FSW-Tech

Friction Stir Welding European Qualifications

Friction Stir Welding Handbook

EUROPEAN FRICTION STIR WELDING SPECIALIST AND ENGINEER

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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 specific knowledge and competences to the personnel who is involved in the qualification process as a Friction Stir Welding Specialist and Engineer.

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. Chapters 1 to 8 are common to both, the Specialist and Engineer, and are the following:

Chapter 1: FSW Fundamentals
Chapter 2: Joint Definition
Chapter 3: Supervision of Welding Process Operation
Chapter 4: Post Processing
Chapter 5: Health and Safety
Chapter 6: Maintenance
Chapter 7: Quality
Chapter 8: Coordination
Chapter 9: Designing of parts

From chapter 1 to 8, the text in blue is dedicated to the EFSW-E only, the knowledge within that information is not included in the EFSW-S guideline. Chapters 10 to 11 are dedicated to the Engineer Profile:

Chapter 10: Designing of Tools
Chapter 11: Implementation
Chapter 12: Case Studies.

Glossary of Terms

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 center of the weld, where a fine-grained, equated microstructure exists.

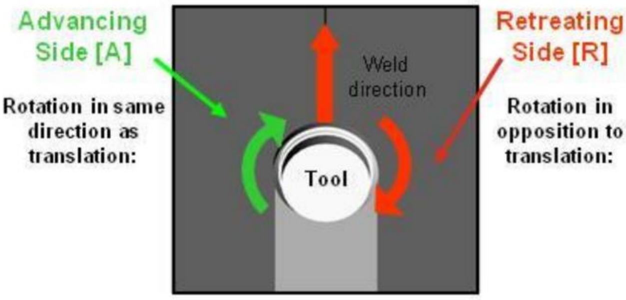
Tilt angle - the angle between the tool's axis and a plane perpendicular to the weld path, when viewed perpendicular to the weld path.

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



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 [1-14].

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 welding specialist have necessary skills and technical knowledge to plan, execute, supervise and test welding operations within a limited technical field involving simple welded constructions. A welding engineer is a type of materials engineer, who acquired an in-depth knowledge of the all aspects of welding that lead to the manufacture of a product.

The following modules main objective to give an overview of the FSW process. It starts with basic information's about FSW and terminology, followed by advantages and disadvantages of this process, characterisation of welding equipment and tools. At the end of module, general concerns about weldability of different base materials are 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 and 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 produce 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 it 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].

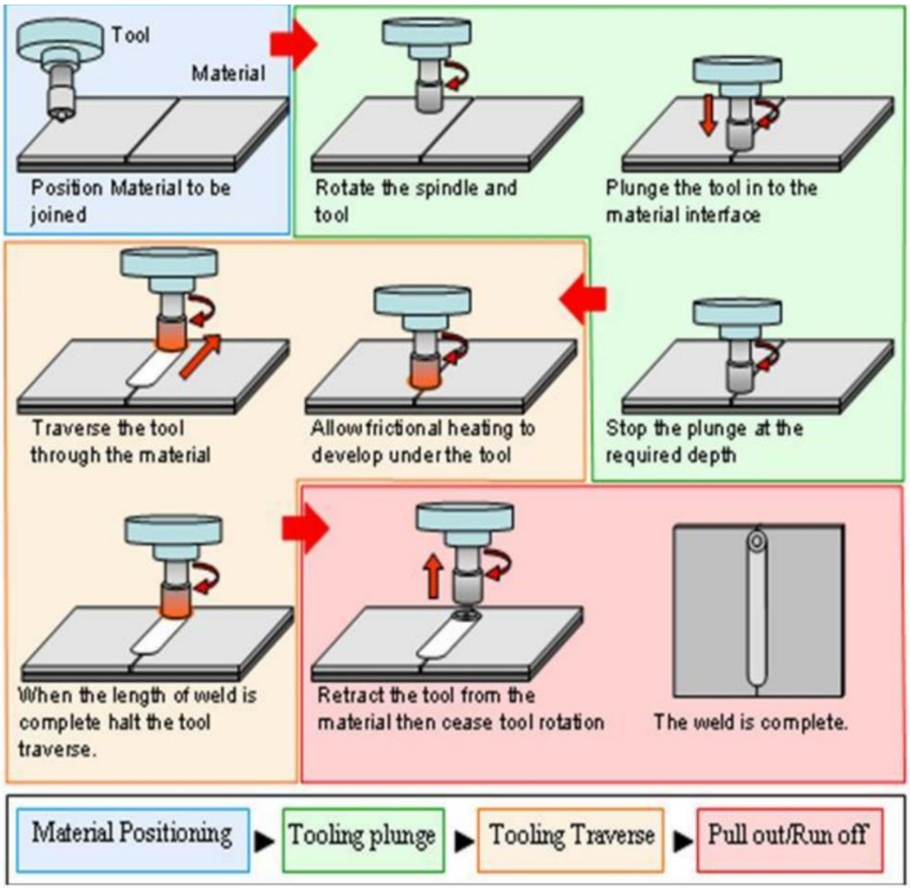


Figure 1-1: FSW process flowchart – Courtesy of [1-6]

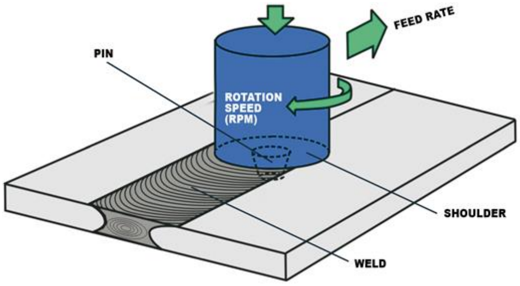
Friction stir processing

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].



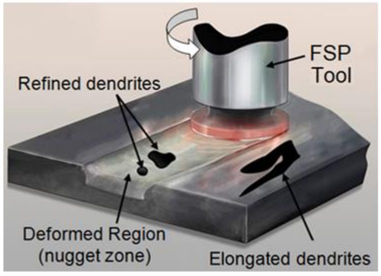


Figure 1-2: Friction Stir Welding (left) and Friction Stir Processing (right) - Courtesy of [1-8, 1-9]

— **Heat distribution**

Heat generated in FSW process is combination of friction and plastic dissipation during deformation of the metal. Heat generation process is sensitive to factors such as weld parameters, thermal conductivities of the workpiece, pin tool and backing anvil, and the weld tool geometry. The temperature field around the pin tool is asymmetric. FSW of aluminium alloys shows higher temperatures on the retreating side. This correlates with tensile test failures, which occur predominantly in the heat affected zone. Majority of the heat generation occurs at the shoulder/workpiece interface, but the heat generated between the pint tool and the workpiece should be also included in defining the heat field. The amount of heat input from deformational heating around the pin tool is in range from 2% to 20%.

Mechanisms of heat generation between the shoulder/workpiece and pin/workpiece interface are due to friction or plastic dissipation, depending on whether slide or stick conditions dominate at the interface. The weld tools can consist geometric features, which influence whether the two surfaces slide, stick, or alternate between the two modes.

As the temperature of the weld metal rises during FSW, the metal softens, torque is reducing, and less heat is distributed to the metal by mechanical work. A temperature-regulating mechanism can be observed, which tends to stabilize the temperature and avoid melting the metal. Alternating the conditions at the interface between stick and slide lead to control of process temperature. If metal cools below a critical temperature, where the deformational flow stress rises above the frictional slip stress, the interaction between the weld tool and workpiece may change from deformational to frictional. If slide occurs between the weld tool/workpiece interface, the heat input could decrease and reduce the temperature of the material. Alternating boundary conditions at the interface can cause stick-slide oscillations [1-1].

— **Material stirring**

Thermally softened, plasticized zone is a region bounded by the tool shoulder, anvil, and parent material. Weld parameters, pin tool design and materials are variables, which control volume of metal heated. A portion of the heat is then swept by the mechanical working portion of the process.

The thermally softened material is transported around the tool in the direction of rotation. It is deposited in the form of bands, which can be viewed in the plan section of an FSW. The spacing of the bands are equivalent to the longitudinal distance the weld tool travels during a single rotation. Geometric and microstructural differences within the refined weld nugget are caused by asymmetrical flow process that occur around the weld centreline. The metal flow can be described using either Nunes Kinematic Model or Arbegast Metalworking model [1-1].

— **Microstructural features**

In the joint material four visually distinct microstructural zones can be distinguished.

Unaffected parent (base) material

This zone is located furthest from the weld, which has the same microstructure and mechanical properties as it had before the FSW process. In this zone there are possible temperature variations, but they are not enough to modify the microstructure and/or mechanical properties. The interface between the stir zone and base material is relatively diffused and smooth on the retreating side of the tool, while it is quite sharp on the advancing side.

Heat affected zone (HAZ)

Moving towards the weld centre, we will find heat affected zone. In this zone microstructure and mechanical properties are affected by the heat generated by FSW process, while there is no plastic deformation.

Thermo-mechanically affected zone (TMAZ)

The TMAZ undergone mechanical deformation the material in TMAZ is plastically deformed and the process is comparable to hot-working of metallic material. TMAZ zone is often defined to be without recrystallization. This is true for aluminium, which is one of the most commonly applied materials in friction stir welding, but other materials can experience recrystallization in this zone. These materials include titanium and its alloys, austenitic stainless steel and copper. There is a generally a distinct boundary between weld nugget and TMAZ.

Stir zone (SZ) or weld nugget

Stir zone is the region, where intense plastic deformation and frictional heating during the FSW process, lead to recrystallized fine-grained microstructure. This zone was previously occupied by the tool pin. The term stir zone is often-used term in friction stir processing, in which large volumes of material are processed.

Central nugget contain fine, equiaxed grains and displays layers of varying thickness, like "onion rings" (also known as the "metallurgical band"). This macroscopically noticeable repetitive pattern on the transverse and lateral section of the weld is unique feature occurring during FSW and related processes.

As the result, fine grain microstructure offers excellent mechanical properties, fatigue properties, enhanced formability and exceptional super plasticity [1-3, 1-5, 1-1].

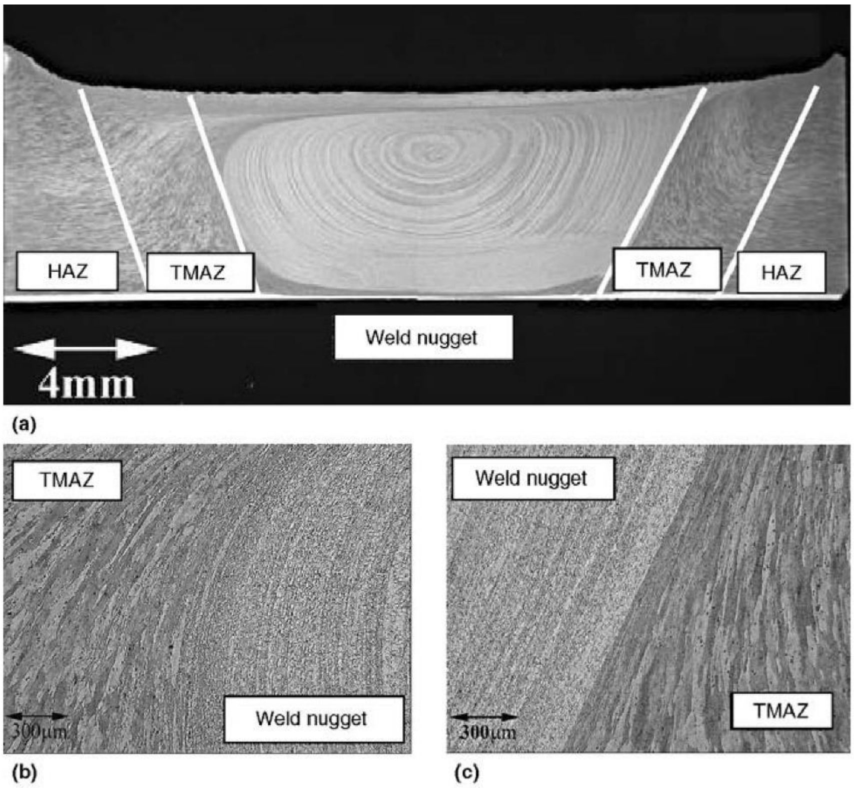


Figure 1-3: (a) Micrograph illustrating different zones in a friction stir welded aluminium alloy. (b) Retreating side. (c) Advancing side – Courtesy of [1-1]

Weld zone phenomena

The weld nugget is bounded by the two adjacent zones – HAZ and thermomechanical affected zone. The size of the nugget depends on generated heat. Hotter welds are reported to have a larger nugget than colder welds. The onion ring pattern is not always apparent in the weld macrostructure. Patterns are more likely visible in colder welds than in hotter welds. The origin of the onion ring structure has not been firmly established yet.

Generation of the onion structure can be explained as follows. Layered (onion) structure has been observed in the surface layers of ductile metals in sliding. The structure is generated during successive shear of thin layers when shear stress from friction force exceeds the yield strength of the material. The sliding is realized between the base metal and plunged FSW tool. An assumption can be made that the interaction in this case if od adhesion nature, because a substantial amount of metal becomes involved in the plastic flow and aluminium sticks to the instrument during welding. The deformation incompatibility between the weld metal and the adjacent base material results in formation of such a structure in FSW. Deformation incompatibility also is the reason behind the weld flaw generation between the base metal and the deformed layer.

Flow of metal is not by a crystallographic mechanism and occurs as a result of mass transfer, which is characterized by the movement of fragments of different scale levels that represent the basic plastic flow carriers. The plasticized layer has an ultrafine sub grain structure being inherent to the severely deformed material. This structure can be also found in weld zone [1-1, 1-10].

— Thermal Management

Thermal management system include: 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 [1-1].

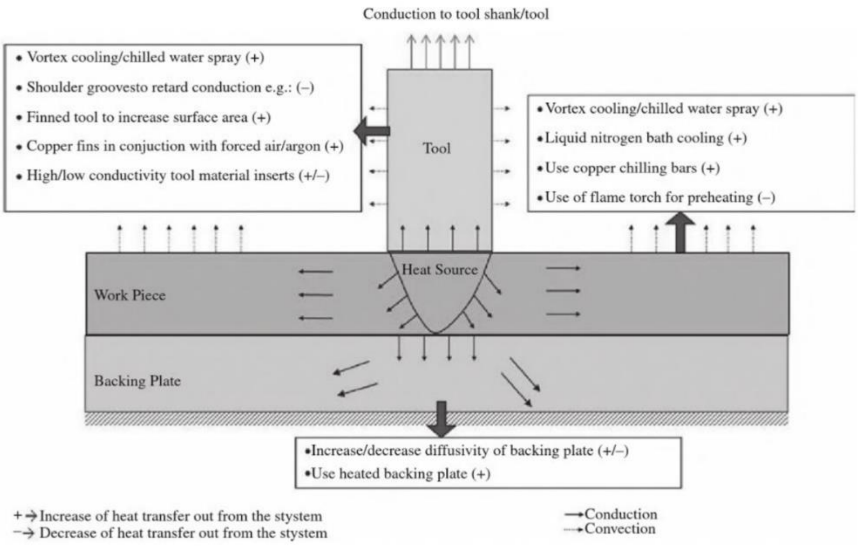


Figure 1-4: Thermal management methods that can be used in friction stir welding process. Arrows indicate heat transfer – Courtesy of [1-11]

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 require 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.

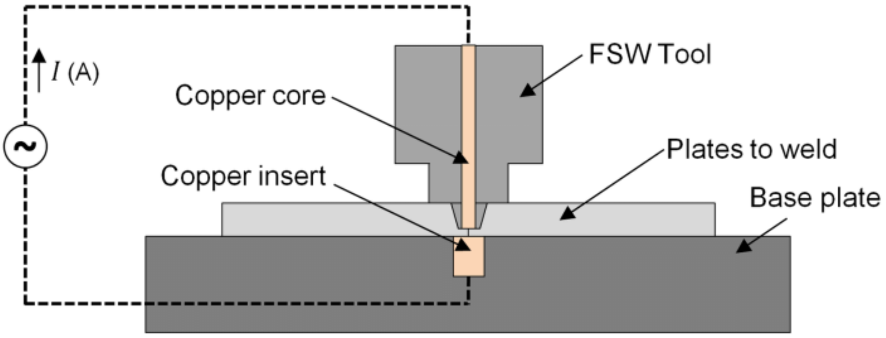


Figure 1-5: Specially designed FSW tool to allow a high intensity electrical current to flow into the weld root aiming to improve the local energy efficiency of the process. – Courtesy of [1-12]

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.

— **Microstructural tailoring**

Microstructure affect the physical properties and behaviour of a material, and we can tailor the microstructure of a material to give it specific properties.

FSW microstructure consist of fine grains and superplastic properties are not degraded. Microstructural tailoring can be done by controlled heat input during FSW, which lead to varied grain size. It is possible to make the superplastic flow stress of the FSW region lower, higher or equal to the parent sheet. This opens new possibilities of sandwich structures using aluminium alloy sheets [1-13].

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, 1-15, 1-16].

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 good 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 [1-17].

Variants of the process and their systems

Friction Stir Dovetailing (FSD)
During FSD process, mechanical interlocks are formed at the aluminium-steel interface and are reinforced by metallurgical bonds in which intermetallic growth has been uniquely suppressed.
FSD plastically deforming the lower melting point material into dovetail grooves machined into higher melting point material to form mechanical interlocks while simultaneously forming an intermetallic bond to further strengthen the joint [1-18, 1-19].

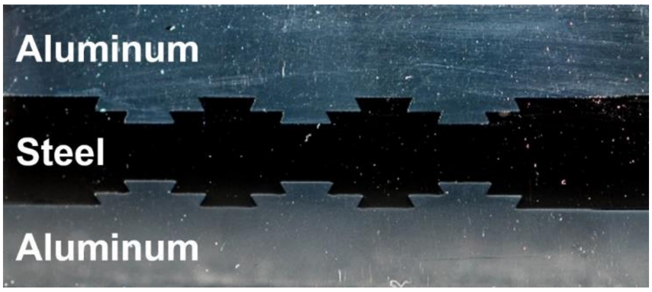


Figure 1-7: Joins made by friction stir dovetailing – Courtesy of [1-20]

Friction Crush Welding (FCW)

Friction Crush Welding (ger. Reibquetschschweißen) is type of friction welding, which is distinguished by a relative motion between the tool and work-piece.
Before FCW process, the edges of the work-piece to be joined must prepared with flanged edges and then placed against each other. Welding process begins, when non-consumable friction disc tool will transverse with a constant feed rate along the edges of the work-piece. The weld joint is created by the action of crushing a certain amount of additional flanged material into the gap formed by the contacting material. As during friction stir welding, grain refinement takes place during FCW process. FCW allows to use a welding wire, which offers the opportunity to use a higher-alloyed additional material and to precisely adjust the additional material volume appropriate for a given material alignment and thickness [1-21].

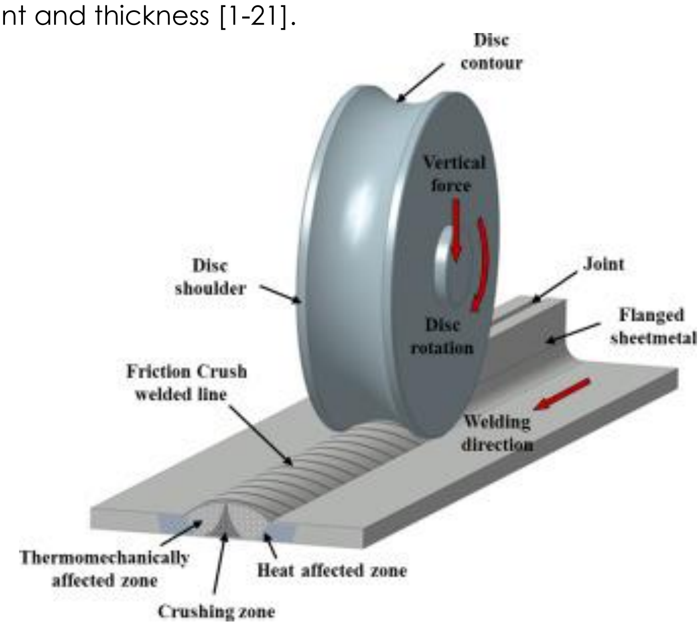


Figure 1-8: Friction crush welding process – Courtesy of [1-22]

Friction stir diffusion process (FSDP)

Friction stir diffusion process (FSDP) promotes joining only by the rapid diffusion of heat generated between the tool and one of the metals, which differentiates it from FSW that joints both metals by diffusion and plastic strain [1-23].

1.2. FSW equipment

— **Essential components**

Basic system components include:

- Spindle.
- Motors.
- motor drive mechanism.
- FSW tool [1-25].

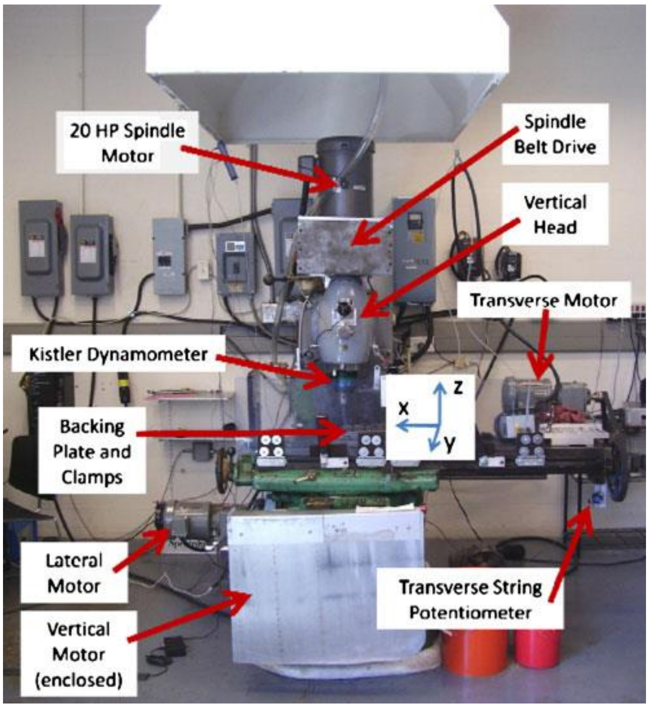


Figure 1-9: Example of FSW system configuration – Courtesy of [1-24]

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 includes: 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 [1-26].

Welding Tool

Figure 1-20: The welding tool – Courtesy of [1-27]

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 [1-28].

Table 1-1: Characteristic of selected FSW tool materials – Courtesy of [1-28]

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 other 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

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 [1-29].

Advantages and Disadvantages of different types of welding tools

Design of tool should surfaces include flat, concave, scrolled, concentric circle etc.

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 [1-28].

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 produce 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 centre. 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, 1-28].

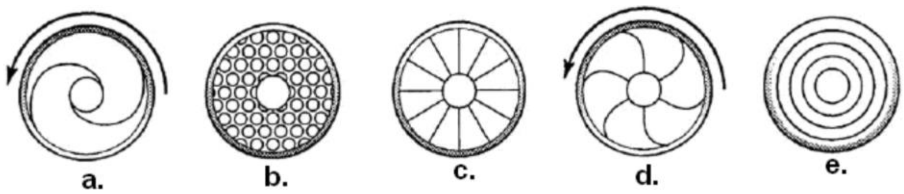


Figure 1-31: Different shoulder features. - Courtesy of [1-30]

Table 1-2: Summary of major welding tool design features [1-17]

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 everyone 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].

1.3. 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 aluminium 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. Below are described the limitations of typical joint types.

Full-Penetration Butt Weld

This type of joint requires the highest relative level of force.

Partial-Penetration Butt Weld

This type of joint requires less force than a full-penetration butt weld in the same thickness. Increased sensitivity of the process may necessitate increased intelligence or sensing requirements. The range of force over which quality welds can be produced may be smaller than for a full-penetration weld.

Lap-Penetration Weld

This type of joint typically requires less force than a butt weld. The lap-penetration weld is insensitive to the location of the FSW tool with respect to the joint line and thus decreases intelligence and stiffness requirements.

Dissimilar-Thickness Butt Weld

The dissimilar-thickness butt weld has many limitations during welding. The concerns are:

– The FSW tool must be tilted backward (travel angle) and sideways (work angle) in a dissimilar-thickness butt weld application. The flexibility requirements of the machine are greatly increased and require usage of five-axis machine. It is also possible to employ complex fixturing that allows for tilting of the parts to access difficult geometry of the joint, but the disadvantage include limited ability to optimize the work and travel angles.

– High stiffness or intelligence requirements (e.g., seam tracking) on the machine.

– With the increase the thickness difference or work angle, the more chance there is that flash will be generated. It can be caused by an off-seam condition or a small difference in work or travel angle. Increased thickness differences also require more flexible machines, which have better control over the work and travel angles.

Lap Fillet Joint

This type of joint has similar requirements to the dissimilar-thickness butt weld, due to the need for both a work and travel angle. Additional design limitations include:

Weld path

The weld path mainly affects the flexibility required from the machine, which is related to the number of axes the machine must possess. The welding paths can be divided into:

– One-dimensional (1-D) paths, which require the least flexibility (fewest axes of motion)., but sometimes 1-D path can still require a five-axis machine. Example of 1-D path with such high requirements is welding of tailor-welded blanks, where dissimilar thickness butt welds are required. One of the most typical 1-D applications requiring the fewest number of axes is the joining of long extrusions
– Two-dimensional (2-D) paths require significantly more flexibility. This is caused by the need to maintain work and travel angles along the path, in most applications. The result is to use a five-axis machine, unless the FSW or FSP tool is held perpendicular to the path. Example of 2-D application with 2-D paths is an FSP application on a flat surface of a casting.
– Three-dimensional (3-D) paths require the most flexibility and thus always require the machine to have at least five axes of motion.

Example of applications requiring 3-D paths are FSP of castings on a complex surface or FSW on complex surfaces.

- Circumferential paths, like tank ends, require a moderate level of flexibility. A single-axis machine, with the aid of an external rotary positioner, can be used for circumferential welding.
- Multiple welds in multiple orientations affect the flexibility requirements of the FSW machine. In most cases a machine with six axes is often the most suitable for economic and technical reasons, although machines with fewer axes still can be used in special cases where external positioners could be used. Using a machine with fewer than six axes requiring multiple setups, which significantly affects productivity in a negative manner.

Part size and weld lengths

Weld length and/or part size affects the required working envelope for the FSW machine.

Lack of access to back side

Applications, where there is not possible to access to the back of the part, require the use of a self-reacting tool (bobbin tool).

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 [1-31, 1-32].

Workpiece and base material thickness limitations

The maximum thickness capability of FSW is limited to around 65 mm [1-33]. As the thickness increase, the force requirements also increase. Thin materials, below 1mm, needs special considerations like:

- increased stiffness requirements, because FSW process sensitivity during thin materials is higher.
- increased intelligence or sensing requirements to overcome increased sensitivity of the FSW process [1-1].

Material

Higher-melting-point materials and highly abrasive metal matrix composites require the use of more advanced tool materials [1-31, 1-32].

1.4. Parent Materials

Basics of Al and other FSW 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 [1-17].

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 aluminium 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 [1-1, 1-4].

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 [1-34, 1-35].

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 [1-1, 1-4].

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].

Metallurgical properties

Aluminium alloys

Aluminium alloys can be classified into heat-treatable alloys (precipitate-strengthened) and non-heat-treatable (solid-solution-hardened), which differs from each other by different hardness profiles when FSW.

In most cases the heating in HAZ is generally high enough for the recovery of cold work and coarsening of precipitates, which leads to changes in mechanical properties in this region. It is possible that TMAZ may present a significant size characterized by lower hardness and increased corrosion susceptibility. Nugget usually consist of fine grain size and is considered to have severe plastic deformations.

Heat-treatable alloys have following properties:

- Hardness profile depends mostly on the dissolution and/or coarsening of strengthening precipitates.
- Achieved temperatures during welding leads to dissolution and growth of the precipitates, which further decrease of hardness in the weld zone.
- A hardness reduction in the weld zone is common in FSW of the artificially aged aluminium 6xxx series.
- The temperature achieved during the FSW has a great impact in over-ageing and in decreasing dislocation density, consequently lowering the local hardness. -Minimum hardness can be found in TMAZ - loss of elongated formed grains occurring, ageing and annealing processes.
- Retreating side shows a smoother change in microstructure than advancing side
- 2xxx aluminium alloys naturally ages at room temperature, which leads to a hardness increase and corresponding improvement in mechanical properties (highest effect occurs in the first ageing week).

Non-heat-treatable alloys are characterized by:

- Softened weld zone is not verified in these alloys.

Heat-treatable alloys and non-heat-treatable alloys:

- Reduction in both strength and ductility compared to unwelded parent metal.
- Different zones have different resistances to deformation due to differences in grain size, precipitate size and distribution.

Copper alloys

- FSW copper alloys show greater dissipation of heat through the workpiece, caused by their higher thermal diffusivity, requiring a higher heat input during welding - appropriate temperatures for a successful FSW joint were defined to be between 460 and 530 °C.
- Nugget zone presents fine recrystallized grains, the TMAZ has deformed large grains, and the HAZ is characterized by equiaxed grains larger than those of the base metal (BM).
- Pure copper FSW joint tensile strength is slightly lower than that of base metal – Failure occurs near the HAZ.

Magnesium alloys

- Occurrence of liquid phases and generation of complex microstructure in the weld is caused by peak temperatures in range from 370 °C up to 500 °C.
- In general, FSW magnesium alloy joints present higher hardness than that of the BM due to a refined grain structure.
- Lower nugget temperature achieved during welding tends to show the best mechanical properties.
- FSW cast magnesium alloys joints show improvement in comparison to base metal, but in wrought magnesium alloys a decrease in these properties is reported.
- Failure of the joint is located mostly at base metal.

Steel

- High temperature during welding (>1000 °C) - Generally the hardness at the central zone is much higher than that of the base material.
- FSW steel joints present higher yield and UTS when compared to base metal.

Titanium alloys

- Allotropic phase transformation together with deformation and continuous cooling, produces a complex weld microstructure.
- Very narrow TMAZ of approximately 30 μm or absence of TMAZ – there is a presence of HAZ and stir zone only.
- Yield and UTS exhibit almost 100% joint efficiency [1-4].

Factors, which influence post weld properties can be a function of factors described in Table 1-3.

Table 1-3: Post weld properties and influencing factors – Courtesy of [1-1]

Factor	Description
Tool travel speed	influences total heat input
Tool rotation rate	influences total heat input
Tool design	shoulder diameter, scroll or concave shoulder, features on the pin, pin length
Tool tilt	depends on the tool shoulder design but typically is 0 to 3°
Material thickness	influences cooling rate and through-thickness temperature gradients
Alloy composition	weld parameters not transferable from one aluminium alloy to another
Initial material temper	influences alloy response
Cooling rate	passive or active cooling
Heat sink	thermal conductivity of materials in contact with the weld, for example, anvil and clamping system
Test sample size, location, and orientation	where the sample is sectioned from the weld, especially through the thickness and longitudinal versus transverse orientation
Surface oxides	potential for more or less of a continuous oxide within the weld
Joint design	lap, butt, fillet
Post weld heat treatment	dependent on alloy composition and pre-weld temper

Factor	Description
FSW test system	specific characteristics for each system, for example, spindle runout, heat dissipation through the spindle, anvil and clamps, and so on
Time between FSW and testing (natural aging at room temperature)	some materials, like the 2xxx and 6xxx aluminium alloys, have their weld zone stabilized at room temperature within few days or weeks

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 copper alloys	<50	Nickel alloys, PCBN, tungsten alloys
	<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 Definition

Before starting a welding operation, some planning must be made to achieve a quality joint. In the following chapters it will be addressed the preparations and considerations which need to be thought out before the actual weld. These preparations take into account the quality requirements of the part and the final application that will be given to the part, as some industry sectors require tighter and superior standards. The following pages will embrace topics ranging from cleaning methods to software programs.

2.1. Considerations for the Joint Design

When welding using FSW several parameters and features must be selected, one of which is joint design. There are several types of joints in welding, which are most suitable for a specific situation. The goal of joint design is to obtain the maximum strength for a given area of a bond, this is obtained by minimizing the concentration of stress [2-1]. Joint design is determined by restraints like work piece material and thickness, desired physical properties, accessibility of the joint, available edge preparation equipment and specifications of regulatory codes (if applicable).

2.1.1. Types of joints

There are many different joint geometries in welding and a lot of them are applicable to FSW, however there are certain limitations and requirements that shorten this list. Since FSW is an autogenous welding process, i.e. it doesn't need filler material like an electrode, some types of joints, e.g. fillet welds, are hard to apply in FSW, although they can be simulated through special materials or fixture designs.

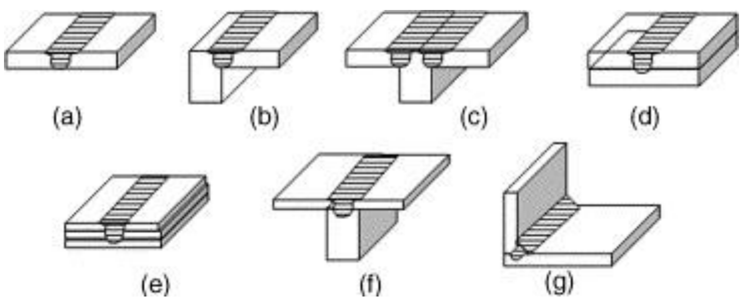


Figure 2-1 Joint configurations for friction stir welding: (a) square butt, (b) edge butt, (c) T butt joint, (d) lap joint, (e) multiple lap joint, (f) T lap joint, and (g) fillet joint [2-2].

The most common joints used in FSW are butt joints, corner joints and lap joints. In a fillet weld, a significant amount of material is added to fill a transition between two workpieces, making it almost impossible to apply in FSW. A way was found to enable a small fillet of plates at some angle using FSW, this is usually achieved at the expense of material from the joint [2-3].

2.1.2. Design considerations

When welding using FSW, joint design should take into account:

– Sufficient area for the welding tool shoulder path;
– Sufficient containment of softened weld metal along the full length of the joint
– Adequate force to prevent motion of the workpieces;
– Adequate heat sinks to dissipate the heat of welding.

The area required for the welding tool shoulder is a function of material thickness and the alloy chosen. Usually, aluminium alloys require 3x to 5x the thickness of the workpiece, while steel and titanium require less shoulder area due to lower thermal conductivity and subsequently smaller shoulder diameter.

Control of the softened weld metal along the joint is essential as it ensures softened metal doesn't push out and provide additional heat sink. Machined features, such as drilled holes or pockets that are too close to a weld joint should be avoided or temporarily plugged during welding.

It's also necessary to ensure a proper restraint of the workpiece so it doesn't move due to the forces applied. The adequate force to apply is assessed through trial-and-error as there is little to no information regarding this subject. Inappropriate clamping may lead to "drop-out", Figure 2-2, this is the result of inadequate vertical force in a butt weld, preventing the workpiece from lifting from the anvil. This is properly prevented by ensuring a good fixture design, rather than trying to correct during the welding process.

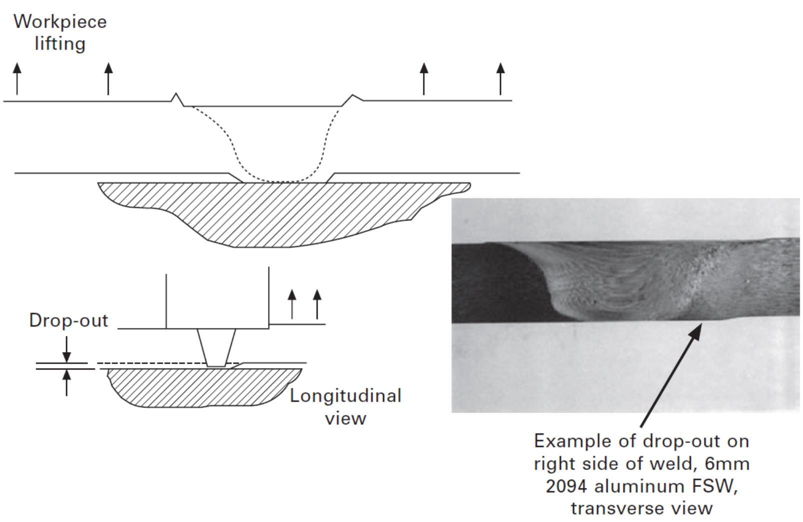


Figure 2-2 Drop-out in a butt weld produced by inadequate vertical holding force on the workpiece

Joint design should also consider an adequate heat sink, as excessive heat build-up may make it impossible to weld.

Besides these points, it's also desirable to consume the original contact surfaces to the greatest extent since remnant oxide bands can provide crack initiation sites. Also, lap joints can be problematic, as they leave remnant oxide band that enters the weld.

Finally, it's important to consider the effect of the joint properties across the weld zone and how it relates to the applied load in service [2-3].

2.1.3. Weld Geometry

The most common weld geometries obtained through FSW are:

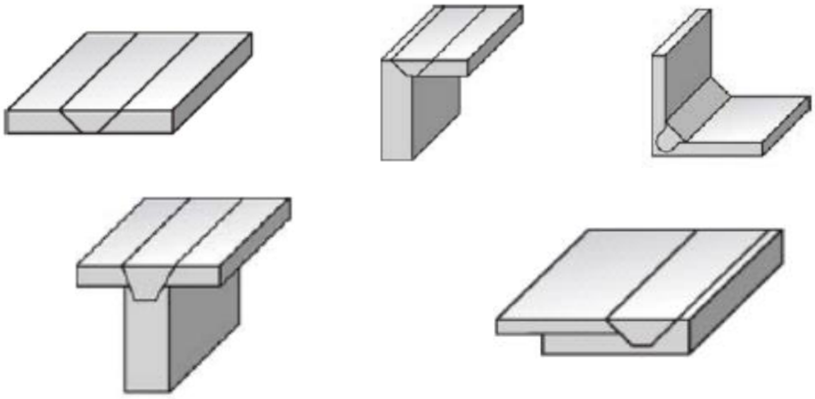


Figure 2-3 Examples of common welds obtained through FSW: (a) butt weld, (b) and (c) corner fillet, (d) T fillet and (e) lap fillet [2-4].

2.2. Cleaning methods

2.2.1. Importance of cleaning

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.

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 [2-3], [2-5], [2-6]. Some other methods of cleaning joints may encompass [2-7]:

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

2.2.2. Advantages and Disadvantages of cleaning methods

Cleaning 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.

Some negative fallouts of improper surface cleaning include poor fatigue loading performance, localized low ductility and volumetric defects produced during post-weld heating [2-3].

2.3. Tools

Traditional FSW process lies on the insertion of a rotational tool, consisting of a pin and a shoulder, into the joined workpieces to be welded and navigating along the weld joint [2-8]. This tool is non-consumable and the key component of the FSW process. The choice of tool material and geometry depends upon the material to be welded, material dimensions, joint configuration and other required specifications [2-9].

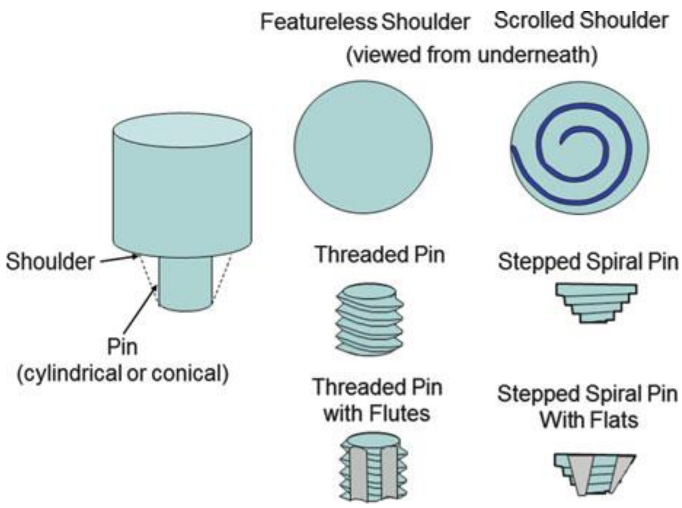


Figure 2-4 Basic tool shoulder and pin features [2-10].

2.3.1. Types of tools and its characteristics

As mentioned previously, one of the important choices when selecting the tool is its material, this has six basic characteristics [2-10], [2-11]:

- Strength at ambient and process temperature
- Fatigue life at process temperature
- Fracture toughness
- Wear characteristics
- Long term thermal stability
- Chemical stability (nil or limited reaction with the workpiece)

For the most common application of FSW which is welding of aluminium alloys, tool steel materials are employed although there is no accepted standard tool material. When welding aluminium alloys from 6 to 12 mm thickness, it's usually employed H13 tool steel. For higher thicknesses or if an increase of productivity is needed, the pin tool can be made of MP129 or a material with higher strength at the welding temperature, but the shoulder of the tool can still be made from H13. Another approach to this, can be the development of a more elaborate tool design, delivering a better performance.

Other materials, such as titanium, steel or copper may require tools made from tungsten-based materials, polycrystalline cubic boron nitride or other high performance materials that endure high temperatures [2-3].

2.3.2. Positioning

Regarding the positioning of the tool, some considerations must be taken to achieve an optimum result, especially when welding dissimilar materials. Some tips regarding the tool position concern:

- *Offset position*

The offset position corresponds to the lateral offset from the tool axis to the faying surface [2-12].

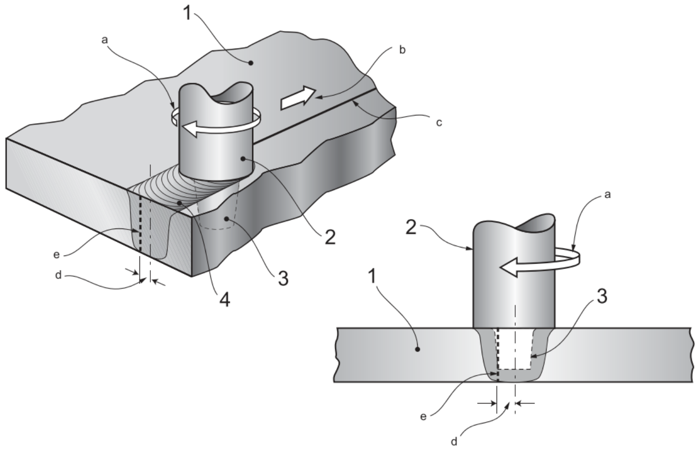


Figure 2-5 Lateral offset showing the centreline of the tool not centred on the joint. 1-Workpiece; 2-Tool; 3-Probe; 4-Weld face; a-Direction of tool surface; b-Direction of source; c-Joint (faying surfaces); d-Lateral offset; e-Location of joint before welding [2-12].

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 [2-4].

- *Z position*

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

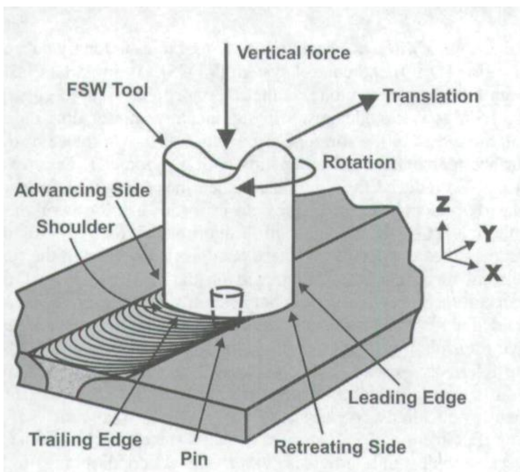


Figure 2-6 Schematic of FSW process[2-13]

The z position of the tool refers to its spatial location on the process which is usually zero at top surface of the workpiece. The force applied along the z position is called axial force and its application has proven to deliver higher quality welds [2-13].

- *Plunge depth*

According to ISO 25239-1 the distance the heel extends into the weld metal is referenced as heel plunge depth [2-12]. The plunged depth is a programmed and critical parameter for position-controlled runs.

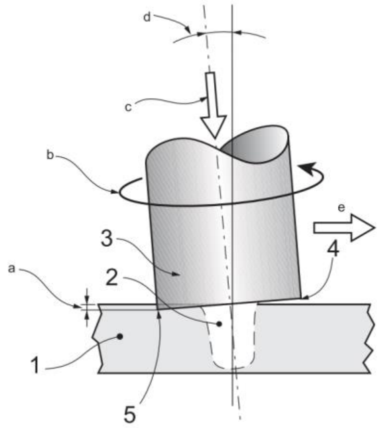


Figure 2-7 Side view of butt joint. 1-workpiece; 2-probe; 3-tool; 4-shoulder (leading edge); 5-heel (shoulder trailing edge); a-Heel plunge depth; b-Direction of tool rotation; c-Axial force; d-Tilt angle; e-Direction of welding [2-12].

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 [2-3]. These parameter, along with rotation and traverse speed, greatly influence the weld quality [2-9].

2.4. Clamping

2.4.1. Clamping methods and its characteristics

Clamping is a method of fixing and positioning the components to be welded, in the desired position. The workpiece can have its position unchanged if the welding travel is only assured by the welding head or have it variable when the welding process requires movement from the welding head and workpiece (or by only the workpiece) [2-14].

There are different types of clamping:

- Mechanical actuation clamps;
- Pneumatic and Hydraulic clamps;
- Vacuum clamping;

The simplest and economical way to clamp sheets or plates is to use clamping claws (mechanical actuation clamps). The advantage of this system is a high clamping force, but it requires a high set-up time to clamp the work pieces, besides the different thermal conductivity in case the clamping claws are mounted close to the weld seam. When clamping wide parts, clamping claws are not easily able to reach along the weld seam.

For series production it can be desirable to design a special hydraulic or

pneumatic fixture so that the set-up time can be reduced. These fixtures are expensive and only reasonable in batch production situations.

Vacuum clamping systems are very flexible systems that are easy to use and allow for clamping of different part sizes, both large and small width and lengths. The set-up time of these systems is low, increasing the production rate. Also, thermal flow from the FSW process is constant over the whole backing bar, compared to conventional clamping, which leads to good weld quality. However, vacuum clamping forces are not always sufficient for thick plates, which may benefit conventional clamping methods [2-15].

2.4.2. Clamping importance

Proper clamping is an important aspect since it's always present during the welding process. The tooling fixture needs to have clamping mechanisms that allow the FSW pin tool to access to the weld path and prohibit the part from sliding lengthwise, bending, or separating due to the torque forces. The clamping system must guarantee to clamp down the work pieces reliably so that no gap can occur during the welding operation. Also, the thermal conductivity of the weld surface and the clamping system can impact the quality of the weld and the welding parameters. The clamping system is an important consideration when planning the welding procedure as it influences weld quality and production cycle [2-15].

2.4.3. Clamping arrangements

Clamp positioning is also a critical part of the overall operation. Ensuring a proper hold of the part against the clamps and the locators without deforming the workpiece isn't an easy task. The purpose of locators is to resist all primary forces generated in the operation, while the clamps need to hold the workpiece against the locators and resist any secondary forces generated in the operation. The clamps should be positioned at the most rigid points of the workpiece, preventing it from damaging the workpiece. The location of the clamps should ensure an equal distribution of forces throughout the whole process.

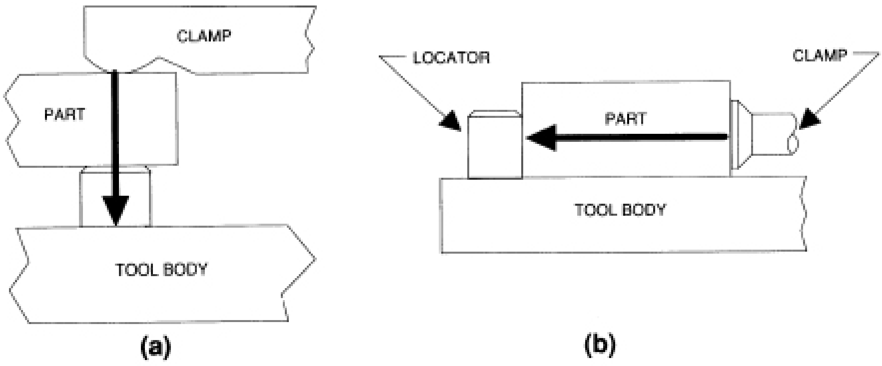


Figure 2-8 Examples of proper clamp positioning [2-16]

Another important consideration when choosing the clamp positioning is to ensure that it doesn't interfere with the welding path of operation.

2.4.4. Influence of the clamping in the welding process

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 [2-17].

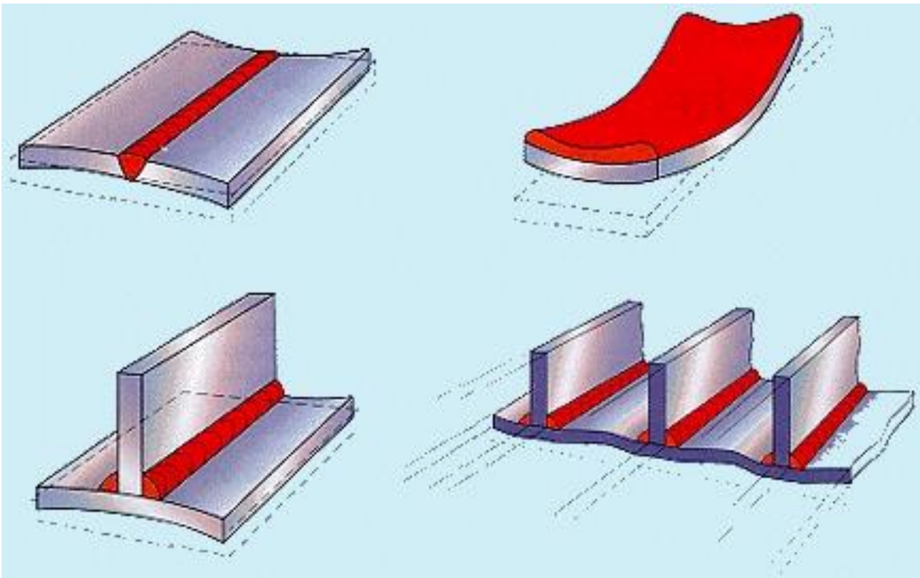


Figure 2-9 Common forms of distortion in welds (source: TWI)

2.5. Backing Plates

Backing plates are required to resist the normal forces employed in FSW, as well as providing a stiff object to clamp the plates or sheets to be welded.

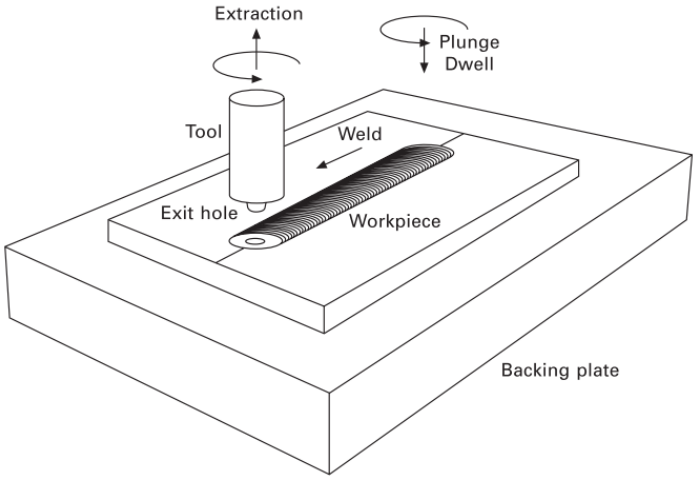


Figure 2-10 Schematics of Friction Stir Welding [2-3]

2.5.1. Material of backing plates

There are many materials employed as backing plates for FSW, these influence the power consumption and the weld quality [2-3], [2-18].

Table 2-1 Thermal conductivity for backing bars [2-3]

Material	Thermal conductivity [W/mK]
Mild steel	40-60
Stainless steel	15-25
X33CrS16 (1.2085)	17
RAMAX	24
Bras	110-150
Copper	180-400
Aluminium alloys	110-235

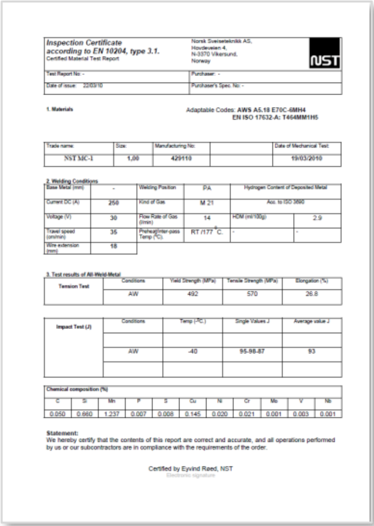
2.5.2. Thermal conditions for back plates

One important parameter in friction stir welding is heat loss and the most prominent heat loss is through the backing plate. It's stated that using a low thermal diffusivity (doesn't dissipate heat that easily) backing plate can reduce energy consumption and help to achieve full penetration welds [2-18].

2.6. Parent Materials

2.6.1. Material Certificates 3.1 and 3.2

A Material Certificate provides traceability and assurance to the end user about the quality of the steel used and the process used to produce it.



Inspection Certificate according to EN 10204, type 3.1. Certified Material Test Report	Norsk Sveiseteknikk AS, Hovdeveien 4, N-3370 Vikersund, Norway — NST
Test Report No: -	Purchaser: -
Date of issue: 22/03/10	Purchaser's Spec. No: -

1. Materials

Adaptable Codes: **AWS A5.18 E70C-6MH4**
EN ISO 17632-A: T464MM1H5

Trade name:	Size:	Manufacturing No:		Date of Mechanical Test
NST MC-1	1,00	429110		19/03/2010

2. Welding Conditions

Base Metal (mm)	-	Welding Position	PA	Hydrogen Content of Deposited Metal	
Current DC (A)	250	Kind of Gas	M 21	Acc. to ISO 3690	
Voltage (V)	30	Flow Rate of Gas (l/min)	14	HDM (ml/100g)	2.9
Travel speed (cm/min)	35	Preheat/inter-pass Temp (°C).	RT /177 °C.	-	-
Wire extension (mm)	18				

3. Test results of All-Weld-Metal

Tension Test	Conditions	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)
	AW	492	570	26.8

Impact Test (J)	Conditions	Temp (-°C.)	Single Values J	Average value J
	AW	-40	95-98-87	93

Chemical composition (%)

C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	Nb
0.050	0.660	1.237	0.007	0.008	0.145	0.020	0.021	0.001	0.003	0.001

Statement:
We hereby certify that the contents of this report are correct and accurate, and all operations performed by us or our subcontractors are in compliance with the requirements of the order.

Certified by Eyvind Røed, NST
Electronic signature

Figure 2-11 Example of Material Certificate type 3.1

The difference between 3.1 and 3.2 Material Certificate is that 3.1 is endorsed only by the manufactures own representative who must be independent from the manufacturing process. Whilst a 3.2 Material Certificate has been additionally countersigned by an independent inspection authority or the purchaser's authorised inspection representative, who can confirm that the testing and inspection process demanded by the specification have been adhered to correctly [2-19].

Material characteristics present in those certificates include [2-20]:

- Chemical analysis;
- Mechanical properties (e.g. tensile, impact, hardness, bend test, among others);
- Heat treatment;
- Plate Condition;
- Corrosion;
- NDT

2.6.2. Adequate Materials for FSW

When TWI invented friction stir welding in 1991, its main application was to join aluminium but since then this has been carried over to a diverse range of materials.
These range of materials spans from [2-3]:
- High temperature alloys (e.g. titanium, steels, nickel)
- Low temperature alloys (e.g. aluminium, magnesium, copper)
- Dissimilar materials (e.g. aluminium to steel, aluminium to magnesium)
- Thermoplastics.

2.6.3. Weldability of materials for FSW

FSW is a solid-state process which improves the weldability of certain materials. Although it has been shown to weld a number of different materials, materials with a higher melting point may not be the most adequate for FSW, so a study on performance and economics must be made beforehand. The main limitation to the weldability of high melting point metals is the availability of suitable welding tool materials that can endure these conditions of operation Another issue that needs to be taken into account, is that the heat generated by friction, plastic work or auxiliary heating must be sufficient to overcome the loss of heat from the welding zone through conduction on the workpiece.

Certain aluminium alloys are difficult or impossible to weld by traditional arc welding processes due to problems with the formation of brittle phases and cracking, so friction stir welding is a viable alternative.

FSW of steel has shown that the lower welding temperature can lead to very low distortion and unique joint properties.

When applying FSW to titanium it's necessary a low heat input of the tool design either by minimizing the shoulder diameter or by eliminating shoulder rotation altogether, due to its low thermal conductivity although titanium is considered a high melting point material.

Copper has been applying FSW on the construction of canisters for storing nuclear waste for several years. Although it was expected that the high thermal conductivity would be a problem it was corrected through high spindle speed, which helped in delivering sufficient heat intensity for high quality welds.

The use of FSW also enables the joining of dissimilar alloys, which can appeal to certain applications [2-3].

2.7. Equipment for FSW

2.7.1. Types of equipment and characteristics

FSW equipment needs to be designed in order to ensure appropriate fit-up, proper hold-down clamping (including enough stiffness to prevent the part from moving) and dissipate the heat generated by the process.

The critical parameters controlled by the FSW equipment are pin tool position, orientation, loads, rotation and travel speeds.

FSW machines are usually designed for a specific application, although there are some general configuration machines that can deal with different situations.

The initial feature to decide for a specific weld involves the definition of the type of welding desired: fixed-pin, adjustable-pin or self-reacting.

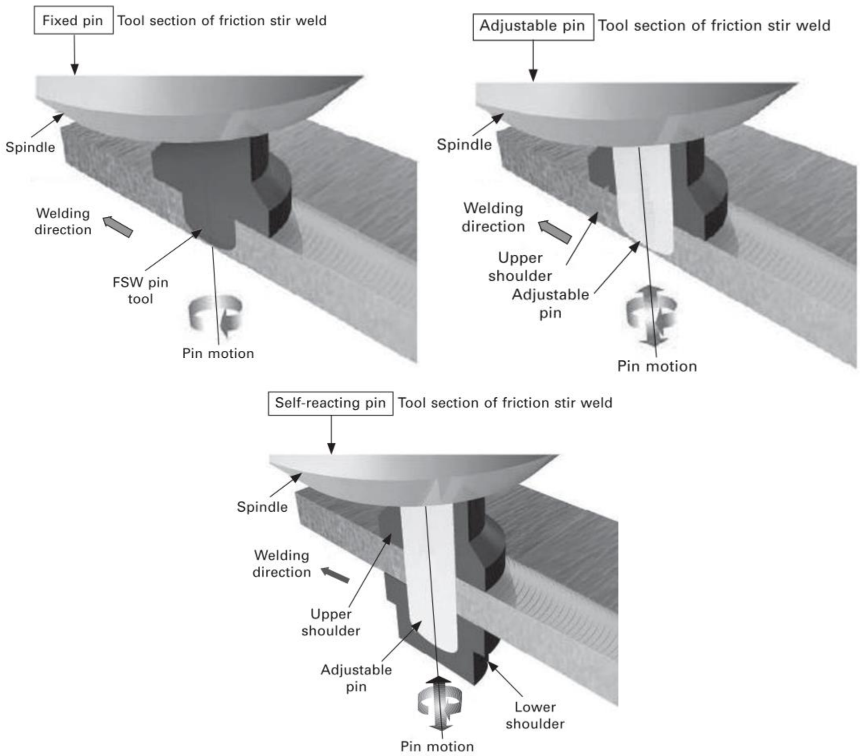


Figure 2-12 FSW types of welding - fixed-pin (left), adjustable-pin (right) and self-reacting pin (bottom) [2-3]

Fixed-pin welding consists of a one-piece tool, shoulder and pin, that translates into a joint motion of the welding head spindle. The position and loads of the shoulder and pin are connected to the motion of the weld head. This is the most traditional form of FSW and the most basic to implement from a machine design and control perspective.

The difference from the adjustable-pin to the fixed-pin welding, relies in the uncoupling between the pin and the shoulder, which can move independently of one another. This can be useful in welding parts with varying thickness or to close-out the pin hole that exists when exiting a fixed-pin from a weld (Figure 2-13).

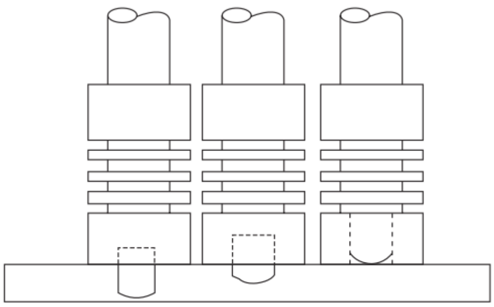


Figure 2-13 Adjustable-pin closing out pin hole [2-3]

This type of welding implies a more sophisticated machine design and control scheme, which can move the pin and should independently, even at different speeds and/or rotation directions.

2.7.2. Productivity and efficiency of the equipment

There is a desire common to all manufacturing processes that is to increase its productivity, which is normally associated with higher processing speeds.

In welding it usually comes down to increasing the welding speed, however in friction stir welding that could lead to many different problems and a defective joint. Increasing the speed of the joining process could lead to increased wear and stresses on the tool, besides the increased incidence of defects in the part to be welded. Increasing the welding speed, also means increasing the rotation speed of the tool to deliver more heat into the part. But it's stated that an excessive rotation speed can break-up material surface. Just increasing the welding speed to improve productivity isn't the ideal solution, so energy should also be sent in optimising the time assigned for joint preparation and loading and unloading of parts [2-3].

Most manufacturing processes have three basic production equipment solutions: manual, fixed automation or robotic solutions. These influence the productivity of the product chain. Since FSW involves the application of high force values, manual solution is generally not possible. But fixed automation and robotic solutions can still be used, and its choice comes down to technical and economic factors.

Fixed automation delivers a machine built for a single purpose and to the exact requirements of a specific application. It tends to have higher stiffness and higher force application capabilities than robotic solutions. However, they are limited to its specific application and are hard to adapt to other product requirements (i.e. geometry and/or dimensions).

Although, its implementation was delayed due to low load capability and low stiffness of industrial robots, robotic solutions have also been implemented and increased productivity in FSW. Robotic solutions have higher flexibility than fixed automation [2-8], [2-10].

Finally, process productivity and efficiency are also influenced by tool design. The implementation of features like step spiral threaded feature to the probe or scrolls implementation on convex shoulders, can eliminate adverse microstructures and defects.

2.8. FSW-Parameters

FSW is usually deemed as a relatively simple process, however, isn't solely the result of an interaction between three processing parameters, i.e. tool rotation speed, weld travel speed and axial force. In the following chapters it will be presented all relevant parameters needed to obtain a good weld.

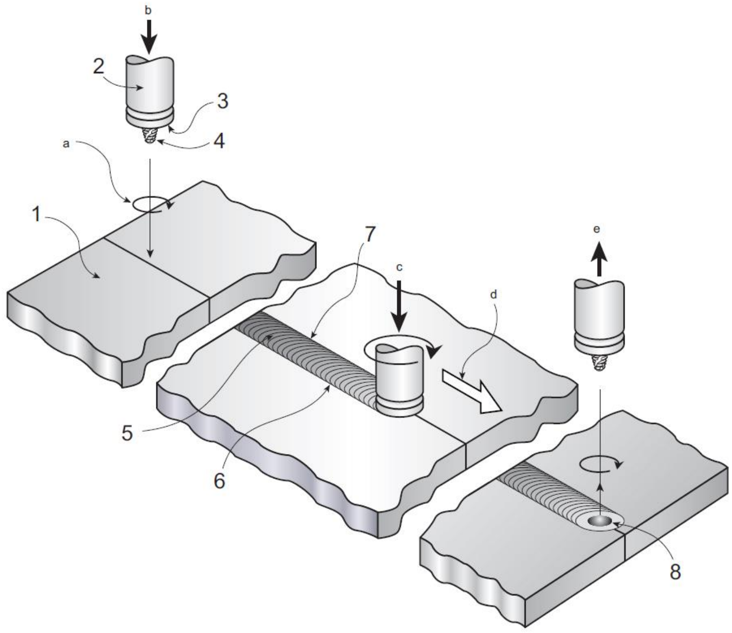


Figure 2-14 Examples of FSW features and parameters: 1) workpiece, 2) tool, 3) shoulder, 4) probe, 5) weld face, 6) retreating side of weld, 7) advancing side of weld, 8) exit hole, a) Direction of tool rotation, b) Downward motion of tool, c) Axial force, d) Direction of welding, e) Upward motion of tool [2-12].

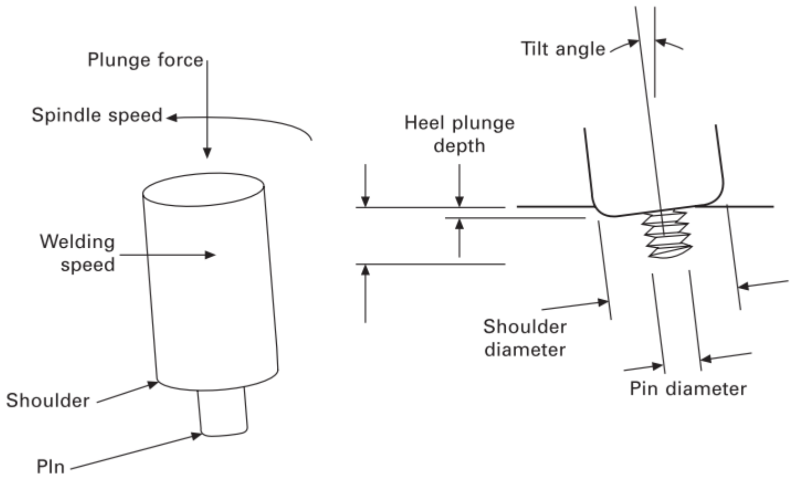


Figure 2-15 Conventional FSW tool and key variables [2-3].

Table 2-2 Main FSW process variables [2-3]

Tool design variables	Machine variables	Other variables
Shoulder and pin materials	Welding speed	Anvil material
Shoulder diameter	Spindle speed	Anvil size
Pin diameter	Plunge force or depth	Workpiece size
Pin length	Tool tilt angle	Workpiece properties
Thread pitch		
Feature geometry		

– **Rotation speed (r/min)**

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, but unlike what's expected the deformation zone will not continuously grow. The stir zone of the weld will decrease in size with ever increasing tool rotation speed due to loss of flow strength and subsequent material slip must occur at the tool/workpiece interface.

Also, higher tool rotation speeds will result in higher processing speed and consequently higher cooling rates. This has an impact on the resultant microstructure. It has been reported (Yan et al. 2007, Colegrove et al. 2007, Peel et al 2006a,b, 2003) that the rotation speed of the FSW tool has substantially greater influence on the microstructure and mechanical properties of friction stir welds than either the influence of weld travel speed or axial force [2-3].

– **Heel plunge depth (mm)**

Heel plunge depth corresponds to the distance the heel extends into the weld metal [2-12]. The axial force (sometimes known as downward force) is directly related to the plunge depth, the deeper the heel plunge depth the higher the axial force [2-3]. The effects of this parameters will be further explained next.

– **Axial Force (kN)**

The axial force is the force applied to the workpiece along the axis of tool rotation [2-12].

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 [2-3].

– **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 [2-12]. 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 [2-10].

– **Side tilt angle (°)**

Side tilt angle is the angle between the centreline of the tool and a line perpendicular to the surface of the work piece, measured in a plane perpendicular to the direction of welding [2-12].

– **Dwell time (s)**

Dwell time is the period of time the tool stays rotating in the same location, it's usually assigned at the beginning and end of the weld.

Once the welding tool is plunged into the workpiece, the tool is typically driven laterally along the joint without delay, but in some materials, it may be necessary to dwell at the plunge location for some time in order to allow the welding tool and workpiece to reach a higher temperature, as thermal softening allows for starting the traverse welding motion [2-3].

– **Welding speed (mm/min)**

Welding speed, sometimes mentioned as tool traverse speed, is one of the crucial parameters of FSW. It's one of the main parameters that affect the power input profile alongside tool rotation rate.

In terms of FSW it is required a certain process temperature, so thermal softening allows the traverse welding motion. That peak process temperatures increase 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. However, there is a limit here, as most materials have a maximum shear strain rate which they can endure, and this is determined by the rate of recovery in the highly deformed material. Also, 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. 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, thus more investment in joint preparation and fit-up [2-3].

– **Preheating temperature (°C)**

Although pre-heating showed good joining results, an additional heating step not only affects the simplicity of the process but also increases the process time [2-21].

– **Post-weld treatments**

FSW is a welding process which can dismiss post-welding processes (thermal or cold work), which increases productivity and lowers manufacturing costs. However, post-weld heat treatments can be employed, such as post-weld aging, to improve static, corrosion and stress corrosion cracking performance of joints, particularly in aluminium alloys. Be aware that this treatment is better suited to materials that are in an under-aged condition to bring the welded materials to a state that offers good corrosion performance with adequate mechanical property, preventing over-aging of certain zones which renders the benefits of the heat treatment pointless. Some aluminium alloys, designed to have a particularly strong aging response, can be welded and given optimal strength by closely following the welding tool with a water quench as the water sprayed over the parts doesn't interfere with the welding process.

Concluding, before choosing a heat treatment it should be analysed the effects of changes to the base metal temper designed to facilitate post-weld aging response, as it may require changes in welding parameters to offset the changes in initial temper [2-3].

– **Heating and cooling rates**

Heating and cooling rates will determine the mechanical properties of the friction stir welded joint. Processing parameters selected based only on optimal heating and cooling rates are generally unable to facilitate constant volume processing and thus influence the resultant microstructural transformations, increasing the potential to produce flaws in the welded joint. So, keep in mind that a high thermal diffusivity delivers a high material cooling rate but a small HAZ of the joint. By contrast, a lower diffusivity leads to slower cooling rates and a larger HAZ [2-3].

All the parameters mentioned above must be kept in mind when planning the welding of the workpiece through FSW, as they are key to a successful and quality weld.

2.9. Jigs and Fixtures

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.

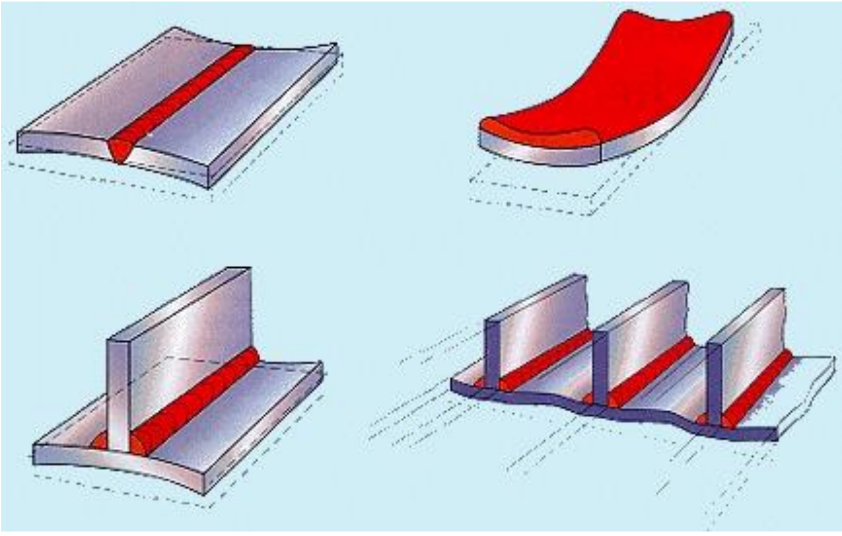


Figure 2-16 Common forms of distortion in welds (source: TWI)

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 [2-17].

2.9.1. Types and Characteristics of jigs and fixtures

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 provided repeatability, accuracy and interchangeability in the process [2-22]–[2-24].

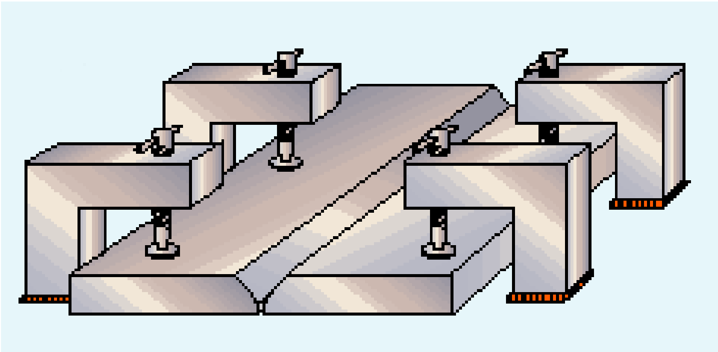


Figure 2-17 Welding jig (source: TWI)

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

Figure 2-18 Drill jig (source: Kreg Jig)

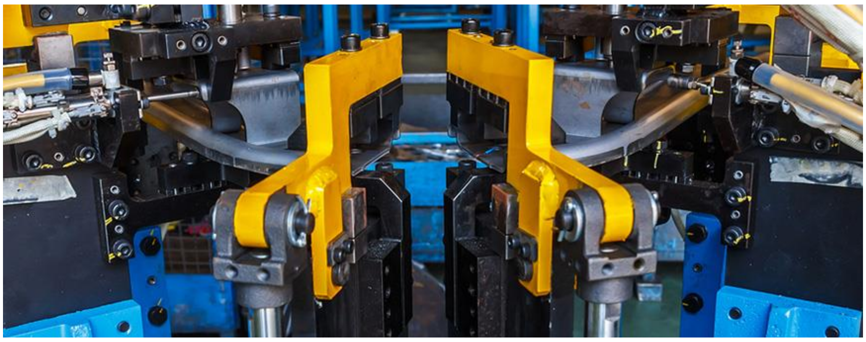


Figure 2-19 Welding jig (source: Tulsa Welding School)

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 [2-24].
Types of fixtures include:

- Frame railing

Figure 2-20: Frame railing

- Railing welding

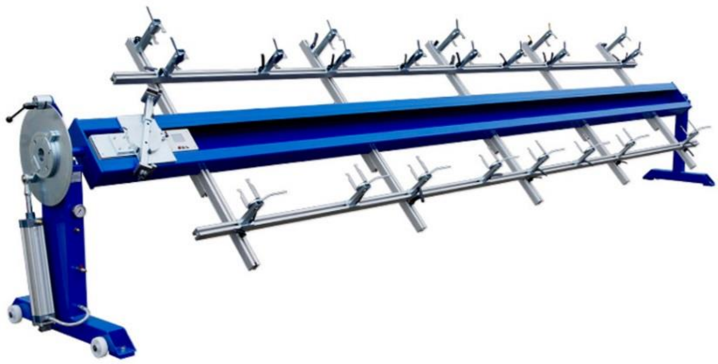


Figure 2-21: Railing welding

- Vacuum clamping

Figure 2-22: Vacuum clamping

2.10. Programs

2.10.1. 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 2-23 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 2-24 Control system developed for FSW (source: ESAB)

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

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

Represented on an 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)[2-25].

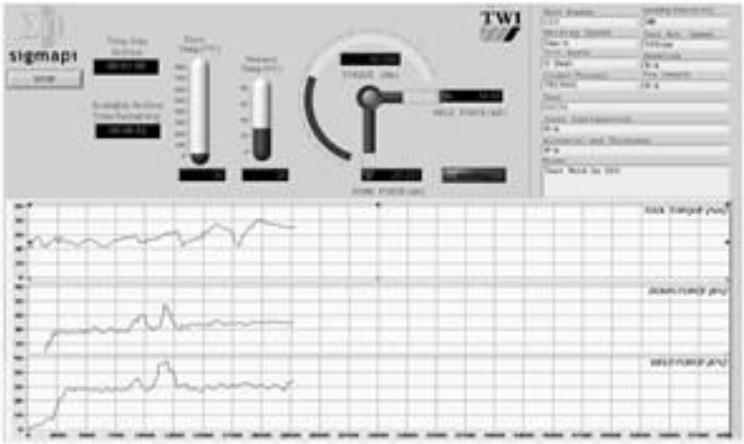


Figure 2-25 Example of display screen interface and parameters (source: TWI)

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3. Supervision of the Welding Process Operation

In order to achieve a sound welded joint, the supervision during entire welding process is necessary. Just the joint fabricated free from defects is considered for a sound joint. Application of the so-called supplementary/auxiliary equipment is one of possibilities how to avoid the defects. Several types of auxiliary equipment are associated with the FSW technology. The functions and tasks of such equipment depend on application and the type of welded joint. The auxiliary equipment is classified to two main groups: navigation and hybrid.

3.1. Navigation Auxiliary Equipment

The navigation auxiliary equipment is used in the applications where it is necessary to control the correct position of welding tool in the welding line direction. This concerns the equipment which controls for example the immersion depth of welding tool and temperature during welding process [3-10, 3-11, 3-12, 3-13].

3.1.1. Depth control (welding tool immersion)

The control of depth of welding tool immersion is another welding parameter advisable to control at repeated welding by FSW process. The immersion depth of welding tool play a significant role in formation of diverse defects in welded joint as insufficiently stirred welded material in the root zone and formation of excessive flash.

These defects unfavourably affect the temperature regulation. Different probes and position sensors are used for measuring the immersion depth of welding tool, see Figure 3-1.

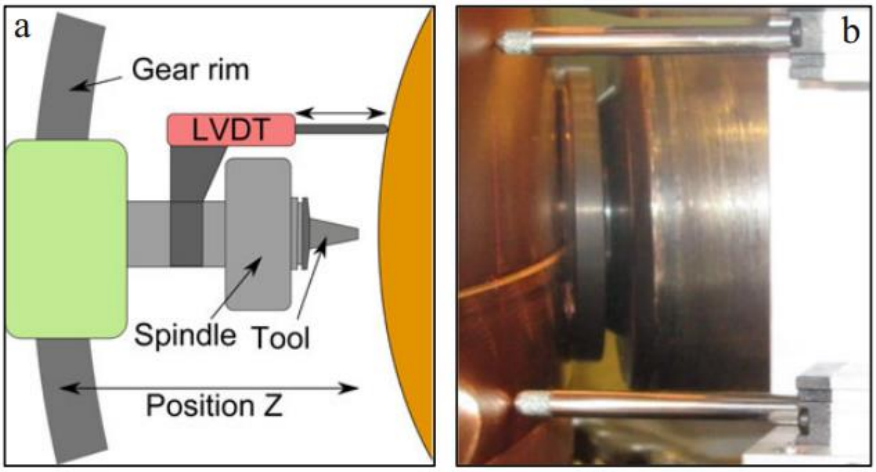

Figure 3-1: a) Configuration of depth sensor; b) 2 Linear differential transformers

The real immersion depth is determined by comparison of the trace of welding tool shoulder which has remained after contact with the welded material, measured by the depth sensors.

The depth sensor makes use of axial force for manipulation with the depth of welding tool immersion. The laser sensors are used as the feedback signals for the controllers.

Experimental results have proved that at application of auxiliary devices (sensors, probes) and a correct setting of immersion depth of welding tool the occurrence of defects like lack of root fusion and excessive flash has drastically reduced [3-8, 3-17].

3.1.2. Temperature control in welding by FSW process

The heat supplied to welded material and the resultant welding temperature can be controlled by adjusting the welding parameters. One of possibilities consists in reduction of: downward force, revolutions of welding tool and welding speed. The factors which may affect the welding temperature and thus also the quality of welded joint involve thickness of welded material, preheating of welded material, ambient temperature, type of support plate material, clamping and the wear of welding tool. The temperature control is especially important for welding materials of intricate shape and with different heat removal. Higher temperature during welding process will result in better plasticizing of material welded.

A rapid drop of strength occurs at increasing temperature in the case of heat-treated alloys. The main issue in strength drop consists in estimation of friction coefficient between the tool and welded material. Due this reason, different auxiliary devices for measurement of temperature during welding were tested. The Tool – Workpiece - Thermocouple (TWT) technique is one of methods serving for measuring the temperature during welding.

The thermocouples used in TWT method are inserted into the welding tool in shoulder vicinity. Though this method is very precise, it necessitates drilling of small openings to welding tool. The thermocouples must be inserted into the holes manually what causes that this method is not suitable for the automated production. By increased downward force we can reduce the time of pin penetration, but it will also cause lower temperature in time when the shoulder hits the material welded. This results in greater distortion of material welded. Welding in the weld joint line is started just at the moment when the desirable temperature is attained.

The temperature is measured by use of a thermo-electric signal between the tool and material welded. The TWT method offers an accurate temperature measurement under the tool shoulder and in the vicinity of tool fringe. It can be used for controlling the immersion depth of welding tool and welding process control as well. Figure 3-2 shows: The thermal boundary between the welding tool made of steel and welded materials of Al alloy (A). Thermo-electric potentials between the tool and welded material (B.C). The recorded difference in voltage (D).

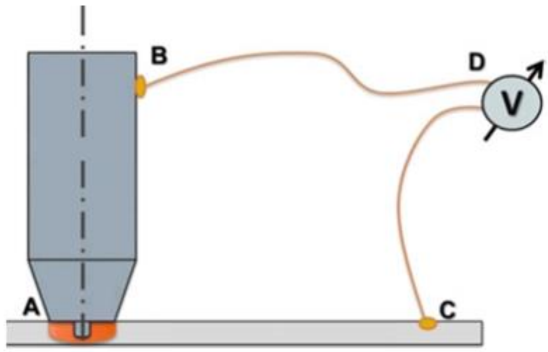

Figure 3-2: Setup for calibration of the temperature measurement method [3-18]

The thermal feedback of measurement performed by TWT method can be applied for the control of diverse aspects in FSW process as for example the immersion of welding tool.

The temperature regulator was successfully implemented for the control of downward force and adjustment of immersion depth of the welding tool. Rotation speed of spindle is used as a control parameter for the regulator. In welding of diverse shapes of material welded, inconstant heat removal is observed.

Another way enhancing fabrication of quality welds consists in temperature measurement by the aid of wireless data transfer. The thermocouples are inserted into the welding tool together with the wireless system for data transfer. The thermocouples should be situated in such a manner that they would be as close as possible to the boundary between the welded material and welding tool. Two through openings 0.8 mm in diameter were made by use of electro spark machining. One 7.1 mm deep opening was made in the shoulder and is spaced by 3.4 mm from the outer fringe of the shoulder. Another opening 17 mm deep is situated in the pin and it is 1.2 mm from the bottom part of the pin. Both through openings are in the same angular position. Schematic representation of distribution of thermocouples is shown in Fig. 3b). The thermocouples type K are mostly used for measurement. After inserting thermocouples into the through openings they were fixed by use of a thermo-metallic cement. Maximum working temperature of this cement is 1426 °C. The cases of thermocouples are in direct contact with the material welded. The thermo-metallic cement is not used between the thermocouple and welded material. Owing to high revolution speed of welding tool, the data transfer to the control system is performed via wireless transfer.

The wireless data transfer is used for transfer of temperature measurement in real time. The system is capable to perform 7 to 12 temperature measurements per one revolution of welding tool. Figure 3-3 (a) shows the tool holder for FSW process [3-6, 3-7, 3-18, 3-20].

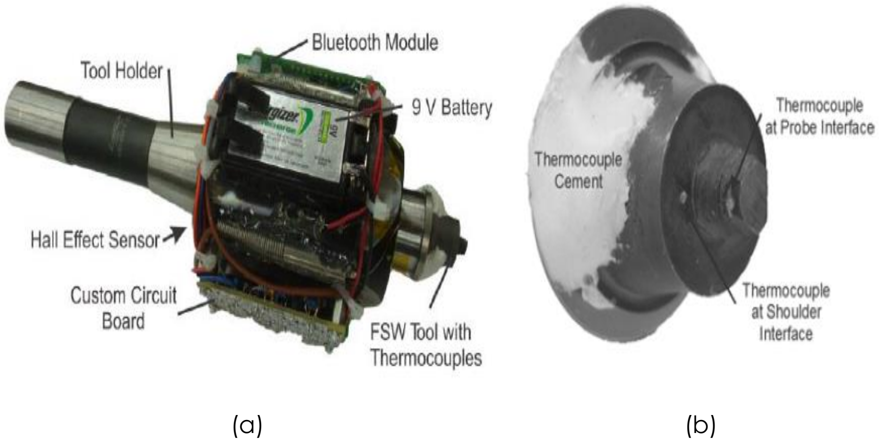

Figure 3-3: (a) Tool holder for FSW process distribution of thermocouples; (b) Detailed distribution of thermocouples [3-20]

3.2. Hybrid welding methods (HFSW)

The so-called hybrid welding processed (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 sources are: GTAW, laser beam, plasma beam, high-frequency heating, induction heating and ultrasound. These methods prolong the life of welding tools and allow a better plasticizing of material welded [3-14, 3-16].

3.2.1. Hybrid auxiliary equipment (GTAW, P-FSW, USE-FSW, TSW)

These technologies omit all issues related with the fusion of parent metals. Figure 3-4 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 3-4: HFSW equipment with participation of a GTAW heat source [3-16]

At application of a hybrid welding with plasma arc assistance (P-FSW) it is possible to weld dissimilar materials, regardless their different chemical 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 a 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 the P-FSW process is shown in Figure 3-5 [3-15].

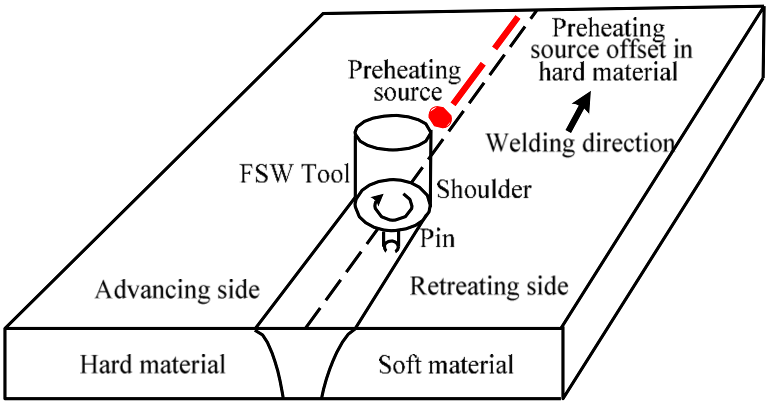

Figure 3-5: Basic principle of plasma-assisted friction stir welding of dissimilar joint [3-15]

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. This process has exerted positive effect upon the resultant microstructure and mechanical properties of welded joint. The principle of welding by USE-FSW technology is shown in Figure 3-6.

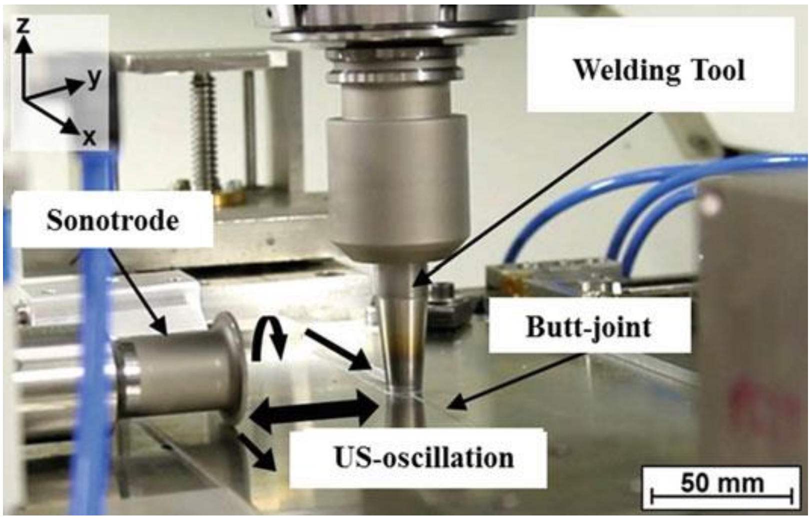

Figure 3-6: Welding by use of USE-FSW hybrid technology [3-21]

After performing the metallographic tests of welded joints fabricated by use of USE-FSW process, there was observed lower occurrence of intermetallic phases on the boundary between the stir zone (nugget) and the thermomechanical 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 [3-21].

Another method applied in FSW process makes use of induction coil as an auxiliary equipment. The induction coil serves for a uniform preheating of welded material. The tool is extremely loaded during welding the materials with a high melting point.

A modified FSW process, called as Thermal Stir Welding (TSW) was developed with the aim to regulate the temperature during welding of materials with high melting point, prolonging thus the life of welding tool. In TSW process (Figure 3-7), the heat source – induction coil is guided ahead the rotating welding tool. The induction coil uniformly preheats the welded material, reducing thus the load imposed upon the welding tool.

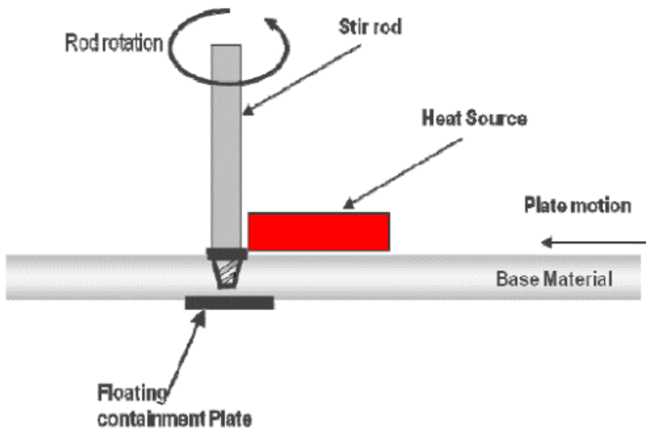

Figure 3-7: TSW terminology showing the tool during a weld

It is well known that the rate of welding force changes non-linearly with increasing welding speed. This means that the heat propagation ahead the tool is reduced. The induction coil will guarantee the maintaining of constant temperature in material welded [3-5, 3-19].

It can be surely stated that the hybrid processes (with auxiliary equipment) are suitable means for achieving sound welded joints and prolonging the life of welding tools [3-9, 3-16].

3.3. Problems Occurring in FSW

As well known the FSW technology is a modification of friction welding, where all defects occurring in the welded joints fabricated by the fusion welding processes, including laser and other processes making use of concentrated power sources, are absent. The most frequent defects, as the hot cracking and porosity, do not occur in FSW technology, since this concerns the joining process realised in solid state. Naturally, as in the case of all welding technologies, the insufficient supervision during welding process may result in occurrence of different problems.

3.3.1. Most common basic problems of FSW during the process and action to solve those problems

The main welding parameters in welding by FSW process include the welding speed and revolutions of welding tool. These welding parameters may cause either sufficient or insufficient heat supply necessary for plasticizing of welded material. Determination of suitable welding parameters is closely related with the issues occurring during welding process. The defects formed during welding process are classified to inner and surface ones. The surface defects, which may be observed also by a naked eye include excessive material formation – flash, surface groove along the welding line and the worn out/damaged welding tool.

These defects may be detected during welding process. The inner defects, which cannot be observed by a naked eye (during the welding process) include insufficiently stirred root – kissing bond, subsurface voids and cracks may be detected just by the destructive inspection techniques after completed welding process. These defects are in details described in the Chapter 4.2.

At the initial penetration of welding tool into welded material, the forcing out of welded plates from the clamping mechanism may occur, what results in undesirable gap which will cause the non-uniform stirring. In the case of such an issue, it is necessary to adjust the immersion depth of welding tool and/or the speed of its penetration into materials welded.

At a slow speed of welding tool penetration into welded materials these will be sufficiently plasticized, what will result in the fact that the welded materials will not separate from each other. Also, poor clamping of welded plates may cause the distortion of materials proper. In most cases it is sufficient to tighten the loosened clamping bolts of jigs serving for fastening the welded materials on the welding support (table).

Another undesirable issue which may occur during welding process consists in the damage of welding tool. The welding tool may collide with the clamping support of welded materials during welding process. Therefore, it is inevitable to pay due attention to correct placing of clamping supports of materials welded in the welding line direction.

Opposite case may result in the damage of geometry in welding tool, clamping support and/or welded material proper. The wear of welding tool may affect the welding speed and revolutions of welding tool.

At insufficient welding speed and revolutions of welding tool the welded material is packed up on the welding tool what results in insufficiently stirred materials welded. Therefore, it is necessary to remove the packed up material from the welding tool either by mechanical or chemical cleaning. However, in both cases an undesirable material wear is concerned [3-1, 3-2, 3-12].

A frequent non-conformity occurring during welding process consists in the fact that the welding tool will force out redundant amount of welded material on the surface, by which it is then deprived. This defect is designated as excessive flash (Fig. 3-8). The main cause of excessive flash formation consists in excessive immersion of welding tool in the material thickness direction. This imperfection may be corrected by a suitable setting of inclination angle of welding tool. This issue may be eliminated also during the welding process proper.

In the case when redundant amount of welded material is forced out on the surface it is sufficient to shift the welding tool axially in upward direction. The redundant material can be easily removed by machine milling. The welded joint with excessive flash exerts an undesirable appearance, though the strength properties may be in several cases acceptable.

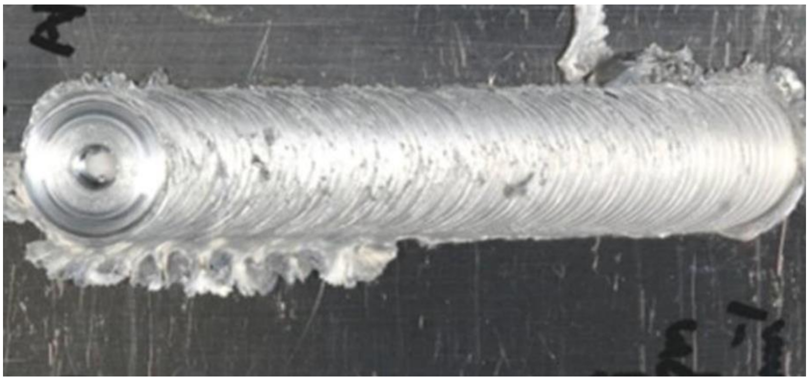

Figure 3-8: Welded joint with excessive flash [3-22]

If too high welding speed is set, an issue in the form of insufficiently stirred welded material may occur. Such an issue is presented by formation of a continuous groove – channel on the surface of material welded. In such a case it is necessary to adjust the welding parameters, mainly the welding speed and to use a suitable geometry of welding tool [3-3, 3-4, 3-22].

Another issue consists in the fact that an imprint of welding tool remains on the material welded. This issue is solved by adding of a splice plate – another piece of material to which the welding tool will pass from the welded materials during welding process.

After weld fabrication the splice plate will be removed by cutting away from the materials welded. High temperatures are generated during welding of steel materials what may result in material sticking on the welding support (table).

In order to eliminate such an issue a continuous layer of powder preventing the adhesive sticking (for example the PCBN powder) is deposited on the welding support.

Similarly, as in the case of all welding technologies also during the FSW process the SHPW (Safety and Health Protection at Work) must not be neglected. In the case of violating the SWPH precautions the following dangers may threaten cutting, skin burning, harm to eyes and face.

Fabrication of a sound welded joint, either by the aid of an auxiliary equipment or without and preventing the mentioned issues is possible only by optimizing the welding parameters [3-11, 3-12, 3-13].

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4. Post Processing

The advantage of welding by use of FSW process with set optimum welding parameters, when compared to classical welding processes, consists in the fact that at the end of welding process none further operations as grinding, cleaning etc. are necessary. Also heat treatment after welding is unnecessary, since the ultimate tensile strength of welded joint exerts even higher value than the base metal. In the quality inspection of welded joint after its fabrication the visual inspection is first performed.

4.1. Visual Inspection

The visual inspection of welded joint is necessary to be performed during entire welding process. As already mentioned in Chapter 3.3.1, it is possible to avoid the defects as excessive flash, welding tool wear and groove formation along the welding line already during the welding process. Prior to welding process, it is also necessary to inspect visually the correct clamping of welded plates and welding tool. In case of insufficient visual inspection prior to welding process and during welding, different imperfections and defects may occur. The graphical scheme shown in Fig 4-1 explains the dependence of temperature generation in welding process on the welding speed and revolutions of welding tool.

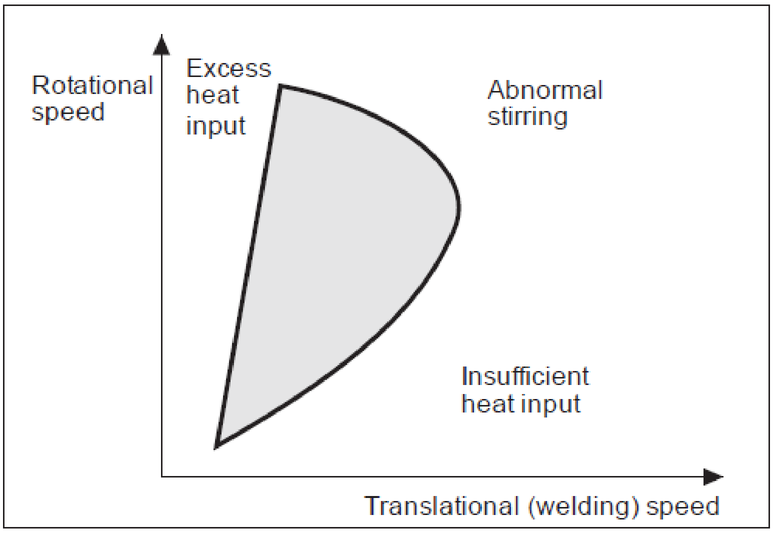

Figure 4-1: The range of suitable parameters for welding by FSW process [4-14]

It can be generally said that there exists a range (envelope) of combinations of these basic parameters which guarantee sound welded joints. Beyond this range, which is warranting the quality of welded joints, both inner and surface defect may be formed [4-1, 4-2, 4-13, 4-14].

4.2. Imperfections and Defects

The surface imperfections and defects are described in Chapter 3.3.1. The Chapter 4.3. depicts the imperfections and defects which cannot be seen by a naked eye during welding process but can be observed just after the end of welding process. The detection of imperfections and defects necessitates the application of destructive inspection techniques. The most frequent destructive methods used for assessment of inner defects in welded joints include: tensile test, bend test, micro-hardness measurement and micro and macro structural analyses [4-3, 4-4, 4-11, 4-12,].

4.3. Causes of imperfections/defects

The heat generated during welding by FSW process tends to create the conditions causing the micro-structural transformation as: recrystallization, grain growth and dissolution of precipitates. Such microstructural transformations occur at different temperatures for different materials and depend on the chemical composition of materials welded.

In the case if not sufficient heat needed for plasticizing of welded material is supplied to welding process, the defects called voids are formed in welded joints. The presence of voids in welded joint is a common imperfection. The dynamics of liquids related with material plasticizing in welded joint plays a key role in void formation. Though the higher welding speed enhance the productivity of welded joints, too high welding speeds lead to void formation under the surface of welded joint or on the advancing side at the weld fringe. The welded joint formed under cold conditions – too fast heat removal (at a high welding speed) becomes microscopically hard and thus poor quality – brittle welded joint may be obtained. In welding process, when the welding tool progresses along the welding line, the plasticized material is transferred around the welding tool gradually layer by layer. In order to maintain sufficient heat inevitable for welding, it is necessary to reduce the welding speed, resulting in better plasticizing of welded material. The experimental results have shown, that the zone where voids had occurred (Fig. 4-2) was significantly extended with increasing welding speed. It was also proved that with increasing diameter of shoulder a greater heat volume enters the process, what results in better plasticizing of material and thus the occurrence of voids in welded joints can be prevented [4-8, 4-10, 4-12, 4-15].

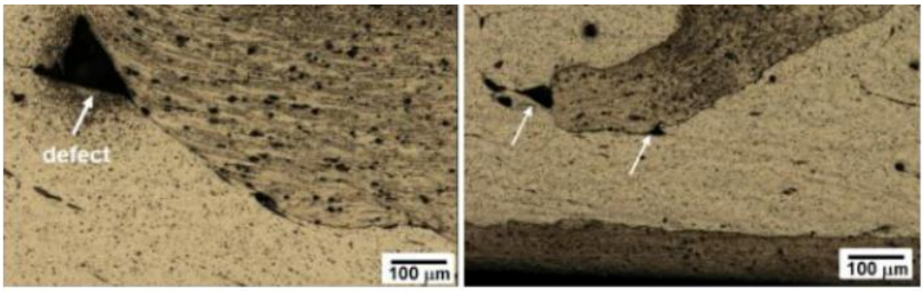

Figure 4-2: Defect of stir zone [4-15]

Another issue within the inner defects consist in insufficiently stirred root. This defect is designated as the kissing bond. The key role in formation of root defects [Fig. 4-3] is played by the process parameters. These defects are formed due to insufficient heat supply and/or due to incomplete decomposition of surface oxide layers. Other reason for defect formation may consist in improperly selected pin length and its immersion depth in relation to welded material thickness. At smaller inclination angles of welding tool, insufficient plasticizing of welded material in its entire thickness may occur, leading to lack of fusion in the root layer. It can be thus said that the small and also large inclination angles of welding tool significantly contribute to formation of root defects. Such defects are considered for unacceptable due to lower strength of welded joint, mainly under e dynamic loading. It is very hard to detect such defects even by the aid of non-destructive techniques.

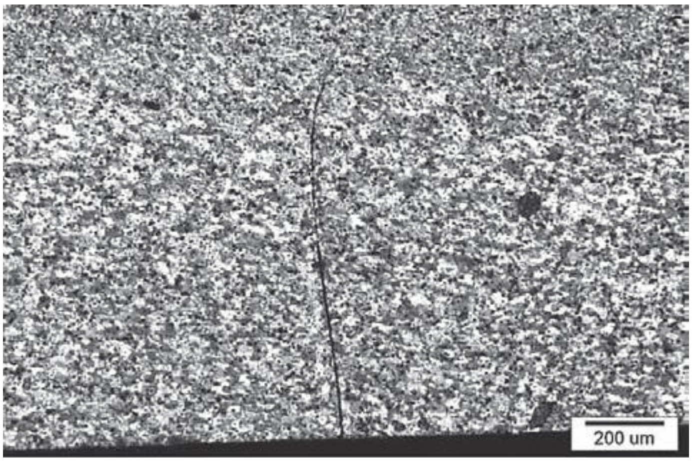

Figure 4-3: Microstructure of welded joint with lack of root fusion made of Al alloy type 5083 [4-15]

In the case of welding Al alloys at high welding speeds and low revolutions of welding tool a partial disruption of the natural Al2O3 layer may occur, restricting thus the plasticizing of materials welded. The fragments of Al2O3 particles will form a continuous undulated defect line in material thickness direction. In contrary, at high revolutions of welding tool sufficient heat input is supplied, enhancing thus a correct stirring of material welded with wide-spread distribution of particles. The average grain size in the stir zone decreases with increasing welding speed and/or decreasing revolution speed of welding tool. The controlled revolution speed of welding tool allows to supress significantly the occurrence of undulated line defects. It was experimentally proved, that a crack which initiated from the weld root through the undulated defect line caused the rupture of welded joint during tensile test [4-5, 4-6, 4-7, 4-9, 4-15].

It can be thus said, that an efficient and correct selection of welding parameters for FSW process eliminates the formation of above-mentioned defects, what significantly contributes to improvement of mechanical properties in welded joints [4-1, 4-2, 4-13].

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5. Health & Safety

Friction Stir Welding (FSW) is a process risk friendly, as there are no major hazards related to it. FSW is described as being friendly to welders and to our environment. By not having liberation of gases, not using of gases, neither having radiations associated (like ultraviolet, infrared and visible light) FSW is a much safer process when compared to other welding processes. Although, this welding process has a high safety ratio, there are still some hazards and health and safety policies that should be considered [5-15].

5.1. Health and Safety Plan (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.

Before handling the machinery, the operator must be aligned with the Safety Regulations for the machinery he/she operates. For that the operator must be presented with a Health & Safety Plan. Such Plan must include the following items [5-6]–[5-7]:

- Company Health and Safety rules and goals
  - ✓ Context
  - ✓ Purpose
  - ✓ Organization
  - ✓ Policy
- Management Plan
  - ✓ Legal Requirements
  - ✓ Administrative Requirements
  - ✓ Accident Reporting and Investigation
  - ✓ Roles and Responsibilities
- Risk and Hazards Identification and Assessment
- Appointments
- Basic Emergency Procedures
- Industrial Regulation

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. General Health and Safety measures

Some Health and Safety measures are harmonized worldwide and applicable to several industries. Below there is a list of different generalized measures to be considered, separated by topics.

Main employer duties:

- ✓ Making 'assessments of risk' to the health and safety of its workforce, and to act upon risks that were identified;
- ✓ Appointing competent persons to oversee workplace health and safety;
- ✓ Providing workers with information and training on occupational health and safety;
- ✓ Operating a written health and safety policy.

Workplace:

- ✓ Adequate lighting, heating, ventilation and workspace (and keep them in a clean condition);
- ✓ Staff facilities, including toilets, washing facilities and refreshment; and
- ✓ Safe passageways, i.e. to prevent slipping and tripping hazards;
- ✓ Health and safety regular simulacrums.

Personnel Protective Equipment (PPE):

- ✓ Ensure that suitable PPE is provided free of charge, wherever there are risks to health and safety that cannot be adequately controlled in other ways.
- ✓ Provide information, training and instruction for the use of the PPE provided.

Manual Handling Operations:

- ✓ Avoid (so far as is reasonably practicable) the need for employees to undertake any manual handling activities involving risk of injury;
- ✓ Make assessments of manual handling risks and try to reduce the risk of injury. The assessment should consider the task, the load and the individual's personal characteristics (physical strength, etc.);
- ✓ Provide workers with information on the weight of each load.

Use and provision of work equipment:

- ✓ Ensure the safety and suitability of work equipment for the purpose for which it is provided;
- ✓ Properly maintain the equipment, and substitute/repair when needed;
- ✓ Provide information, instruction and training on the use of equipment;
- ✓ Protect employees from dangerous parts of machinery.

Reporting injuries or illness:

- ✓ Death of any person;
- ✓ Specified injuries including fractures, amputations, eye injuries, injuries from electric shock, and acute illness requiring removal to hospital or immediate medical attention;
- ✓ 'Over-seven-day' injuries, which involve relieving someone of their normal work for more than seven days as a result of injury caused by an accident at work;

Reportable occupational diseases:

- ✓ Cramp of the hand or forearm due to repetitive movement;
- ✓ Carpal tunnel syndrome, involving hand-held vibrating tools;
- ✓ Asthma;
- ✓ Tendonitis or tenosynovitis (types of tendon injury);
- ✓ Hand-arm vibration syndrome (HAVS), including where the person's work involves regular use of percussive or vibrating tools; and
- ✓ Occupational dermatitis;

Working Time:

- ✓ A 48-hour maximum working week averaged for a maximum of 17 weeks. Employers have a contractual obligation not to require a worker to work more than an average 48-hour week (unless the worker has opted out of this on the workers contract);
- ✓ minimum daily rest periods of 11 hours, unless shift-working arrangements have been made that comply with the Regulations;
- ✓ An uninterrupted 20-minute daily rest break after six hours' work, to be taken during, rather than at the start or end of the working time.
- ✓ Employers have the right to ask their staff to enter into a written agreement to opt out of the 48-hour limit, for a specific period or indefinitely. However, if such an agreement is opted into, a worker is entitled to bring the agreement to an end without the employer's consent. [5-7]; [5-8]; [5-9]; [5-10]; [5-11]; [5-12]

5.3. Specific Health and Safety measures for FSW

FSW is an operator friendly process, as the risk associated to it is very low. While using FSW there is nil production of fumes, gases, etc. Furthermore, radiations like ultraviolet, infrared and visible light which are mostly produced in arc welding, laser welding, soldering, and torch welding are not produced in FSW.

Although, the risk is low there are still Health and Safety measures for FSW. Those measures can be divided into two distinct groups: Built in Machine Safety Features and General Operator's Cautions.

On one hand, we have safety features related with the control of the robotic system incorporated on the machinery. These features aim to reduce the risks of the operator while conducting his work. 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].

The machine can be equipped with multiple sensors to collect different information which will be used to control the equipment through an embedded control solution. By applying load control, excessive loads and loss of contact between FSW tool and work pieces are prevented. As a result, the damage of the components involved in the process (FSW tool, machine, work pieces, etc.) is reduced and worker safety is guaranteed [5-14].

On the other hand, besides the 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 [5-2].

5.4. Causes of Risks & Accidents

In an industrial environment there are several causes that lead to accidents. While FSW is a technique that is risk friendly there are still some actions/lack of actions that may lead to accidents. Most of these actions are common to all industry processes and some major examples are listed as follows.

- ✓ Bad assessment of workers capabilities.
- ✓ Operator poorly informed of risks for operating the machine.
- ✓ Inadequate machinery training.
- ✓ Operator does not comply with health and safety measures.
- ✓ Workplace is not in conformity with Health and Safety requirements.
- ✓ Operator behaves carelessly when operating with the equipment.
- ✓ Operator exceeds safety recommended work hours.
- ✓ Operator violates procedure.
- ✓ Lack of monitoring and supervision.
- ✓ Management pressure on operator to meet production targets.
- ✓ Communication issues (e.g. between shifts, between personnel and management).
- ✓ Tests and inspections not carried out properly.
- ✓ Inappropriate factory layout, without considering risk assessment.
- ✓ Inadequate maintenance of machinery.
- ✓ Programmed maintenance skipped.
- ✓ Defects on safety system.
- ✓ Inappropriate conduction of safety test.
- ✓ Inadequate control and monitoring of the machinery.
- ✓ Defects on machinery not identified on quality measurements procedures.
- ✓ Inadequate risk assessment plan.
- ✓ Failure to learn lessons from past incidents. [5-13]

5.5. Measures to prevent or minimize risks

Risk assessment is one of the most relevant aspects to take into consideration when developing a safety plan. Only by conducting a proper risk analysis we can further engage into developing measures to mitigate the risk/ defining contingency strategies.

Risk mitigation concerns to risk prevention measures, so that the probability of occurring a risk is reduced. On the other hand, risk contingency concerns with defining steps/actions to take upon the occurrence of a risk, so that the impact is minimized.

While considering FSW technology, risk mitigation processes are most likely to occur as it is a technology that operates under a low risk policy and takes advantage of a robotic control system. Furthermore, some contingency plans must also be considered as procedures to be taken after a risk occurs.

A proper risk identification is crucial to this process, so that the risk measures can be well defined and applied.

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 [3].

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.

5.6. Risks associated to FSW and associated accidents

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. Furthermore, the hazards also 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.

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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. Backing 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.

6.2. Tolerances for backing plate

Weld joint gap of 10 % of the weld thickness “T” is tolerable before the weld quality is affected. According to requirements of NASA PRC-0014D allowable joint gap is 0,4 mm, regardless to weld thickness. 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.

Backing plate should be in an absolute plane. Tolerances of the wavy surface of backing plate are limited to 0,1 mm. Backing plate should be on the same leves as the weld table so that there are no mismatches between the parts being welded.

6.3. 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.

6.4. Tolerances for probe/pin/tool

Three different tolerances are possible for FSW tool:

- Main tilt angle φ – between the ideal vertical axis of tool rotation z and actual axis of rotation (this angle shall be nominally > 0°), figure 6-1 a.)
- Side tilt angle ψ – between the ideal vertical axis of tool rotation z and tool orientation according to x axis (this angle shall be nominal 0°), figure 6-1 b.)
- Tool (pin) lateral offset y -between the ideal weld seam (gap) between two workpieces and actual longitudinal path of the tool, figure 6-2.

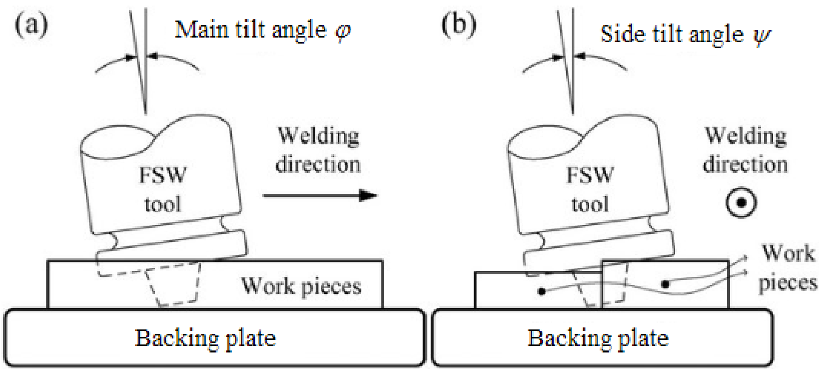

Figure 6-1: Main tilt angle φ and side tilt angle ψ of FSW tool

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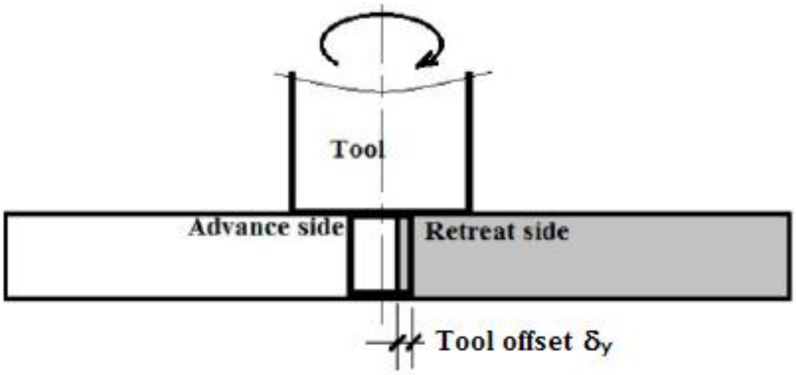

Figure 6-2: Tool (pin) lateral offset δ_y of FSW tool

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.
– Depending of the FSW process parameters and the tool geometry, sound welds can be obtained by tolerances of main tilt angle ± 1°, side tilt angle ± 2° and lateral offset ± 2 mm.

6.5. Clamping/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.

6.6. Tolerances for clamping/positioning devices

Clamping plays a key role in counteracting welding distortions during FSW. Moving clamps closer to the weld centreline increases this effect. The increasing clamping force limits distortion, but above a certain threshold has diminishing returns. The distortion is in close connection with the tolerances of workpiece. 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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7. Quality

Different destructive and non-destructive examinations are applicable to examine quality of FSW weld joints. Extent of these examinations and acceptance criteria depends on the FSW manufacturing standard used. All requirements regarding acceptance criteria of FSW weld joint are currently valid only for aluminium alloys. Test specimens and procedures for performing of destructive and non-destructive examinations are presented in established testing standards for fusion welding.

7.1. Destructive testing (DT)

7.1.1. Standards for destructive testing of FSW

Destructive testing of welded joints in FSW is connected with the qualification of welding procedures (WPQR) and with qualification of welding operators. Majority of the commercial applications of FSW involve aluminium and aluminium alloys. Main standards that include destructive testing of FSW weld joints are:

- ISO 25239-4:2011 Friction stir welding – Aluminium – Specification and qualification of welding procedures
- AWS D17.3/D17.3M:2016 Specification for Friction Stir Welding of Aluminum Alloys for Aerospace Applications
- ABS Guide for the approval of friction stir welding in aluminium (2011)
- NASA PRC-0014D (2012) Process Specification for Friction Stir Welding
- NKK (ClassNK) Guidelines on Friction Stir Welding (2010)

Butt weld joints represent more than 85 % of all welds, produced by FSW process. Lap weld joints are appropriate only for thin sheet. Welds of tubes/pipes are butt weld joints. ABS Guide gives requirements only for butt weld joint.

7.1.2. Destructive tests

Extent of destructive tests on FSW weld joints depends on type of standard that is used for qualification of FSW (procedures and/or welding operators) and on type of weld joint (butt or lap). Tables 1 and 2 show number of test specimens depending of qualification standard.

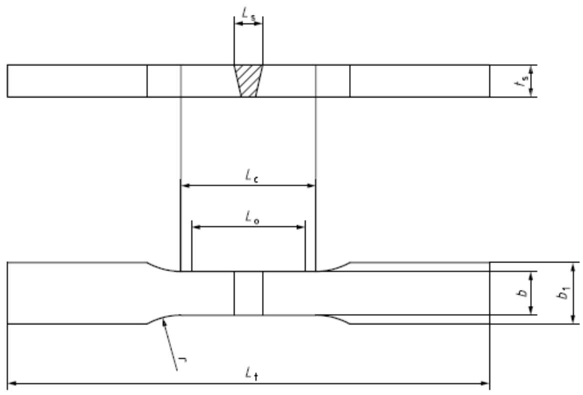
Table 7-1: Extent of destructive tests on FSW butt weld joints (no. of specimens)

Type of testing	ISO 25239-4	AWS D17.3	ABS	NASA	ClassNK
Transverse tensile test	2	4	3	5	2
Transverse bend test (wrought materials)	2 (root) 2 (face)	/	3 (root) 3 (face)	2 (root) 2 (face)	2 (root) 2 (face)
Fracture test (cast materials)	2 (root) 2 (face)	/	/	/	/
Macroscopic examination	1	2	3	2	1
Microscopic examination	/	/	/	/	1

Table 7-2: Extent of destructive tests on FSW lap weld joints

Type of testing	ISO 25239-4	AWS D17.3
Macroscopic examination	2 specimens	2 specimens
Shear test	If required	2 specimens

<u>Transverse tensile testing of butt weld joints in plate and sheet:</u> All test specimen shall be prepared according to EN ISO 4136. Figure 3 show dimensions of test specimen. Note that parallel length L_c for aluminum alloys and copper alloys shall be minimum $L_c > L_s + 100$ *[mm]*, where L_s is width of weld face.



Denomination	Symbol	Dimensions
Total length of the test specimen	L_t	to suit particular testing machine
Width of shoulder	b_1	$b + 12$
Width of the parallel length	b	12 for $t_s \leqslant 2$ 25 for $t_s > 2$
Parallel length [a]	L_c	$\geqslant L_s + 60$
Radius at shoulder	r	$\geqslant 25$
[a] For some other metallic materials (e.g. aluminium, copper and their alloys) $L_c \geqslant L_s + 100$ may be necessary.		

Figure 7-1: Dimensions of test specimen for transverse tensile test

<u>Transverse bend testing of butt weld joints in plate and sheet:</u> All test specimen shall be prepared according to EN ISO 5173. The advancing and retreating sides of the test specimens shall be marked prior to testing.

<u>Fracture testing of butt joints in plate:</u> This test is carried out only for FSW welding of butt welds on Al-alloy castings or combination between Al-alloy castings and wrought materials. Test is performed through the weld face and weld root. Test specimens shall be prepared according to EN ISO 9017.

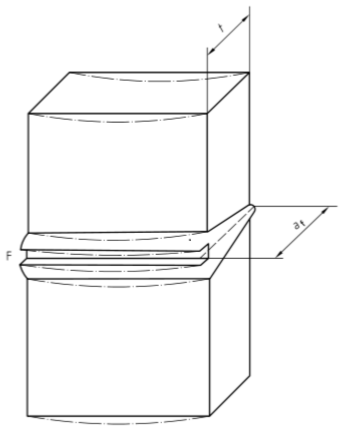


Figure 7-2: Preparation of test specimen for fracture test of butt weld

Fracture tests may be carried out by dynamic strokes with hammer, with bending machine or by applying load with a tension. The fracture surface shall be examined visually in accordance with EN ISO 17637. For clear detection and identification of imperfections a low magnifying glass (up to 5×) may be used.

Shear (tension-shear) testing of lap joints in sheet: It is necessary to provide the single-lap test specimens with packing pieces in the grip regions in order to balance the offset axes of the lapped details and minimize bending effects. Figure 5 show test specimens for performing shear test on lap weld joints.

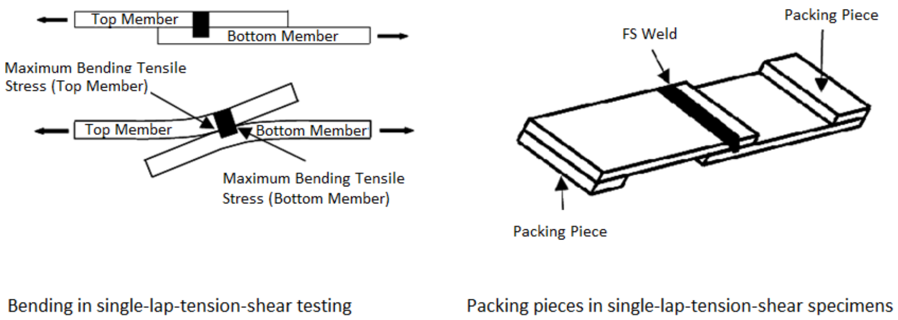


Figure 7-3: Test specimen for shear test of lap weld

Macroscopic examination (ME) of butt and lap joints: The test specimen shall be prepared and examined in accordance with EN ISO 17639 on one side to clearly reveal the weld region. The macroscopic examination shall include unaffected parent material. Macrostructure examination is to include about 10 mm of unaffected base material and heat-affected zone (HAZ).

Microscopic examination (ME) of butt joints: The test specimen shall be prepared and examined in accordance with EN ISO 17639. Microphotographs are to be taken in the center of the stirring part (welded metal), heat process affected part, heat-affected zone (HAZ) and base material at their respective positions in the joint cross section, to check that there is no abnormal re-crystallized grain coarsening.

7.1.3. Special destructive testing methods

These methods can be used as supplementary to standard destructive test methods. Some of methods are used for more stringent requirements applied to FSW weld joints.

<u>Fracture toughness testing of butt weld joints:</u> This test method is expensive and is justified only when the highest requirements for mechanical properties of FSW weld joint is expected. Results of fracture toughness tests can generate fracture mechanics information, such as fatigue crack growth data (*da/dN*), using the compact tension specimen (CT). The notch may be aligned with any direction of interest. to generate region-specific data. The ultimate information from these testing is size of fracture toughness K_{IC} *[MPa* $\sqrt{m}$*]* and plot of stress intensity factor ΔK versus crack growth rate *da/dN*. Figure 6 show standard compact tension specimen (CT).

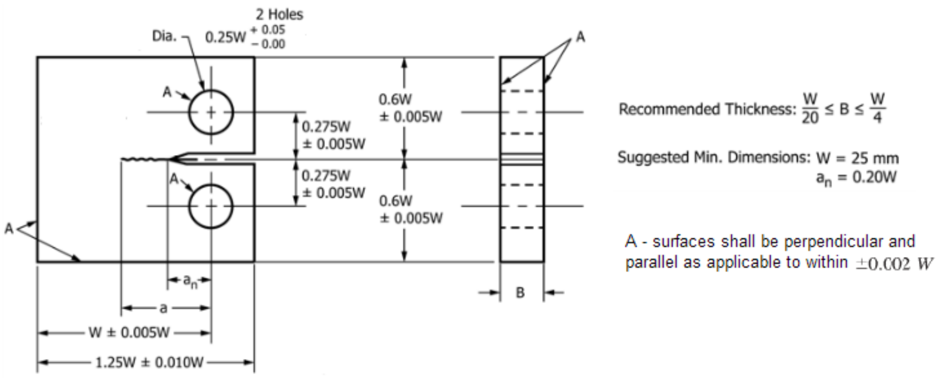


Figure 7-4: Standard CT specimen for performing fracture toughness testing

Orientation of test specimen notches can be arbitrary, but for practical testing only three orientations are important: along the HAZ, along the weld metal (WM) and transverse to weld joint (figure 7).

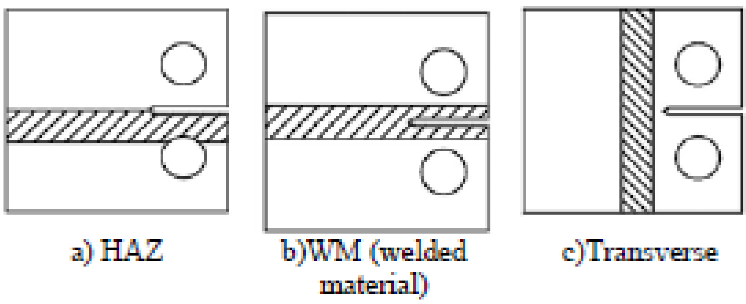


Figure 7-5: Notches orientations at fracture toughness testing of FSW weld joints

<u>Hardness testing:</u> This supplementary examination is more appropriate for steel, nickel alloys and titanium alloys. However, it can be carried out also on Al-alloys, but it is not mandatory according to international standards for FSW. For Al-alloys and Mg-alloys microhardness testing is more appropriate. Standard EN ISO 9015-1 shall be used when perform hardness testing on FSW weld joints on steel and nickel alloys.

Microhardness (usually HV 1) shall be done in accordance with EN ISO 9015-2.

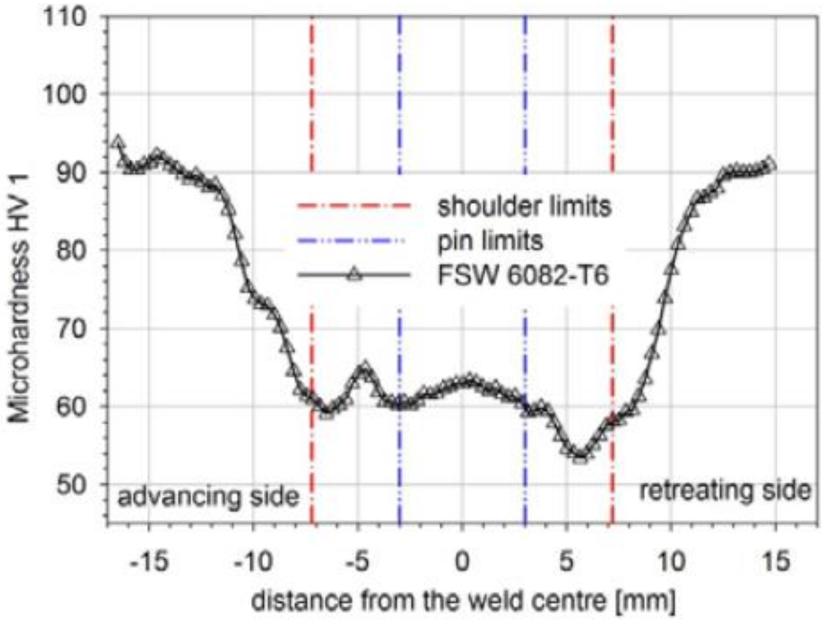


Figure 7-6: Microhardness profile (HV 1) for FSW weld joint on aluminium alloy AA6082-T6

Advantages and disadvantages of destructive testing methods

Advantages of destructive tests on aluminium alloys can be beneficial for determination mechanical properties of FSW weld joints, most notably transverse tensile test due to lower tensile strength of weld metal.

The primary disadvantage of destructive testing is that an actual section of a weldment must be destroyed to evaluate the weld. This type of testing is usually used in the qualification process for welding procedures and for welding operators. For production welding it is necessary to perform destructive tests on periodic intervals for maintain weld quality.

7.1.4. Importance of destructive testing

Application of destructive testing of FSW weld joints include welding procedure qualifications (WPQR), welding operator qualification testing, sampling inspection of production welds, research inspection and failure analysis work. Methods of destructive testing of weld joints are used to determine weld joint integrity or performance.

7.2. Non-destructive testing

7.2.1. Standards for NDT of FSW

Depending on applicable international/national standards for FSW qualification (ISO, AWS, ABS, NASA), methods for NDT are applied as they are specified in these standards. AWS D17.3 and ABS Guide require execution of NDT examinations in accordance with relevant ASTM standards. On the other hand, NASA specification require execution of NDT examinations in accordance with relevant NASA specifications. ISO 25239 series require application of relevant ISO standards for NDT examinations.

<u>Penetrant testing (PT), method:</u>

– EN ISO 3452-1:2013 – Penetrant Testing – General principles
– ASTM E1417-16 – Standard Practice for Liquid Penetrant Testing
– NASA PRC-6506E (2011) – Process Specification for Liquid Penetrant Inspection

<u>Radiographic testing (RT), method:</u>

– EN ISO 17636-1:2013 – Radiographic testing-X- and gamma ray techniques with film
– EN ISO 17636-2:2013 – Radiographic testing-X- and gamma ray techniques with DDA
– ASTM E1742-18 – Standard Practice for Radiographic Examination
– NASA PRC-6503D (2011) – Process Specification for Radiographic Inspection

<u>Ultrasonic testing (UT), method:</u>

– EN ISO 17640:2017 – Ultrasonic Testing-Techniques, testing levels, and assessment
– ASTM E164-13 – Standard Practice for Contact Ultrasonic Testing of Weldments
– NASA PRC-6510A (2011) – Process Specification for Ultrasonic Inspection of Welds

<u>Phased array ultrasonic testing (PA-UT), method:</u>

– EN ISO 13588:2012 – Ultrasonic testing - Use of automated phased array technology
– ASTM E2700-14 – Standard Practice for Contact Ultrasonic Testing of Welds Using Phased Arrays

<u>Eddy current testing (ET), method:</u>

– EN ISO 17643:2015 Eddy current examination of welds by complex plane
– ASTM E2261-17 Standard Practice for Examination of Welds Using AC Current Fields Measurement Technique
– NASA PRC-6509D (2011) Process Specification for Eddy Current Inspection

7.2.2. Non-destructive tests

Liquid penetrant testing (PT): This is widely applied, and low-cost inspection method used to locate surface breaking imperfections in all non-porous materials (metals, plastics, ceramics). PT is based upon the capillary action, where low surface tension fluid (dye) penetrates into clean and dry surface-breaking discontinuities. After adequate penetration time has been allowed, the excess penetrant is removed, and a developer is applied. The developer helps to draw penetrant out of the imperfection where indication becomes visible to the inspector. Testing is performed under ultraviolet (UV) or white light, depending upon the type of the dye used – fluorescent or non-fluorescent (visible).

Surface preparation for PT of FSW weld joints in Al-alloys: PT testing is unacceptable in as-welded condition due to poor detection and excessive background noise produced by surface. Prior to PT inspection, the surfaces to be inspected shall be sanded or etched to remove a minimum of material, but at least 0.025 mm using a sanding or etching process.

Radiographic testing (RT): It is used widely in the examination of castings and weld joints, particular where there is a critical need to ensure freedom from internal (volumetric) imperfections. For Al-alloys less than 6 mm thick, radiographic testing (RT with X-rays) utilizing Class 1 film and aluminium IQIs may be substituted for UT in discretion of the UT Level III personnel.

Ultrasonic examination (UT): It uses high frequency sound energy to conduct examinations and make measurements. UT examination enables detecting internal imperfections which do not come up to the surface. UT can be applied for testing joints on one side. In practice, both single (back-echo) and phased-array transducers are used. It is possible to apply various surface scanning methods. FSW welds are examined with sector scan (UT pulse-echo), which can create different inspection angles with the same probe and alloy inspection of complex shape parts, the volume coverage can also be accomplished with focused beams. The UT procedure shall include an attenuation check between the FSW weld joint and the parent material using a two-transducer shear wave pitch-catch arrangement. Any measured increase in attenuation noted in the FSW weld material shall be compensated for by adding the appropriate number of dB to the instrument after calibration on the weld calibration block.

7.2.3. Special NDT Methods

Phased array-Ultrasonic examination (PA-UT): This method provides linear scan with full coverage of weld bead, which can cover the weld joint in one-line pass. Its advantages over conventional ultrasonic inspections come from the use of multiple wave generating elements and the ability to focus and stir the ultrasonic beam without movement of the probe, while the images are formed by constructive interference. The PA-UT inspections can be performed from the tool side (opposite to the discontinuity side) using a linear array of 8 - 128 elements, creating waves 0,5-18 MHz frequency. The wedge and array assembly are able to generate a beam spread between 40° and 70° in the tested part. The colour intensity is proportional to the reflected signal amplitude and, consequently, to the lack of penetration (LOP) size.

Eddy current testing (ET): This inspection use the principle of electromagnetism as the basis for conducting examinations, eddy currents are created through electromagnetic induction. When alternating current (AC) is applied to the conductor (copper wire), a magnetic field develops in and around conductor. If another conductor is brought into close proximity to changing magnetic field, current will be induced in this second conductor. Eddy currents are induced electrical currents that flow in circular path. In the presence of imperfection, the flow of eddy currents is disturbed, creating a perturbation in the magnetic field at the surface of the examined part. The frequency of AC used to induce the eddy currents and the electrical conductivity of the material being inspected determines the depth and penetration of the eddy current field and the resulting depth of the examination. ET testing is a surface and near-surface method due to limited penetration of the eddy currents in the depth.

7.2.4. Advantages and Disadvantages of NDT methods

Table 7-3: List of advantages and disadvantages of NDT methods for FSW:

NDT	Advantages	Disadvantages
PT	- Inexpensive - Sensitive - Minimal equipment - Application to irregular shapes - Versatile - Minimal training	- Non-porous surfaces only - Detection of surface imperfections only - Ventilation requirements - Messy
RT	- Sensitive to finding imperfections throughout the volume of materials - Easily understood permanent record - Full volumetric examination - Portability	- Radiation hazard - Relatively inexpensive - Long set-up time - Necessary access to both sides of the weld joint - Depth of indication not shown - High degree of skill required for xecution and interpretation of results
UT	- Fast method - Only single-sided access is required - Full volumetric examination - Minimal part preparation is required - Instanteneous results - Detailed images can be produced automatically - Permanent record - Can be used for thickness measurements	- Surface must be accessible and smooth - Test results depend on the operators experience - Location of an imperfection in relation to a wave affects imperfection detectability - Interpretation can be difficult - Need for reference standards and calibration blocks - Difficulty with complex geometries of weld joints - Mandatory use of couplant - Not allowed UT examination in area of previous PT inspection

NDT	Advantages	Disadvantages
ET	- Fast - Inspection is done in one pass - Full coverage of the weld joint - C-scan imaging for easy interpretation - Easy to operate - Automation available - Permanent record available - Specimen contact not necessary	- Manual surface testing is slow - Interpratation may be difficult - Depth of penetration is limited - Imperfection orientation is critical - Specimen must be electrical conductive - Sensitive to many specimen parameters - Surface roughness can produce non-relevant indications

7.2.5. Importance of NDT

Nondestructive testing (NDT) methods of inspection make it possible to verify compliance to the standards on an ongoing basis by examining the surface and subsurface of the weld joint and surrounding base material. Majority of the failures are attributed to improper design of weld joint, residual stresses, inspection procedures and operating parameters. One way to minimize the failures of welded components is to impart NDT procedures immediately after the fabrication to make sure the welded joint is defect-free and during the service life of welded components to ensure that no unacceptable imperfections are present and grow.

7.3. Acceptance criteria

7.3.1. Acceptance criteria for DT in accordance with EN ISO 25239-4/5

Transverse tensile test: Ultimate tensile strength of the test specimen from aluminium and aluminium alloys shall not be less than the corresponding specified minimum value $\sigma_{min,\ pm}$ of the parent material required in the relevant international standard (EN, ISO, ASTM). For heat-treatable Al-alloys, the specified tensile strength $\sigma_{min,\ w}$ of the welded test specimen in the post-weld condition shall satisfy the minimum requirement:

$$\sigma_{min,w} = \sigma_{min,pm} \times f_e$$

$$where: \begin{cases} \sigma_{min,pm} - specified\ minimum\ tensile\ strength\ of\ the\ parent \\ \qquad material\ [MPa] \\ f_e - joint\ efficiency\ factor\ \text{(Figure 7-4)} \end{cases}$$

For combinations of different aluminium alloys, the lower $\sigma_{min,w}$ value of the two alloys shall be required. Note that values of the joint efficiency factor are used for all types of aluminium alloys, welded with FSW.

Table 7-4: Efficiency for tensile strength of butt joints

Material type	Temper condition of parent material before welding[a,b]	Postweld condition	Joint efficiency factor f_e
Pure aluminium	All temper conditions	As welded	1,0[d]
Non-heat-treatable alloys	All temper conditions	As welded	1,0[d]
Heat-treatable alloys	T4	Natural ageing[c]	0,7
	T4	Artificial ageing[c]	0,7[e]
	T5 and T6	Natural ageing[c]	0,6
	T5 and T6	Artificial ageing[c]	0,7[e]

[a] Refer to ISO 2107.

[b] For parent material in tempers not shown, $\sigma_{min,w}$ shall be in accordance with the design specification.

[c] Ageing conditions shall be in accordance with the design specification.

[d] Irrespective of the actual parent material temper used for the test, $\sigma_{min,pm}$ is based on the specified minimum tensile strength of the "O" condition.

[e] Higher properties can be achieved if a full postweld heat treatment is applied; $\sigma_{min,w}$ shall be in accordance with the design specification.

Transverse bend testing: For all Al-alloy parent materials, the minimum bend angle shall be 150°, using the calculated maximum former diameter *d* based upon the parent material minimum elongation *A* as (for *A* > 5 %):

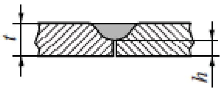
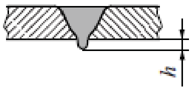
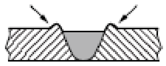
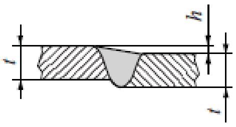
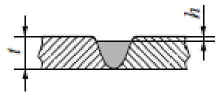
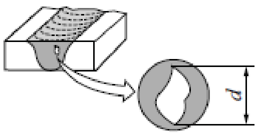
$$d = \frac{100 \times t_s}{A} - t_s$$

t_s – thickness of the bend test specimen (this includes side bends) [mm]

For an elongation of *Al-alloys A* ≤ 5 %, annealing shall be carried out before testing. The former diameter shall be calculated with the elongation given by the specified "O" temper conditions. If the bend tests fail due to grain growth that occurred during the annealing process, additional bend tests shall be performed. During testing, the test specimens shall not reveal any single crack > 3 mm in any direction.

Macroscopic examination (ME): Macroscopic examination before etching shall reveal no cracks. Care should be taken when etching certain alloys to avoid producing false indications. The specimens are to be examined by eye or low-powered (5x – 50x) lens for any indications. The acceptance levels of ISO 25239-5, Annex A, shall apply (see Figure 7-5). Other imperfections shall be within the specified limits of the relevant requirements or the design specification.

Table 7-5: Imperfections, testing and examination, acceptance levels according to ISO 25239-5

Designation of imperfection	Remarks	Testing and examination in ISO 25239-4[a]	Acceptance levels[a]	Reference number in ISO 6520-1[3]
Surface imperfections				
Incomplete penetration		ME	Not permitted	—[c]
Excess penetration		VT, ME	$h \leq 3$ mm	504
Toe flash		VT, ME	—[b]	—[c]
Linear misalignment		VT, ME	$h \leq 0{,}2t$ or 2 mm, whichever is less	507
Underfill		VT, ME	$h \leq 0{,}2$ mm $+ 0{,}1t$ for $t \geq 2$ mm: $h \leq 0{,}15t$ for $t < 2$ mm	—[c]
Irregular width	Excessive variation in width of the weld	VT	—[b]	513
Irregular surface	Excessive surface roughness	VT	—[b]	514
Internal imperfections				
Cavity		ME	$d \leq 0{,}2s$ or 4 mm, whichever is less	200
Hook		ME	—[b]	—[c]

Symbols and abbreviated terms

d maximum transverse cross-sectional dimension of cavity (mm)

h height of an imperfection (mm)

s nominal butt weld thickness (penetration) (mm)

t nominal thickness of the parent material (mm)

ME macroscopic examination

VT visual testing

[a] When required, non-destructive testing should be carried out in accordance with ISO 3452-1 (penetrant inspection), ISO 17636 (radiographic testing) and ISO 17640 (ultrasonic examination). Testing and examination of other imperfections and their acceptance levels shall be in accordance with the relevant requirements or the design specification.

[b] Acceptance levels shall be within the specified limit of the relevant requirements or the design specification.

[c] See ISO 25239-1.

7.3.2. Acceptance criteria for DT in accordance with AWS D17.3

General requirements: The dimension of any indication shall be defined by its largest dimension. Two or more indications shall be treated as one when the spacing between them is less than the largest dimension of the larger indication. Indications that will be removed in subsequent machining shall not be a cause for rejection.

Any weld with unacceptable indications, which has gone through a subsequent manufacturing operation that affects the metallurgical characteristics (other than stress relief or post-weld heat treatment) or that cannot be re-welded without affecting the final metallurgical or surface characteristics, shall be rejected. Removal of unacceptable weld metal is allowed, provided the minimum weld size is met.

Shear testing of lap joints: Shear strength of lap weld joint test specimen shall not be less than 60 % of the minimum specified tensile strength of the parent (base) material $\sigma_{min,pm}$.

Macroscopic examination (ME): The macroscopic test specimens shall meet the requirements of Table 7-6 at magnification no greater than 50x, except where partial joint penetration weld joints are specified in the Referencing Document.

Table 7-6: Acceptance criteria according to AWS D17.3

Indication	Class A	Class B	Class C
Cracks	None	None	None
Incomplete joint penetration[b]	None	None	None
Inclusions			
a. Individual size (maximum)	.33T or 0.06 in [1.5 mm], whichever is less	0.50T or 0.09 in [2.3 mm], whichever is less	Not applicable
b. Spacing (minimum)	Four times the size of the larger adjacent discontinuity	Two times the size of the larger adjacent discontinuity	Not applicable
c. Accumulated length in any 3 in [76 mm] of weld (maximum)	1.33T or 0.24 in [6.1 mm], whichever is less	1.33T or 0.24 in [6.1 mm], whichever is less	Not applicable
Internal cavity, or cavity open to surface	None	None	Reject only cavities open to the surface
Linear mismatch across joint (maximum) Butt welds only	1.05 times the base metal thickness tolerance	1.075 times the base metal thickness tolerance	Not applicable
Overlap (cold lap)	a	a	a
Angular distortion (degrees) (maximum) Butt welds only	3 degrees	3 degrees	Not applicable
Underfill (maximum) Applies only if the weld face will not be postweld machined			
a. For the full length of the weld (maximum depth)	0.05T	0.075T	0.10T
b. Individual defect (maximum depth)	0.07T or 0.03 in [0.76 mm], whichever is less	0.10T or 0.03 in [0.76 mm], whichever is less	0.125T or 0.03 in [0.76 mm], whichever is less
c. Accumulated length in any 3 in of weld (maximum)	0.20 in [5.1 mm]	0.60 in [15 mm]	1.0 in [25 mm]
Weld flash (maximum height)	a	a	a

a) When required, all flash, overlapping metal, or other protruding metal along the edges of the weld shall be removed after VT, but before other NDT examinations.

b) Acceptance criteria of incomplete joint penetration does not apply to partial joint penetration welds.

7.3.3. Acceptance criteria for DT in accordance with ABS Guides

Transverse tensile test: Ultimate tensile strength U_{al} of the test specimen from aluminium alloys series 5000 and 6000 shall not be less than those required in 2-5-A1/Table 2 in ABS Rules for Materials and Welding Part 2 – Aluminium and Fibre Reinforced Plastics (FRP).

Macroscopic examination (ME): The macroscopic specimens are to be examined by eye or low-powered (5x) lens for any imperfections, including porosity, lack of bonding, joint line remnant, inadequate penetration greater than 0.8 mm or 10% of the thickness of the weld, whichever is less, or lack of one central nugget. If a macroscopic test fails, the FSW manufacturer shall investigate production welds back to the previously accepted macroscopic test.

7.3.4. Acceptance criteria for NDT testing according to ISO 25239-5

When radiographic testing (RT) of lap joints or partial-penetration butt welds is required, the design specification shall determine the acceptance levels. When immersion ultrasonic examination (UT) or phased-array ultrasonic examination (PA-UT) is used, the design specification or relevant requirements shall determine the applicable standards or requirements. For ET examinations relevant requirements or design specifications shall be used for determination of acceptance levels because this method is used when stringent requirements for weld integrity are required.

Applicable standards for determination of NDT acceptance criteria of Al-alloys (applicable level shall be determined when design of FSW weld joints is carried out):

- EN ISO 23277:2015 – NDT of welds-Penetrant testing – Acceptance levels
- EN ISO 10675-2:2017 – NDT of welds-Acceptance levels for radiographic testing-Aluminium and its alloys
- EN ISO 11666:2018 – NDT of welds-Ultrasonic testing – Acceptance levels
- EN ISO 19285:2017 – NDT of welds – Phased array ultrasonic testing (PA-UT)-Acceptance levels

7.3.5. Acceptance criteria according to NKK (Class NK) Guidelines

Visual testing (VT): Welded surface shall be regular, uniform and free from cracks, undercuts and overlaps. Burrs that are caused by grinding are not to be treated as an imperfection. The assessment of imperfections shall satisfy the requirements for Quality level B according to ISO 10042 (as applicable only for aluminium and copper alloys).

NDT examinations: The result of NDT examinations shall perform that in FSW weld there are no cracks, lack of penetration (LOP), lack of fusion and other severe imperfections. The assessment of imperfections shall satisfy the requirements for Quality level B according to ISO 10042 (as applicable only for aluminium and copper alloys)

7.3.6. Acceptance criteria according to NASA PRC-0014D

Visual testing (VT): The designation „T" mean the nominal base material thickness of the thinnest component in the weld joint. In addition, the term "weld length" shall be the distance from end to end of the weld deposit or to a sharp change in direction of the weld where the angle of change in any direction is greater than 30° at a radius of < 12 mm. Weld concavity depth (face and root) shall not exceed that specified in Table 7. This requirement shall not apply where the weld is specified to be machined to the extent of being indistinguishable from the adjacent base metal. Weld joint misalignment shall not exceed that specified in Table 7. Weld surface finish (roughness) shall not exceed 3,2 μm. This requirement shall not apply where the weld is specified to be machined to the extent of being indistinguishable from the adjacent base material.

Table 7-7: Weld concavity depth limits and weld misalignment limits (whichever value is less)

Weld class	Concavity depth [mm]	Misalignment [mm]
Class A	0,5 or 10% of T	0,25 or 10 % of T
Class B	0,75 or 15 % of T	0,5 or 15% of T
Class C	1,1 or 20% of T	0,63 or 20% of T

NDT examinations: Weld indications exceeding the maximum allowable sizes for the applicable Class in Table 8 shall not be allowed. Linear indications shall be defined as having a length to width ratio of 3:1. Rounded indications shall be defined as having a length to width ratio 3:1. A crack shall be defined as a fracture type indication characterized by a sharp tip and a high ratio of length to width. For base material thicknesses (T) ≥ 3 mm, the following shall apply to Table 7-8. Class A - Any indication, except cracks and linear indications < 0.25 mm at its greatest dimension, shall not be considered.

- Class B - Any indication, except cracks and linear indications < 0,8 mm at its greatest dimension, shall not be considered.
- Class C - Any indication, except cracks and linear indications < 1,6 mm at its greatest dimension, shall not be considered.

Table 7-8: Maximum allowable indication sizes

Type of indication	Class A	Class B	Class C
Cracks in the weld or base material (1) (Includes surface tearing)	None allowed	None allowed	None allowed
Incomplete penetration and incomplete fusion(1) (Includes wormholes, residual oxide layers, joint line remnant, and lack of adequate forging)	None allowed	0,63 mm or 0.3T, whichever is less	2,4 mm or 0.6T, whichever is less
Linear (1)	None allowed	0,8 mm or 0.4T in length, whichever is less (3) Sum of all visible indications shall be 9,5 mm or T in length, whichever is less, in any 25 mm of weld length and < 19 mm in any 300 mm of weld length (4)	1,6 mm or 0.6T in length, whichever is less (3) Sum of all visible indications shall be 12,5 mm in length, in any 25 mm of weld length and < 45 mm in any 300 mm of weld length (4)
Rounded (1)	Surface 0,63 mm or 0.3T diameter D, whichever is less (2)	2,4 mm or 0.4T diameter, whichever is less (2) Sum of all visible indications shall be 9,5 mm or 1,5T in length, whichever is less, in any 25 mm of weld length and < 19 mm in any 300 mm of weld length (4)	3,2 mm or 0.6T diameter, whichever is less (2) Sum of all visible indications shall be 12,5 mm in length, in any 25 mm of weld length and < 45 mm in any 300 mm of weld length (4)

(1) For all indications approaching a free edge (see Figure 9 below) that are being considered, the closest edge of the indication shall have clearance from the free edge C ≥ 3X the largest of its dimensions or, C ≥ 2X the nominal weld throat, whichever is greater.
(2) Adjacent rounded indications separated by ≤ 1X the length of the longest dimension of the larger indication shall be considered a single indication.
(3) Adjacent linear indications separated by ≤ 3X the length of the longest dimension of the smaller indication, shall be considered a single indication.
(4) For weld lengths less than 300 mm, the total sum of indications shall be an equivalent proportion of the weld length, to that given.

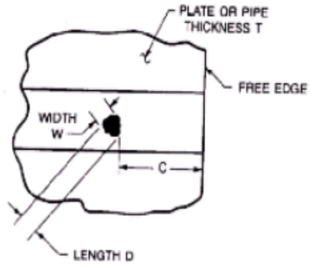


Figure 7-7: Clearance spacing (C) between closest edge of indication and free edge

7.4. Equipment Calibration

Meters, gages, and dials installed on automatic, mechanized, or robotic welding apparatus shall be calibrated using an established procedure. The manufacturer shall establish and document applicable calibration procedures.

7.5. References

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[7-7] T. Santos, P. Vilaça, L. Quintino: Developments in NDT for Detecting Imperfections in Friction Stir Welds in Aluminium Alloys, Welding in the World (2008), 52:30-37, also document IIW-1866-07

[7-8] C. Mandache, D. Levesque, L. Dubourg, P. Gougeon: Non-destructive detection of lack of penetration defects in friction stir welds, Science and Technology of Welding and Joining (2012), 17:295-303

[7-9] V. Rubtsov, S. Tarasov, E. Kolubaev, S. Psakhie: Ultrasonic Phase Array and Eddy Current Methods for Diagnostics of Flaws in Friction Stir Welds, International Conference on Physical Mesomechanics of Multilevel Systems 2014, AIP Conf. Proc. 1623, 539-542 (2014)

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8. Coordination

Welding coordination in FSW welding includes qualification of welding operators and activities connected with contractual obligations between manufacturer and customer. Typically, qualification of welding operators depends on which standard is used for qualification. FSW welding process is mechanized and from this point of view range of essential variables in qualification of welding operators is larger than in fusion welding. Up to now, only qualifications in FSW welding of aluminium alloys are developed and used in practice. Manufacturing plan / Inspection and testing plan (ITP) are essential part of tasks which rely on welding coordinator for FSW.

8.1. Standards for certification/qualification of welding personnel

The majority of the commercial applications of FSW involve aluminium and aluminium alloys, and so existing standards for certification and qualification of welding personnel (operators) deals only with this metal:

– ISO 25239-3:2011 Friction stir welding – Aluminium – Qualification of welding operators
– AWS D17.3/D17.3M:2016 Specification for Friction Stir Welding of Aluminium Alloys for Aerospace Applications
– ABS Guide for the approval of FSW in aluminium
– NASA PRC-0014D (2012) Process Specification for Friction Stir Welding

8.1.1. Welding operator qualification according to EN ISO 25239-5

Welding operator shall be qualified by one of the following tests and qualification methods:

– standard welding test
– welding procedure test
– pre-production welding test or production welding test
– production welding sample test

In addition, the welding operator's knowledge of the welding unit to be used for the qualification test shall be tested. Any of the welding operator qualification tests can be supplemented by a test of knowledge related to welding technology. Such a test is recommended, but it is not mandatory.

<u>Qualification methods:</u>

a) <u>Qualification based on standard welding test</u>: The following test piece shall be used for the standard welding test. A welding operator who has successfully completed the welding test shall be considered qualified for the method and type of welding machine used for the test.

b) Qualification based on welding procedure test: A welding operator shall have successfully completed a welding procedure test in accordance with ISO 25239-4, Clause 6, to be considered qualified for the method and type of welding machine used.
c) Qualification based on pre-production welding test or production welding test: A welding operator shall have successfully completed a pre-production welding test in accordance with ISO 25239-4, Clause 7 or a production welding test, to be considered qualified for the FSW method and type of welding machine used for the test.
d) Qualification based on production welding sample test: A production part shall be considered qualified if representative samples of the items that are produced are approved by the examiner or the examining body. This testing of production samples shall be in accordance with the requirements of ISO 25239-3 or the requirements of the contracting parties, whichever is more stringent.

Testing and acceptance levels of test welds

a) VT testing: shall be carried out in accordance with ISO 25239-4. The weld shall have an as-welded surface and shall be free of cracks or cavities. The weld width shall not show any variations due to insufficient tool pressure. If a full penetration weld is specified, then there shall be no incomplete penetration.
b) Bend test: Shall be performed in accordance with ISO 25239-4. Two face and two root bend test specimens shall be taken from the test weld. For material over 12 mm thick, four side bend test specimens may be substituted for the face bend and root bend test specimens. During testing, the test specimens shall not reveal any single crack > 3 mm in any direction.
c) Macroscopic examination (MA): One test specimen for shall be taken from the test weld. The acceptance levels shall be as specified in ISO 25239-5, Annex A.
d) NDT: 100 % tested with an appropriate non-destructive volumetric testing method (RT or UT), when bend test is not performed.

Period of validity

a) Initial qualification: The welding operator's qualification is valid from the date of welding of the test pieces, provided the required tests have been carried out and acceptable test results are available. The welding operator's qualification test certificate is valid for a period of 2 years, the period of validity ending on the last day of the month.
b) Confirmation of the validity: The welding coordinator or the person responsible from the employer shall confirm that the welding operator has been working within the initial range of qualification. This shall be confirmed every 6 months. If such a confirmation is not given and the qualification expires, the welding operator shall be required to pass a new qualification test before resuming welding.
c) Prolongation of the qualification: The welding operator's qualification test certificates can be prolonged every 2 years by an examiner or examining body. Before prolongation of the

certification takes place, the specifications of confirmation of validity shall be satisfied and the following conditions shall be confirmed:

- all records and evidence used to support prolongation shall be traceable to the welding operator and shall identify the WPS(s) used in production;
- evidence used to support prolongation shall be of a volumetric nature (RT or UT) or, for destructive testing (bend or fracture), shall have been made on two welds during the previous 6 months - evidence relating to prolongation shall be retained for a minimum of 2 years;
- welds satisfy the acceptance levels for imperfections specified for test welds.

8.1.2. Welding operator qualification according to AWS D17.3

To become qualified, the welding operator shall demonstrate their skill by producing an acceptable test weld in accordance with an approved WPS. Qualifications, certifications, re-qualifications, and re-certifications do not transfer from one manufacturer to another.

Vision test: The welding operator shall have vision acuity of 20/30 or better in either eye and shall be able to read the Jaeger No. 2 Eye Chart at 400 mm. Corrected or uncorrected vision may be used to achieve eye test requirements. Vision shall be tested to these requirements at least every 2 years.

Test weld: The test piece shall be welded in accordance with a WPS. The operator being qualified shall verify all aspects of the weld that would normally be required to make the weld in the production operation, in accordance with the WPS. When none of the test piece described above are applicable to a given production weld, then a special welding operator qualification that is limited to the specific application may be achieved with a test piece consisting of the given production weld or a test weld representative of the given production weld.

Qualification/certification validity:

- Initial certification: Successful completion of welding operator qualification tests shall be justification for issuance of a certification valid for a period of 2 years from the acceptance date of the qualification test results.
- Extended certification: A welding operator's certification may be extended indefinitely, provided an auditable record is maintained from the date of the initial qualification that verifies the welding operator has used the process within the previous 6-month period and adheres to the 2-year vision test requirement.
- Identification: The manufacturer shall assign a unique number or other identification to each welding operator upon certification.

8.1.3. Welding operator qualification according to ABS Guide for the approval of FSW in aluminium

The FSW manufacturer shall perform the destructive and NDT tests for FSW welding operator qualification test pieces. The operator qualification test piece size shall be the same as for welding procedure qualification test (WPQR). The size of the test piece shall be sufficient to permit removal of the required test specimens from the nominal start, middle, and end of the weld joint.

Requirements for mechanical properties of the weld joint:

a) Transverse tensile testing: The tensile strength of each specimen, when it breaks in the weld, is not to be less than the minimum specified tensile strength of the parent material $\sigma_{min,pm}$. When broken in the parent material and the weld shows no signs of failure, is not to be less than 95 % of the minimum specified tensile strength of the parent material.
b) Bend testing: Guided bend tests after bending shall not show any cracking or other open defect exceeding 1,6 mm.

8.1.4. Welding operator qualification according to NASA PRC-0014D

Welding operator shall be qualified and certified in accordance with AMS-STD-1595. Sufficiently detailed records shall be maintained to demonstrate continuity of operator performance on the welding system (machine tool) or systems on a semi-annual (6 month) basis. These records shall be made available to the NASA/JSC M&P organization upon request. A Welding Operator Performance Qualification (WOPQ) is certified documentation which ensure, that a welding operator has been tested in accordance with the requirements of NASA PRC-0014D and shown competent to produce a sound weld for a specific welding process/base material/base material thickness combination. WOPQ records shall show the limits of the operator qualification.

8.2. Process constraints and limitations

8.2.1. Limitations of welding operator qualification according to EN ISO 25239-5

The qualification of welding operators is based on essential variables. For each essential variable, a range of qualification is defined. If a welding operator is required to weld outside the range of qualification, then a new qualification test is required. FSW is a mechanized process. However, because it is also a solid-state welding process, the essential variables are different from those applicable to fusion welding processes.

FSW methods: A successful welding operator qualification test made with any type of FSW method qualifies an operator only for that welding method. This applies to FSW methods that include, but are not limited to, robotic, single spindle, multiple spindle, bobbin tool, retractable probe, or any other FSW method defined in the WPS used for that qualification test.

Parent materials: A successful test weld made in any aluminium alloy qualifies an operator for all aluminium alloys. A successful test weld of any parent material thickness qualifies an operator for all parent material thicknesses. A successful test weld of any parent material form (sheet, plate, tube, castings, forgings or extrusions) qualifies an operator for all parent material forms and for all tube diameters.

Weld joint geometry: A successful test weld made in any weld joint geometry qualifies an operator for all weld joint geometries.

Welding equipment: The following changes require a new qualification

- Change from welding with a joint sensor to welding without, although welding without a joint sensor also qualifies an operator to weld with a joint sensor.
- Change from one type of welding machine to another type of welding machine that requires additional training to operate - a test made with any type of machine qualifies only that type of machine, although the addition or removal of jigs and fixtures, feeding units and other ancillary equipment does not change the type of machine.
- Addition, removal or change of control system.

8.2.2. Limitations of welding operator qualification according to AWS D17.3

FSW methods: A test weld made with any type of FSW method qualifies only for that FSW method.

Parent materials: A test weld made in any aluminium alloy qualifies for all aluminium alloys. A test weld made with any parent material thickness shall qualify the welding operator to weld any parent material thickness. A successful qualification of any test weld qualifies the welding operator to weld all material forms (plate or pipe) and joint types.

Weld type: A successful qualification of a special welding operator qualification test weld qualifies the welding operator to weld that particular production weld joint.

8.2.3. Limitations of welding operator qualification according to ABS

FSW methods: Shall indicate whether fixed-probe or self-reacting/ bobbin or adjustable probe/retractable pin mode is employed.

Parent materials: Qualifying an FSW welding operator with one 5000 or 6000 series Al-alloys with thickness *T* qualifies that operator to weld all 5000 or 6000 series parent materials 2/3*T* to 4*T* of the original test within the requirements of ABS Guide. Series 5000 do not cover series 6000 of Al-alloys and vice versa.

Weld joint: Joint type used in qualification testing with allowable range ± 1 mm.

Thickness range: Specific thickness used in qualification test with allowable range ± 5 %.

Travel speed: Specific speed used in qualification test with allowable range ± 5 %.

Tool rotational speed: Setting used in qualification test with allowable range ± 5 %.

Process load forces: Setting used in qualification test with allowable range ± 10 %.

8.3. Contract requirements typical items

Drawing information requirements: The engineering drawing shall show the form, shape and dimensions of a weld joint. Welding symbols shall be in accordance with ISO 2553. Special conditions shall be fully explained by adding notes or details on the engineering drawing.

Essential information for all welds on aluminium and Al-alloys:

- aluminium alloy type and its temper at the time of welding
- weld joint preparation not defined in WPS
- final weld contour and weld finishing requirements (as-welded or subsequently finished)
- weld classification (class of weld joint, e.g. according to AWS D17.3, NASA PRC-0014)
- post-weld heat treatment (PWHT), if required
- mechanical properties (static tensile strength, fatigue strength, fracture toughness, microhardness)
- corrosion properties (stress corrosion cracking resistance, general corrosion resistance requirements)
- extent of NDT examinations on weldments

8.4. Subcontracting activities

8.4.1. Rules for subcontracting

When a manufacturer intends to use subcontracted services or activities (e.g. welding, inspection, NDT inspection, heat treatment), information necessary to meet applicable requirements shall be supplied by the manufacturer to the subcontractor. The subcontractor shall provide such records and documentation of his work as may be specified by the manufacturer. A subcontractor shall work under the order and responsibility of the manufacturer and shall fully comply with the relevant requirements. The manufacturer shall ensure that the subcontractor can comply with the quality requirements as specified. The information to be provided by the manufacturer to the subcontractor shall include all relevant data from the review of requirements and the technical review. Additional requirements may be specified as necessary to assure sub-contractor compliance with technical requirements.

Review of requirements:
- the product standard to be used, together with any supplementary requirements.
- statutory and regulatory requirements
- any additional requirement determined by the manufacturer
- the capability of the manufacturer to meet the prescribed requirements/contract.

Technical review:
- parent material specification and weld joint properties
- quality and acceptance criteria for welds
- location and sequence of welds, including accessibility for inspection and for NDT
- welding procedure specifications (WPS), NDT procedures and heat treatment procedures

8.4.2. Standards referring to subcontracting

Standards for fusion welding shall be applied also for FSW, since up to now there is currently no international standards which deals with quality requirements for FSW in terms of quality assurance/quality control for welding production:
- EN ISO 3834-2:2005 Quality requirements for fusion welding of metallic materials - Comprehensive quality requirements
- EN ISO 3834-3:2005 Quality requirements for fusion welding of metallic materials – Standard quality requirements

8.5. Work management principles

8.5.1. Communication

The manufacturer/fabricator shall determine the internal and external communications relevant to the quality management system, including:
- on what it will communicate,
- when to communicate,
- with whom to communicate,
- how to communicate,
- who communicates.

8.5.2. Risk management

A risk is a positive or negative deviation from the expected. Addressing a risk could mean pursuing a new opportunity. Organizations are required during planning of their Quality Management Systems (QMS) to address both risks and opportunities. Opportunities can include the adoption of new customers, products, technology or practices. The ISO

9001:2015 around risks and opportunities do not require a formal risk management system. However, it does require that manufacturer determine what they are and how they will be addressed. When evaluating risk, it is helpful to use two parameters:
- severity (if the risk occurs, how serious is it),
- probability (what is the probability of the risk occurring).

8.6. Manufacturing plan

8.6.1. Planning for production

The manufacturer shall carry out adequate production planning. Items to be considered shall include at least:
- specification of the sequence by which the construction shall be manufactured (e.g. as single parts or sub-assemblies, and the order of subsequent final assembly);
- identification of the individual processes required to manufacture the construction;
- reference to the appropriate procedure specifications for welding and allied processes;
- sequence in which the welds are to be made;
- specification for inspection and testing, including the involvement of any independent inspection body;
- allocation of qualified welding personnel;
- arrangement for any production test.

8.6.2. Inspection and testing plan (ITP)

ITP comprises the minimum requirements related to the activities in the field of quality control and supervision in the execution of projects. Applicable inspections and tests shall be implemented at appropriate points in the manufacturing process to assure conformity with contract requirements. Location and frequency of such inspections and/or tests will depend on the contract and/or product standard and the type of construction.

Indicative content of ITP:
- name and number of the document (ITP) and the name of production;
- name of the manufacturer and the purchaser;
- name and signature of the QA/QC staff who made ITP (manufacturer and purchaser);
- history of ITP audits (audit number, date, change description);
- reference documents for manufacturer testing procedures (WPQR);
- reference standards (ISO, AWS, ABS, national ...).

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From this chapter on, the contents are directed for the European Friction Stir Welding Engineer Profile only.

9. Designing of Parts

There is a variety of friction welding techniques: Rotary Friction Welding — most popular type of friction welding and used for parts where at least one piece is rotationally-symmetrical such as tube or bar; Linear Friction Welding — used for jet engine components, near-net shapes, and more where the limitation on the parts is only based upon the mass of the moving part; not the geometry of the interface and Friction Stir Welding — often used for aluminium plates, extrusions, and sheets where seam or butt welds are made between thin components without a restriction on the component length.

9.1. Types of Friction Stir Welds

How does the different processes work?

- Rotary Friction Welding: a solid-state process in which one part is rotated at a high speed, and then pressed against another part that is held stationary. The resulting friction heats the parts, causing them to forge together.
- Linear Friction Welding: a solid-state process in which one part moves in a linear motion at a high speed. This is pressed against another part that is kept stationary. The resulting friction heats the parts, causing them to forge together.
- Friction Stir Welding: A solid-state joining process in which a pin tool rotates against the seam, between the two stationary parts, to create extremely high-quality, high-strength joints with low distortion.

Table 9-1: Advantages

Rotary Friction Welding	Linear Friction Welding	Friction Stir Welding
100% bond at the contact area Ability to join dissimilar materials Minimal joint preparation required Fast weld cycles, allowing more parts to be joined in less time Less inventory required to create part families Eco-friendly since no consumables are used Scalable to any size weld	A rapid, repeatable, and flexible process Ability to join nearly any number of shapes with complex part geometries Ability to join dissimilar metals Minimal joint preparation required; resulting in faster production Eco-friendly since no consumables are used Scalable to any size weld	Affords new joining applications for difficult manufacturing challenges- from extrusions to sheets and more Virtually defect-free bonding Accommodate parts up to 55 feet long Ability to join dissimilar alloys Ability to use dual head feature for fast panel welding Minimal distortion of joined parts, for extremely high-weld strength Eco-friendly since no consumables are used

Table 9-2: Top applications

Rotary Friction Welding	Linear Friction Welding	Friction Stir Welding
Aerospace Agricultural Automotive Construction Consumer products Oil and Gas Military	Aerospace Automotive Military Oil and Gas	Aerospace Electronics Marine Military Transportation

– Types of Friction Stir Welding

Friction stir welding (FSW) is a known technique for welding light alloys and has found particular effectiveness for butt-welding of work plates together along a joint line, which is defined by abutting edges of work plates. Even though the FSW leads to low defect rates, the process needs to be controlled and the weld need to be inspected to ensure that no defect is present that could compromise the structural integrity. One of the challenges in FSW is to detect the faults in the welded joints, because some of the faults associated with FSW are difficult to observe non-destructively.

A "worm hole" fault, which is a void in the weld line, may exist completely below the weld surface and therefore be unobservable to a human inspector. These faults can severely weaken the integrity of the weld. In order to improve the robustness and reliability of FSW process, the development of an in process monitoring system is essential, which can also be engaged for quality control of welded joints. Friction welding is a forging technique that produces ultra-strong bonds for diverse applications. This process has been the answer to many manufacturing and engineering challenges for over five decades. From aerospace to automotive, friction welding is continually opening the possibilities for ongoing technological advancement.

Types of friction stir welding:

– Friction Stir Spot Welding
– Double Sided Friction Stir Welding
– Stationary Shoulder FSW

9.1.1. Friction Stir Spot Welding

Friction Stir Spot Welding (FSSW) is a solid-Phase welding process for overlap welding of sheets with similar Joint designs as in resistance spot welding. It generates individual spots instead of continuous welds.
The process is mainly used in the automotive industry, the railway rolling stock manufacture and in aircraft production. For instance, the rear doors of the Mazda RX8 and the boot lid of the Toyota Prius are welded by this process in high-volume production.

Figure 9-1: FSSW Tool

FSSW is particularly beneficial for welding aluminium sheets either to aluminium, copper and steel. Similar and dissimilar material combinations are possible. The work-pieces do not melt but get only plasticized, because a high forging force is applied similar to that in extrusion presses or forges. The oxides on the work-piece surfaces get disrupted by the rotating tool and are stirred into the Nugget which is compressed by the tool.

Table 9-3: Details on FSSW welding thickness, material and applications

Material	Welding Thickness	Structure	Application Field
All series of AL-alloy	0.5~1 mm	Separate	Aero-space Aero-craft Automobile
Mg-alloy, etc	0.5~4 mm	Separate	Electronic Circuit board Electron, etc.

(a) (b) (c)

Figure 9-2: (a) Sketch map of Spot FSW; (b) Appearance of Spot FSW joint; (c) Spot FSW product for aero-craft

9.1.2. Double Sided Friction Stir Welding

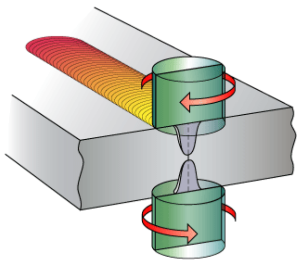

Figure 9-3: Double Sided Friction Stir Welding tool

– Stationary Shoulder Friction Stir Welding

In Stationary shoulder friction stir welding (SSFSW) the probe rotates and protrudes through a hole in a stationary shoulder/slide component. The stationary shoulder adds no heat to the surface, so all of the heat is provided by the probe and the weld is made with an essentially linear heat input profile. The key welding mechanism consists of a rotating pin running through a non-rotating shoulder component, which slides over the surface of the material during welding. The weld surface is very smooth, almost polished, with no or minimal reduction in cross-section.

Using the SSFSW technique on a robot can reduce issues associated with controlling the depth of the tool during welding. The robot structure is prone to deflection as it holds the FSW tool on the material's weld line, meaning changes in the material's softness and subsequent resistance can alter the depth at which the tool operates, producing flaws and defects.

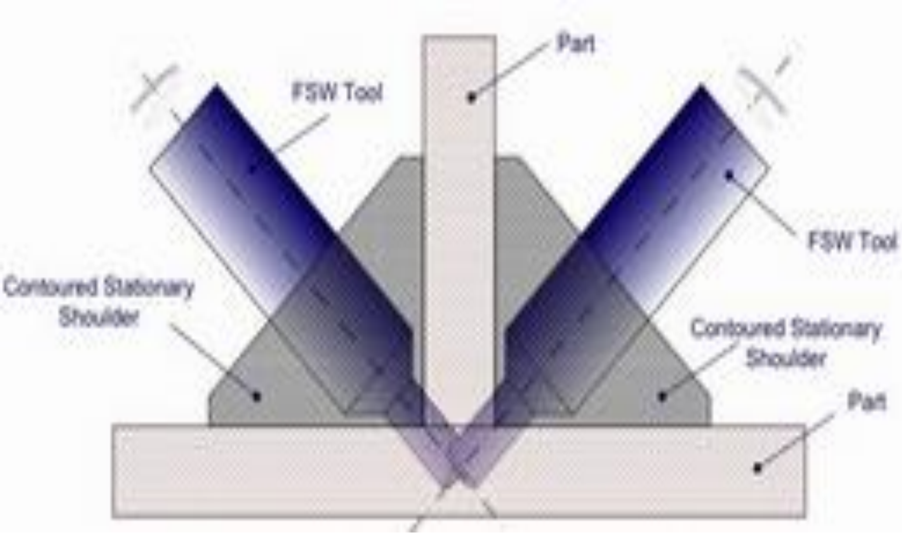

Figure 9-4: Corner SSFSW joint

Table 9-4: Details on SSFSW welding thickness, material and applications

Material	Welding Thickness	Structure	Application Field
All serials of Al-alloy, Mg-alloy, etc	8~15 mm	Separate	Aero-space Automobile
	15.1~30 mm	Separate	Railway Aero-craft
	30.1~45 mm	Separate	Electronic Electron, etc

(a) (b) (c)

Figure 9-5: (a) Corner stationary shoulder FSW tool model type; (b)8 mm thickness Al-alloy Corner Seam Sample welded by stationary shoulder FSW; (c) Corner Stationary Shoulder FSW Tool Application in shipping

9.2. Technical specifications for the final products

Technical specifications of the final products are imposed by the beneficiary, usually the components that came to be welded in laboratory or industry has some specifications that need to be followed. The specifications are imposed by the designer because the designer knows the loads and the distribution of the components. Each component needed to by examine after the weld in concordance with the specification received.

In the following pictures it can be observed some components of the structures of the planes or trains and also it can be observed that are important components and it is very important to comply with the technical specifications imposed by designers and beneficiaries.

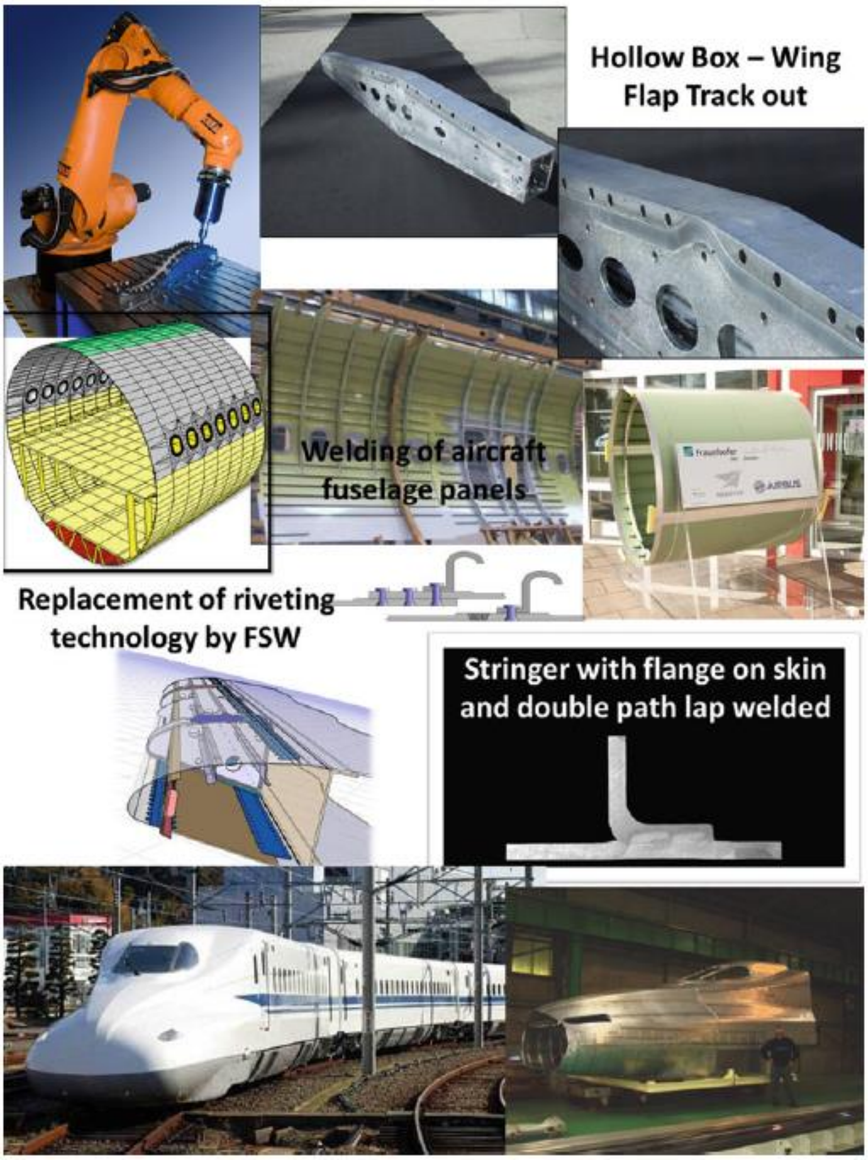

Figure 9-6: Illustrative examples of FSW implementation (Courtesy of Airbus group, Ottobrunn, Germany and Shinkansen photographs courtesy of Mr. Gilbert Sylva)

9.3. Guidance's for Design in FSW

Friction Stir Welding Steel can be used in Aluminium alloys, Titanium Alloys dissimilar material and it is used predominantly for Aerospace and Avionics.

Recent research lied that now can be welded using FSW titanium in thicknesses of 3 mm and 8mm (HZG- Hamburg). Excellent results have also been achieved with exotic aluminium alloys from 2mm – 35 mm in a range of challenging configurations.

The infrastructure includes:

- Table Friction Stir Welders

Figure 9-7: Example of a table used at FSW Machine

Typically used for educational purposes or for the manufacture of small components, in table models all processes can be shielded in the machine chamber. Table models are particularly suited to welding thin wall sections. Examples include hydraulic cylinders, suspension dampers and heat exchanger components.

- Static Gantry, Moving Table Friction Stir Welders

Figure 9-8: Example of the moving table used at FSW Machine

Available in a range of sizes and capabilities, static gantry machines have found particular favour in experimental work, particularly that involving the development of aircraft wings and bodies. Static gantry machines have also been used in the advancement of space technology, with FSW welds enabling a reduction in the wall thickness of various components.

– FSW machine

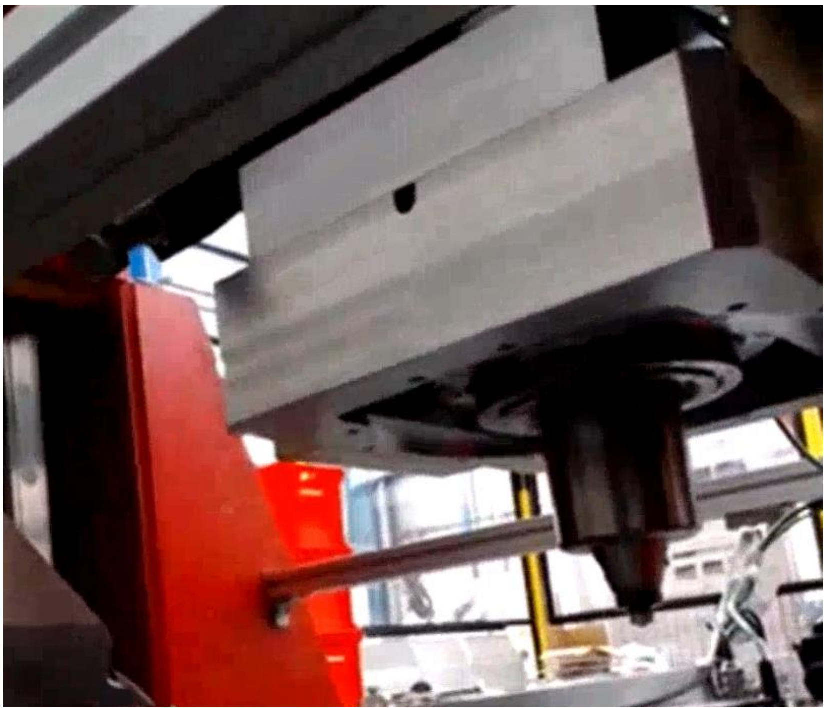

Figure 9-9: Example of FSW machine

On this type of FSW machine can be used simple table as in figure 6. Usually this type of machine is moving, and the table is statically.

– Probe shapes

The pin can produce deformational and frictional heating. Ideally, it is designed to combine the two surfaces of the pieces of the work piece by milling, mixing the material in front of the sample and transmitting it behind the pine of the tool and moved the material behind the tool.

The depth of deformation and tool travel speed are mainly governed by the probe. The end shape of the probe is either flat or domed. The flat bottom probe design that emphasizes ease of manufacture is currently the most commonly used form.

The main disadvantage of the flat probe is the high force during plunging. In contrast, a round or domed end shape can reduce the force and tool wear upon plunging, increase tool life by eliminating local stress concentration and improve the quality of the weld root directly at the bottom of the probe.

These benefits are apparently maximized when the dome radius is 75% of the probe diameter. As the dome radius decreases, the weld quality was often comprised.

This can be reasoned on the basis of the surface velocity of a rotating cylindrical probe that increases from zero at the centre to a maximum value at the edge. The local surface velocity coupled with the friction coefficient between the probe and the metal determines the deformation during friction stirring. The higher surface velocity at the probe edge can increase its stirring power and hence promote the metal flow under the probe end.

The lowest point of a round bottom probe has a lowest velocity and the least stirring action. The FSW/P probes usually have a cylindrical outer surface, but a tapered outer shape can also be used as indicated in Figure 9-10.

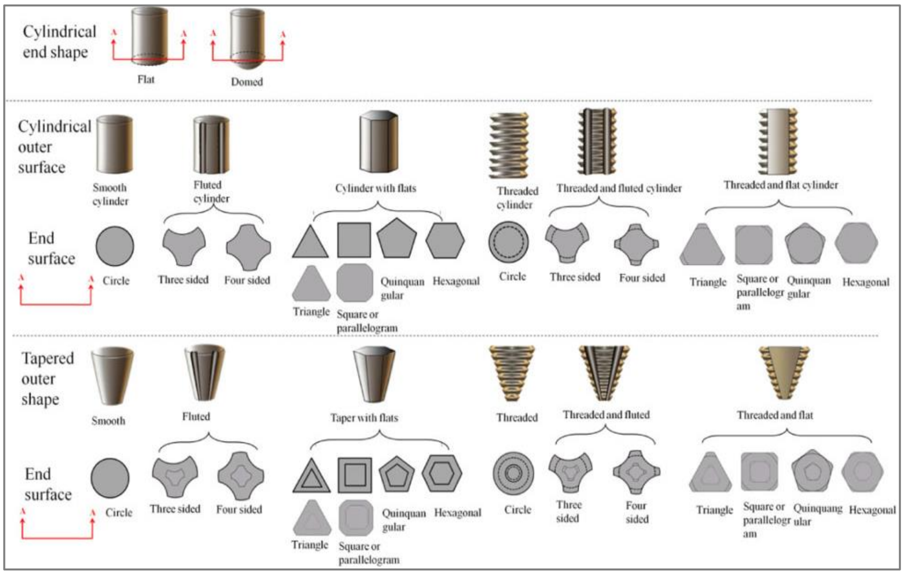

Figure 9-10: Example of the shape of tools

In particular, cylindrical probes have been widely used for joining plates up to 12 mm thick, but for thicker plates the process operating window to maintain weld integrity becomes considerably limited (low travel speed, high rotational speed). With the tapered probe, the higher frictional heat increases the plastic deformation because of the larger contact area of the probe with the work piece.

The tapered probe also promotes a high hydrostatic pressure in the weld zone, which is extremely important for enhancing the material stirring and the nugget integrity. However, the high temperature and hydrostatic pressure may lead to severe tool wear.

– Design of joint configuration for FSW:

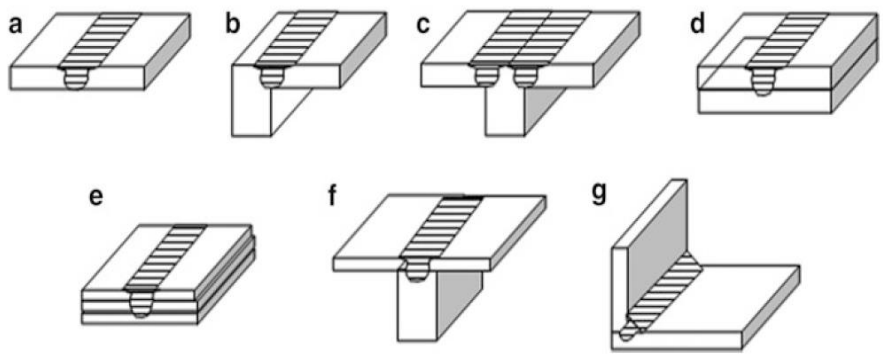

Figure 9-11: Joint configurations for FSW: (a) square butt; (b) edge butt; (c)T butt joint; (d) lap joint; (e)multiple lap joint; (f) T lap joint; (g)fillet joint (courtesy of Elsevier, 2005)

Tool position and penetration depth are maintained by either position control or control of the applied normal force. On the other hand, for a lap joint configuration, two lapped plates or sheets are clamped, and a backing plate may or may not be needed depending on the lower plate thickness. A rotating tool is vertically plunged through the upper plate and partially into the lower plate and traversed along the desired direction joining the two plates However, the tool design used for a butt joint, where the surfaces are aligned parallel to the tool rotation axis, would not be optimum for a lap joint where the faying surfaces are normal to the tool rotation axis.

Usually in case of this process the specimens that need to be welded in solid faze in general don't need special preparation, usually are butt welds and the surface of the specimens are only fixed in the clamping system, other stages of preparation are not achieved. In the case of FSW, it is desirable to perform as possible a number small of preparations before and after welding.

Figure 9-12: Specimens welded without join surface preparation

9.4. References

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10. Designing of tools

Welding tool is an inseparable component for welding by FSW process. The welding tool serves for plasticizing and stirring of the material welded. The following requirements are laid upon the welding tool: the simplest possible shape in order to reduce the costs, resistance against high temperatures and wear, high fracture toughness, low thermal expansivity, good machinability and low price.

10.1. Good practices for FSW tools development

The welding tool (Figure 10 1) is composed of two parts – the shoulder and pin. At the contact of welding tool pin with welded material, heat generation, necessary for plasticizing of the material welded takes place. The tool shoulder executes the pressing and forging function for the plasticized material. The tool progresses along the welding line. The welded joint is created (formed) behind the welding tool. The FSW tool is subjected to heavy loading and high temperatures, mainly in welding the materials with high melting point above 900 °C (steels and titanium alloys). The commercial application for these alloys is limited by the price and short life of the tools. Significant progress in the field of welding steels by FSW process was observed in the last two decades, connected with development in the field of fabrication, microstructure control and assessment of properties of welded joints. The first TWI development design, made in the field of welding of Al and its alloys, has employed the tool of concave cylindrical shape with a thread. The welding tools were made of tool steel. The manufacture of welding tool necessitates correct selection of material, design of suitable geometry and desirable heat treatment [10-1, 10-3, 10-13].

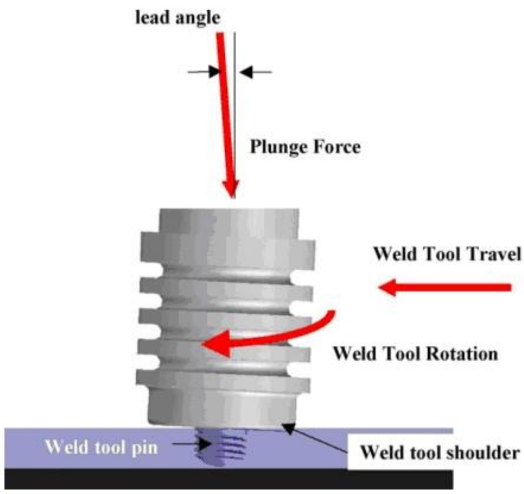

Figure 10-1: Welding tool [10-1]

10.1.1. Tool Geometry

Geometry of welding tool affects the rate of heat generation, downward force, torque and thermodynamically aspects of material welded. The flow direction of plasticized material is affected by the tool geometry but also by the linear and rotary movement of the tool. The main parameters of welding tool are shoulder diameter, angle of shoulder, pin geometry, including its shape and size. The shoulder geometry may be divided to two parts: *geometry of the shoulder and geometry of the pin (point)* of welding tool.

- Shoulder Geometry

The tool shoulder serves for heat generation on the surface and in the surface vicinity of material welded. At heavier thicknesses of welded material, the heat generated by the tool shoulder does not exert such effect upon formation of a sound weld as the heat generated by the pin. The tool pin generates greater volume of heat at heavier thicknesses of material welded. The shoulder performs the forging and pressing function and forms the weld surface area. The shoulder can deform the welded material what leads to improvement of friction rate. The shoulder may be of different shapes: striated, with grooves, concentric circles and blades. Different shapes of tool shoulder are shown in Figure 10-2.

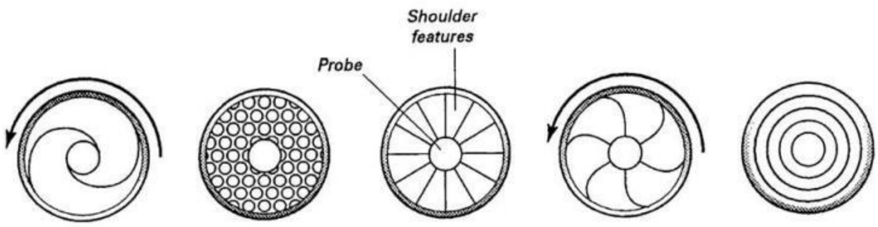

Figure 10-2: Types of surface areas of tool shoulder [10-1]

The diameter of welding tool shoulder is important, since the shoulder generates and maintains most of heat inevitable for plasticizing of material welded. Experimental studies have shown that the highest strength of welded joint can be achieved at optimum diameter of welding tool shoulder. It was experimentally proved that the microstructure of welded joint may be significantly altered by replacing the tool shoulder of flat shape with a concave shape.

The results of MKP modelling have shown that the angle of shoulder affects the downward force in dependence on tool radius. It was also observed that the convex shoulder improves the stability of FSW process.

These observations resulted in reducing the downward force and immersion depth of welding tool. Application of a convex shape of welding tool shoulder has resulted in minimum occurrence of excessive flash, when compared to the concave shape of shoulder. The concave shoulder of welding tool may result in a high thermal gradient and high surface temperatures during welding, what may lead to deteriorated quality of welded joint [10-1, 10-5, 10-9].

– Tool pin (point) geometry

In welding by use of FSW process, the tool pin causes the friction and material deformation on the weld joint line. The tool pin is designed in such a manner to allow its easy penetration into material welded. The pin geometry significantly affects the welding parameters as welding speed and rotation speed of the tool. The shape of tool pin affects the degree of deformation and stirring. Different geometries of tool pin are shown in Figure 10-3.

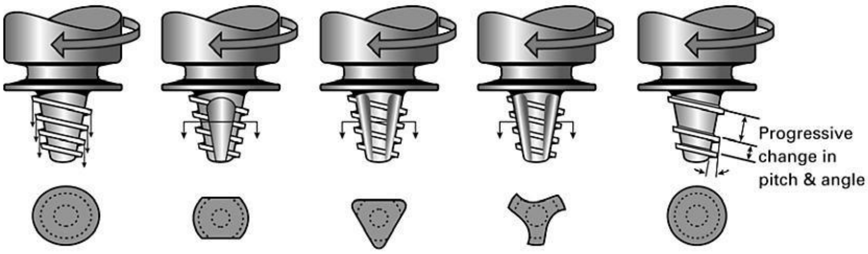

Figure 10-3: Geometry of tool pin [10-1]

Tool geometry affects the flow of plasticized material and thus it affect the properties of welded joint. Fig. 4 shows different shapes of welding tool. Experimental studies have shown that the pin of triangular shape enhances the material flow, when compared to the pin of cylindrical shape. The triangular shape of pin is recommended for welding harder materials.

The rate of downward force and direction of material flow in welding tool vicinity are affected by the orientation of threads on the pin surface. Several types of pins were approved for welding of Al alloys. It was finally observed that the conical pin with a thread has allowed to fabricate the welds with minimum defects. The threads and grooves on the pin increase the measure of heat generation due to larger boundary area, improve the material flow and affect the axial and transverse forces. 4 types of pin shape for welding of Al composite reinforced with SiC were compared in the studies.

The following shapes were used in experiments: circular without thread, circular with a thread, triangular and a square one. The pin of square shape has exerted a more homogeneous structure of SiC particles, when compared to other shapes. The circular shapes were less worn than the flat shapes of the pin. Increasing the angle between conical surface of the pin and its axis leads to a more uniform distribution of temperatures along the vertical direction. By application of a longer pin, the shear and tensile strength was increased [10-2, 10-4, 10-11].

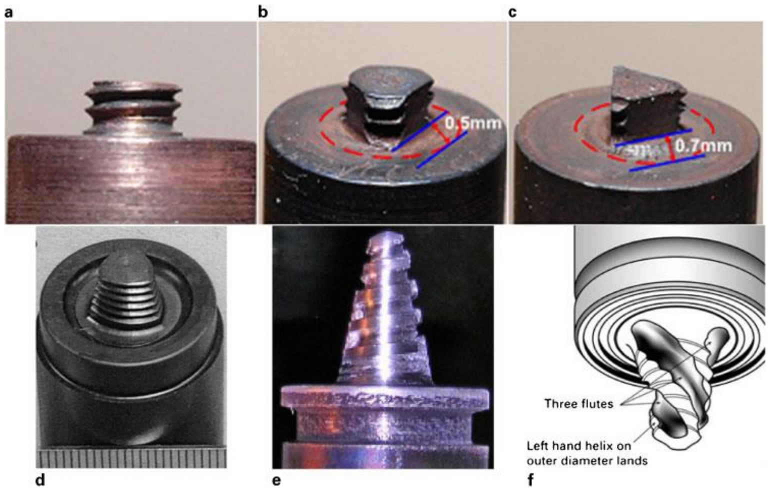

Figure 10-4: Geometry of welding tool pins: a. cylindrical threaded; b. three flat threaded; c. triangular; d. Trivex; e. threaded conical; f. schematic of a triflute [10-2]

10.2. Characteristic of the tool material

The material of welding tool destined for welding materials with high melting point must exert good properties at the temperatures above 900 °C. Besides the demands on strength, fatigue resistance and toughness at elevated temperatures, the welding tool material must be resistant also to mechanical and chemical wear. The Polycrystalline Cubic Boron Nitride (PCBN) and refractory metals are the mostly used materials, meeting the properties for welding tool manufacture.

The PCBN material exerts high strength and hardness at high temperatures and it also offers a high thermal and chemical stability. The geometry of welding tool is permanently developed. The first welding tools had nonspecial features (Figure 10-5, a) i. e. a smooth concave shoulder and the cylindrical pin without thread and/or in the shape of a truncated cone were used. The helical thread was machined on the welding tool pin in 2003 (Figure 10-5, b). These features have enhanced the process productivity and removed the undesired defects, which were observed in the case of welding tools of previous design.

Figure 10-5: PCBN tool design evolution: (a) early featureless design, (b) step spiral probe, and (c) convex scrolled shoulder step spiral probe [10-14]

A survey of materials used for manufacture of welding tools is shown in Figure 10-1.

Table 10-1: Materials for manufacture of welding tools [10-7]

Alloys	Thickness [mm]	Weld tool materials
Mg	< 6	Tool Steel
Al	< 12	Tool Steel, MP 159
Cu	< 50	Alloys Ni, W, PCBN
Ti	< 6	W alloys
Stainless Steel	< 6	PCBN, W alloys
Low alloy steel	< 10	WC, PCBN
Ni	< 6	PCBN

Each material of welding tool has the defined maximum temperature for which it may be applied. The excessive wear of welding tool causes the change in tool shape, what impairs also the weld quality and the probability of defects is thus increased. The tool wear may be caused by the adhesive, abrasive and chemical wear. The welding tool may be worn by the interaction mechanism between the welded material and tool material.

In the case if the tool is made of PCBN material, the adhesive wear occurs at low tool revolutions, whereas at high tool revolutions the abrasive wear is observed. Oxidation may cause the change in material wear resistance. The tool reactivity may be suppressed by application of shielding gases supplied to welding process zone.

The stresses formed at first tool contact with material welded may result in tool rupture. To prevent such a failure, mainly slow rate of pin penetration is efficient.

The complex computer simulation and the strength requirements based upon experimental tests are performed for selection of a suitable tool. There exists a big choice of tools with different geometry at present. The special tools have appeared recently, where such parameters as the pin height, revolution speed of the pin and the shoulder may be altered [10-7, 10-12, 10-14].

Manufacture of welding tool of PCBN, PCBN-WRe materials

The tools made of PCBN material are used for welding of alloys with high melting point: austenitic stainless steel, duplex stainless steel, super martensitic stainless steel, Ni alloys, tool steels.

A new grade of PCBN material was developed at present, using WRe as a binder. The PCBN-WRe grade of tool steels offers significantly improved toughness, compared to PCBN material proper. The austenitic stainless steels generally exert the highest rate of welding tool wear. Welding parameters play a significant role in the wear rate of welding tools. For the tool made of PCBN material, a rule stating that the temperature of welding tool should not exceed 900°C is applied.

If the wear of functional parts on a welding tool made on the basis of PCBN-WRe material occurs, these worn parts can be several times profiled, what results in prolonged life of welding tool. The high stresses formed during tool penetration, together with material fatigue at bend load during welding are the primary causes of welding tool rupture. In order to suppress the tendency to rupture, it is advisable to drill preliminary a hole in the point of supposed welding tool penetration. The PCBN-WRe material exerts considerably higher resistance against the rupture than the PCBN material proper. The best results with strength properties of PCBN material are achieved at the thickness up to 8 mm. At the thickness over 8 mm, better properties are achieved with the welding tools made of PCBN-WRe material.

The tools of refractory metals

The Tungsten–Rhenium alloy became a popular refractory material used for manufacture of welding tool destined for welding of steels in the past decade. The addition of Rhenium element significantly improves the material strength at high temperatures. Rhenium reduced the pin deformation during penetration and it also reduced the wear of tool pin. In spite of that, the wear rate is still high. Therefore, a simple shape of welding tool is preferably selected.

The shoulder and pin made of refractory material type WRe are smooth without the thread helix. Also small amounts of hafnium carbide (HfC), were added to refractory materials. Other experiments were performed with the materials as: WC-Co, W-La, La_2O_3, Si_3N_4. Though the quality of welded joints fabricated with the tool of the mentioned materials was acceptable, the tool life and costs have limited their application mostly for the research purposes.

The tools of light alloys

The Ni and Co based super alloys are used as the tool material for welding of steels by FSW process. The tool made of Co-based alloy, which shows a good wear resistance is used for welding of high-carbon steel. The welding tools made of light alloys are manufactured similarly as the tools made of refractory metals. Simple shape of shoulder and pin of welding tool is preferred. The pin of welding tool is in the shape of a truncated cone.

The tool steels

The materials as Al, Mg alloys and composites of Al matrix are currently welded by the welding tool made of a tool steel. The welding tool made of a tool steel is used for welding of dissimilar materials. The wear of welding tool in welding the metal matrixes of composites is higher, when compared to welding of soft alloys, owing to presence of hard abrasive particles in the composite materials.

The experiments have proved that the welding tool which welded the composites of Al matrix was worn during welding and attained a new, own – optimised shape, with which the wear was significantly reduced. This shape depends on the process parameters and it can generally reduce the wear as in the case of initial tool shape, supposed that the integrity of welded joints is preserved. The overall wear of welding tool increases with increasing rotation speed, while it is reduced with lower welding speed. The correct setting of welding parameters will result in lower wear of welding tool. Several studies have pointed out, that to modify the geometry of welding by a helix thread is of low significance.

The high hardness, low coefficient of thermal expansion and high thermal conductivity make the Si_3N_4 material suitable for manufacture of welding tool. The coating of welding tool with an inert material as diamond or TiC, may lead to further improvement of wear resistance at high temperatures [10-2, 10-7, 10-14].

Wear, deformations and failures of the welding tool

The welding tool is worn during welding (rotation and material stirring). The welding tool may be plastically deformed, owing to reduced strength limit at elevated temperatures and load. If the loadings are higher than the load capacity of welding tool, a failure may occur.

The main wear mechanisms include the adhesive, abrasive and chemical wear. Figure 10-6 shows the initial stages of thread wear of the tool made of hard steel. After initial wearing out of the thread on the pin of a hard welding material, the wear rate has significantly reduced and, in spite of that, the smooth pins allowed to fabricate sound welded joints. The high-strength materials as PCBN and W are selected in order to reduce the plastic strain of welding tool. The high fracture toughness of welding tool material is essential in order to reduce the probability of a rapid brittle fracture. When comparing the pin and shoulder of welding tool, the wear and deformations in the pin section of the tool mostly occur for the following reasons.

The pin of welding tool is immersed into the welded material, where it must exert higher resistance against its movement, compared to the shoulder, which is immersed into welded material just partially. The pin of welding tool exerts much lower load capacity that the shoulder. The high loadings combined with the torque and bend stresses lead to higher load exerted on the pin, compared to the shoulder of welding tool.

The composite tools made of harder materials resistant to wear (PCBN, WC) used for pin and relatively softer material (W-Re alloy) used for the shoulder of welding tool may be the solution for issues regarding the tool life and reducing the costs for tool manufacture. In case of welding the overlapped joints of a harder and a softer material, the welding tool is situated into the softer material. The contact between the welding tool and harder material will be prevented, in order to reduce the wear of welding tool.

Further research in the field of wear leads to experiments oriented to welding at slower welding speeds, preheating the material welded and application of shielding atmosphere [10-2, 10-8, 10-10, 10-14].

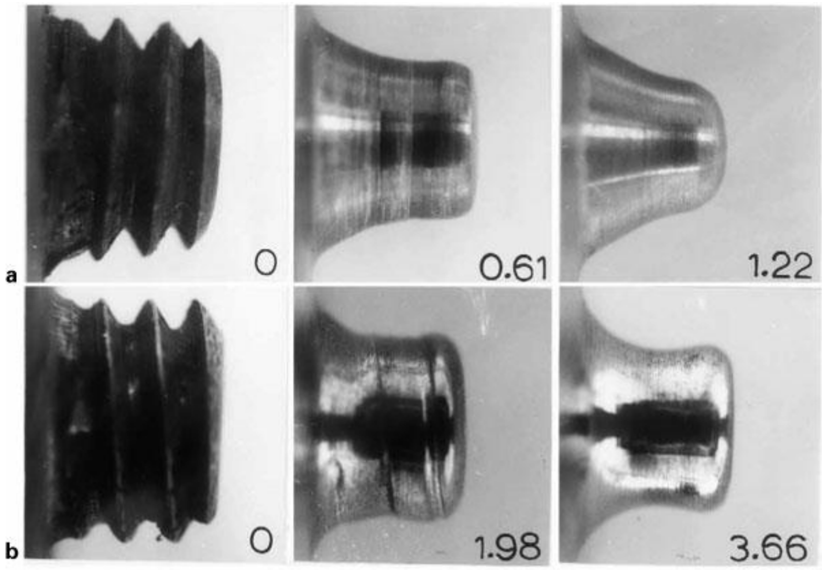

Figure 10-6: Evolution of tool shape due to wear in FSW of Al 6061z20 vol.-%Al2O3 metal matrix composite with 01 AISI oil hardened steel tool at 1000 rev min21 and travel speeds of a 3 mm s21 and b 9 mm s21: distances traversed by tool in metres are indicated [10-2]

The tool costs

The power costs in welding of Al alloys are considerably lower when compared to welding of steels. It is given mainly by the material price and mainly by the price of its processing. The PCBN material is often used for welding harder materials. The costs for manufacture of welding tool made of PCBN material are high. The welding tools made of W-RE and W-La alloys are relatively cheaper than the tools made of PCBN material, but regarding the wear, they exhibit faster wearing, owing to their lower strength and hardness at elevated temperature [10-6, 10-13].

Due to above mentioned reasons, it is necessary to invest to research oriented to further development of more affordable and more reliable tool materials [10-11].

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11. Implementation the FSW system

As with every manufacturing process, FSW has associated costs, either for implementation it but also operational. This chapter gathers the relevant information associated to the topic.

11.1. FSW Costs

In term of the cost this issue depends on the size of FSW machine, if we speak about a small robot that has a small table on which the specimens will be welded, we can reach around 100,000 Euro and if we discuss about huge machine, we can reach around 3-4 million Euro. Also, the price is different from a provider to another provider. In the past ESAB was the leader but now the market of FSE machine increase and from this reason the price decreased and is more flexibility in the field of FSW Machine.

– Requirements for FSW system installation

Machine characteristics and applications

Machines used in FSW present different characteristics which concerns to its physical configuration. Depending on the application (welding joint), the equipment that displays the most suitable characteristics must be chosen according to different technical capabilities:

- force, stiffness, accuracy, sensing, decision-making, and flexibility. These capabilities will be analysed in detail in the following sections.

FSW machines

Three kinds of machines are reported in literature as viable to perform FSW. These machines are:

– Conventional machine tools such as milling machines;
– Dedicated FSW machines or custom-built machines;
– Industrial robots.

Conventional FSW machines

The process of FSW is similar in terms of equipment principle of operation like others manufacturing processes such as machining, deburring, grinding or drilling. Thus, a **conventional machine**, such as a milling machine, can be used to perform FSW of thin aluminium alloys parts.

The loads involved in FSW are higher than the loads generated in the milling process.

For this reason, conventional machine tools have to be strengthened in order to increase their **load** and **stiffness capabilities**.

Figure 11-1: FSW- Conventional machines

Dedicated FSW machines

Dedicated FSW machines tend to have the **highest load capability**, **stiffness**, **accuracy** and availability [23].

Typically, dedicated FSW machines are relatively expensive and **their cost increases with the flexibility capability**.

The use of dedicated FSW machines is recommended for high series weld production of thick/thin parts in applications where:

- high stiffness is required;
- single or multi-axis applications;
- long weld paths.

Figure 11-2: FSW- Dedicated machines

Conventional machine tools

The process of FSW is similar in terms of principle of operation of the equipment to other technological manufacturing processes such as machining, deburring, grinding and drilling. Basically, all of these processes consist in moving a rotating tool through a work piece, producing dragging of material which constitutes the work piece. Thus, it is plausible to assume that a conventional machine tool, such as a milling machine, can be used to perform FSW. However, the loads generated during the FSW process gain more relevance when this equipment is used. The loads involved in FSW are higher than the loads generated in the milling process. For this reason, conventional machine tools must best strengthen in order to increase their load and stiffness capabilities.

Thus, there are potential opportunities to modify existing equipment to perform FSW. The machine modifications can be made on several levels: structural, flexibility, decision-making and sensing. The structural modifications are performed in order to make the equipment more robust (some parts of equipment can be replaced such as ways, guides, rails, motors, spindles, etc.). The flexibility can be increased by the introduction of additional motors that provide additional degrees of freedom to the equipment. Owing to the high loads involved in the FSW process, most of the solutions have implemented force control to prevent equipment damage and ensure human safety and to achieve good weld quality. The decision-making of the equipment can still be improved providing movement in more directions at the same time. Besides that, the machine can be equipped with multiple sensors to collect different information which will be used to control the equipment through an embedded control solution.

These machines are very popular since they are widely used in industry for machining purposes, which is one of the most common technologic processes used in industry. Therefore, the existence of this kind of equipment in industry is guaranteed as well as knowledge to operate it. In FSW the use of modified machine tools is recommended for:

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

Friction Stir Spot Welding (FSSW) Machines

Figure 11-1: FSSW Machine

FSSW Machines are easy to operate by an intuitive human-machine interface (HMI) and their programmer logic Controller (PLC) uses unique close-loop force-displacement algorithms. The machine operator sets the parameters such as rotation speed, downward force and plunge depth via a touch screen panel depended on the work pieces to be welded. The process may be split into several phases, such as plunging and dwelling.

The machines are specified for a variety of different material combinations, such as:

– Aluminium-aluminium;
– Aluminium-copper;
– Aluminium-steel.

Dedicated FSW machines

Weld Seam Tracking Laser System

Figure 11-4: Dedicated Machine and parameters

Table 11-1: FOOKE FSW

FOOKE FSW 35	FOOKE FSW 60	FOOKE FSW 150
Maximum axial force of up to 35 KN	Maximum axial force of up to 60 KN	Maximum axial force of up to 150 KN
Welding depth of up to 12 mm(6xxx)	Welding depth of up to 12 mm(6xxx)	Welding depth of up to 50 mm(6xxx)
Welding rate up to 3.000 mm/min	Welding rate up to 3.000 mm/min	Welding rate up to 3.000 mm/min
Feed rate up to 40 m/min	Feed rate up to 40 m/min	Feed rate up to 20 m/min
5-axis simultaneous during FSW-Process	5-axis simultaneous during FSW-Process	3+1-axis operation
		4-axis simultaneous during FSW-Process
Load and temperature symmetrical construction	Load and temperature symmetrical construction	Load and temperature symmetrical construction
Position controlled process	Position controlled process	Position controlled process
Force controlled process	Force controlled process	Force controlled process

Industrial robots

Figure 11-5: Industrial robots

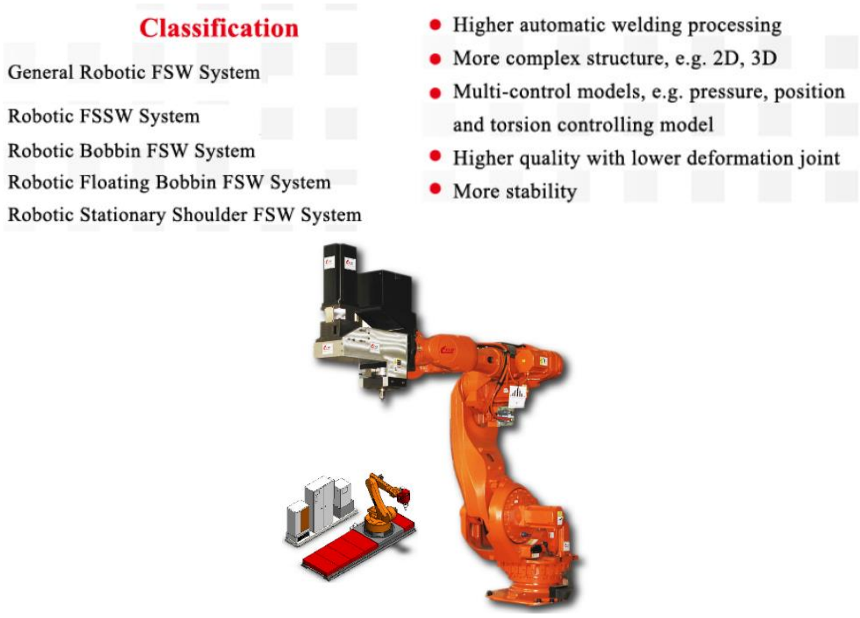


Figure 11-6: FSW robots

The robotic-based solutions are available in two basic categories:

- Articulated arm robots
- Parallel-kinematic robots

Articulated arm robots present **high repeatability** and **flexibility** but **low accuracy** that worsens when they are subjected to high loads.

Comparing articulated robots to dedicated FSW machines, these robots display **higher flexibility** and **decision-making capability** besides the fact that they are remarkably lower in cost. However, these types of robots have relatively **low stiffness** and **moderate load capability** which limit their application.

Figure 11-6: Robotic FSW system

Equipment force capability

A challenging issue in FSW is to have a machine able to support the high loads generated during the welding process, which depends greatly on the type of material and thickness of the work pieces. The most relevant loads acting on a machine during the FSW process are the axial force (F_z), the traverse force (F_x), the side force (F_y), and the torque (M_z),Table 11-. The directionsof these loads are displayed in Figure 11-.

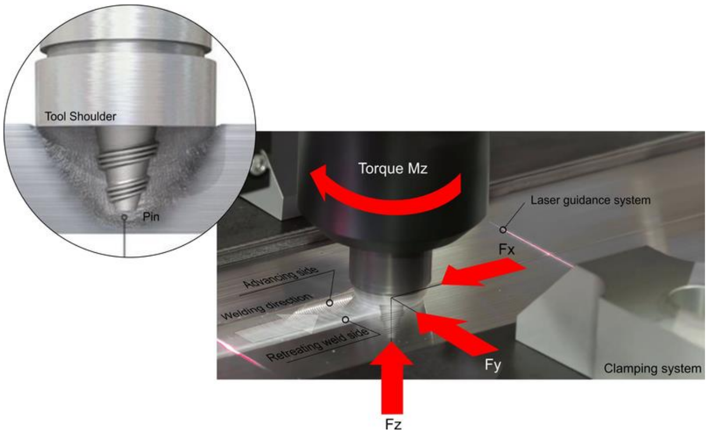


Figure 11-7: Loads directions

Table 11-2: Relevant loads for FSW process

Axial Force (F_z)	Axial force is one of the main process parameters. It is responsible for the friction between the FSW tool and the work pieces, contributing to heat generation in the FSW process. Furthermore, axial force is responsible for applying forging pressure which is vital to obtain good weld formation
Transverse Force (F_x)	Transverse force is responsible for supporting material resistance to the tool movement along the joint line
Side Force (F_y)	The side force arises due to the asymmetry of the FSW process, caused by the direction of the tool rotation. The advancing side of the weld is warmer than the retreating side of the weld, consequently, the material on the advancing side is softer and less resistant. This force has the direction from the retreating side to the advancing side of the weld
Torque (M_z)	Torque is also responsible for friction between the FSW tool and the work pieces. This friction is one of the main heating sources for the process of FSW

All of these loads play an important role in the process. They are a prerequisite to choose or develop FSW equipment. They also play an important role in the control the FSW process, for example maintaining a given axial force or torque allows conferring a good quality to welded seams.

Force capability

The **down force** Fz is not set up and his maximum value is depending on processing parameters. Usually the plunging force is greater than the welding force.

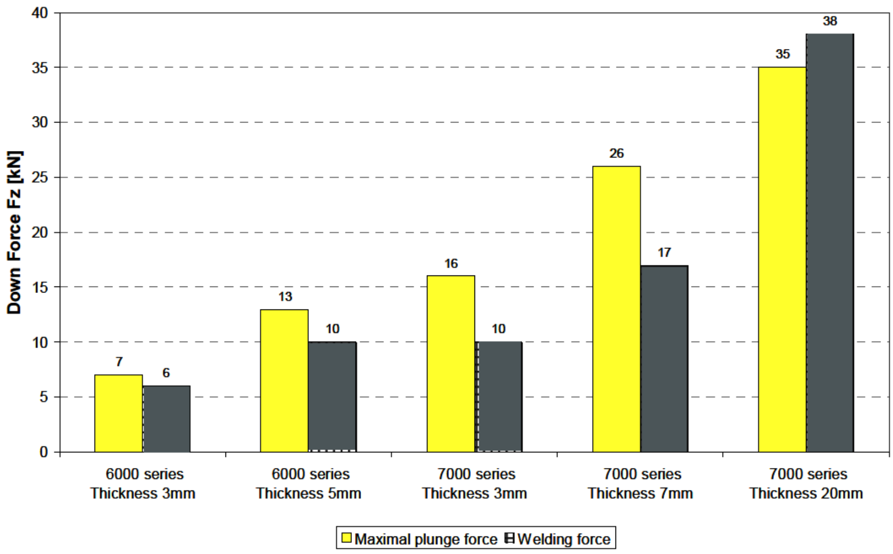


Figure 11-8: Comparison between the maximal plunging force and the applied welding force

- The maximal plunge force could be reduced by decreasing the plunge velocity or by adding a drilling hole before plunging.
- For the configuration, welding a 7000 aluminium series of 20mm, the plunging phase was done with the help of a drilled hole.

The plunging force has to be considered for the qualification of the structure.

Equipment

Equipment is designed with a rigid framework for high performance during high-load conditions with a working range (welding head travel) from 1 and 5 meters. It comprises heavy-duty bearings and the welding head travel is actuated using a ball-screw system.

The welding head is hydraulically actuated, which allows the high FSW forces to be applied minimizing the space required. The contact force conditions is controlled by the PLC, which provides a dedicated close-loop controller for this vital process parameter.

The spindle is driven by an AC-motor, which provides the torque and spindle rotation needed for the intended applications. Liquid cooling is provided to minimize the wear on the spindle components and the pin tool.

Control System

All machines are controlled using the latest of PLC technology and high accuracy drives. This allows the machine's axes position and speed to be controlled delicately and precise. The Z-axis control works in either on position or on set force control mode.

The menu driven 15'' touch-screen HMI interface is designed specifically for FSW. It is the interface for setting up the process parameters, the welding path as well as the most common machine parameters. It also provides monitoring capabilities of the process parameters, alarms and system status.

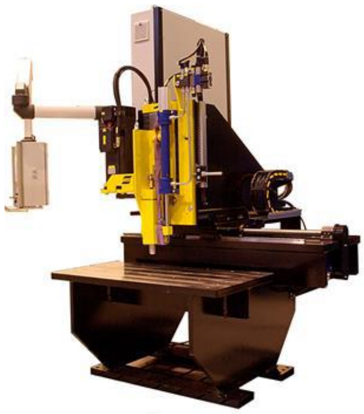


Figure 11-9: Friction Stir Welding Machine

Figure 11-10: Friction Stir Welding Systems

Figure 11-11: FSW Standardized & Modular

Standardized Robotic:

Based on a standard industrial robot ABB IRB 7600-500

- 3D work envelope
- 360° workstation layout
- Integrated welding equipment
- Increased capacity
- Maximized stability
- Teach-in or fully integrated offline programming
- Path planning and simulation based on CAD models
- Welding thickness up to 7 mm

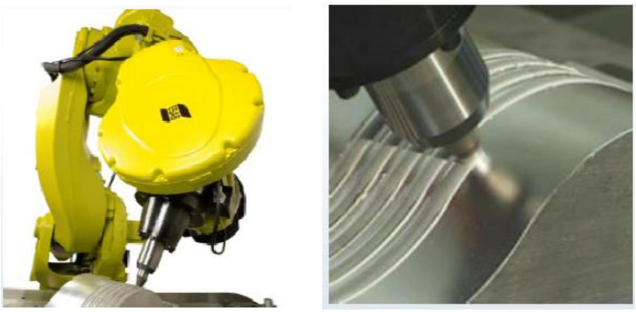


Figure 11-12: FSW Robot

FSW System Implementation

Stiffness and accuracy capability

This is the ability of FSW equipment to withstands loads **without undergoing deformation** or **deflexion**.

When a FSW machine presents **low stiffness** its FSW tool deviates from the desired welding path, **strongly affecting weld quality**.

Moreover, low stiff machines tend to cause **excessive vibration** which in turn can lead to FSW process instability.

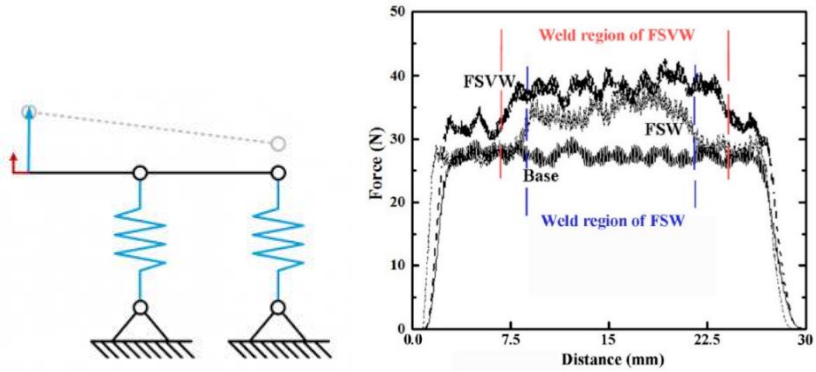


Figure 11-13: Deformation in weld region of FSW

Sensing capability

– **Sensing** consists on the **machine ability** to be aware of some **phenomena that are occurring in the weld joint**, i.e. values of **direct** and **indirect welding variables** involved in FSW process that reflect the evolution of the welding material and consequent welding formation.

– **direct welding variables** the welding parameters that some how can be actuated in a direct way (the **rotational** and **traverse speeds**, the **tilt angle** and the **external heat input**)

– **indirect variables** all those variables that cannot be actuated in a direct way, they depend on other variables. This group of variables is composed by the loads involved in the welding process (**axial force, traverse force, side force and torque**), the **temperature** reached in the welding area, the **stirred material flow** and the **stirred material mixture**.

Decision-making capability

Control methods can be implemented in the control system of the equipment in order to **allow process self-adaptation**.
The data provided from sensors (values of the direct and indirect variables) are used as **feedback** to the **control system**.
Therefore, indirect monitored variables converge to desired states and values in which FSW process provides good quality welds.

Flexibility capability

The flexibility of a machine limits the complexity of a welding path (linear, curve) that can be performed. The number of axes (degrees of freedom—DOF) that a machine possesses usually establishes the flexibility of the machine. A one-dimensional (1D) welding path is the least complex requiring the least flexibility (smaller number of axes).

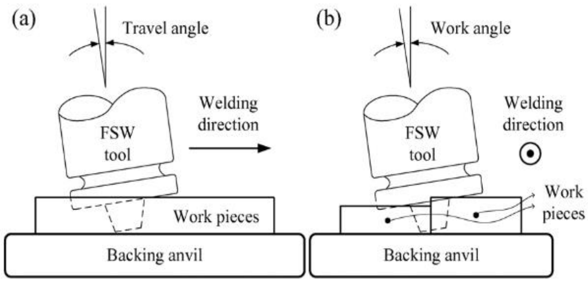


Figure 11-14: Travel angle

The simplest version of this machine possesses just two axes. On the other hand, a two-dimensional (2D) welding path requires more flexibility, not only to move the FSW tool through the two directions but also to maintain work and travel angles. A three-dimensional (3D) welding path is the most demanding in flexibility, a machine to perform the simplest 3D path must have at least five axes. In addition, in many applications' multiple welds with multiple directions and with multiple orientations are required, which demands the required flexibility of the machine.

Table 11-3: Parameters for FSW for different materials: thickness vs. axial force

Material	Thickness [mm]	Axial Force [kN]
AISI 409M	4	24
AA2195-T6	6.35	13.8
AA6061-T6	6.35	12.5
AA7075-T6	5	8
ACD12	4	6.9
C11000	3.1	7
Cu-DHP R240	1	7
AZ31B	6	3
AZ61A	6	5
High nitrogen austenitic steel	2.4	20
AA6082-T6/AA7075-T6	8	12
AA5083-H111/Cu-DHP R240	1	7
Cu/cuZn30	3	5.5
Al-4.5%Cu-10%TiC	5	6
AA2124-SiC	15	8.5
AA6061/0-10 wt.% ZrB_2	6	6
AA7005/10 vol.% Al_2O_3particles	7	12
AA6061-T6/AlN_P	6	3-7
ABS	6	2

Flexibility capability - The flexibility of a machine limits the complexity of a welding path (linear, curve) that can be performed (the number of axes).

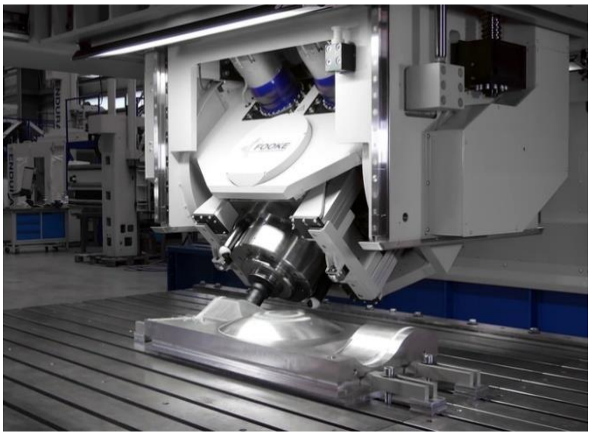


Figure 11-15: The flexibility of a machine limits the complexity of a welding path

Equipment components

- Rigid framework
- Strong and fast motion components
- Advanced tool control system (CNC)
- 5 axis for 3D weld path
- Position & Control Force System
- System for recording & monitoring the welding parameters
- FSW heads with bobbin technology for welding thicker parts
- Laser seam tracking solutions
- Video system monitoring

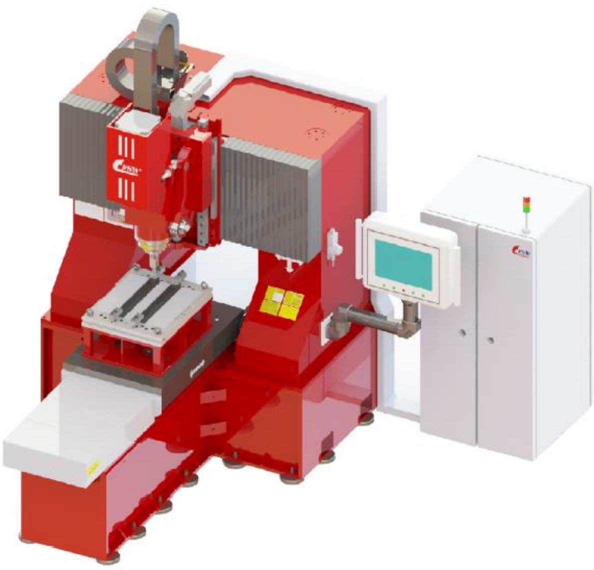


Figure 11-16: FSW Equipment

- The equipment is designed with a rigid framework for high performance during high-load conditions with a working range (welding head travel) from 1 and 5 meters. It comprises heavy-duty bearings and the welding head travel is actuated using a ball-screw system.

- The welding head is hydraulically actuated, which allows the high FSW forces to be applied minimizing the space required. The contact force conditions is controlled by the PLC, which provides a dedicated close-loop controller for this vital process parameter.
- The spindle is driven by an AC-motor, which provides the torque and spindle rotation needed for the intended applications. Liquid cooling is provided to minimize the wear on the spindle components and the pin tool.

Clamping system

Advanced clamping systems can be individually controlled according to the tool position. The clamping shoes are lifted and lowered automatically based on the FSW tool position. It can be done using proximity sensors or by a code program.

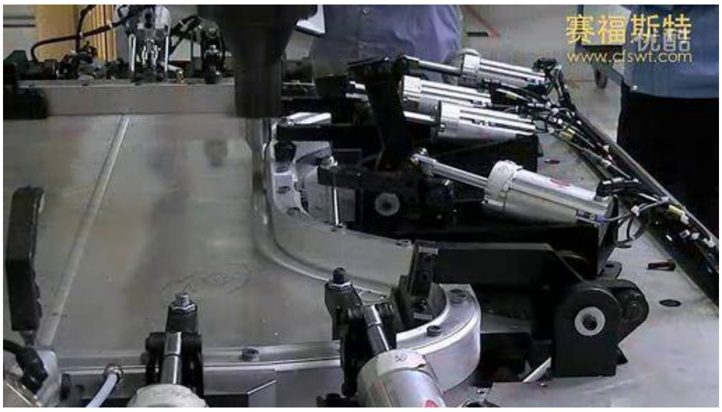
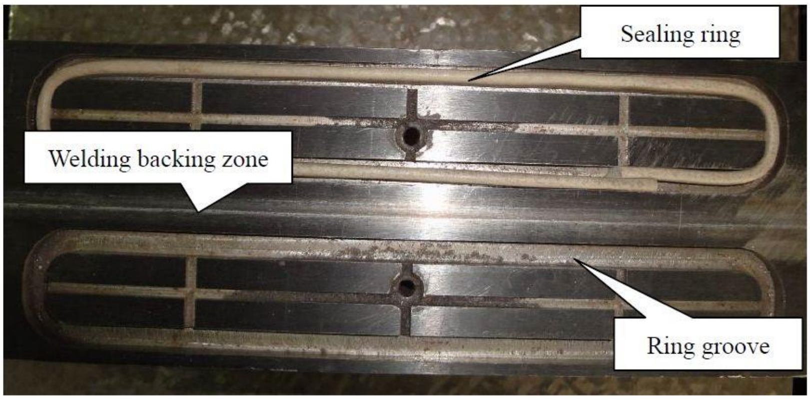


Figure 11-17: Clamping system 1

Pneumatic action/control of the clamping system composed by multiple shoes that assure proper components fixture.



Vacuum adsorbing backing plate

Figure 11-18: Clamping system 2

Air clamper

Figure 11-19: Clamping system 3

Cooling system

Gpm – gallon per minute

1 Gpm = 3.78 Liters per minute

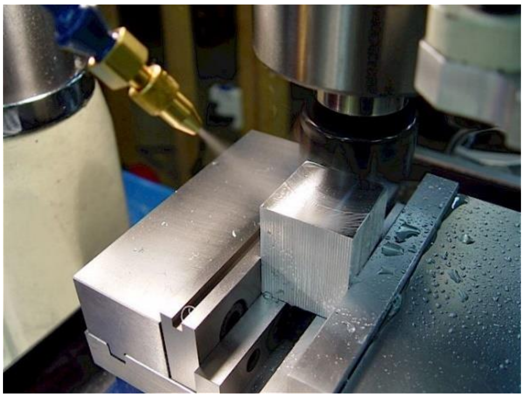


Figure 11-20: Cooling system

- a coolant rate 0.01 Gpm for direct cooling
- a coolant rate 0.1 Gpm for internal cooling
- cool air or gas is sprayed in the fins

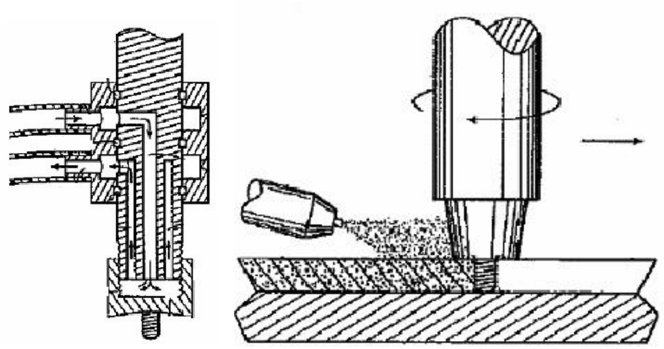
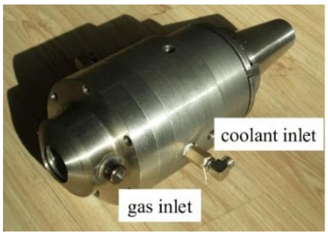


Figure 11-21: Internal cooling



Temperature at the pin center was higher than than the surfac

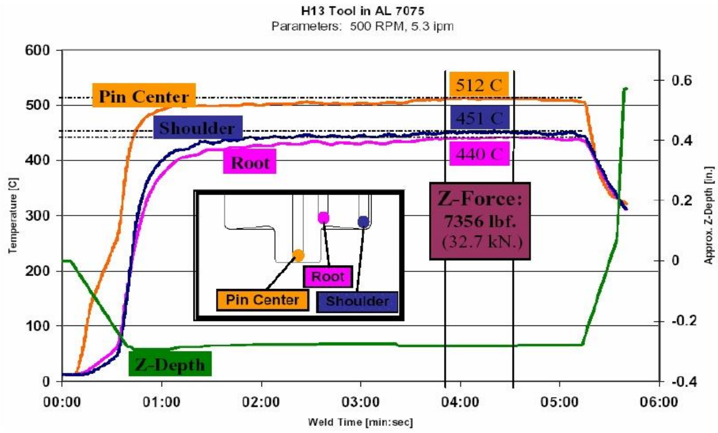


Figure 11-22: Temperature distribution in tool

Laser tracking system

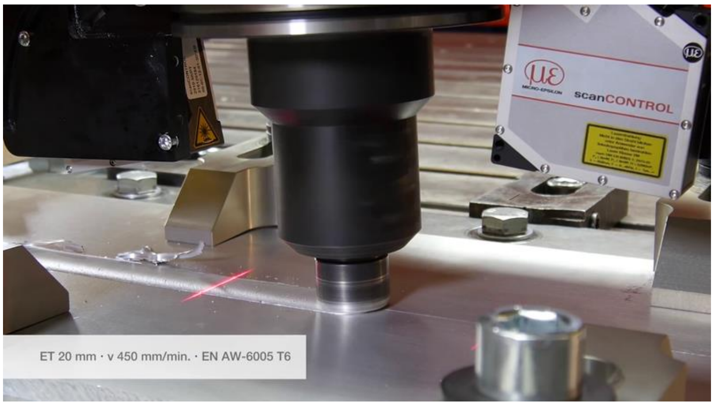


Figure 11-23: laser tracking system

Production running costs

In term of the cost this issue depends on the **size** of FSW machine, if we consider a small robot that has a small table on which the specimens will be welded, the price could be around 100,000 Euro and if we discuss about large equipment the price can reach up to 3-4 million Euro.

Machines selection for FSW should consider:

- the workpiece size,
- the volume production,
- forces involved in the FSW,
- system stiffness,
- accuracy capability,
- sensing capability,
- decision-making capability,
- flexibility capability.

Parameter	Specified Range
Spindle speed range	0 - 3000 rpm
Z axis traverse speed	0 - 1500 mm/min
X axis traverse speed	0 - 3000 mm/min
Z axis travel	500 mm
Z axis max workpiece size	750 mm
X axis travel	2000 mm
Y axis travel	2000 mm
Spindle tilt angle	0 - 5°
Z axis load	0 - 30 KN
X axis load	0 - 20 KN
Spindle torque	0 - 80 N-m

Bringing FSW to the production floor,

However, is neither a simple nor risk-free end ever? Successfully implementing this rapidly evolving process requires considerable process expertise, **a sound development plan**, and **reliable, technologically advanced equipment.**

Carefully weighing such factors as **budgetary limitations, time constraints**, and your organization's level of FSW **process development expertise.**

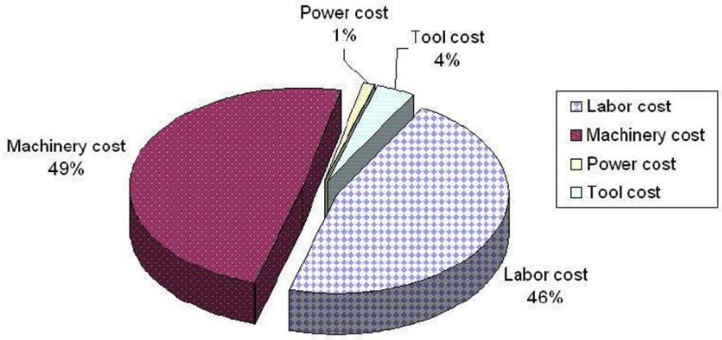
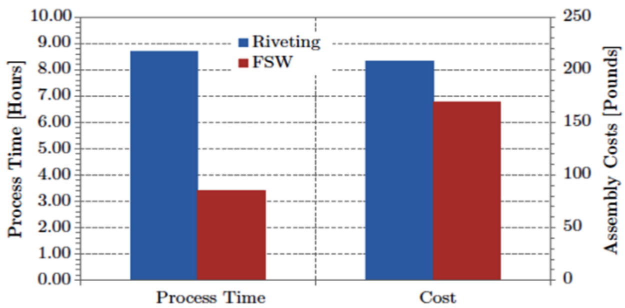


Figure 11-24: Distribution of cost components of FSW process



Process time and costs, comparison between riveting and FSW, [244].

Figure 11-25: Friction Stir Welding – Process time and costs

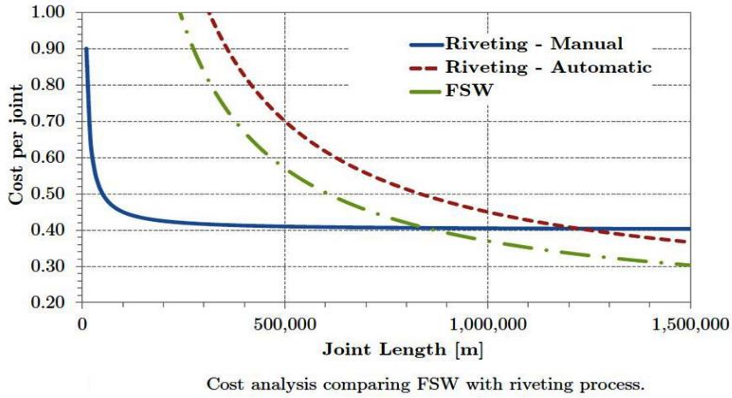


Figure 11-26: Friction Stir Welding – Process time and costs

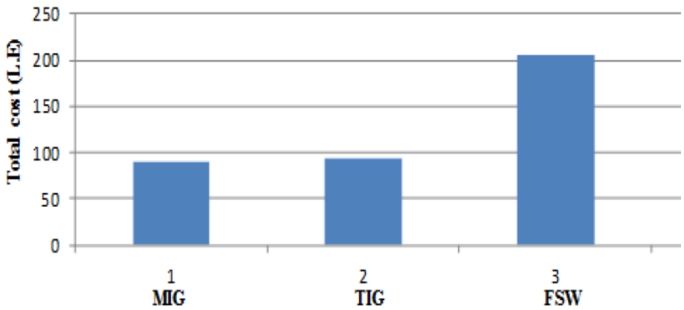


Figure 11-27: MIG and TIG vs FSW– Process costs

Requirements for FSW system installation

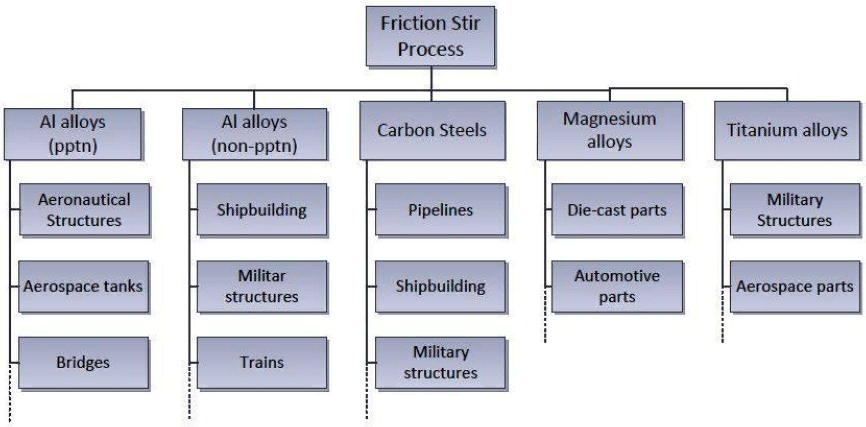


Figure 11-28: Friction stir process, materials and applications

Examples of FSW applications:

– **in the shipbuilding industry**: panels for decks, sides, bulkheads and floors, hulls and superstructures, helicopter landing platforms, off-shore accommodation, masts and booms, refrigeration equipment etc.

– **in the railway industry**: high speed trains, rolling stock of railways, underground carriages, trams, railway tankers and goods waggons, container bodies, roof and floor panels.

– **in manufacturing automotive mechanical components**: 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.

– **others high tech industries:** aeronautics, space vehicles, nuclear plants…

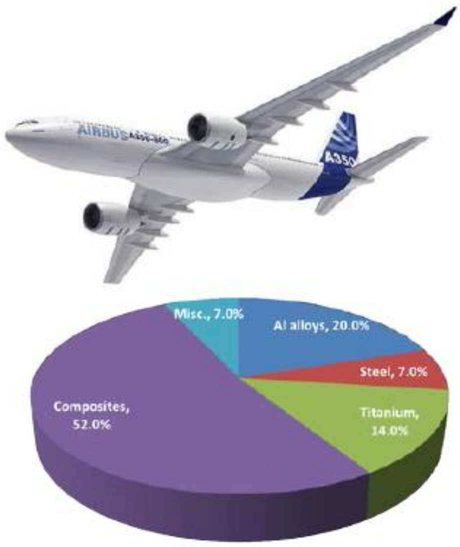
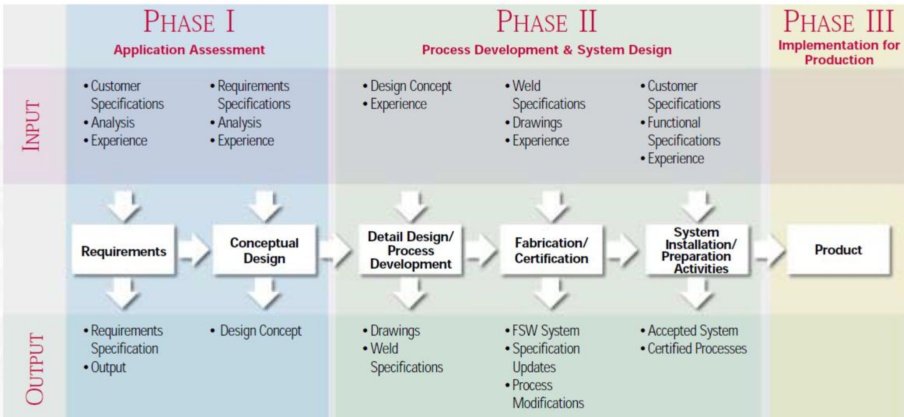


Figure 11-28: Example of FSW application – Airbus A350 XWB, 2013 (Courtesy of Airbus)

FSW Production Implementation



The ISOLATED FOUNDATION is required to reduce both active and passive vibrations. Vibration isolation mountings are required to reduce the transmission of vibration and shocks.

A foundation block or vibration isolation mountings for high dynamic machines like FSW machines, power press, forging hammers, compressors, engine test rigs etc. is required in order to reduce the transmission of vibration and shock to nearby precision equipment or building structures. To control the source of vibration disturbance through the use of resilient insulating materials is known as ACTIVE VIBRATION ISOLATION.

When it is not possible to prevent or sufficiently lower the transmission of shock and vibration from the source, a resiliently supported vibration insulating foundation block can be used for the PASSIVE VIBRATION ISOLATION of sensitive equipment like CNC equipment, Measuring & Control Systems, and Laser Tracking Systems.

ISOLATED FOUNDATION lowers the center of gravity of the machine foundation system and adds to the stability of the machine. Machine remains aligned during dynamic load changes and rapid movements within the machines.

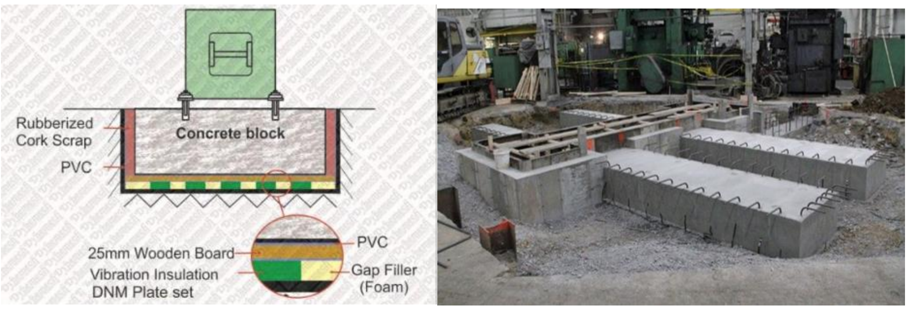


Figure 11-29: Example of foundation block or vibration isolation mountings for high dynamic machines

The mass of machine and foundation acts downwards together and it is saying m_f which acts at the center of gravity of the system. The mass of soil which acts upwards is say m_s.

The elastic action of soil due to vibration of system is dependent of stiffness k. Resistance against motion is dependent of damping coefficient c.

So, these three mass, stiffness and damping coefficient are required to complete the analysis of machine foundation.

Quality control- Examination

All the welds obtained by FSW will be examined visually in first instead and after that can be done the examination type what the beneficiary need (visual, tensile, bending, macro, micro, etc).

ISO 25239:

- Visual testing
- Tensile test
- Bend test
- Macroscopic test

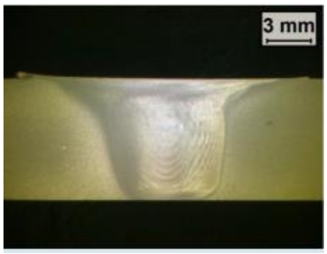


Figure 11-30: Examination after FSW weld

Logistics

These customer expectations define the purpose of a logistics system—it ensures that the right goods, in the right quantities, in the right condition, are delivered to the right place, at the right time, for the right cost. In logistics, these rights are called the six rights.

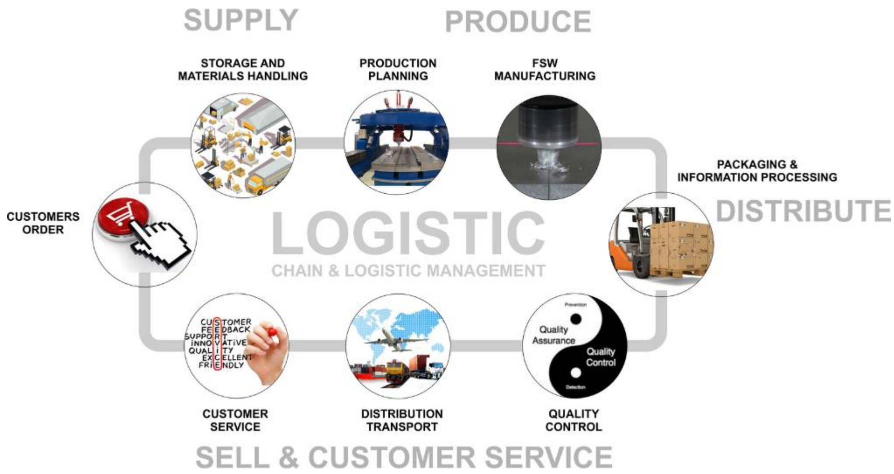


Figure 11-31: Logistics schedule

Post processing operations FSW

Post processing operations FSW is for example Key-hole filling and in HZG –Hamburg the researcher developed a technology through which they can fill the crater formed at the end of the weld, they use they use a filler that fills the defect created by Friction Riveting.

Grinding operations if is necessary, if the crater is too big and it can be filled, in general, it is preferable not to do too many operations in the FSW case.

FSW Machine – pin tool

Auto adjustable pin tool:

- For welding materials of varying thickness
- Pin can be incrementally withdrawn from the workpieces thus eliminating any crater or keyhole in the weld

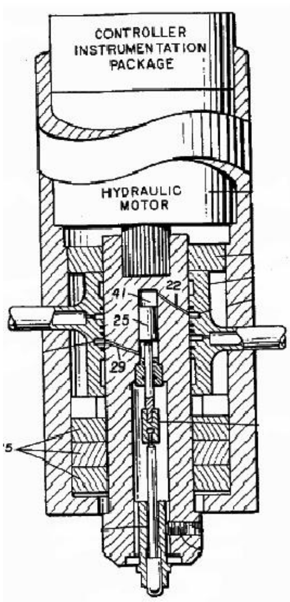


Figure 11-32: FSW with adjustable pin (Patent: Sept. 1997, DING R JEFFREY, NASA, US5893507)

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12. Case Studies

Friction stir welding, which was invented and patented in 1991, led to many worldwide applications. It is mainly used to weld large aluminum components and panels.

12.1. Case study number 1: Autoclave fixtures

APCO Technologies SA from Switzerland made large autoclave table for curing composite satellite components. The table was produced using multiple plates and FSW. The final table surface plate was to measure 6.1m by 4.3m with a thickness of 20mm and made from four the aluminium-magnesium alloy AA5083 plates. Welding on both size results in minimized distortion. Additional processes include post-weld stress relieving heat treatment and plate machining. The welds could not be distinguished from the rest of the plate and are within the tolerances [12-1].

12.2. Case study number 2: Vibration test tables

Vibration test table allows to mount specimen onto a vibration table and transmits forces, which are produced by vibration table. Proper design and manufacturing methods should be involved to ensure safe operation of fixture. Aluminium is most commonly used for manufacturing shake tables and fixtures. Other materials include steel and aluminium. Fixture should be designed to be as rigid as possible to avoid unnecessary vibrations.

There are three possible ways to manufacture rigid structure:

– subtractive manufacturing starts with a single block of solid material and portions of the material are removed until the desired shape of fixture is reached. Main disadvantage of this approach is generation of a scrap material. It is most expensive way to manufacture test table.
– casting provides a more rigid attachment than welded structures. Cast constructions are more flexible than welded fixtures.
– welded construction has associated inherent weakness root cracks or blow holes.

As an alternative, friction stir welding can be implemented to manufacture vibration test tables. Comparing FSW to conventional welding methods, friction stir welding has the advantage that it breaks up the coarse silicon particles and heals any pores by the mechanical processing in aluminium alloys. It also offer lower distortion, lower heat input and lower shrinkage [12-2, 12-3, 12-4].

12.3. Case study number 3: Crack repairs

Crack repairs using FSW was introduced by Boeing Company for the first time. Method consist:

- Preparing a surrounding surface of the crack for repairing
- Welding a first portion of the component on a first side of the crack
- Welding second portion of component on a second side of the crack to form a fused crack area.

Advantages over existing crack repairing techniques include minimal distortion, low residual stress and alteration of chemical and physical properties. The method is more durable and longer lasting than traditional repairing techniques [12-5, 12-6].

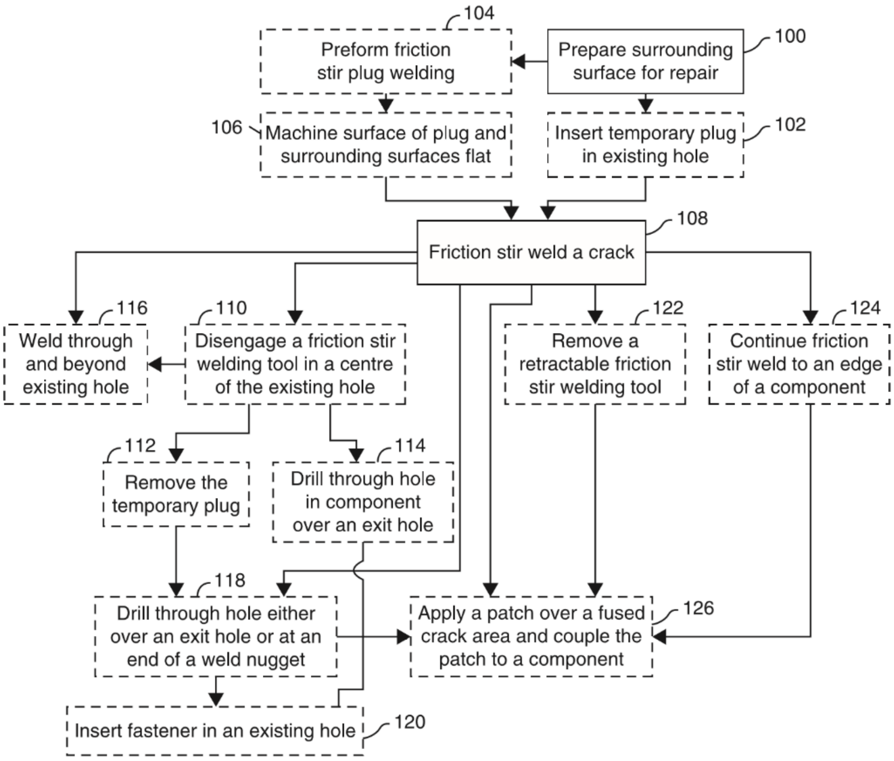

Figure 12-1: Logic flow diagram illustrating the method of repairing the crack – Courtesy of [12-5]

12.4. Case study number 4: Underground vehicles

Bombardier use FSW to join stiff longitudinal extrusions, which constitute the car body's sidewalls. Vehicles were used to upgrade Victoria Lane, which is a London Underground line [12-9].

12.5. Case study number 5: Solar panels

Aluminium collector made from aluminium can be welded using FSW. This approach is used by company Grenzebach. The thin parts can be joined with minimal distortion. FSW reduce risk of leakage, because the welds are free from defects like porosity and heat cracks [12-7].

Figure 12-2: Solar roof collector before painting – Courtesy of [12-7]

Figure 12-3: Roof made with solar roof collectors – Courtesy of [12-7]

FSW is also used to join heat sinks with high density fins by Walmate [12-8]. They field application include wind and solar energy sectors.

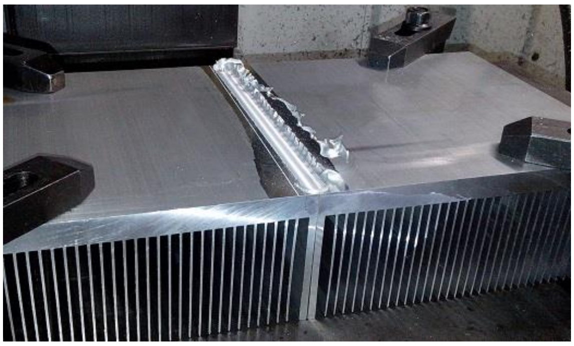

Figure 12-4: Friction stir welded heat sink – Courtesy of [12-8]

12.6. Case study number 6: Naval shipbuilding panels

The easily available extrusions, which are produced in standard size extrusion presses, can be joined using FSW. As a result, the wide panels for shipbuilding industry can be made. Main advantage in comparison to fusion welding, are low heat input, low distortion and reduced thermal stresses. FSW is approved process by international surveying bodies, including:

- ABS – American Bureau of Shipping
- BV – Bureau Veritas
- DNV – The Norske Veritas
- GL – Germanischer Lloyd
- LR – Lloyd's Register of Shipping
- RINA - Registro Italiano Navale etc. [12-10]

Figure 12-5: Super Liner Ogasaware – Courtesy of [12-11]

The Super Liner Ogasaware, built by Mitsui Engineering and Shipbuilding in Japan is reported to be the largest ship constructed using friction stir welding.

Table 12-1. Standards and specifications – Courtesy of [12-12, 12-13]

Standard	Description
AWS D17.3/D17.3M:2010	Specification for Friction Stir Welding of Aluminium Alloys for Aerospace Applications
ISO 25239-5:2011	Friction stir welding -- Aluminium -- Part 5: Quality and inspection requirements
ISO 25239-4:2011	Friction stir welding -- Aluminium -- Part 4: Specification and qualification of welding procedures
ISO 25239-3:2011	Friction stir welding -- Aluminium -- Part 3: Qualification of welding operators
ISO 25239-2:2011	Friction stir welding -- Aluminium -- Part 2: Design of weld joints
ISO 25239-1:2011	Friction stir welding -- Aluminium -- Part 1: Vocabulary
JSC -NASAPRC-0014, Rev. B	Process Specification for Friction Stir Welding
MSFC - NASA-STD(I)-5006A	Welding Requirements for Aerospace Flight Hardware (pending)
AWS D8H: 20xx	Specification for Automotive Weld Quality—Friction Stir Welding (early stages of development)

Choice of materials

The choice of tool material includes:

– properties of the weld metal;
– required quality of the joint;
– strength of the work material, which determines the stresses induced to the tool;
– tool material properties related to heat generation;
– tool material properties related to coefficient of thermal expansion – thermal stress introduced by FSW;
– tool material selection can be also based on hardness, ductility and reactivity of the work materials [12-14].

Tools and welding procedures

FSW – weld procedure specification (WPS) and Welder Performance Qualification Record Requirements (WPQR) shall be developed and qualified prior to production welding. If needed there should be also prepared qualification of weld repair procedure. Special considerations shall be taken for fixturing. Tool is characterised by:

– Tool and probe material
– Tool and probe geometry/design, e.g., shoulder diameter, probe diameter, probe length, probe shape (conical, cylindrical, etc)
– Threads or no threads
– Number of flats (if applicable)
– Tool ID
– Probe ID (if two-piece tool) and shoulder design]
– Fabrication process (i.e., fixed, bobbin, retractable). [12-16]

Tolerances on weld preparation and fit-up

The process can accommodate a gap of up to 10% of the material thickness without impairing the quality of the resulting weld [12-15]. Additional requirements can be found in FSW standards.

For example, ABS in guide for "THE APPROVAL OF FRICTION STIR WELDING IN ALUMINUM" require a joint setup with sweep (horizontal) or joint misalignment (vertical) no greater than ±1 mm. If it is greater than ±1 mm, a separate procedure is required. Sweep and misalignment should be verified prior to production welding as to joint setup and checked after welding to confirm shifting of the joint did not occur during welding. It is possible that FSW can be done using automated seam tracking or joint position and alignment. In this case monitoring of misalignment can be eliminated.

In the time of inspection during production FSW corrective actions can be implemented if necessary. There is a need to verify that fixtures used for restraining the work are capable of maintaining the joint within the parameters of the weld procedure. This solution results in manufacturing welded parts inside tolerance limits.

Dimensional inspection after production FSW requires, for example, that weld concavity depth (face or root) is not to exceed 0.8 mm or 10 percent of the adjacent base metal thickness, whichever is less. Another requirement is related to butt joint alignment and width of the weld [12-16].

Post weld heat treatment, NDT and quality control

Post weld heat treatment (PWHT) can be deployed successfully with aluminium alloys, especially 2xxx and 7xxx aluminium alloys. Effects of heat treatment depends on type of heat treatment and can include:

- uniform hardness distribution;
- improved or lowered tensile properties of the joint;
- improved fatigue performance;

General approaches include:

- leaving the material in the as-welded condition,
- applying a low temperature stabilizing heat treatment (e.g. 25 hours at temperature near 100°C),
- applying a solution heat treatment to the material after welding and then age to desired temper,
- applying additional post-weld aging to material originally in T6 or earlier temper to arrive at the final desired temper,
- applying a localized post-weld treatment. [12-17, 12-18]

Quality control should be conducted before welding, during production, and after FSW.

Verification before welding should be conducted to verify that operator has a valid qualification/certification for the intended job/ It is also needed to ensure if essential elements of the production job are consistent with the approved qualification. Joint setup variability should be also checked.

During production FSW needs continuous in-process monitoring of all friction stir welds. After production FSW it is needed to perform 100% visual inspection.

Other inspection after FSW can include macro tech (destructive testing), penetrant testing, ultrasonic testing and radiographic testing.

Visual Inspection practice

Visual inspection is performed to evaluate physical attributes of the friction stir weld. It confirms that proper operating conditions were maintained during fabrication. Both top and bottom of each friction stir weld shall be inspected to the maximum extent possible, for attributes include:

- Exit hole uniformity,
- Flash,
- Chevron markings,
- Dimensional variations in thickness,
- Misalignment,
- Cracks,
- Porosity,
- Lack of penetration [12-16].

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