FSW-Tech

Friction Stir Welding European Qualifications

Friction Stir Welding Handbook

EUROPEAN FRICTION STIR WELDING OPERATOR

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Foreword

"Friction Stir Welding Handbook" is an educational material dedicated to the training of the personnel involved in this welding process. It contains the main information that will be able to offer minimum specific knowledge and competences to the personnel who is involved in the qualification process as a Friction Stir Welding Operator.

The book is the result of an intellectual output of the project **E+ 2017-1-SK01-KA202-035415,** Harmonized Friction Stir Welding Technology Training across Europe, project cofinanced by the European Commission through ERASMUS+ program, and it can be used as teaching or learning support.

The chapters of the book were elaborated by the members of the consortium which implemented the project:

Chapter 1: FSW Fundamentals

Chapter 2: Joint Preparation

Chapter 3: Welding Process Operation

Chapter 4: Post Processing

Chapter 5: Health and Safety

Chapter 6: Maintenance.

1. FSW Fundamentals

Friction stir welding is a material joining process where two or more metal workpieces are joined by the friction heating and mixing of material in the plastic state caused by a rotating tool that traverses along the weld. FSW is considered to be the most significant development in metal joining in a decade. The friction stir welding machine is operated by a competent FSW operator who performs fully mechanized or automatic friction stir welding.

The following modules main objective to give an overview of the FSW process. It starts with basic information about FSW and terminology, followed by advantages and disadvantages of this process, characterisation of welding equipment, tools and base materials. At the end of module, general concerns regarding the health and safety of the operators is described.

1.1. Introduction to FSW

- **Invention and History of FSW**

Friction stir welding is classified as a one of the solid-state welding techniques. It was invented and patented in 1991 by The Welding Institute (TWI) of the United Kingdom for butt and lap joining of ferrous, non-ferrous metals and plastics. It was initially applied to aluminium alloys, because of benefits, such as less sensitivity to contaminations, less distortion and improved strength and fatigue properties, compared to fusion welding. Implementation of FSW has occurred in industries such as automotive, aerospace, railway and maritime. It is being used increasingly to weld materials, which are traditionally considered to be not weldable, for example aluminium alloys 2XXX and 7XXX. Further studies aiming at widening the set of materials applicable for friction stir welding, which include Mg-, Cu-, Ti-, Al-alloy matrix composites, lead, stainless steels, thermoplastics and dissimilar materials [1-1, 1-2, 1-3, 1-4].

The development of lightweight construction, materials, and design play important role in economy and fuel consumption. Road, railway, water and air transport is based on the use of aluminium and its alloys, because of economic and ecological reason. The MIG and TIG welding processes are characterized by high heat input, occurrence of problems of thermal deformation and formation of aluminium oxide. Riveted assemblies are more expensive to make, have more weight than welded assemblies and holes required to insert rivets cause stress concentration. Another problem related to riveted assemblies is that they are not tight and leak proof. The introduction of FSW solved these problems.

Friction Stir Spot Welding (FSSW) was first developed at the Mazda Motor Corporation and Kawasaki Heavy Industry, respectively. This new spot welding technique is intended to replace other joining techniques include resistance spot welding, self-piercing rivets and clinching. FSSW is primarily intended for joining Al alloys, to reduce cost of consumables using during assembly manufacturing (self-piercing rivets) or in the case of resistance spot welding, reduce the electricity consumption and cost of electrode dressing due to physical properties of aluminium. Mazda RX-8 rear door panels were manufactured using FSSW in 2003 and Mazda claimed 99% reduced energy consumption comparing to conventional earlier process. The process consists of only the plunge and retract phase and it can be described as pure spot FSW.

Development of friction stir spot welding is to be further developed and improved and nowadays it can be classified in three categories:

- Pure spot FSSW,
- Refill FSSW,
- Swing FSSW.

Refill FSSW solves the problem of presence of keyhole (exit hole) due to retraction of the tool at the end of the weld, in the middle of the joint. Exit hole occurring in conventional friction stir spot welding and it is avoided in refill FSSW, which can also be used as a repair process. The forming of fully consolidated weld is possible because the welded region is produced in a process similar to a back extrusion.

Swing FSSW is a third variation of FSSW. This process produces a spot that is elliptical in shape. In comparison to the perfect circle obtained during conventional spot FSSW, elongated spot offers larger area of contact and this results in higher joint strength [1-1].

- **Fundamentals of FSW**

The FSW process starts with a machine initiating rotation of a friction stir tool. A non-consumable pin and shoulder is plunged into the joint line between two rigidly clamped materials on a backing plate support. During plunge phase, the tool and the workpiece are at ambient temperature, except the region surrounding tool and workpiece interface.

Rate of temperature rise, and extent of plasticity depends on the rate of insertion. The plunge phase is finished when the tool shoulder is in contact with the substrate. Local heat via friction and plastic deformation is created, which softens the material to be welded. The tool shoulder produces more heat than the pin surface. However, the deformation is generated by rotation of the tool pin which leads to the generation of additional heat. At this stage, force starts to drop as the metallic workpiece reaches critical temperature for plastic flow. When welding metals with higher melting points, it is possible that the rotating tool can be intentionally held in this position for a pre-determined time, known as hold time (also called dwell time), so as to reach the desired temperature needed for plastic flow.

When plunge reach the selected plunge depth, the FSW machine starts the traverse of the friction stir tool along the weld path. The rotation of the tool is maintained, geometric features on the shoulder and probe displacing and mixing (stirring) material along the weld joint. The tool shoulder restricts metal flow to a level equivalent to its position, i.e. close to the initial workpiece top surface. When the friction stir tool reaches the end of the path, it is retracted from the joint. This is the actual welding phase and, depending on the type of FSW machine, can be controlled by displacement, force, power, torque, temperature etc. [1-1, 1-2, 1-4, 1-5].

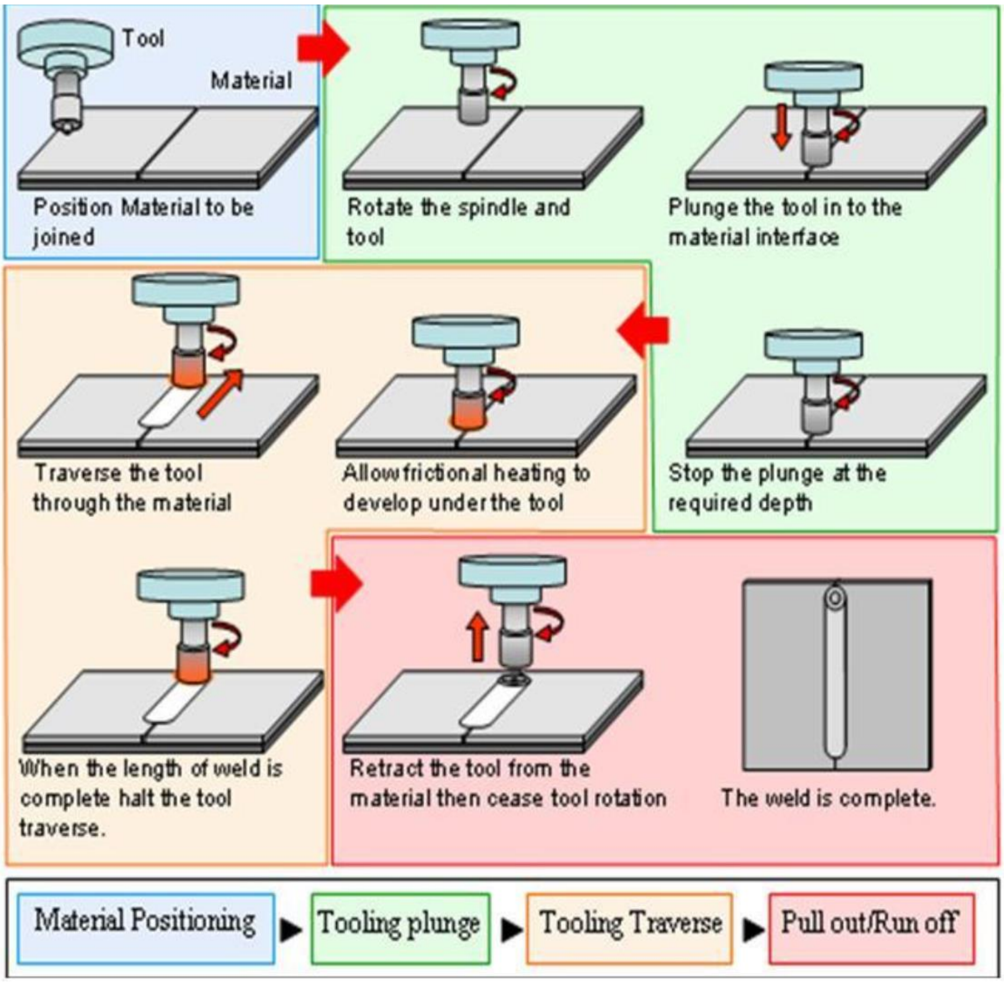


Figure 1-1: FSW process flowchart - Courtesy of [1-6]

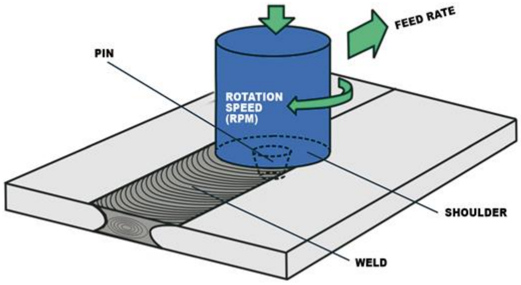
Friction stir processing

Friction stir processing use similar working principle to FSW and it is known as the surface modification technique. It can be used to improve mechanical and tribological characteristics. The difference between FSW and FSP is that they do have different purposes in practical applications. In FSW process the goal is to join two plates together, however, the FSP aims at modifying the microstructure of single component.

As a result of obtained plastic deformation, which refines the microstructure of a material, is improving mechanical properties of material. This process does not change the shape and size of the base material. It can be carried out selectively on a part for specific property enhancement, without affecting the properties in the rest of the material. In comparison to FSW, the pin of the FSP tool is often shorter than the thickness of the sheet.

Friction stir processing can also incorporate second phase particles into a material to process composites and produce surface composite layers. It can be done by inserting the powder (for example ceramic powder) in the processing zone by creating the groove, pouring the powder into it and then FSP.

The FSP can be also used to eliminate casting defects and homogenizing the as-cast microstructure in cast alloys. FSP can improve strength and ductility of the cast alloy by breaking the dendritic microstructure [1-5, 1-7].



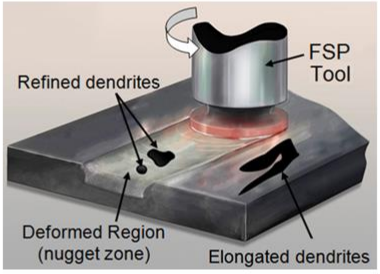


Figure 1-2: Friction Stir Welding (left) and Friction Stir Processing (right) - Courtesy of [1-8, 1-9]

- **Terminology**

FSW related terminology

- Advancing side of weld - the side of the weld where the direction of tool rotation is the same as the direction of welding.
- Anvil - the structure supporting the root side of the joint.
- Axial force - force applied to the work piece along the axis of tool rotation.
- Bobbin tool - an FSW tool with two shoulders separated by a fixed length or an adjustable length pin. The self-reacting bobbin tool allows the shoulders to automatically maintain contact with the workpiece.
- Direction of tool rotation - the rotation as viewed from the spindle that is rotating the tool.
- Dwell time at end of weld - the time interval after travel has stopped but before the rotating tool has begun to withdraw from the weld.
- Dwell time at start of weld - the time interval between when the rotating tool reaches its maximum depth in the parent material and the start of travel.
- Entrance block - a sacrificial piece of metal that is secured to the beginning of a FSW joint, and provides filler material as the tool enters the edge of a workpiece.
- Exit block - a sacrificial piece of metal that is secured to the end of a FSW joint, and by providing filler material, eliminates an exit hole in the weldment. The exit hole will be relocated to the exit block.
- Faying surface - the surface of one component which is intended to be in contact with, or in close proximity to the surface of another component to form a joint.
- Fixed pin - a fixed length pin protruding from the shoulder and the pin's rotation is the same as the shoulder during welding.
- Flash - material expelled along the weld toe during FSW.
- Force control - method to maintain the required force on the tool during welding.
- Heel - part of the tool shoulder that is at the rear of the tool relative to its forward motion.
- Heel plunge depth - distance the heel extends into the workpiece.

- Hook - faying surface that curves upward or downward along the side of the weld metal in a friction stir welded lap joint.
- Hole plug - a piece of filler metal which has been machined to allow its insertion into a hole and will be joined to the structure by FSW.
- Lateral offset - the distance from the tool axis to the faying surface.
- Multiple spindles – a friction stir welding system with two or more spindles.
- Pin - part of the welding tool that extends into the workpiece to make the weld.
- Position control - a method to maintain the required position of the tool during welding.
- Retreating side of weld - side of the weld where the direction of tool rotation is opposite to the welding direction.
- Self-reacting tool - a tool with two shoulders separated by a fixed length probe or an adjustable-length probe.
- Shoulder - the portion of the tool contacting the surface of the parent material during welding.
- Single spindle - a friction stir welding system with one spindle.
- Side tilt angle - the angle between the tool's axis and an axis normal to the base material surface, measured in a plane perpendicular to the weld path.
- Stirred zone - the oval shaped region in the centre of the weld, where a fine-grained, equiaxed microstructure exists.
- Tilt angle - the angle between the tool's axis and a plane perpendicular to the weld path, when viewed perpendicular to the weld path.
- Thermo-mechanically affected zone (TMAZ) - the area of weld joint that has been plastically deformed by the tool and has also had its microstructure and properties altered by the heat of a welding process.
- Tool (friction stir welding) - a FSW tool is the rotating component consist of the shoulder and pin. As base material thickness is increased, the shoulder diameter and pin length are also increased. Various pin designs include, but are not limited to, threaded, scrolled, fluted, or smooth. Pins may also have adjustable length and, with a special spindle, counter-rotating. A tool usually has a shoulder and a pin, but a tool may have more than one shoulder or more than one pin. Also, a tool may not have a shoulder or a pin.
- Tool rotation speed - angular speed of the welding tool in revolutions per minute.
- Travel speed - rate at which the welding operation progresses in the direction of welding [1-10].

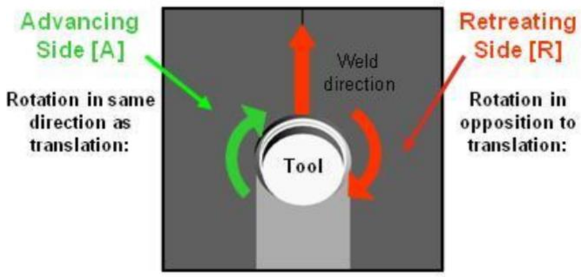


Figure 1-3: Difference between advancing and retreating side - Courtesy of [1-6]

Welding (including FSW) related terminology

Complex weld joint - a continuous weld joint with variations in section thickness and/or tapered thickness transitioning.

Heat affected zone (HAZ) - the area of weld joint which has had its microstructure and properties altered by the heat of a welding process.

Multi-run welding - welding in which the weld is made in more than one run.

Plasticity - the softening of metal material before it reaches its melting point. The mechanism usually becomes dominant at temperatures greater than approximately one third of the absolute melting temperature.

Single run welding - welding in which the weld is made in one run [1-10].

- **Advantages and disadvantages of FSW**

The benefits of the FSW process can be divided in three categories: metallurgical benefits, environmental benefits and energy benefits.

Metallurgical benefits:

- Solid phase joining process,
- Small distortion,
- High dimensional stability and repeatability,
- No loss of alloying elements,
- Excellent mechanical properties in joint,
- Fine recrystallized structure,
- Non-occurrence of solidification cracking.

Environmental benefits:

- No shielding gas required,
- Requires minimum surface preparation,
- Eliminates grinding wastes,
- Eliminates solvent cleaners and degreasers,
- Savings in consumable materials,
- Absence of harmful emissions.

Energy benefits:

- Reduced energy consumption compared to laser welding,
- Minimized weight of joint lead to decreased fuel consumption in automotive, ship and aircraft applications,
- Reduction in weight results from improved material use.

Disadvantages of FSW process include:

- As it is a solid-state process, a great amount of tool wear takes place during the plunging stage as the work piece material is cold at this time
- Weld speeds in FSW are slower and lead to poor productivity
- Equipment used for FSW is massive and expensive, because of high welding forces
- High melting temperature materials, such as steel and stainless steel are known to have welding tool limitations

- Absence of a filler wire means that the process cannot easily be used for making fillet welds
- Presence of an exit hole after conventional FSW process [1-4, 1-11, 1-40].

Main applications of FSW

Aeronautics and aerospace industry

FSW process reducing manufacturing costs and offers weight savings. Typical joints include skins to spars, ribs and stringer. This process can be used to manufacture wings, fuselages, empennages, floor panels, and aircraft landing gear doors, cryogenic fuel tanks for space vehicles and aviation fuel tanks.

Shipbuilding

The FSW process can be used to weld panels for decks, sides, bulkheads and floors, hulls and superstructures, helicopter landing platforms, off-shore accommodation, mast and booms, refrigeration plants.

Railway industry

In railway industry FSW is used to manufacture high speed trains, rolling stock of railways, underground carriages, trams, railway tankers and goods wagons, container bodies, roof and floor panels.

Automotive industry

The FSW process is currently being used in manufacturing of automotive mechanical components, because it is suitable to produce different welds, long, straight and curved. The following component can be made using FSW: trailer beams, cabins and doors, spoilers, front walls, closed body or curtains, drop side walls, frames, floors, bumpers, chassis, fuel and air containers, engine parts, air suspension systems, drive shafts, engine and chassis cradles.

Construction industry

FSW can be applied in the construction of aluminium bridges, façade panels, window frames, aluminium pipelines and heat exchangers.

Other industries

In last few years FSW has expanded in other application fields like the electrical (e.g. motor housings), oil and gas (e.g. land and offshore pipelines) and nuclear industry [1-12].

Co-funded by the Erasmus+ Programme of the European Union

1.2. Welding equipment

Articulated Arm Robot

Parallel-kinematic robot (tricept)

Dedicated FSW Machine

Modified Milling for FSW

Figure 1-4: Examples of various friction stir welding machines – Courtesy of [1-13, 1-14, 1-15, 1-16]

Conventional machine tools

The machines used in the FSW process are similar in terms of principle of operation of the equipment used in subtractive manufacturing (i.e. machining, deburring, grinding and drilling). All of these processes consist of moving a rotating tool through a workpiece, producing dragging of material which constitutes the workpiece. Therefore, it is possible to use conventional machine tool, such as milling machine, to perform FSW.

However, the main concern during FSW process is the stiffness of the machine, because the loads involved in FSW are higher than in the loads generated in the milling process. Due to this problem, conventional machine tools have to be strengthened in order to increase their load and stiffness capabilities. The machine modification can include several levels: structural, flexibility, decision-making and sensing.

The structural modification can be performed by replacing some parts of equipment, such as the ways, guides, rails, motors, spindles etc. The flexibility can be improved by the introduction of additional motors, which provide additional degrees of freedom to the equipment. During FSW process there is a need to implement force control solutions to prevent equipment damage, ensure human safety and to achieve good weld quality. The decision-making of the equipment can be further improved by providing movement in more directions at the same time.

Conventional machine tools are widely used in industry for machining purposes, which is one of the most common technologic processes used in industry.

Modified machine tools are recommended for:

- Prototyping and small series production
- Welding long or small work pieces
- Welding thick or thin work pieces
- Applications where high stiffness is required
- Single- or multi-axis applications

The main limitation is low production performance, so basically the modified machine tools can be used for prototyping and small series production.

Dedicated FSW machines

Dedicated FSW machines are characterized by high load capability, stiffness, accuracy and availability. They can assume different configurations thus presenting levels of flexibility. The custom-built machines, like machines used to weld parts for decks of ships, belongs to this category. The dedicated FSW machines are rather expensive, and their cost increases with the increase in flexibility. The dedicated FSW machines recommended usage, include high series production of the same part types.

The use of custom-built machines should be considered only for application where the alternative solution does not exist or is expensive. The welding of high temperature materials, such as steel, stainless steel, titanium, nickel alloys, requires high load support. The dedicated FSW machines are more robust and structurally sound, that is why they are recommended to weld these materials.

Current trends lead to development of portable FSW machines. This type of machines will be used in remote locations as well as in-situ repair and addition of components to large structures. The main design limitations include weight of equipment and reduction of the loads required to perform FSW.

Dedicated FSW machines and modified conventional machine tools can be applied for:

- Welding long or small workpieces
- Welding thick or thin workpieces
- High-stiffness applications
- Single- or multi-axis applications

Robotic FSW machines

Recent developments in industrial robots, especially increased load capability (payload) and stiffness, have led to use of robots in FSW applications. The main advantages of robotic FSW machines are flexibility and process automation. The productivity increases because the robot allows welding on multiple sides of the work piece in a single setup. Application recurring to 3D welding paths have become increasingly attractive, this kind of application just needs an industrial robot with five DOF (most common robots in the market possess five or six DOF). The robotic-based solutions can be divided into two categories:

- Articulated arm robots
- Parallel-kinematic robots

Articulated arm robots are characterized by high repeatability and flexibility. The main disadvantage is low accuracy that worsens when they are subjected to higher loads. These robots display higher flexibility and decision-making capability in comparison to dedicated FSW machines. However, articulated arm robots have relatively low stiffness and moderate load capability, which limit their application. Given their flexibility and relative low cost, the can be used as the lowest-cost with limited range of materials on which they can perform FSW. The most robust robots are capable of welding up to 6 mm thick aluminium grade material. Welding capability in higher-melting point materials tend to be somewhat less. The robotic FSW systems can be also used for friction stir spot welding (FSSW). The use of articulated arm robots can be applied for:

- Relatively thin materials (up to 6 mm),
- Multiple side welding in a single setup,
- Dissimilar-thickness butt welds (tailor-welded blanks)
- Multi-axis applications
- High work volume applications
- Parallel-kinematic robot supports higher loads and have significantly higher stiffness than articulated arm robot. Their cost can be notably higher, and their volume is significantly lesser than the articulated arm robot. Parallel-kinematics can be applied for:
- Relatively small volume applications
- Welding workpiece near or close to the horizontal plane
- High stiffness applications [1-17].

Table 1-1: FSW equipment characteristics – Courtesy of [1-17]

	Milling Machine	**FSW Machine**	**Parallel Robot**	**Articulated Robot**
Flexibility	Low	Low/Medium	High	High
Cost	Medium	High	High	Low
Stiffness	High	High	High	Low
Work volume	Medium	Medium	Low	High
Setup time	Low	High	Medium	Medium
Number of programming options	Low	Medium	High	High
Capability to produce complex welds	Low	Medium	High	High
Control type	Motion	Motion/force	Motion	Motion

FSSW machines

In this variant of FSW the traverse part of the FSW process is eliminated. The equipment requires only two axes of motion (rotary and vertical). Like FSW it requires significant force but fixturing does not have to be as robust as with FSW. The equipment used for FSSW can be divided into four categories: pedestal units, benchtop units, C-frame units, and a poke solution.

The pedestal unit is a self-contained stand-alone solution, which need operator or robot to manipulate the parts under the pedestal machine. The second type of machine is a table top or benchtop system, which is a smaller stand-alone system that will sit atop a stiff table. It can be operated in the same manner as the pedestal type unit.

The purpose of the C-frame is to contain the welding forces internal to the unit, which means that the robot or operator does not have to generate any of the forces required for the process. Smaller robots can be used for C-frame FSSW than for FSW. The robot arm only handles and manipulates the C-frame unit through space to the part that is to be welded. C-frame can also be used in a manual mode, where the C-frame hangs from a counterbalance unit, and the operator manually moves the unit up to the part.

If there is lack of access to the backside of the part, the FSSW process can be used in "poke mode". A robot is typically used to poke the part and forces the FSSW tool down into the part. Thus, the robot must be capable to generate the high force required for the FSSW process.

The last variant of FSSW is "stitch" FSSW, where the tool is traversed a short distance. Main disadvantage of this process is that it eliminates the fixturing benefits introduced by FSSW. It offers higher strength than FSSW if the weld is long enough [1-1].

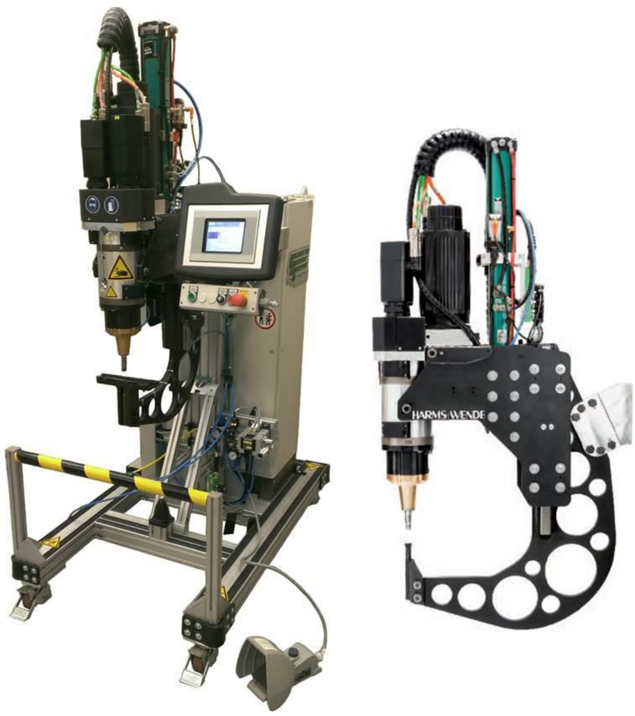


Figure 1-5: Pedestal FSSW machine (left) and C-frame FSSW unit (right) – Courtesy of [1-18]

- **Essential components**

Basic system components include:

– Spindle,
– Motors,
– Motor drive mechanism,
– FSW tool [1-19].

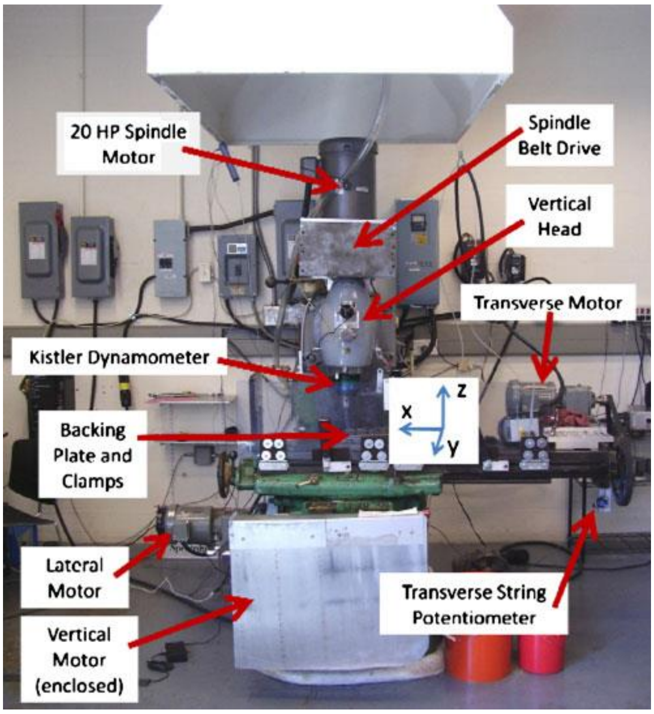


Figure 1-6: Example of FSW system configuration – Courtesy of [1-20]

The differences between machines are mainly due to type of machine: robotic or conventional FSW machine.

Additional features, that can be incorporated into a machine, include:

- **CNC control** - full CNC process control, typically comprising advanced touchscreen interface, data acquisition and weld monitoring systems.
- **Production monitoring -** the operator can select the type of control to perform the weld. Possible options include position, force or height control. Camera-fed visual monitoring can provide safe viewing of the weld production environment.
- **Weld temperature monitoring -** remote IO stations around the FSW machine allow features such as non-contact 'spot' measurement of the weld to be constantly relayed back to the machine control system in real time.
- **Joint tracking –** the tracking system is used to automatically follow the seam of the weld - the FSW control software monitors the tracking system and moves the Y axis to ensure the welding tool stays on the weld seam.
- **Gas shielding -** gas shielding protects the welding area from atmospheric gases to create an inert gas atmosphere when working with parent materials that produce high temperature welds (e.g. steel and titanium).
- **Machine Fixturing -** special machines fixtures, like side clamps, mandrels and supports, can be incorporated into the machine design.
- **Data Acquisition System -** machines can be equipped with data acquisition system to measure and record all available weld data, which is archived to the local hard disk. Recorded process variables include: axial down force, traverse forces, rotation speed of spindle and tool traversing speed and direction.
- **Height Sensing -** non-contact measuring heads can continually measure the relative position of the tool to the component, holding it within the narrow tolerance band [1-21].

– **Welding equipment**

Tool

Figure 1-7: The welding tool – Courtesy of [1-22]

The tools used in FSW process compromising three generic features, a shoulder, a pin (or so-called probe) and external features. The differences between tools can include various shape of features and materials. The material used should have characteristic, which include:

- wear-resistant;
- no adverse reactions with the parent materials;
- high strength, dimensional stability and creep resistance at ambient and elevated temperatures;
- ability to withstand repeated thermal cycles without fatigue;
- good fracture toughness needed during plunging and holding phases;
- low thermal expansion coefficient;
- good machinability to allow manufacturing of external features on the shoulder and the pin;
- acceptable tool life;

Possible tools materials, which are similar or same to that of used in specialist machining applications, and include: tool-steel, silicon nitride, molybdenum-based alloys, polycrystalline cubic boron nitride (PCBN) and tungsten-based tool materials [1-4].

High hardness of tool is desired mostly for welding wide range of materials. PCBN, which is characterized as super hard material, is suitable for FSW of high-strength materials, like titanium and steel. PCBN have excellent mechanical and thermal performance, but it has poor machinability, which makes forming of FSW tool geometry very difficult. Problems with machinability affects also tungsten carbide, for which machining of complex pin geometry is very difficult [1-23].

Table 1-2: Characteristic of selected FSW tool materials – Courtesy of [1-23]

Tool material	Advantages	Disadvantages
H13	Easy machinability, good elevated temp strength	Severe tool wear for high-strength materials or metal matrix composites (MMS)
SKD16	Good thermal fatigue resistance	Tool wear with complex pin profiles
HCHCr	High hardness compared to another tool steel	Difficult to machine in hardened condition
Tungsten	High hot hardness and strength. Suitable for high-strength materials.	Poor machinability, expensive, low coefficient of friction with aluminium

The FSW tool geometry can be divided into three categories: fixed, adjustable and self-reacting.

The fixed probe tool is a single-piece tool, consisting of the shoulder and probe. Fixed probe tool, which is characterized by fixed probe length, is used only to weld components with specific and constant thickness.

Adjustable tools comprise the shoulder and the probe as independent elements. It thus makes it possible to adjust the probe length to make up different configuration of shoulder/probe and weld of a large number of various components. In adjustable tools it is possible to manufacture the pin and the shoulder using different materials, the probe can be easily exchanged, or its length modified.

Self-reacting tools have three different components, which are the top and bottom shoulders and the probe. The self-reacting tools can only operate perpendicularly to the workpiece surface, contrary to fixed and adjustable tools that can be tilted longitudinally and laterally to the workpiece [1-5].

Tool shoulder

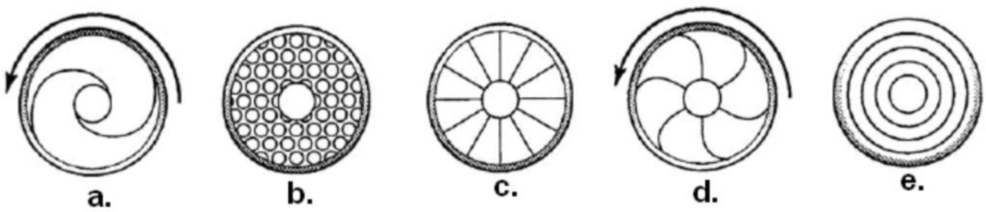


Figure 1-8: Different shoulder features – Courtesy of [1-24]

The tool shoulder has three main functions

- Generating heat due to friction, which is necessary for softening the base material being welded
- Forging the material, which is being stirred behind the tool pin
- Restricting material from extruding outside the shoulder

Design of tool surfaces include flat, concave, scrolled, concentric circle etc. [1-5]

Pin

The functions of pin are:

- the primary source for material deformation,
- the secondary source for heat generation in the nugget.

The tool can have additional features on the pin, which discontinuously displacing the material [1-25].

Welding Tool

The tooling must be able to hold the part in known location and react the axial and radial forces generated by the process. The tooling fixture needs to have clamping mechanisms that allow the FSW tool access to the workpiece for the given weld head articulations and prohibit the part from sliding lengthwise, bending or separating due to the torque forces. The thermal conductivity of the weld surface and the clamping system can impact the quality of the weld and the welding parameters.

During fixed-pin and adjustable-pin welding, the tooling needs to have a backing surface that directly supports and presses against the back side of the part. If there is not proper fit-up, the FSW tool will dive into the material, as there will be a decrease in the welding load and due to the change in force, system will move into the part. This situation can occur whether the system is in either position or load control but will be more pronounced when it takes place during load control as controller will attempt to move into the part until the desired axial load is achieved or a position limit is triggered.

With fixed-pin and adjustable-pin welding it is especially important to select the appropriate material for backing plate, because of the impact that the backing plate can have on the thermal flow of the part. Depending on the backing bar on anvil material, the thermal flow could lead to higher or lower parameters set. This effect can be used if more heat is needed on the root side. The backing bar material should be included in the weld process specification (WPS). Sometimes to monitor the back-side temperatures it is possible to embed thermal-couples into a channel in the backing bar area.

The weld quality strongly depends on the manufacturing accuracy of the weld table and clamping system – dimensional tolerances of the finished part are crucial. The backing bar or anvil should be on same level as the weld table to prevent mismatches between the parts being welded. The clamping system must clamp down the workpieces reliably to ensure that no gap can occur during the welding operation. The welding process is easier to handle if the backing bar or anvil is in absolute plane, so the distance from the backing bar or anvil should be constant to the weld tool Z axis. In case of a wavy backing (i.e., waves or variations greater than 0.1 mm), the FSW machine must be able to compensate for these waves to provide a constant pin ligament (i.e., distance of the pin tip to the back of the weld).

The exact hold-down clamping force is dependent on:

- Material
- Pin tool
- Part geometry
- Joint type
- Weld schedule

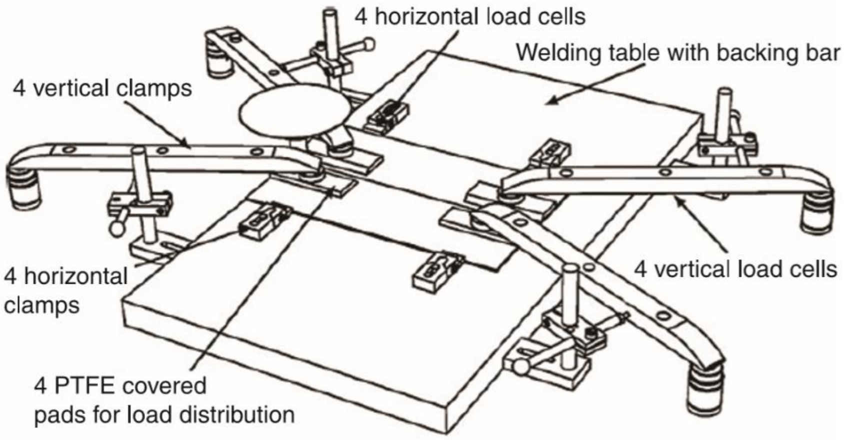


Figure 1-9: Example of clamping system – Courtesy of [1-5]

The clamping system should always be selected individually according to specific application. Clamping claws are the simplest and cheapest way to clamp sheets or plates. This system offers high clamping force, but it has several disadvantages like high set-up time to clamp workpieces, the different thermal conductivity if clamping claws are mounted close to the weld seam and during clamping wide parts, clamping claws are hard to reach along the weld seam. The problem of different heat sinking can be solved if pressure bars are used beside the weld region.

Serial production requires to design clamping system using special hydraulic or pneumatic fixture to reduce set-up time. Application of such equipment should be economically justified before production, because it is very expensive.

Possible alternative to the mechanical clamping systems is vacuum clamping. The set-up time for vacuum clamping is negligible and a high rate of parts can be processed quickly. The vacuum plate can be mounted on a weld table, or it can be designed to be used as the weld table. Beside flat tables, it is also possible to manufacture 3D vacuum clamping systems, which can only be used for specific weld application. Costs of vacuum clamping systems, especially 3D, are much higher than for standard mechanical clamping systems.

Typically, vacuum clamping system consist of:

- backing bar (no vacuum clamping)
- vacuum plate with vacuum fields
- vacuum pump with valves to control different vacuum fields
- round rubber sealing
- open holes for mounting of additional clamping and mechanical fit-up and reaction points
- support system for wide sheets.

In case of variable vacuum clamping system, it should consist of independent vacuum areas and a grid of grooves for sealing to be more flexible in clamping different part geometries. The main advantage of this solution is to clamp easily compliant, flexible work pieces. In this situation, the sealing has to be larger to reduce the space between work piece and the sealing in order to generate the vacuum.

Tapped holes are needed to mount some physical stops along the workpiece to increase clamping force in case of insufficient vacuum clamping forces, or to clamp the run-in and run-out with additional clamping claws. The main advantage of vacuum clamping systems is their flexibility for clamping different part sizes. The thermal flow from the FSW process is constant over the whole backing bar and lead to good weld quality. Although, vacuum clamping forces are not always enough for thick plates [1-26].

- **Cooling system**

Thermal management system includes: the tool (and connection to spindle), workpiece and backing anvil. Proper thermal management should concentrate sufficient heat in friction stir region to allow efficient thermomechanical deformation while dissipating heat from unwanted regions in the friction stir machine like spindle and bearings. Depending on the type of material to be welded, the FSW tools and anvil can be heated or cooled. Cooling of tool may be realized by ambient air, forced air, or a circulated coolant. Heated tools use resistance heating. The same methods of cooling and heating are applied to anvil. Besides, high thermal conductivity materials used for anvil and tool can affect the heat input into the workpiece, because they will tend to act as heat sinks.

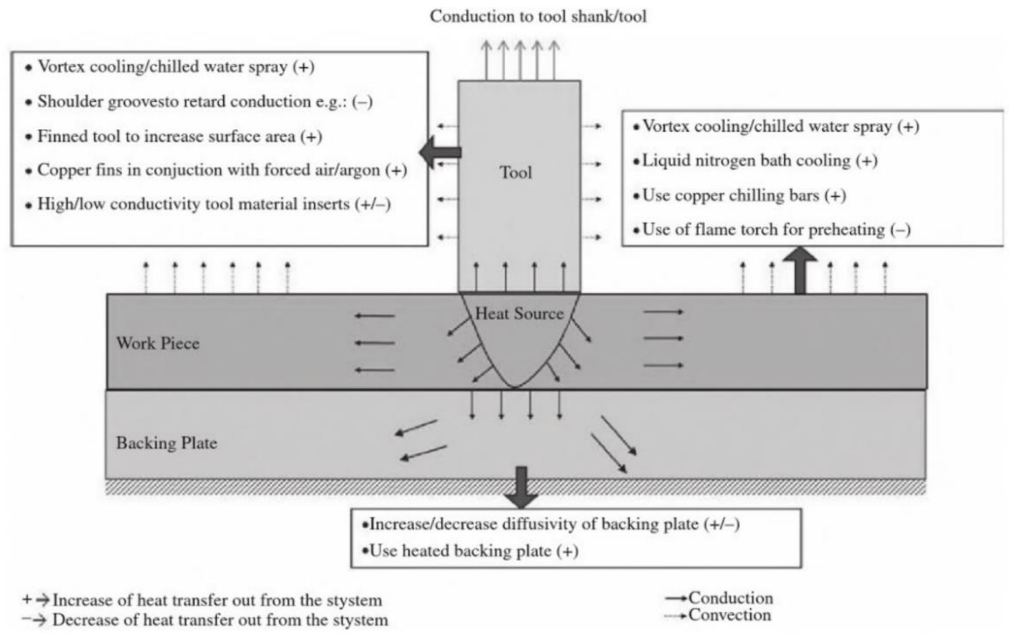


Figure 1-20: Thermal management methods that can be used in friction stir welding process. Arrows indicate heat transfer [1-27].

Preheating of workpiece can be implemented using resistance heating, laser, arc and ultrasonic energy. Cooling of workpiece is done using cooling medium like water, liquid CO2, and liquid nitrogen.

Aluminium and magnesium alloys can be welded with ambient air-cooled tools and anvils. Coolant cooling of the tool provide equilibrium temperature for the entire tool, especially it can be used for long welds and rapid tool changes.

Cooling the anvil has a minimal impact on the friction stir weld, the more important parameters are tool rotation rate, travel speed, and tool depth. The shape of workpiece affects quality of the weld. Complex shapes (e.g. extrusions) can be difficult to weld, because they have complicated cross sections, with features that quickly dissipate heat from the friction stir weld. As a result the tool heat input necessary to create a quality friction stir weld is much higher than for flat plates.

Steel, titanium, stainless steel and higher-temperature alloys are friction stir welded with coolant-cooled tools. FSW process during welding mentioned materials produce large temperature and load gradients. The main concern during FSW of the higher temperature aluminium alloys is that the tool governs heat flow which is opposed to the lower-temperature aluminium alloys, where the workpiece governs heat flow. Cooling of the FSW tool is necessary to produce a consistent heat flow at the tool and to prevent thermal energy from moving into the FSW machine spindle and away from the workpiece. Passive cooling, which mean cooling of only the spindle bearings or nor no liquid cooling, can produce excessive heat of the spindle and steady-state FSW condition was not achieved.

In contrast to cooling, the tool or workpiece can be heated during welding. The heating can minimize tool wear (especially the plunge) and increase the tool travel speed. Proper heating requires to not input too much thermal energy to allow surface melting to occur and to localize the thermal input to the FSW region. Workpiece surface heating during FSW for improved tool travel speed can be realized with flame or arc/plasma and lasers. The benefit of preheating can reduce of thrust, side and normal load and also the tool torque. The current passing between the tool and anvil can reduce the normal forces during tool plunge and increase travel speed in comparison to conventional FSW [1-1].

Cooling enhanced FSW

Cooling enhanced FSW is a hybrid method in which workpiece is welded under the effect of different cooling mediums such as water, liquid CO2, and liquid nitrogen. The superior fine grain microstructure can be obtained only using the cooling enhanced FSW. Additional benefit of this hybrid method is significant restriction to the formation of intermetallic compounds due to cooling effect. Underwater FSW requires special purpose fixture to keep the workpiece under water. Cooling enhanced FSW is used for dissimilar welds with reduced formation of intermetallic compounds.

Heating

Electrically assisted FSW

Electrically assisted FSW is a technique in which workpiece is subjected to resistance heating through electrical current. The Joule effect causes electro plastic heating and leads to the additional material softening to the workpiece. In contrast to arc assisted FSW and laser assisted FSW, the electrically assisted FSW doesn’t require bulky set-up. This hybrid method can reduce forces generated on tool due to softening effect, which lead to improved wear resistance and longer life of the tool. Because of initial preheating of the workpiece it is possible to increase welding speed. During welding dissimilar materials, it is possible to rise temperature at single workpiece and obtain improved dissimilar joint. Only electrically conductive materials can provide resistance heating effect.

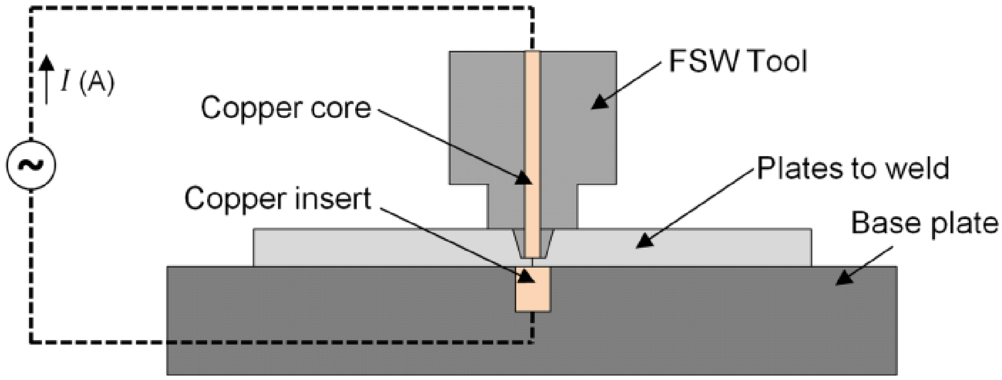


Figure 1-31: Specially designed FSW tool to allow a high intensity electrical current to flow into the weld root aiming to improve the local energy efficiency of the process [1-29].

Laser assisted FSW

Laser assisted FSW use laser as preheating source. The laser beam is flexible and precise source of heating, which focus heat at the specific point. Laser assisted FSW can improve properties of dissimilar joints utilizing flexible laser source.

Arc assisted FSW

Arc assisted FSW can be used either with GTAW or plasma preheating for dissimilar combinations. The external torch of GTAW or plasma welding is attached in front of FSW tool. Arc and shielding gas is supplied to a material which Is harder than the other material. The role of shielding gas is to prevent atmospheric contamination during preheating. Materials like cooper affected by oxidation at higher preheating current can produce weak aluminium-copper joint. Arc assisted FSW can be applied to non-metallic materials too.

Ultrasonic energy assisted FSW

Ultrasonic vibrations can be applied to preheat workpiece. This hybrid process is considered as a sustainable hybrid FSW process. It is used to weld dissimilar materials and similar materials [1-28].

- **Maintenance of the equipment**

The key components of FSW machine include:

– welding head and its motor,
– guide rails and its components,
– hydraulic units.

To ensure a long term and trouble-free operation, there should be prepared maintenance or repair plan. The FSW machine inspections and service should be carried out at specific and frequent intervals. The design of machine needs to ensure that there is adequate access to the various components to allow service engineers to monitor wear, provide routine maintenance (e.g. grease bearings) and replace components if necessary.

There should be access to documents like operating manuals of machine and control system with machine specifications, detailed operating instructions for machine operation, setting of machine parameters, precautions and machine safety details. Documents should also contain programming manuals of machine and control system necessary drawings.

The manufacturer shall provide a documentation package, which describes the machine and include:

- Detailed maintenance manual of machine, which include all drawing of machine assemblies and parts, hydraulic circuit diagrams.
- Operation and maintenance manuals.
- Manufacturing drawing for all supplied tool holders, adapters, sleeves, fixtures etc.
- Commissioning, maintenance and interface manuals for systems like CNC, spindle, feed drives etc.
- PLC program printouts.
- PLC program, NC data, and PLC data on CD [1-30, 1-31].

1.3. Welding processes

- **Design implications of FSW**

Mechanical limitations

The process forces generated during FSW are typically too high to allow hand operation. Even during welding very thin materials, where the forces may be low, the tool path should be controlled by mechanical means. Such control is needed to ensure the accuracy. The forces along the tool axis and the travel direction can be very high, e.g. during welding 25-mm thick 5083 aluminum plate it is possible to achieve force over 44 kN in axis and 15 kN in travel direction. It is also worth mentioning that the required torque in this situation will be around 360 N-m . As a result, it is often necessary to run machine in near continuous production operation, thus maximizing the economic value of goods produced by the process.

Fixture limitations

FSW requires that the workpiece be rigidly held in position during welding. It is important that joint does not separate under the force of the welding tool. To achieve smooth weld, it is necessary to ensure that the workpiece stays in intimate contact with the anvil during welding. Special fixture requirements cause economic costs and restrict on the size of workpiece that can be produced. It is difficult to restrain the thin and very large workpieces against the anvil. Requirement to restraint lateral separation of the joint can be hard to comply with very thick workpieces.

Joint design limitations

It is impossible to make a typical fillet weld, where a significant amount of material is added to fill a transition between two workpieces. However, it is possible to form a small fillet during FSW of plates at some angle, because it can be achieved at the expense of material from the joint. FSW is suitable to produce butt welds, corner welds and lap welds.

FSW lap weld needs to be differentiated from all other lap welds, because of its uniqueness. Conventional FSW is an asymmetric process, for example one side of the weld is heated more than the other side. Another example of asymmetry during FSW process is the difference in strength between the advancing side and retreating side of the weld. Depending on whether the advancing side or the retreating side of the weld is near the edge of the sheet, then the stronger or weaker side of the joint should be placed on the stressed side of the weld.

Keyhole limitations

FSW produce keyhole during process and as a result, in some applications it is necessary to consider how the welded joint will be started and finished to result in expected product characteristics, such as in the construction of cryogenic fuel tanks and in welding marine structures. The starts and stop ends should be cut away from main portion of the assembly and discarded. Alternative method uses run-on/run-off tabs to reduce the loss of base metal. It is possible to use friction tapered plug welding, arc welding or even a sealed fastener to eliminate keyhole after FSW process, especially for structures like sealed tanks.

There is possibility that the presence of an exit hole does not affect structural integrity and the hole may be left in a "no-fill" condition. However, careful engineering analysis should be conducted, and appropriate non-destructive testing should be used to confirm the absence of flaws in this area [1-32, 1-33].

Workpiece and base material thickness limitations

The maximum thickness capability of FSW is limited to around 65 mm [1-34].

Material

Higher-melting-point materials and highly abrasive metal matrix composites require the use of more advanced tool materials [1-32, 1-33].

- **Welding probe/pin/tool**

Flat shoulder

Flat shoulder is simplest in design and easy to make. It can be used for welding aluminium alloys, excluding cases where enhanced stirring action and material consolidation are required.

Concave shoulder

Concave shoulder was the first and most common shoulder design in FSW, which is also referred to as the standard-type shoulder. They are designed to restrict the stirred material within shoulder, which lead to minimized flash formation. The shoulder concavity is determined by a small angle between the edge of the shoulder and the pin, typically from 6 to 10 degrees. During plunging phase, material displaced by the probe is fed into the cavity within the tool shoulder. This material is utilized for forging action of the shoulder. Forward movement of the tool forces the new material into the shoulder's cavity and pushes remaining material into the flow of the probe. This probe operating properly if the rear edge of the tool shoulder produces a compression force on the forging welding. This is usually achieved when the tool is tilted between values from 2 to 4 degrees. Welds produces with concave shoulders are mainly linear. To produce nonlinear welds, it is necessary to use machine design, which can maintain the tool tilt around corners (i.e. multiaxis FSW machine). Concave shoulders are characterized by simple design and for this reason they are easily machined. This shape allows to produce good quality friction stir welds.

Convex shoulder

Early designs of convex shoulders experience problem with pushing the material away the probe. Addition of scroll to convex shape cause movement of material from the outside of the shoulder in toward the pin, thus making welding thicker materials possible.

A major benefit of convex shoulder is that the outer edge of the tool need not be engaged with the workpiece, so the shoulder can be engaged with the workpiece at any location along the convex surface. Therefore, a sound weld is produced when any part of the scroll is engaged with the workpiece, moving material toward the probe. The design of profile of the convex shoulder can be tapered or curved. Advantages of convex shape include greater flexibility in the contact area between the shoulder and the workpiece, (amount of shoulder engagement can change without any loss of weld quality), improvement the joint mismatch tolerance, ease weld creation between different-thickness workpieces and improvement the ability to weld complex curvatures.

Scroll shoulder

Scrolled shoulder tool compromises flat surface with spiral channel cut from the edge of the shoulder toward the center. Spiral channel directs the material flow from edge of the tool to the pin, which eliminate the use of high tool tilt, reduce thinning of weld region, eliminate undercut produced by concave shoulder and prevent expelling of material outside the shoulder. Removing the tool tilt ensure simply friction stirring machine design and made possible to produce complex nonlinear weld paths. Spiral groove promotes plastic deformation and frictional heat, because material within the channels is continually sheared from the plate surface. Tendency to lift away tool from the workpiece surface occurs when the tool travel speed is increased, which is typical for concave shoulder tools. Scroll shoulders reduces tool lift and increase welding speed in comparison to concave shoulders.

Scrolled shoulder tools does not allow to weld complex curvatures and fail to accommodate workpiece thickness variation in the length of weld line. Scroll shoulder is not suitable for welding materials with different thickness, because some amount of material from thicker plate is expelled in the form of flash. Combining of convex shoulder design with scroll end surfaces offers greater flexibility in the contact area between the shoulder and the workpiece, which enables improved mismatch tolerance of the joint, ability to weld complex curvatures, welding of different thickness materials and reduce tool lift during high speed welding processes. The scrolled shoulder tools work normal to the workpiece and the normal forces are lower than for concave shoulder tools. In concave shoulder tools load is applied in both normal and transverse direction to keep the shoulder in sufficient contact [1-1, 1-5, 1-23].

Table 1-3: Summary of major welding tool design features – Courtesy of [1-26]

Feature	Intended effect
Threads on pin	Compression of weld zone against anvil
Flats or other re-entrant features	New mode of plastic work, thicker section welding, higher heat input
Flat pin tip	Improved TMAZ penetration, higher penetration ligaments – better robustness
Frustum pin profile	Reduced lateral forces, thicker section welding
Flare pin profile	Wider root profile
Shoulder scroll	Elimination of tool tilt requirement, containment of softened work piece material
Tapered shoulder	Variable shoulder contact width, variable shoulder penetration

Complex motion tool design focus on increasing the tool travel speed, increase the volume of material swept by pin-to-pin volume ratio, and/or increase weld symmetry.

Skew-Stir tool

Skew-Stir tool can process larger volume of material by offsetting the axis of the pin from the axis of the spindle, thus producing an orbital motion. The orbital motion creates more deformation at the bottom of the pin and decreasing the incidence of root defects.

Com-Stir tool

Com-Stir tools maximize the volume of material swept by combining rotary motion (tool shoulder) with orbital motion (tool pin). Effect of orbital motion include wider weld and increased oxide fragmentation on the interfacial surfaces. It also produces lower torque than typical rotary motion FSW tool, thus reducing the amount of fixturing necessary to securely clamp the workpiece.

Re-Stir tool

The Re-Stir tool avoids the inherent asymmetry produced during friction stirring by alternating the tool rotation. It can be done either by angular reciprocation (direction reversal during one revolution) or rotary reversal (direction reversal every one or more revolutions). The effect of alternating the tool rotation, is eliminating the asymmetry issues like lack of deformation on the retreating side.

Dual-Rotation tools

Dual-Rotation tool consist of the pin and shoulder, which rotate separately at different speeds and/or in different directions. Dual rotation allows the pin to be rotated at a high speed without the corresponding increase in shoulder velocity, therefore reducing possibility of overheating. The decrease In workpiece temperature can lead to increased microhardness after natural aging and reduced corrosion susceptibility.

Two or more FSW tools

Two or more FSW tools can improve speed and efficiency of FSW process. Thick plates can be welded with two counterrotating FSW tools on either side of the plate. Counterrotating tools offers reduction of the fixturing required to secure the workpiece as a consequence of decreased torque. The main advantages include thinning defects between the two tools, reduction in workpiece fixturing, improving the welding speed, increasing deformation and fragmentation of the faying surfaces oxide layer. The motion of counterrotating tandem Twin-Stir is similar to the Re-Stir toll, but the Twin-Stir allows faster travels speeds [1-1].

1.4. Parent Materials

Friction stir welding can be used in joining a number of different materials, ranging from aluminium up to materials like copper, magnesium, steel, thermoplastics and titanium. It is also possible to perform dissimilar material welding. However, welding of high melting point materials is more difficult, because the welding tool material is working in harsh operating conditions. It is worth remembering that performance and economic justification must be developed in order to make practical use of the process.

Some general rules, based on the nature of the friction stir welding of aluminium, can be defined for welding of other materials. Thermal softening of the workpiece material is necessary for the welding process to commence and the welding process will take place at a temperature that is near the melting point of the workpiece material. It is necessary that heat be generated with sufficient intensity to overcome the loss of heat from the welding zone through conduction into the workpiece. It is needed to achieve heat generation, either by friction, plastic work, or by auxiliary heating, at the full spectrum of temperatures from initial material temperature up to welding temperature.

Shielding gas may be needed for some materials to prevent reactions with atmospheric gasses, but it is not normally needed for FSW of aluminium.

Welding of high melting point materials is limited by availability of suitable welding tool materials. New welding tool materials and geometries allows to join materials such as steel and titanium in the laboratory environment and in a limited number of production applications. Friction stir welding of steel offers lower welding temperatures, which lead to very low distortion and unique joint properties.

Friction stir welding of titanium has been demonstrated in the laboratory environment and it can be used in the construction of relatively large prototype structures which are more difficult to fusion weld. Despite titanium Is considered a high melting point material, its low thermal conductivity requires reducing the heat input into the tool, either by minimizing the shoulder diameter or by eliminating shoulder rotation altogether.

Friction stir welding of copper, even thick workpieces, is possible with relatively high spindle speed to obtain sound and high-quality welds [1-26].

Aluminium

Friction stir welding of aluminium alloys is the most common application of the FSW process. The principal FSW variables, which are controlled by operator, include tool design and the tool movement parameters. Factors like machine characteristics, workpiece thickness and control mechanism also affect the weld quality.

Different welding machines, even when all factors remain the same, will result in weld quality variation. Machine parameters will vary form one machine to another, because it is caused by machine factors like stiffness, tool eccentricity and control precision. Machine requirements will vary significantly based on the alloy, because the alloy affects the force requirements of the machine. For example, an FSW butt weld in 6 mm 1100 aluminium alloy can require 2.5 kN or less welding force, whereas a butt weld in 6 mm 7xxx aluminium alloy can require five times or more force.

The tool materials commonly used for FSW of aluminium alloys are tools steels which possesses a combination of high temperature strength and toughness.

Copper

Pure copper melts at 1083°C, which is one of the lowest melting temperature metals welded with FSW. Temperatures as well as forces during FSW of copper and its alloys will impose limits on the choice of tool materials. Conventional hot work die steels, like H-13, and pure tungsten perform well with the normally pure copper materials but poorly with alloys. Sintered carbide tools perform poorly duet to brittleness, while polycrystalline cubic boron nitride tools perform well with alloys.

Magnesium

Magnesium alloys may require a little higher thrust force than an equivalent-thickness aluminum alloy.

Steel

Steel requires the most significant level of force as well as very high level of machine stiffness. The current FSW tool materials are sensitive to vibration and runout and thus dictate the requirement for a very stiff machine for welding steel.

Thermoplastics

There are three kinds of polymeric materials – thermoplastic, thermosets and elastomers. Only thermoplastics are the weldable polymers, because they have ability to be reshaped after heating below their degradation temperature. Examples of such polymeric materials include Polyvinyl chloride (PVC), Polystyrene (PS), Acrylonitrile Butadiene Styrene (ABS), Polymethyl methacrylate (PMMA), low-density and high-density polyethylene (PE), Polypropylene (PP), Poly tetra fluoro ethylene (PTFE), nylon-6 (PA 6), and polycarbonate (PC).

Rotational speed is the major process parameter in FSW process, because higher rotational speed results in the degradation of the polymer, whereas lower rotational rate gives poor mixing thus producing voids in stir zone. Polymers with high melting temperature and viscosity, require higher rotational speed and low welding speed.

The pin profile plays a decisive role in determining the strength of the joint. Usage of threaded pin, due to its ability to adequately mix the plasticized material, can result in good welding results. High surface area of threaded pin generates a higher frictional heat which is an essential pre-condition to produce a weld. However, the conical pin is reported as best profile for acrylonitrile butadiene styrene and high-density polyethylene.

Preheating before FSW process can increase strength of the joint, but it is an additional heating step, which not only affects the simplicity of the process but also increases the process time.

Another approach is to perform welding under water to obtain higher tensile value of the joint when compared with welding performed in air. It is called submerged FSW. Elimination of root defect in FSW of polymer improve welding strength.

Titanium

Much higher hot working temperatures of titanium alloys relative to Al alloys limit the choice of tool materials to refractory metals such as tungsten (including tungsten-rhenium) and molybdenum alloys or robust cermets such as WC/Co. Tool life is concern for these materials, because hot titanium is an excellent solvent for many of the components of these tools.

The reactivity of the titanium alloys as well as the refractory metals require use of inert gas shielding. The gas shielding eliminates atmospheric contamination by limiting nitrogen, oxygen and hydrogen from the atmosphere around tool and workpiece in order to avoid embrittlement. Preferred solution is to use of an inert gas chamber that can be backfilled with inert gas prior to each weld.

Dissimilar

Dissimilar metal joining has great potential in practical applications to replace riveted joints leading to huge costs and weight savings. The challenges during FSW of dissimilar materials include differences in the mechanical, physical, chemical metallurgical and thermal properties. Generally, dissimilar metals and alloys can be joined by FSW. It is achieved by severe plastic deformation (SPD) of both materials being joined together. SPD may result in grain dynamic recrystallization, which permits the flow of plasticized material occurring in solid state. This lead to recrystallized, equiaxed and usually submicron grains, which form in the weld zone after being frozen. During welding nonferrous material such as aluminium, brittle intermetallic phases often form at the weld interface of dissimilar welds. Weld interfaces in dissimilar joint are associated with sharp changeovers in the resulting properties, due to heterogeneous nature of the welds. The FSW of dissimilar materials with good joint integrities are better achieved when the tool pin is offset and when the material with the high melting temperature is placed on the advancing side during the welding procedure. The offset should be made into the material with lower melting temperature, shifted from the weld centre line.

The possible combination of dissimilar joints includes dissimilar aluminium alloys, aluminium and magnesium alloys, aluminium alloys and steel, aluminium and titanium, aluminium and copper [1-5].

Thickness

Stiffness and force handling are major factors for the FSW machine, which limits the thickness of workpiece. Material thickness should be in range from 0.8 mm to 65 mm.

Table 1-4: Summary of current friction stir welding tool materials and possible thicknesses – Courtesy of [1-1].

Alloy	**Thickness, mm**	**Tool material**
Aluminium alloys	<12	Tool steel, WC-Co
	<26	MP159
Magnesium alloys	<6	Tool steel, WC
Copper and its alloys	<50	Nickel and tungsten alloys, PCBN
	<11	Tool steel
Titanium alloys	<6	Tungsten alloys
Stainless steels	<6	PCBN, tungsten alloys
Low-alloy steel	<10	WC, PCBN
Nickel alloys	<6	PCBN

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2. Joint Preparation

As with any welding operation, so too in Friction Stir Welding (FSW) there are recommended and mandatory preparations before the actual operation. These tasks for joint preparation range from cleaning to software.

2.1. Cleaning methods

A necessary step towards a successful joint is to clean the areas participating in the procedure, as well as the immediately surrounding areas that may be possible sources of impurities. Therefore, any dust, grease or moisture must be removed as they can adversely affect the quality of the joint [2-1].

Some negative fallouts of improper surface cleaning include poor fatigue loading performance, localized low ductility and volumetric defects produced during post-weld heating [2-2].

Although no special preparation is needed for FSW, it's usual to degrease the joint with a solvent and wiping it down with a paper towel [2-2]–[2-4]. Some other methods of cleaning joints may encompass [2-5]:

- Grinding;
- Wire Brushing;
- Paint Removers;
- Pickling;

These methods aren't usually employed in FSW as they increase the price of the process, although some special cleaning may be recommended according to the material type and the quality standard required.

2.2. Measuring Processes and Devices

One important variable which must be considered when welding is the thickness of the parts to be welded. Friction stir welding parameters are selected to minimise the variation of tensile residual stress through the thickness.

Geometric flaws may arise from improper thickness measurement and subsequent incorrect parameters to compensate for thickness mismatch, plate thickness variation, workpiece gap or incorrect tool pin length in relation to workpiece thickness. For example, in order to avoid workpiece gap, the material through thickness should be measured along the weld length and for both sides of the joint line so that the length of the pin stick-out from the tool shoulder is correct and within tolerance for the material [2-2].

2.2.1. Measuring processes

There are many ways to measure thicknesses although the most common used while in a workshop is through mechanical devices.

Mechanical devices use a more direct approach of comparing the distance between the edges of the part and a ruler.

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2.2.2. Measuring devices

Thickness gauges is a mechanical device used to measure the distance between two opposite sides of an object.

Figure 2-1 Dial indicator thickness gauge (Mitutoyo)

The dial exposed on Figure 2-1 gives readings with a graduation of 0,01mm and every millimetre corresponds to a full turn of the dial, providing a good accuracy of the workpiece thickness.

Another common mechanical device used for thickness measurement (besides a metallic ruler) is the Vernier calliper.

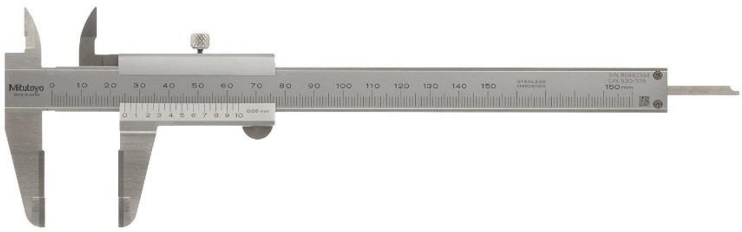


Figure 2-2 Vernier calliper (Mitutoyo)

The Vernier calliper gives a direct reading of the distance between its jaws (or depth probe) with high accuracy and precision.

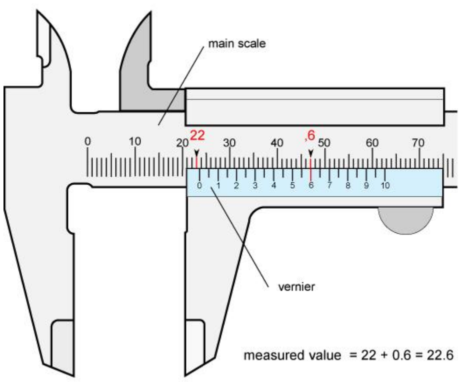


Figure 2-3 How to read a Vernier scale

2.3. Positioners

In the interest of achieving a proper weld, the plates to be welded must be properly positioned and fixed, as a misalignment of the tool path can lead to a flawed weld or even a work accident caused by the high strength employed by these machines on the plates [2-2], [2-3], [2-6].

2.3.1. Types of jigs

A jig is a device designed to keep a welding project stable in face of pressure, heat, motion and force. It used to be a welder's most well-kept secret when welding was a traditional craft, as it provides repeatability, accuracy and interchangeability in the process [7]–[9].

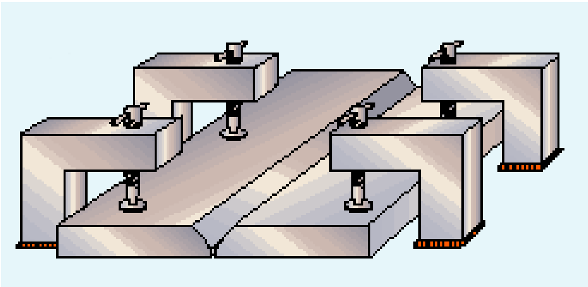


Figure 2-4 Welding jig (source: TWI)

There are different types of jigs, according to the type of work to be done, i.e.:

Figure 2-5 Drill jig (source: Kreg Jig)

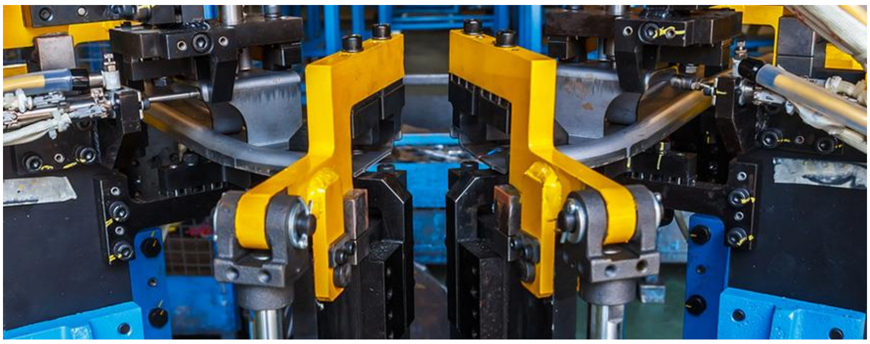


Figure 2-6 Welding jig (source: Tulsa Welding School)

2.3.2. Types of fixtures

Jigs and fixtures are somewhat similar, although a fixture allows for both tool and workpiece to be moved together while a jig stays still and may allow the work piece to move [2-9].

Types of fixtures include:

- Frame railing

Figure 2-7: Frame railing

- Railing welding

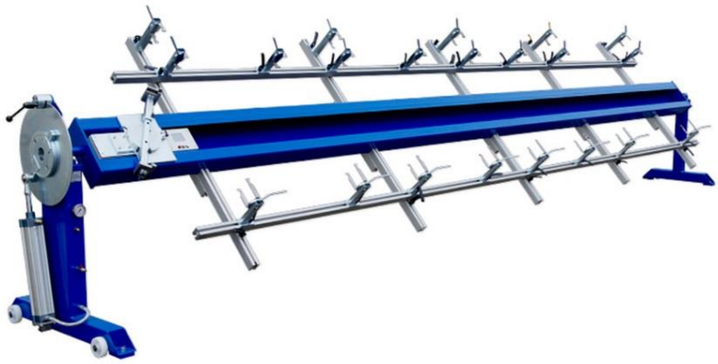


Figure 2-8: Railing Welding

- Vacuum clamping

Figure 2-9: Vacuum clamping

2.3.3. Clamping systems

The parts to be welded must be securely clamped, to prevent their movement as it influences the accuracy, quality and production cycle time of the work. A clamping device holds the workpiece securely in a jig or fixture against the forces applied during the operation [2-8].

There are different types of clamping:

– Mechanical actuation clamps;
– Pneumatic and Hydraulic clamps;
– Vacuum clamping;
– Magnetic clamping;
– Electrostatic clamping;

2.3.4. Clamping principles

A good clamping device ensures a good hold of the workpiece without damaging it. The principles of clamping concern:

– Position – direct the clamping force on a robust and supported part of the workpiece;
– Strength – enough to ensure a secure hold without damaging the workpiece;
– Productivity – clamping time should be reduced with the aid of knobs and handles to achieve a higher productivity;
– Ergonomics – the whole process of clamping should be operator friendly, reducing fatigue.

If required, clamps may be equipped with fibre pads to avoid damaging fragile workpieces [2-8], [2-10].

2.3.5. Influences of the clamping system on the weld

The clamping system is one influencing parameter that isn't often considered, even though it's constantly present during the welding process to secure the workpiece.

Influencing factors on the final distortion of the weld include clamp location, clamping time, clamping release time and pre-heating of the clamps. The pre-heating of the clamps provides a more homogeneous deformation, reducing the buckling amplitude. Longer release times are effective in reducing angular distortion and longer clamping times reduce bending amplitude. Also, the closer the clamps are to the weld, the smaller the final distortion [2-11].

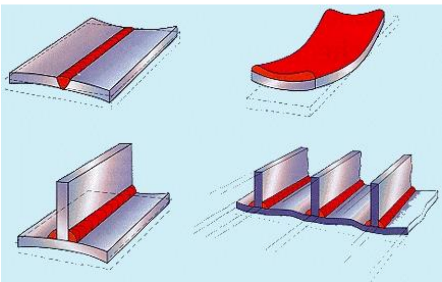


Figure 2-10 Common forms of distortion in welds (source: TWI)

2.4. FSW programs

2.4.1. Types of FSW programs

In order to apply the welding procedure to the workpieces, the operator needs to input the necessary parameters into the machine responsible for the process.

Figure 2-11 Example of machine and control panel (source: Grenzebach)

Different control panels are found across the manufacturers, but all have optimized software for the friction stir welding process allowing the operator to create welding programs. The usual inputs delivered to the software encompass the welding path, FSW-process parameters, clamping fixtures control or other components.

Figure 2-12 Control system developed for FSW (source: ESAB)

Some systems are even capable of recording, controlling and analysing the process in real time.

2.4.2. Basics on FSW programs ('What is include in a program?')

Represented on a FSW program are the parameters of the process for a given weld path trajectory. It contains the machine motions required through the weld, like plunge (start of the weld), retract (exiting the weld) and any parameter variations that are made during the weld (e.g. change in travel speed or spindle rotation speed) [2-12].

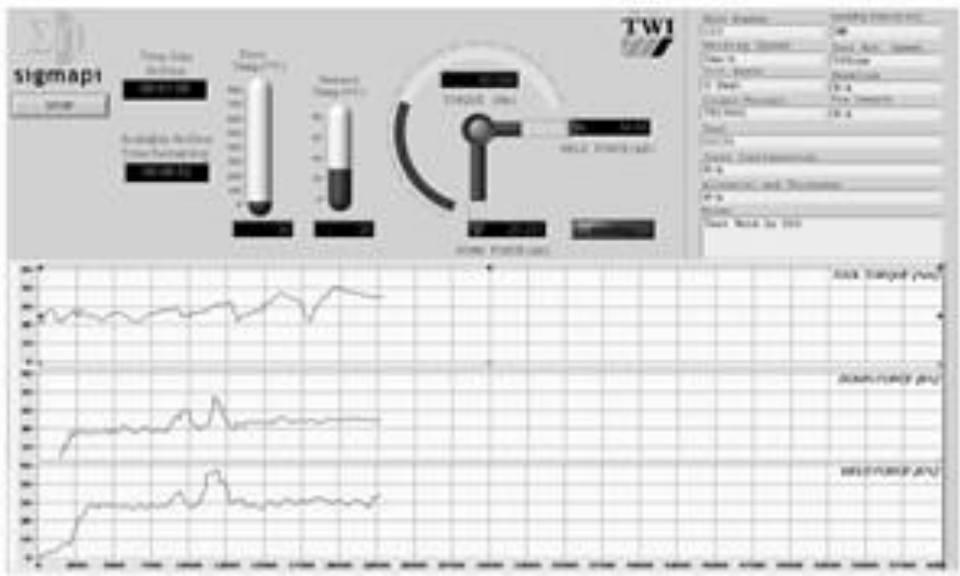


Figure 2-13 Example of display screen interface and parameters (source: TWI)

2.5. FSW Parameters and limits

FSW is a relatively simple process but isn't solely the result of an interaction between three processing parameters, i.e. tool rotation speed, weld travel speed and axial force, as most people think. In the following chapters it will be presented all parameters expected to find in the control system.

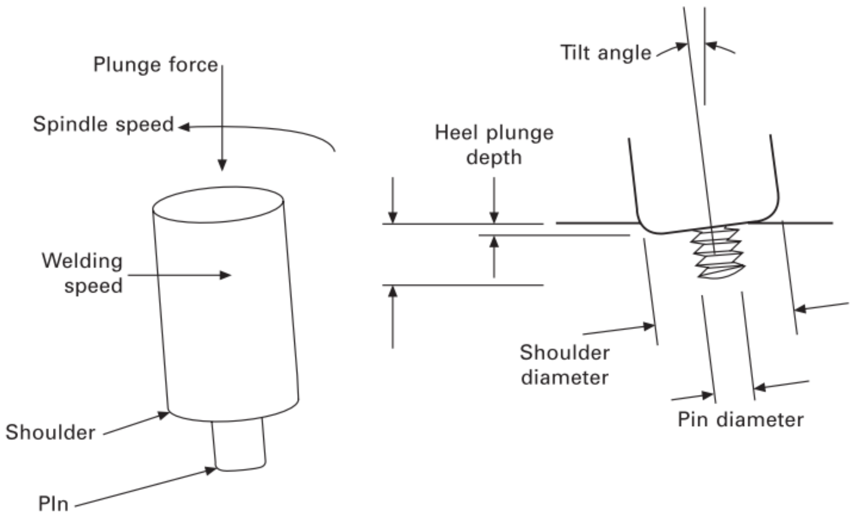


Figure 2-14 Conventional FSW tool and key variables [2-2].

2.5.1. Control system

The control system has fixed and variable parameters during the welding procedure. The parameters which influence the weld and minimize the weld's defects when used correctly are:

– Welding speed or Traverse speed:

Welding speed, sometimes mentioned as tool traverse speed, is one of the crucial parameters of FSW. One important condition linked to welding speed is the peak process temperature. That peak process temperature increases with decreasing weld travel speed as well as increasing rotation speed of the tool. Heat input can be assumed to be inversely proportional to welding speed, so if we want to increase the welding speed, it's needed to increase rotation speed to keep the temperature needed for the operation.

High welding speed has been proved to increase stresses and wear on the tool. These can lead to an increased incidence of defects and require repairs or deliver scrapped components. Meaning that the optimum welding speed is therefore not normally the fastest possible speed.

Another issue as the welding speed increases is the requirement for tighter process tolerances, this results in more investment in joint preparation and fit-up [2-2].

– Tool rotational speed;

Rotation speed is the rate at which the tool rotates around its axis and is one important parameter in FSW. It's directly related to the increase of the processing temperature and can be manipulated to increase welding travel speeds.

The increase of the rotation speed results in a higher processing speed. Higher tool rotation speeds will result in higher processing speed and consequently higher cooling rates [2-2].

– Plunge depth;

Heel plunge depth corresponds to the distance the heel extends into the weld metal [13]. The axial force (sometimes known as downward force or tool's plunge force) is directly related to the plunge depth, the deeper the heel plunge depth the higher the axial force. The effects of this parameters will be further explained next [2-2].

– Axial force or Tool's plunge force;

The axial force is the force applied to the workpiece along the axis of tool rotation [2-13]. The downward force applied ensures the continuous contact between the shoulder and the workpiece surface, in order to generate heat from the friction of these two surfaces. This force is necessary to ensure a constant heel plunge depth and a good weld. A proper axial force must be applied to deliver adequate pressure, essential to achieve a good bonding of the joint [2-2].

– Tool tilt angle

Tilt angle is the angle between the centreline of the tool and a line perpendicular to the surface of the work piece, opposite to the direction of welding [2-13]. A featureless shoulder usually employs a tilt angle, leaning backwards in respect of the welding path, which means there is more open room in front of the tool, and the back of the tool does the forging of material behind the pin [2-14].

– Dwell time

Corresponds to the time in which the material is preheated by a stationary, rotating tool in order to achieve a sufficient temperature ahead of the tool. This period may also include the plunge of the tool into the workpiece.

2.6. WPS

A preliminary welding procedure specification (pWPS) is a document with the necessary variables of the welding procedure to guaranty repeatability during the production welding which needs to be qualified. A welding procedure specification (WPS) is a pWPS which has been qualified [2-15].

Preliminary welding procedure specification

Manufacturer's pWPS No.: ______

Manufacturer's WPQR No.: ______

Friction stir welding operator's name: ______

Parent material type, temper, and reference standard(s): ______

Parent material thickness (mm): ______

Outside diameter of tube (mm): ______

Equipment identification (model, serial number, and manufacturer): ______

Tool identification (sketch)[1]:

Clamping arrangement (sketch)[1]:

Tack welding: ______

Joint preparation and cleaning methods: ______

Joint design

Joint design and joint configuration	Welding sequences
(Sketch)[1]	

Welding details

Run	Tool motion, rotation speed r/min	Heel plunge depth mm or axial force kN	Tilt angle °	Side tilt angle °	Dwell time s	Welding speed mm/min others

Welding position: ______

Pre-weld heat treatment: ______

Preheating temperature (°C): ______ Preheat maintenance temperature (°C): ______

Interpass temperature (°C): ______

Shielding gas: ______ Designation: ______ Gas flow rate (l/min): ______

Postweld processing: ______

Postweld heat treatment: ______

Time, temperature, method: ______

Heating and cooling rates: ______

Other information[1] ______

....

Manufacturer

Name, date and signature

______

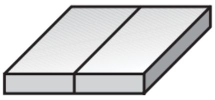
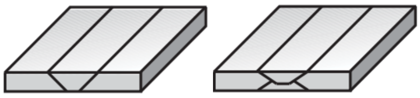
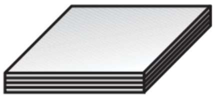
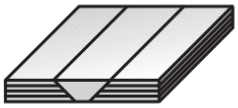
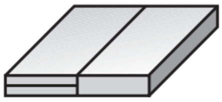
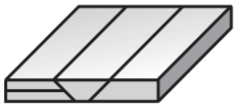
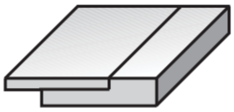
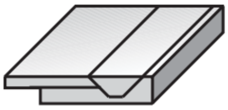
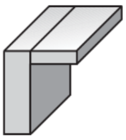
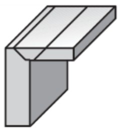
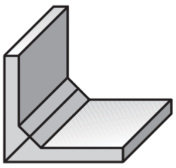
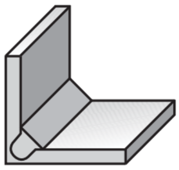
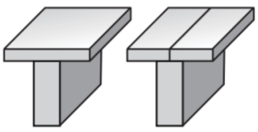
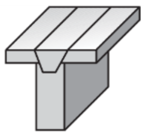
1) If required.

Figure 2-15: Example of a pWPS [2-16] .

2.6.1. Joint design

The special requirements and essential information will be defined in given documentation. Furthermore, the welds need to be produced in accordance to the WPS and to inspection requirements. Consequently, to guaranty the design requirements are fulfilled in the weld, essential process controls must be defined [2-17]. On Table 2-1, it is possible to observe different examples of friction Stir Welded possible joints.

Table 2-1: Weld joints for FSW, before and after welding. Adapted from [2-17].

Joint Design	Before Welding	After Welding
Butt joint		
Butt joint		
Lap joint		
Lap + Butt joint		
Lap + Butt joint		
Corner joint		
Corner joint		
T-joint		

The depth of the joint and the distance between the centreline of the tool with the edges of the member must be specified in the WPS.

For the joint symbolisation, please consult ISO/FDIS 2553:2013-Welding and allied processes-Symbolic representation on drawing -Welded joints.

2.7. Types pin/probes/tools

The FSW tool used will be critical to produce a joint free of defects. The tool is composed by a profiled pin, which aids in the creation of the frictional force, and the shoulder, which avoids material spilling from the forging line (Figure 2-16) [2-18].

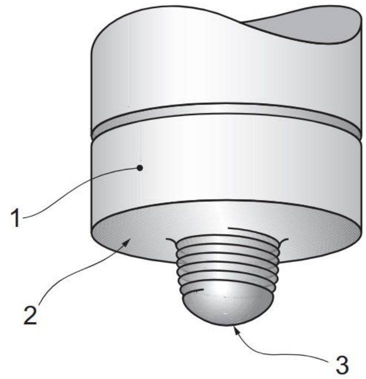


Figure 2-16: Example of a FSW tool. 1-Workpiece; 2-Shoulder; 3-Probe [2-13].

The shoulder of the tool may have different profiles: flat, concave, stepped, smooth or grooved [2-19]. Furthermore, depending on the thickness of the base plates and the material to be welded, the pin profile can be cylindrical threaded, tapered or flared-triflute, as shown in Figure 2-17 [2-19].

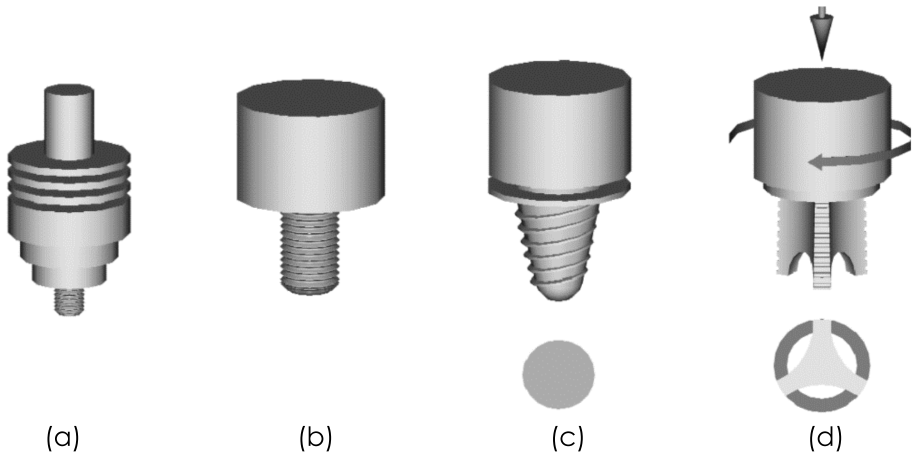


Figure 2-17: Tool shapes for FSW. (a) Stepped shoulder with cylindrical threaded pin; (b) Flat shoulder with cylindrical threaded pin; (c) Flat shoulder with tapered pin; (d) Flared-triflute pin [2-19].

For thicknesses of 12 mm or less, the recommended pins are the cylindrical pins, and for thicknesses above this number, tapered or fared-triflute are more suited.

The choice of tools for the material to be joined is typically made as follows: For light materials, such as magnesium, aluminium or copper, the material used for tooling is steel. However, for materials with similar or highest hardness, such as other steels, there's the requirement of a tungsten-based or polycrystalline cubic boron nitride-based tools [2-18]. Furthermore, an adjustable probe tool can be used to decrease the toe flash at the start and end of the welding, as illustrated in Figure 2-18 [2-13].

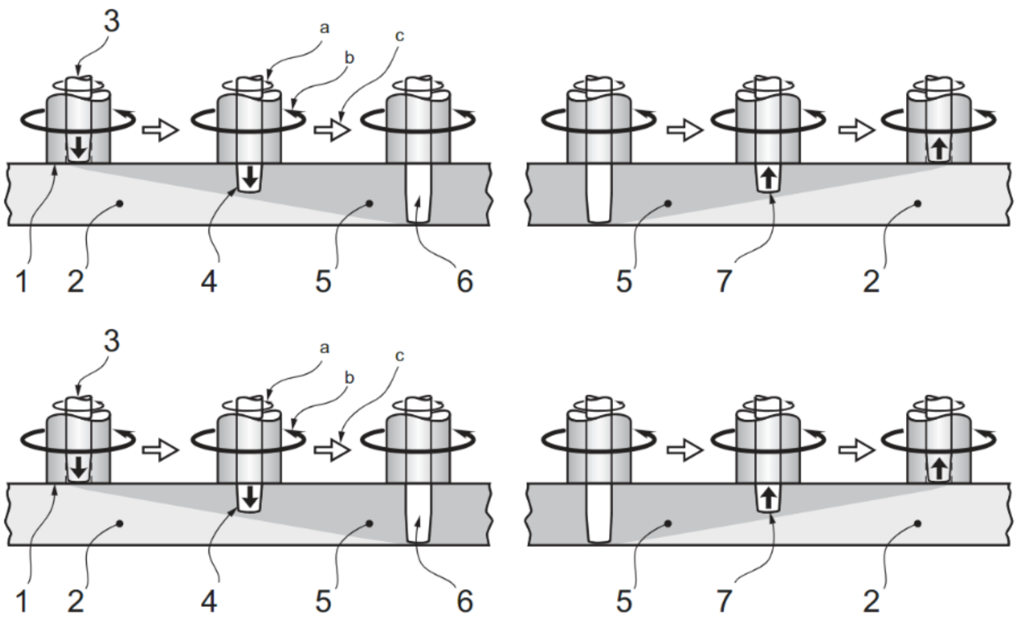


Figure 2-18: Illustrative reproduction of an adjustable tool probe.1-Shoulder; 2-Unwelded Workpiece; 3-Probe; 4-Probe moving downward; 5-Welded Workpiece; 6-Probe at Required Position for Welding; 7-Probe moving upward [2-13].

This means that the pin has an independent movement from the shoulder and may be adjusted during the welding process to compensate the thickness difference or to close the exit hole [2-5].

2.7.1. Offset position

The offset position corresponds to the lateral offset from the tool axis to the faying surface [2-13].

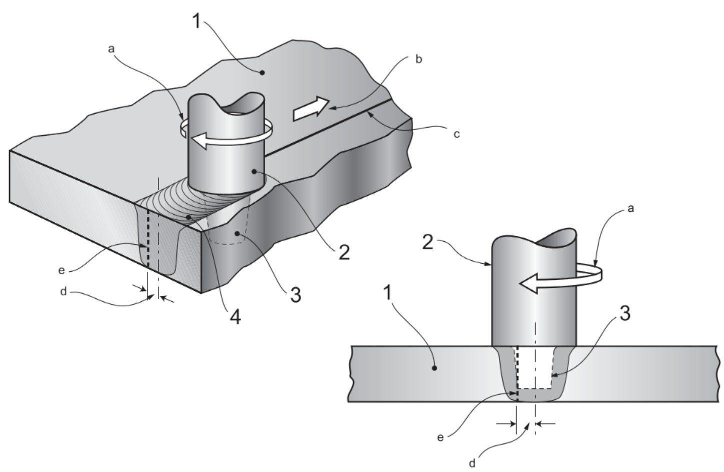


Figure 2-19 Lateral offset showing the centreline of the tool not centred on the joint. 1-Workpiece; 2-Tool; 3-Probe; 4-Weld face; a-Direction of tool surface; b-Direction of source; c-Joint (faying surfaces); d-Lateral offset; e-Location of joint before welding [2-13].

When joining dissimilar materials, it's recommended that the tool pin should be offset from the joint centreline in the direction of the softer material so that the outer surface of the pin is aligned with the edge of the harder material [2-20].

2.7.2. Z position

Tool movement across the workpiece is predetermined along three-dimensions (x, y, z).

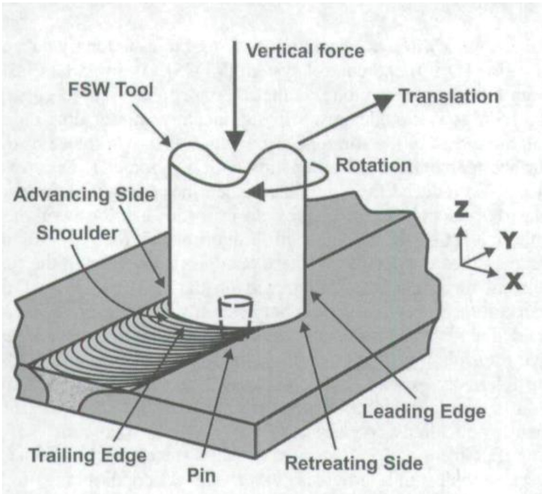


Figure 2-20 Schematic of FSW process [2-21]

The z position of the tool refers to spatial location on the process which is usually zero at the top surface of the workpiece its. The force applied along the z position is called axial force and its application proved to deliver higher quality welds [2-21].

2.7.3. Plunge depth

According to ISO 25239-1 the distance the heel extends into the weld metal is referenced as heel plunge depth [2-13]. The plunged depth is a programmed and critical parameter for position-controlled runs.

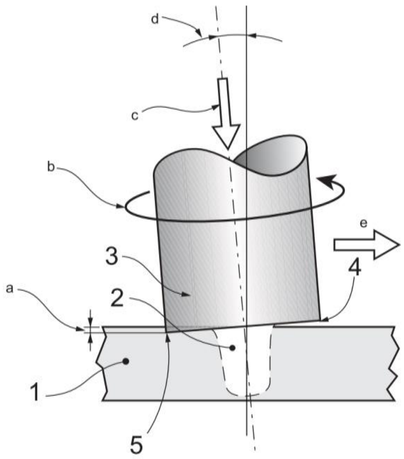


Figure 2-21 Side view of butt joint. 1-workpiece; 2-probe; 3-tool; 4-shoulder (leading edge); 5-heel (shoulder trailing edge); a-Heel plunge depth; b-Direction of tool rotation; c-Axial force; d-Tilt angle; e-Direction of welding [2-13].

The plunge phase is where the welding starts through the frictional heating and pressure applied by the tool at a specific rate or force which displaces material from the workpiece around the pin [2-2].

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3. Welding Process Operation

Several types of auxiliary equipments are associated with the FSW technology. The function and task of these equipments depend on the application and type of welded joint. The so-called hybrid welding processes are concerned. These are used in order to improve the welding productivity. The hybrid welding processes make possible to weld dissimilar materials with different melting point.

3.1. Hybrid welding methods

The so-called hybrid welding processes (HFSW) are getting ever popular nowadays. The friction stir welding has a lot of modifications. There exist hybrid systems of welding where external heat sources (auxiliary equipment) are used. The most frequently used heat sources are: GTAW, laser beam, plasma beam, high-frequency heating and ultrasound. These methods prolong the life of welding tools and allow a better plasticizing of material welded. These technologies omit all issues related with the fusion of parent metals. Figure 3-1 shows a HFSW equipment with participation of a GTAW heat source.

The friction stir welding can in one process use even several welding tools at the same time. This concerns diverse welding processes making use of special welding heads and/or special welding tools.

Figure 3-1: HFSW equipment with participation of a GTAW heat source

At application of a hybrid welding with plasma arc assistance (P-FSW) it is possible to weld dissimilar materials regardless their different affinity, physical and mechanical properties. The heat from plasma arc provides the preheating of welded material with a higher melting point.

Plasma arc is guided ahead the rotating tool. Lower force is thus necessary for the travel of welding tool as in the case of conventional welding, what results in lower wear of welding tool. Plasma arc provides a unique combination of high arc stability, concentrated power density and low equipment costs. By making use the priority of plasma arc preheating, the mechanical properties of welded joint can be enhanced. Welding of dissimilar materials by P-FSW process is shown in Figure 3-2.

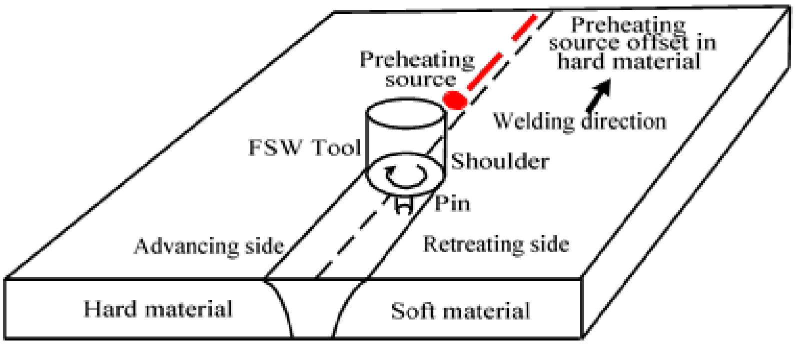

Figure 3-2: Basic principle of plasma-assisted friction stir welding of dissimilar joint

As another hybrid FSW process employed for welding of an aluminium alloy with a magnesium alloy and an aluminium alloy with a steel, the so-called technology of ultrasonic welding (USE-FSW) was successfully applied. The USE-FSW technology has exerted favourable effect on the resultant microstructure and mechanical properties of welded joint. Welding by use of USE-FSW hybrid technology is shown in Figure 3-3.

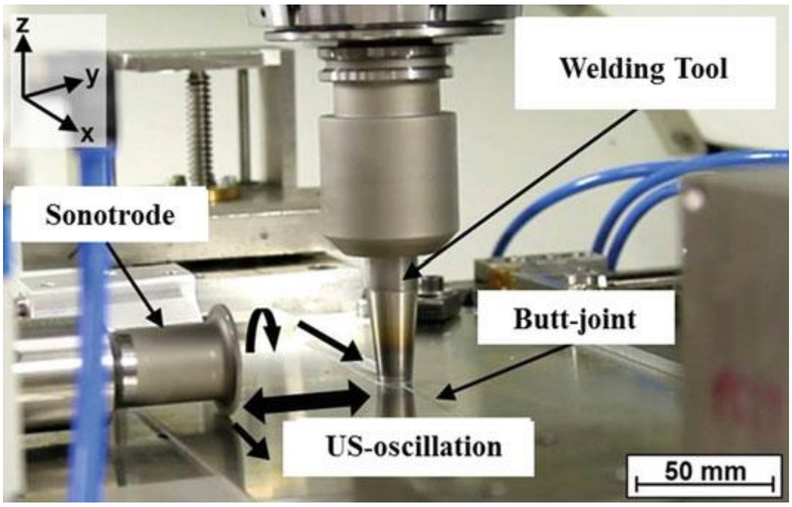

Figure 3-3: Welding by use of USE-FSW hybrid technology

After performing the metallographic tests of welded joints fabricated by use of USE-FSW process, there was observed lower occurrence of intermetallic phases in the boundary between the stir zone (nugget) and the thermo-mechanically affected zone than in the case of welding with conventional FSW process. The fatigue and tensile tests have shown improved quality of welded joints fabricated by use of USE-FSE process, when compared to conventional FSW process. The strength of Al-Mg joint increased by 25% against the classical welding. In case of welding the Al-steel combination a more intense stirring was observed than in case of welding Al-Mg combination. The resultant structure exerted a finer microstructure. It can be surely stated that the hybrid processes (with auxiliary equipment) are suitable means for attaining sound welded joints.

As well known, the FSW technology is a modification of friction welding, where all defects in welded joints fabricated by the fusion welding technologies, including laser and other concentrated heat sources are absent. The most frequent defects as hot cracking and porosity do not occur in welding by FSW process, since a joining process in the solid state is concerned.

The heat input supplied during welding by FSW process has the tendency to create the conditions leading to microstructural transformations such as: recrystallization, grain growth and dissolution of precipitates. Such microstructural changes occur at different temperatures for different materials and depend on the chemical composition of the materials welded. The main issue occurring in fusion welding consists in the drop of mechanical properties of welded joint, mainly in the HAZ. Similarly, also in the case of solid state welding a certain drop of mechanical properties in the HAZ may be expected.

The main issue occurring at FSW process consists in insufficiently stirred parting plane between the materials welded. This issue may occur mainly at setting too high welding speed when the welding tool is incapable to stir sufficiently the welded materials mutually between each other. This defect is called as the linear void. Another issue may consist in improperly set plunge depth of welding tool and/or application of a short pin. At insufficient depth and/or short pin length the welding tool does not stir the welded material in the root zone but just on the surface of the materials welded. Such a defect is classified as the kissing bond. In an opposite case, when the welding tool is plunged too deep, the welded materials is forced out on the surface. Such a defect is classified as excessive flash. The only way how to achieve a sound joint is to optimise the all above-mentioned parameters.

3.2. Auxiliary Equipment

The sound welded joint is such a joint which was fabricated free from any defects. One of possibilities how to avoid the defects consists in application of auxiliary equipment. Several types of auxiliary equipment are connected with the Friction Stir Welding technology. The functions and tasks of such equipment depend on the application and type of welded joint. The auxiliary equipment may be classified in two basic groups: navigational and hybrid.

3.2.1. Navigational auxiliary equipment

The navigational auxiliary equipment is used in applications where it is necessary to control the correct position of welding tool in welding line direction. This concerns the equipment which controls during welding process for example the immersion depth of welding tool and the generated temperature. Setting the correct immersion depth of welding tool is essential, especially in the case of repeated welding.

The control of immersion depth of welding tool plays an essential role in formation of different defects in welded joint, as insufficiently stirred welded material in the root zone and the formation of excessive flash. These defects unfavourably affect the temperature control. The auxiliary equipment, as different types of probes and position sensors of welding tool are used for immersion depth measurement. The real plunge depth is determined by use of the depth sensors by comparing the measured trace of welding tool shoulder, which has remained after contact with the welded material. The depth sensor makes use of axial force for manipulation with plunge depth of welding tool shoulder. The laser sensors are used as the feedback signals for the position control systems.

The temperature control is especially important in the case of welding materials with a complex shape and different heat removal. Higher temperature generated in welding process will result in better plasticizing of material welded. However, in the case of welding heat treated (hardened) alloys, a rapid strength drop occurs with increasing temperature during welding. The main issue of strength drop consists in a correct estimation of friction coefficient between the tool and material welded. For this reason, different pieces of auxiliary equipment for the temperature measurement during welding were tested experimentally. One of the methods applicable for temperature measurement during welding consists in the Tool-Workpiece-Thermocouple (TWT) method. The thermocouples used in TWT method are inserted into the welding tool in the vicinity of its shoulder. The temperature is measured by the aid of a thermo-electric signal between the welding tool and material welded. The TWT method offers an exact temperature measurement under the tool shoulder and in vicinity of welding tool fringe. Another method, which assists in fabrication of sound welds in welding process consists in the temperature measurement by the aid of wireless data transfer.

The thermocouples are inserted into the welding tool together with a wireless system for data transfer. The thermocouples are situated in such a manner to be as close as possible to the boundary between the welded material and welding tool. The thermocouples type K are mostly used for such a temperature measurement. Owing to high rotation speed of welding tool, the wireless system for data transfer to control system is employed. The wireless data transfer is used for the transfer of measured data in real time. This system is capable to capture 7 to 12 measurements per one revolution of welding tool.

3.2.2. Hybrid auxiliary equipment

The so-called hybrid welding methods (HFSW) have become popular nowadays. There exist hybrid welding methods where an external heat source of auxiliary equipment is employed. The most often used auxiliary equipment for heating may include the GTAW, laser beam, plasma beam, high-frequency heating, induction heating and ultrasound. In the case of these methods, all issues connected with the preheat of material welded are omitted. Application of the mentioned methods results in prolonged life of welding tool and also in better plasticizing of material welded.

In application of hybrid welding with plasma arc assistance (P-FSW) it is possible to weld the dissimilar materials regardless their different chemical affinity, physical and mechanical properties. The heat from plasma arc causes the preheating of welded material with higher melting point. The plasma arc is led ahead the rotating welding tool. It is thus necessary to exert less force for the travel of welding tool than in the case of classical welding, what results in lower wear of welding tool. Plasma arc provides a unique combination of a high arc stability, concentrated power density and low equipment costs. Utilizing the priorities of welded material preheat by plasma arc allows to improve the mechanical properties of welded joint.

The Thermal Stir Welding (TSW) process makes use of an induction coil as an auxiliary equipment in welding process. The induction coil serves for a uniform preheating of material welded. The welding tool is extremely loaded during welding the materials with a high melting point. Therefore, a modified FSW process was developed with the aim to control the temperature during welding the materials with a high melting point. The induction coil uniformly preheats the welded material in order to reduce the loading of welding tool. It is well known that the rate of downward force is changed indirectly with increasing welding speed. This means that at higher welding speeds the heat propagation ahead the welding tool is reduced. The induction coil thus guarantees the maintaining of a constant temperature during the entire welding period.

It may be for sure stated that in application of an auxiliary equipment, both the navigational and hybrid ones, reduces the risk of defect occurrence, what results in fabrication of sound welded joints and prolonged life of welding tool.

3.3. Problems within FSW

As well known, the FSW technology is a modification of friction welding, where actually all defects occurring in the fusion processes, including the laser and other concentrated power sources are absent. The most frequent defects as the hot cracking and porosity do not occur in FSW process because this is a solid-state joining process.

3.3.1. Most common basic problems of FSW during the process

The welding speed and the tool rotational speed may be considered for the main parameters of welding by FSW process. These two main parameters will cause either sufficient or insufficient heat supply necessary for plasticizing the material welded. The selection of correct welding parameters is closely related with the quality and/or issues occurring during the welding process. The insufficient stirring of welded material, voids, excessive flash and the cracks may be included among the most common basic problems of FSW process. The defects are classified to the internal and surface defects.

3.3.2. Actions to solve those problems

The excessive material – flash may be included among the most frequent defects. The main reason for excessive flash formation consists in excessive depth of welding tool in material thickness direction. This drawback can be corrected by a suitable setting of inclination angle of welding tool. The welded joint with an excessive flash exerts unacceptable visual appearance, though the strength properties of welded joint may be acceptable. The defect of excessive flash can be very easily removed by the machine milling. In the case if not sufficient heat, needed for plasticizing the material welded is supplied to welded zone, the defects called the voids are formed in welded joint. In spite of the fact that the higher welding speeds enhance higher productivity in fabrication of welded joints, too high welding speeds result in void formation under the surface of welded joint. It was experimentally proved that with enlarging diameter of welding tool shoulder a greater heat volume enters to welding process, what results in better plasticizing of welded material and thus the defect occurrence in welded joint is prevented. The process parameters play a key role in formation of the root defects. These defects occur due to insufficient heat supply and/or as a consequence of incomplete disruption (decomposition) of the surface oxide layers. Owing to insufficient length of welding pin and its immersion depth related to material thickness may results in defects as the lack of root fusion. Such defects are considered for unacceptable due to lower strength of welded joint, mainly in the case of a dynamic loading. It is very hard to detect such defects by the use of non-destructive test techniques. It may be thus stated that an effective selection of welding parameters eliminates the formation of mentioned defects what contributes to improvement of mechanical properties of welded joints.

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4. Post Processing

Other important steps of the Friction Stir Welding process comes after the weld has been performed, with all the post process operations that are carried out. This include operations ranging from the unclamping to the basic quality assurance steps that should be performed.

4.1. Unclamping precautions

In order to prevent the injuries of personnel in application of welding equipment, due caution and keeping of the safety precautions is necessary. The most frequent injuries may occur due to burns with a hot welding tool and welded material. Therefore, it is inevitable to keep the following safety precautions:

– The welding equipment can be operated by a competent operator only, who was instructed about the safety and health protection at work (SHPW) and trained for work with the given equipment.

– Each equipment operator must be properly dressed (using the protective working means).

– Prior to welding proper the operator must make sure whether all clamping nuts in the tool holder are properly tightened and the clamping mechanism of welded material must be also thoroughly checked.

– All redundant materials on the working table (hammer, screw driver, wrenches, rags), impairing the welding process, must be removed.

– The operator can by no means leave the welding equipment during performing the welding operation.

– The manipulation with welding tool and welded material immediately after welding completion must be avoided – owing to the risk of burnings.

– At the end of welding (working shift), the operator is obliged to switch off the mains switch of welding equipment.

4.2. Visual inspection

Visual inspection of welded joint quality is necessary during entire period of welding process. The clamping of welded material and welding tool must be visually inspected prior to start of welding process. In the case of improper visual inspection prior to and during the welding process, different imperfections/defects may occur.

4.3. Imperfections/defects

Imperfections/defects occurring in the welding process may be classified to the surface and internal defects. The most frequent surface defects which may be observed by a naked eye include excessive material – flash, surface groove along the welding line and the worn-down welding tool. The most frequent internal defects which cannot be observed by a naked eyed include unstirred root – kissing bond, subsurface voids and the cracks. These defects may be observed just on the specimens prepared for the metallography.

Elimination of the mentioned defects and thus improvement in mechanical properties of welded joints can be guaranteed only by an effective selection of welding parameters as the revolutions of welding tool and the inclination angle of welding tool.

4.4. Causes of imperfections/defects

Imperfections/defects may occur during the entire welding process, At the onset of welding process, at the first tool penetration into welded material, the welded plates may be pushed aside, what results in formation of an undesirable gap causing non-uniform stirring of materials welded. If this imperfection would occur, it is inevitable to inspect the clamping mechanism of welded plates. In most cases it is sufficient just to tighten the relieved clamping bolts of the jigs, serving tor fastening the welded material against the welding support (table). Another way how to solve this issue consists in reduced speed of welding tool immersion. At slower speed of welding tool penetration into welded plates the welded material will be better (more sufficiently) plasticized, what would result in the fact that the welded plates will not be separated.

Also damaging of welding tool, which would impact upon the clamping support during the welding process may be considered for an imperfection (non-conformity). Therefore, due attention should be paid to arrangement of clamping supports along the welding line. In an opposite case, the threat of damage to geometry of welding tool, clamping support and the welded material proper may occur.

A frequent imperfection occurring during welding process consists also in forcing out redundant welded material (flash) on the plate surface by welding tool. This defect is classified as an excessive material – flash. The main cause of flash formation consists in an excessive immersion of welding tool in the thickness direction of material welded. This issue can be eliminated by a proper setting of inclination angle of welding tool. This imperfection can be prevented also during the welding process proper by a controlled immersion depth of welding tool. In the case if the welding tool would force out excessive welded material on the surface, it is sufficient just to shift the welding tool axially upwards. The redundant material (flash) can be easily removed by the machine milling. The visual appearance of a weld with flash is unacceptable, though the strength properties of welded joint may be acceptable in same cases.

The imperfection classified as insufficient stirring of welded material may occur at too high welding speed. This imperfection is typical by formation of a continuous longitudinal groove (channel) on the surface of material welded. In the case of such imperfection it is necessary to adjust the welding parameters, especially the welding speed and a suitable geometry of welding tool should be preserved.

An imprint from welding tool remains on the material welded at the end of welding process. This imperfection is solved by attaching the additional plate to welded materials, where the welding tool will pass and terminate at the end of welding operation. This additional plate is then removed (cut off) from the welded material. In the case of welding steel materials high temperatures occur, what may cause the sticking of material welded to the welding support (table).

In order to prevent this issue a continuous layer of powder (for example the BN powder), preventing the adherence of welded plates is deposited on the welding support. Table 4-1 presents the most frequent examples of accidents (imperfections).

Table 4-1: Accidents example

Accident	Cause	Preventive Action
Inappropriate tool material/ diameter for the operation	Insufficient clamping	Proper tightening of clamping bolts
	Collision with the clamping system of welded material	Check correct program selection Check the arrangement of clamping means
	Setting deeper immersion depth of welding pin than the welded material thickness	Application of auxiliary equipment for plunge depth measurement
	Life termination of welding tool	Plan replacement of welding tool
Burned skin	Direct contact of human skin with hot material welded Hot welding tool Hot metal chips	Wearing the gloves, goggles and proper clothes
Welded material damage	Distortion of welded material caused by poor clamping on welding support (table)	Use of suitable clamping system
	Sticking of welded material to welding support (table)	Spraying of welding support (BN)
Damage to eyes/face	Metal chips can be released during welding with high revolutions, and/or worn material is detached from the surface of welding tool	Use of goggles
Cutting	By removal of chips stuck on the welding tool Unmachined edges of material welded	Use of gloves

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5. Health & Safety

Friction stir welding (FSW) is one of the most operator friendly welding operation. FSW dismisses UV or IR radiation protection for the operator, since it doesn't emit radiation in those wavelengths which is harmful to the human health (skin and eyes). It's also one process that generates little to no smoke, discarding the use of exhaust systems. Noise levels originating from this welding procedure are also barely non-existing [5-1]–[5-4].

The most common hazards in FSW may come from common electrical or mechanical hazards from the machine design or by the human-machine interface, like the handling of produced parts or parts adjustment while the process is running.

5.1. Safety Regulations

There are no specific safety regulations regarding the friction stir welding process as it doesn't represent any particular hazard (e.g. radiation, toxic products) to the operator, but common cautions must be taken regarding ergonomics and machine-to-operator interaction.

BS EN ISO 13857:2008 - Safety of machinery. Safety distances to prevent hazard zones being reached by upper and lower limbs.

5.2. Common hazards derived from FSW

The most common hazards during FSW process include skin burns or cuts from metal debris. These are caused by handling hot parts, like the tool or the welded piece, or scraping near sharp edges. Electrical, mechanical and noise risks are also associated to the implementation of the FSW technology and are described below.

Electrical, Mechanical, Noise risk

FSW allows avoiding many of the safety issues associated with conventional welding methods. Although it is considered to be safe process, the physical hazards include mechanical, electrical, noise and heat may occur during operating the FSW machine. By taking general precautions, such as using appropriate protective equipment and emphasizing routine safety, physical hazards can be easily minimized.
Only fully recognized trained and qualified persons can use the machines. The equipment should be always turned off before leaving area. Safety can be increased by ensuring that equipment is well maintained. Operator should be aware:

– oils, coolants and grease can irritate skin,
– accidental starting of the machine can cause a hazard,
– manual handling of heavy items can be a hazard [5-6].

Electrical

The main risks related to electricity are electrical shock and fire.

Frayed cord and loose or broken connections can create a short circuit. To minimize the risks operator should always:

- check visually external wiring and equipment before use,
- verify normal function before making equipment before use,
- check that equipment used near sinks or other water sources is properly insulated and grounded,
- switch current off at the wall outlet or unplug immediately if coolant gets into the electrical components.

Mechanical

Machinery with rotating parts, like FSW machine, can catch loose clothing, hands or hair, potentially lead to serious injuries. There is also a possibility that uncovered parts may fly off and create additional risk, especially for eye injuries. To minimize risks, operator should always:

- carry out "daily machine check" before starting FSW machine to ensure that rotating shafts, belts and pulleys are covered by guards, lids or covers,
- always check devices, which are attached to a rotor before use, to ensure that they are tightly fastened,
- during welding always wear eye protection, because the tool is an uncovered rotating part, which can fracture and violently ejected from the machine,
- do not touch sharp objects (e.g. sharp edges on workpiece) with bare hands, use protective gloves instead, but the gloves must not be worn when using the machine,
- check if there is a sufficient space around the machine, to avoid being pushed by machine, which can result in injury,
- secure long hair and loose clothing, remove any dangling jewellery,
- wear safety boots that have a protective reinforcement in the toe, to protect the foot from falling objects.
- Mechanical risks related to conventional machine tools and dedicated FSW machines.

During operation of conventional machine tools or dedicated FSW machines, operator should:

- be careful during closing movement of parts, which can result in finger trapping;
- be aware of heavy objects, which can fall from table [5-7].

Mechanical risks related to robotic FSW machines

During operation of robotic FSW machines, operator should remember:

- unauthorized entry into a safeguarded area by someone who is unfamiliar with safety operation of robots can result in body crashing.
- there is possibility of fault within the power system (hydraulic, electrical, pneumatic), control system, software, electromagnetic interference, and radio frequency interference, which can create erratic behaviour and increase in the hazardous energy potential of the machine [5-8].

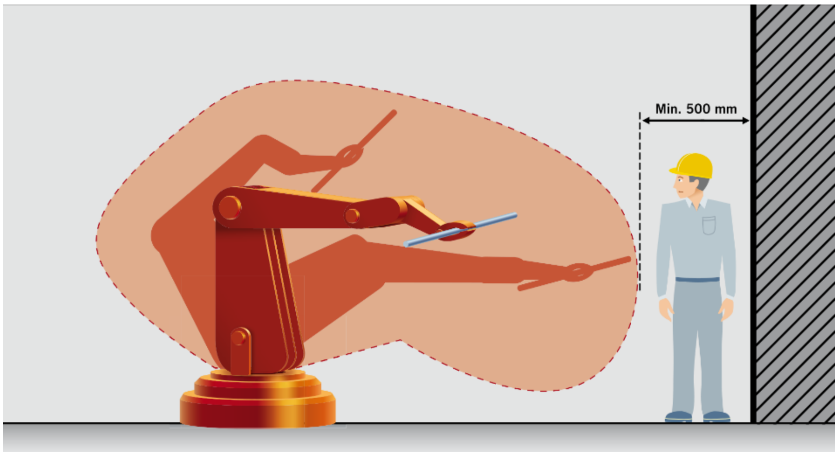

Figure 5-1: Gap between the robot and the guard. Operator should be aware about robot working envelope – Courtesy of .

Noise risk

The FSW process can emit noise at high levels, but main risk can come from sheet metal work before or after welding.

Long exposure to sound in excess of 85 decibels (dB) contributes to cumulative damage to inner ear hair cells, which can further lead to permanent loss of hearing at the specific frequencies to which the lost hair cells were sensitive. If operator work in conditions above the upper level of 85dB, the employer must provide hearing protection and ensure that it is worn. In other cases, hearing protection should be available on request to employees.

High-impact noise cause eardrum perforation. The eardrum perforations will heal, but every time this happens scar tissue build up on the eardrum and makes it less sensitive to sound waves [5-6, 5-9].

Heat risk

During FSW the heat is generated by friction - the maximum temperature can reach of 0.8 of the melting temperatures, so the workpiece and the tool can be hot. Heating can create fire and injury hazards. Directly after the weld is completed, the operator should wear heat-resistant gloves during manipulating with workpiece or tool.

Operator should allow ample time for heated objects (workpiece and tool) before touching them. The temperature of the workpiece can be checked using pyrometer.

The health hazard related to welding can especially occur in hybrid methods, like laser and arc assisted FSW. Immediate and acute hazards include burn to the skin, slash burns to the eyes and fire. Operators can be also exposed to welding fume and gases, which originate from the base metal and any coatings presented on the base metal [5-10]. It is worth note that there is no evidence that friction stir welding of magnesium generates any significant fire risk [1-26].

Table 1-5: Possible health disorders due to emission of solid particles – Courtesy of [5-10]

Manganese	Acute inflammation of the Lungs, Severe disorder of nervous system, Parkinson disease
Chromium	Acute and chronic intoxication, dermatitis and Asthma
Chromium (VI)	Occupationally carcinogen
Nickel	Potentially Carcinogenic and irritating respiratory track
Cadmium	Lung irritation, Pulmonary edema
Iron Oxide	Irritation of nasal passages, throat and lungs
Aluminum	Oxide Severe Pneumoconiosis
Fluorides	Irritation to eyes, nose and throat, Pulmonary edema and bone damage
Phosgene	Gas Reacts with moisture in Lungs to produce HCl and destroys lung tissue
Ozone	Cause irritation to all mucous membranes; Headache, chest pain, pulmonary edema
CO	Pounding of the heart, a dull headache, flashes before eyes, dizziness, ringing in the ears and nausea.
NOx	Irritation to eyes, nose and throat; Shortness of breath, chest pain and pulmonary edema

5.3. Preventive measures

Current friction stir welding machines provide safety features built-in to ensure operator safety. This are meant to reduce the risk of injury while the operator is interacting with the machine and consist of guard rails with e-stop triggers at access points, pressure pads and ladders, all designed to follow the local safety requirements [5-5].

Besides this built-in machine safety features, operators are obliged to wear appropriate clothing, i.e. work overall and gloves suitable for this task. While in operation, workers should stay clear of the machine since the rotating pin "picks up" everything it touches (i.e. gloves, clothes, rags) and may cause an accident.

Personal Protective Equipment

As with any welding process, operator should follow proper guidelines to avoid injury. Personal protective equipment should be used only as a last resort, after all other control measures have been considered, or as a short-term contingency during emergency / maintenance / repair or as an additional protective measure. PPE, used during FSW, can include basic equipment such as protective glasses, hearing protection, safety boots and heat-resistant gloves.

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6. Maintenance

Maintenance of FSW equipment is essential for constant quality of welding works. Because main parts of equipment are different items that are subjected to wear, attention is paid to provide all important parts of FSW system (backing plate, tool, shoulder, clamping and positioning devices) to have narrow tolerances and to be as rigid as possible to obtain high quality weld joint

6.1. Back plate conditions

For carrying out a proper FSW process, the material diffusivity of backing plate material is an important factor. Materials such as mild steel, stainless steel, medium carbon steel, tool steel, aluminium alloys, titanium alloys, pure copper, granite, marble, ceramic floor tile, asbestos, can be used as a backing plate. The high thermal diffusivity materials such as pure copper, aluminium alloy results in increased heat extraction rate. Lower thermal diffusivity materials such as asbestos, ceramic floor tile, granite etc. result in lower heat transfer rate. Back plate has significant effect on the forge force which is another important process parameter of FSW. As heat transfer from the weldment through the backing plate increases, the optimum forge force also increases.

Extremely high thermal diffusivity materials such as copper and aluminium are not suitable as a backing plates because it results in excessive heat transfer rate at bottom of workpieces. Low thermal diffusivity backing plates like granite maintains uniform temperature distribution through the material thickness. As back plate thermal diffusivity increases forge force also increases so as to maintain sufficient high temperature. Low thermal diffusivity back plate is suitable to reduce power requirement and to make FSW process more energy efficient. Appropriate choice of backing plate is more important during FSW of thinner sheets/plates.

FSW requires a rigid backing plate made from stronger material than the weldment material. The backing plate receives a proportion of the heat transferred by the weld nugget and so must not warp or deform under the heat applied. The downward force exerted by the tooling is resisted by the backing plate and prevents some distortion of the weldment.

6.2. Probe, Pin and Tool Conditions

Welding tool material selection is important consideration in developing successful FSW process. Careful consideration shall be given to useful life of tool and limitations that the tool strength might place on the welding speed. The rotation and translation of tool through the workpiece result in its wear. Diffusion and abrasion are the expected wear mechanisms. Reaction of the tool material with its environment, including both the workpiece and the surrounding gases, is also expected to contribute to the tool wear.

Tool materials selection is more challenging for FSW of high temperature alloys (steels, nickel alloys, titanium alloys). For all high temperature tool materials wear and reactivity to oxygen are the most important. Wear mechanisms are linked with reaction of tool material with weldment or atmospheric oxygen and subsequent removal of reaction products from the tool surface.

Abrasion wear is significant in the presence of harder secondary phase in base material, like in aluminium metal matrix composites. Compared with the tool shoulder, the tool pin suffers much more severe wear and deformation, and the tool failures almost always occur in the pin. Lower welding speed, preheating of the base material and use of sufficient inert gas shielding can reduce tool wear.

Influences to the FSW weld quality due to improper tool positions/tolerances:

– Too high lateral offset causes incomplete penetration of the weld. In the case of welding dissimilar base materials, it is important to offset a tool from direction in harder base material (e.g. in FSW welding of aluminium to copper FSW tool shall be offset in copper side).

– Too much tilted tool in the direction of the main tilt angle leads to incomplete penetration of the weld, too.

– If the main tilt angle is almost 0° (perpendicular to the plane of base material), the tool plunge increases leading to the excessive penetration.

– If the side tilt angle is not equal to 0°, this leads to the thinning of the workpiece at one side and excessive flash at the other side.

6.3. Clamping and Positioning devices conditions

Exact vertical and lateral clamping forces are dependent on base material, pin tool, workpiece geometry, weld joint type and weld schedule. FSW requires that the workpiece shall be rigidly held in position during welding to ensure that the weld joint does not separate under the force of the welding tool and to ensure that the workpiece stays in close contact with the backing plate.

Requirement to restrain the workpiece against the backing plate (vertical restraint) make it difficult to secure very large and thin workpieces. Requirement to restrain lateral separation of the weld joint (lateral restraint) can be difficult for very thick workpieces. For serial production it is desirable to have a special hydraulic or pneumatic clamping devises, although these items are expensive. Vacuum clamping system is a good alternative to mechanical clamping. Besides flat vacuum clamping systems, also 3D systems are available. These systems are not adequate for thick plates.

Three main parameters affect the level of workpiece distortion:

– rotation speed of the welding tool,
– clamp pitch (distance between two adjacent clamps),
– clamping force in vertical direction.

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