume the radius of curvature the C axis (rotation about the Z axis) is small, and that the weld is being done without any welding tilt. To change direction from +X to +Y, the X axis drive motor simply decelerates while the Y axis drive motor accelerates, Figure 5. Now, with one or two degrees of tilt, the X axis and Y axis must decelerate and accelerate respectively as before, but the rotary axes must quickly reorient the tilt to be steadily in the correct direction. The smaller the radius, the higher the acceleration required to perform this move.

For welds performed on the X-Y plane, it is possible for machine designers to skew the axis of rotation for the rotary axes so that the acceleration required for these moves is a lot smaller. For example, if the C axis is at an angle of 22.5° to vertical, the motors are able to accelerate enough to perform much tighter radius corners than if that axis were rotating directly about Z. The graphs in Figure 5 show a weld path with a small radius for a machine using a 22.5° inclination angle of the C axis. The weld performed in the example uses a 0.5° tilting angle. The B axis is required to move quickly to achieve the radius, but the speed required to achieve this move using a vertical C axis would exceed the respective motor capability. Another way to understand this is to compare axis velocities of the two machine designs. Another machinery related consideration for complex contour welding is the relationship between tool tip velocity and motor axis velocity. In the example of an inside radius in the X-Z plane, the X axis motor velocity can actually reverse direction while the B axis accelerates rapidly in order to maintain feed rate, see graph of X and B axis velocities during this weld.

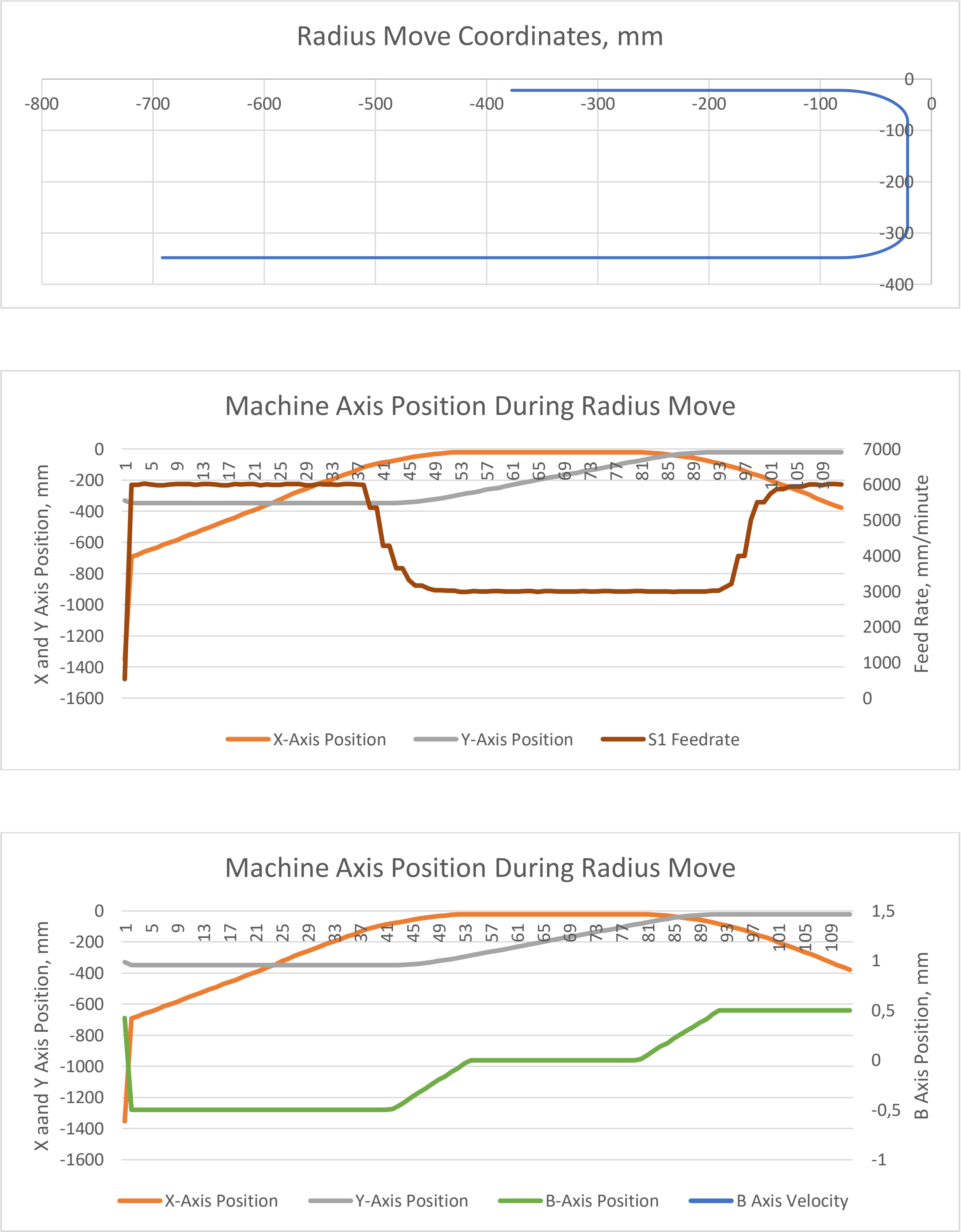

Figure 5: B Axis shows a rapid change in position as tool executes small radius at higher speed

Table 2: Comparison between a vertical and an inclined C axis performing a theoretical 90-degree radius executed within one second

	Vertical C Axis	**Inclined C Axis 22.5°**
C AXIS Initial position, deg	0	0
C AXIS Final position, deg	90	1.5
C AXIS Velocity deg/sec	90	1.5
B AXIS Initial position, deg	0.5	0.5
B AXIS Final position, deg	0	0
B AXIS Velocity, deg/sec	0.5	0.5

Temperature control

Friction stir welding is a thermo-mechanical joining process and its main phenomena – material flow and heat balance – are interacting strongly. By this, the temperature in the welding zone can be used as a quality criterion and control variable for well-established welding processes. Temperature control of the weld has been demonstrated both in the laboratory and in production to be beneficial especially for deeper and slower welds [7, 16].

In high volume production of shallow and fast welds, controlling the temperature of the weld may not be sufficient since temperature measurement is usually too slow compared to the process phenomena and target welding speeds beyond 3000 mm/min. Nevertheless, controlling or at least tracking the temperature can be beneficial for identifying process trends, tool wear or changes between batches etc. Another type of temperature control in high speed welding can be found regarding anvil and spindle. After performing several welds, the tool holder begins to heat up, and this heat is transferred to the spindle assembly. Additionally, heat is also transferred into the anvil and on into the fixture and work holding system. Closed loop coolant flow through the tool holder has been used by machine manufacturers for years, but temperature control of the fixture is not as common. In order to ensure that weld after weld is of a consistent temperature in a high-volume production environment, the most thorough method is to manage the heat input to the weld using closed-loop temperature control, maintain steady state temperature of the tool holder using coolant through the spindle, and adjust the heat balance of the anvil and work holding tooling using coolant to the fixture.

Process and clamping forces

While clamping is an essential success factor for many FSW applications, correct and rigid clamping is absolutely critical to the successful welding of complex contour parts especially in a high-volume production. Castings can shift, extrusions can vary, and stampings can be inconsistent. Factors such as die wear, uneven cooling during part manufacture and other variables contribute to the requirement that parts be consistently constrained during welding. Since high traverse speeds usually cause high normal and traverse forces, the FSW process may cause work pieces to move easily, and the clamping forces used to hold parts in place must overcome a few important obstacles:

First, any distortion in part geometry requires that the work holding system bring parts into intimate contact for welding. This often requires clamping forces sufficient to

conform parts to a registration geometry by deforming them. Stampings and extrusions often require such forces to bring the parts into intimate contact with each other.
In some cases, it is necessary to perform finite element modeling to determine the force required to bring parts together in intimate contact, given a known amount of distortion. This applies in particular to component radii and transitions where the negative target geometry of the respective part location should ideally be used for the clamps due to a wide variety of tolerance possibilities. Thermo-mechanical coupled simulation can furthermore help to understand the mechanisms while simultaneously optimizing the heat balance and forces of the process [17, 18].

Second, clamping systems must resist process forces that act to separate parts. Forge forces can surprise manufacturers used to designing fixtures for metal cutting. These forces can be significantly higher than those to which milling machines and robots are accustomed. When performing butt joint welds, separation forces may reach the order of up to 50% of the forge force. Clamping systems must resist those separation forces, which are caused by a combination of traverse and cross-seam forces.

Third, the plastification during FSW causes the material in the joining zone to flow to a path of least resistance. Therefore, containment is another aspect of work holding (and of course tool design) that must be considered. Hollow extrusions are a good example of a material type that can be vulnerable to lack of containment if not properly addressed. Well-designed hollow extrusions include a vertical rib beneath the weld zone with sufficient cross-sectional area to prevent loss of containment, Figure 6.

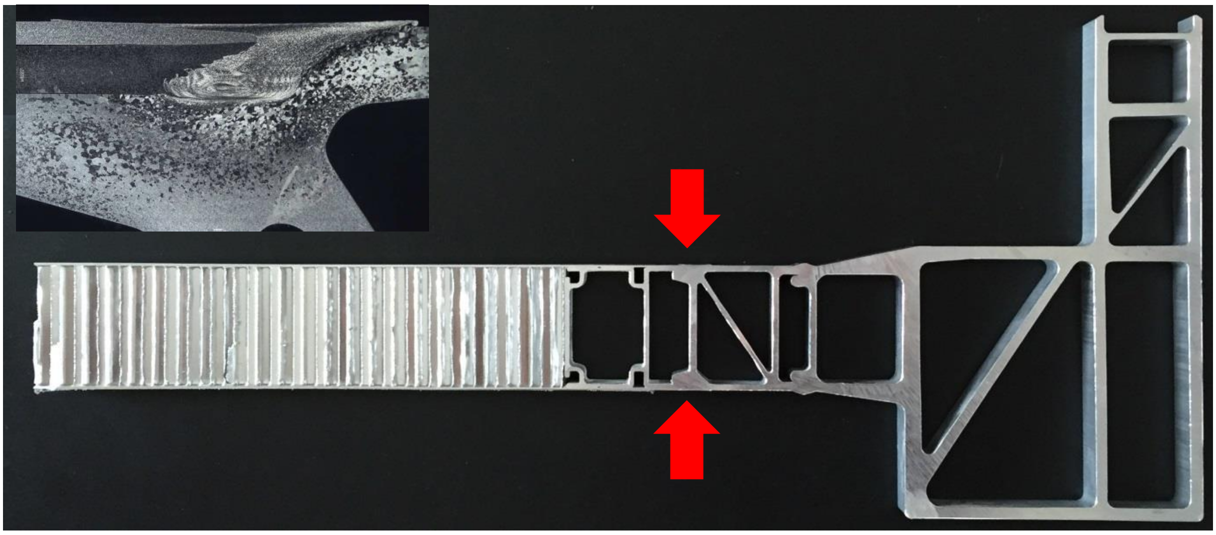

Figure 6: Sandwich design of a railcar with hollow extrusion profiles designed for Friction Stir Welding (red arrows) and macro detail of multi-sheet joint design [19, 20]

Summary and outlook

Over the last 25 years Friction Stir Welding (FSW) has been moving from research over first applications into mass production. Today, requirements for consistently high-quality welds occur in parallel with a demand for high throughput as well as production flexibility. With the maturing of the technology, FSW has started competing more and more with other established joining processes and therefore has to face the same requirements regarding all key factors.

To further support the dissemination of FSW and to exploit its advantages mainly two issues have to be solved: On the one hand, designers and engineers have to be educated regarding the unique capabilities offered by FSW but also its process and design requirements. But on the other hand and even more important in the author's eyes, the industrial welding speeds of FSW have to be increased significantly compared to the state of the art while simultaneously downstream processes have to be consequently eliminated. By doing so FSW becomes significantly more competitive in many industrial branches and applications.

One possibility to reach this goal is the high speed welding of complex three-dimensional contours. The design concept uses especially the capabilities of multi-purpose five and six axis FSW machinery to produce parts with 3D features that are already at or very close to the final geometry. Ideally, the weld becomes a design element for the component by itself. The concept of complex 3D contours is based on the welding of usually inexpensive and easy-to-source basic materials such as drawn or stamped, cold rolled aluminum sheets that are welded together forming the target component geometry. To avoid costly narrow tolerances and material specifications the joining of the parts is usually carried out as force-controlled overlap weld while target speeds range between 3000 and 5000 mm/min. By this the machinery throughput is maximized while the simple joining concept avoids downtimes, scraps parts, rework, error sources, and complexity and so maximizes the Overall Equipment Effectiveness (OEE).

For implementing the concept successfully, some requirements have to be met, which result mainly from the high welding speed and the low part tolerances. This includes the need for high speed advanced force control methods and an intelligent methodology for the clamping design for sustaining high quality welds. Furthermore, to develop a robust high speed welding process a good understanding of the machine characteristics is needed, especially regarding rigidity and kinematics.

Outlook

Purpose-built FSW machines have the ability to gather and analyze large amounts of process data in real time. To date, little has been done in commercial application to implement analysis of this data that can produce in process assessment of weld quality. Steps are being taken by industry leaders to develop robust algorithms that identify weld characteristics in the frequency domain that can determine whether the weld process is remaining in the range that is shown to produce acceptable parts. This goal is initially achievable for production applications that perform consistent, repeatable welds like automotive, shipbuilding, and rail car industries. Further benefits are possible using machine learning algorithms that can be applied to more challenging applications that include higher product mix such as contract welding operations. Implementation of in-process quality capabilities may reduce process development and documentation time and effort, while providing manufacturers the ability to make real-time decisions about product quality during high volume production of complex contour parts.

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