



AILEEN

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them. PROJECT REFERENCE NO. 101103507



Co-funded by
the European Union

Friction Stir Welding Process

Azeem Uddin Azeem Islam



CenSec
CENTER FOR DEFENCE, SPACE & SECURITY



PRI
PERFORMANCE REVIEW INSTITUTE



Fraunhofer
FIT



SICNOVA



Outline



AILEEN

- Friction Stir Welding Process
 - Heat generation, welding parameters, joint preparation.
 - Equipment and accessories.
 - Process applications and limitations.

FSW – Introduction

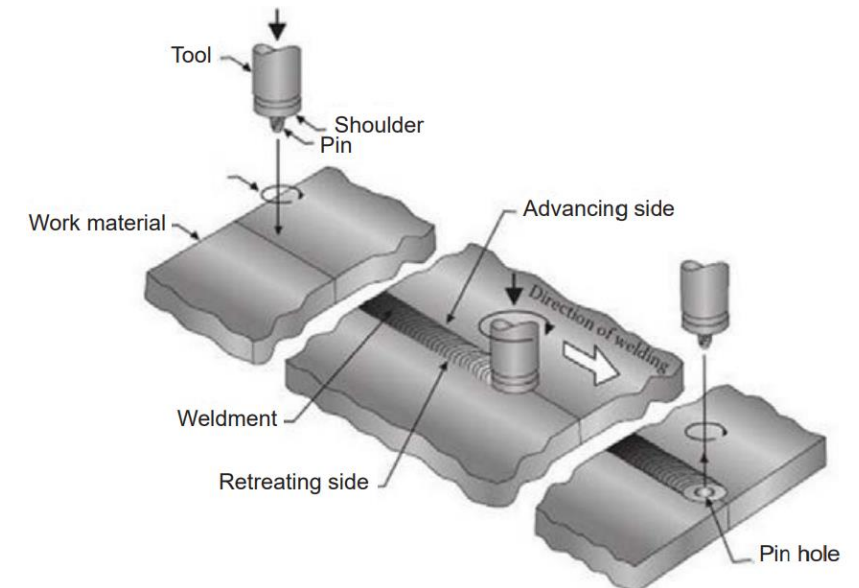


– History of FSW

- The Welding Institute, TWI (UK) patented in 1991
- Overcomes many of the problems associated with traditional joining techniques
- FSW is a solid-state process which produces welds of high quality in difficult-to-weld materials such as aluminium, and is fast becoming the process of choice for manufacturing lightweight transport structures such as boats, trains and aeroplanes.
- A solid-state process that mechanically mixes metals together to form a bond.

FSW – Introduction

- In the process, a rotating FSW tool is plunged between two clamped plates. The frictional heat causes a plasticised zone (below melting point of materials) to form around the tool. The rotating tool moves along the joint line. A consolidated solid-phase joint is formed.
- One TWI machine has a vacuum clamping table
 - Sheet thickness: 1mm - 25mm aluminium
 - Work envelope: 5 x 8 x 1m
 - Maximum down force: 60kN (6t)
 - Maximum rotation speed: 5000rev/min



– Process capabilities

- The benefits include the ability to join materials that are difficult to fusion weld, for example, 2XXX and 7XXX aluminium alloys, magnesium and copper.
- FSW can use purpose-designed equipment or modified existing machine tool technology.
- The process is also suitable for automation and is adaptable for robot use (R-FSW).
- Low distortion and shrinkage, even in long welds
- Excellent mechanical properties in fatigue, tensile and bend tests
- No arc or fumes, no porosity, no spatter, no filler wire required, no gas shielding
- Can operate in all positions
- Low cost and Energy efficient

FSW – Introduction



– Process capabilities

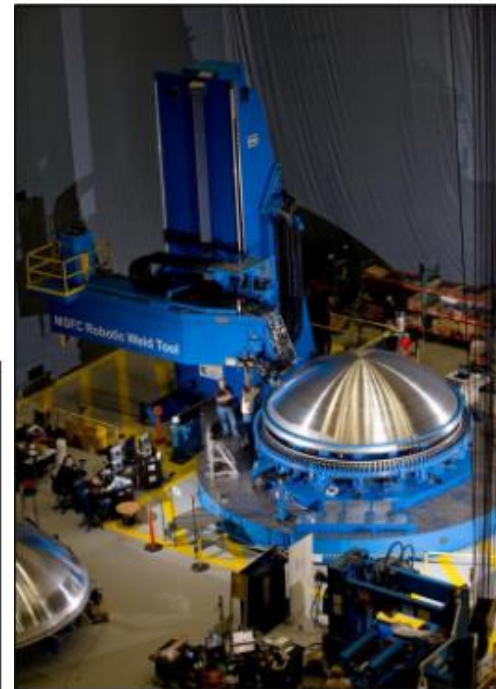
- Tool life typically be used for up to 1000m of weld length e.g., 6XXX series Al alloys
- Some tolerance to imperfect weld preparations - thin oxide layers can be accepted
- No grinding, brushing or pickling required in mass production
- Can weld aluminium and copper of >75mm thickness in one pass.
- Component thicknesses from 0.3mm - 75mm have been joined successfully.



FSW – Equipment

– Equipment:

- For smaller products, the equipment may vary from a manually controlled sturdy CNC machine to an automated robot line for multi-axes welds.



FSW at NASA

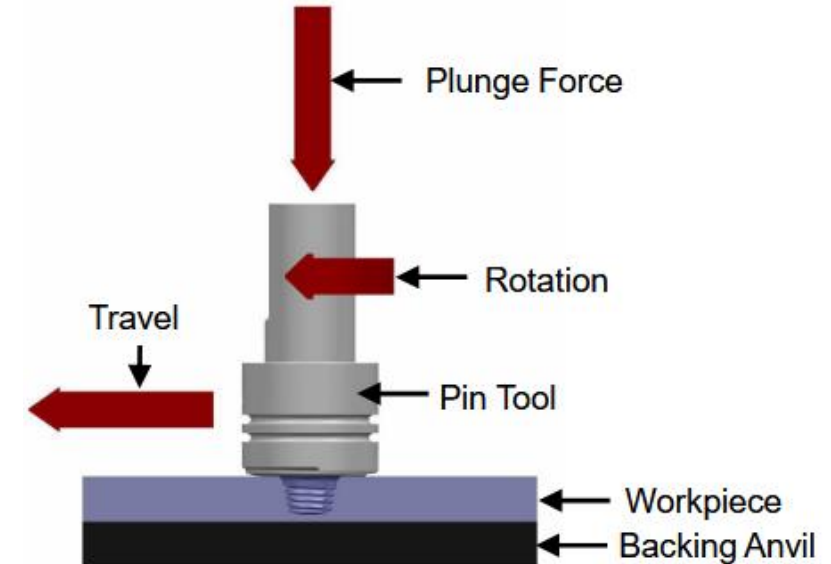
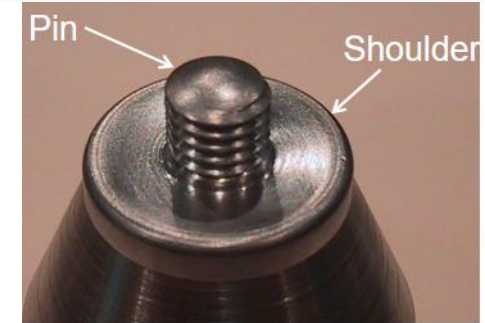
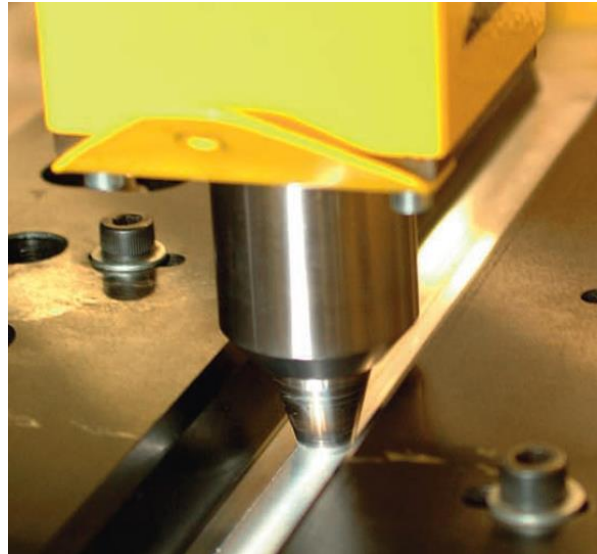


Robotic - FSW

FSW – Equipment

– Equipment:

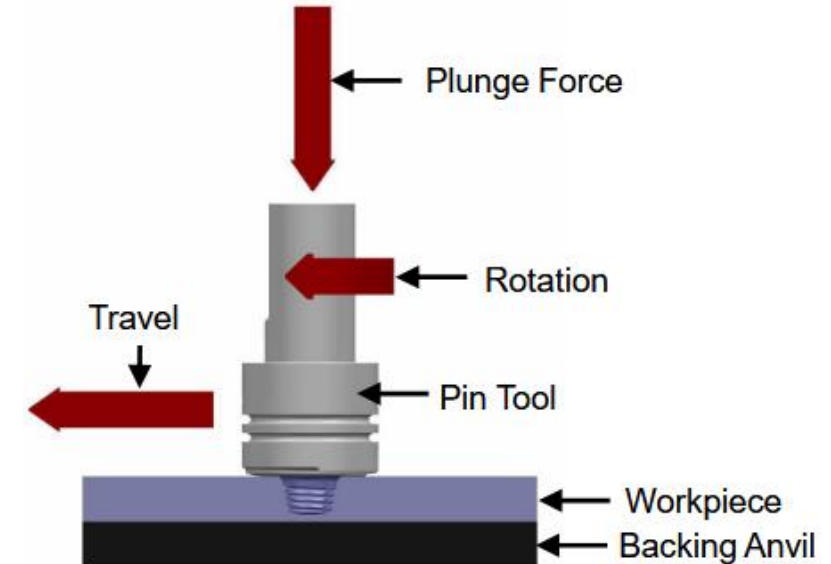
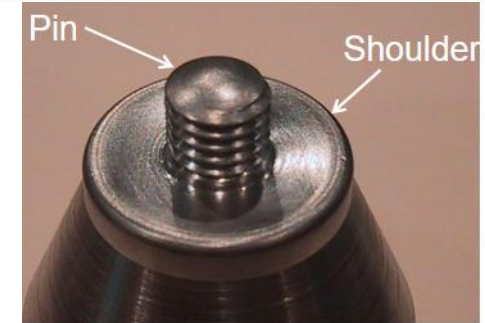
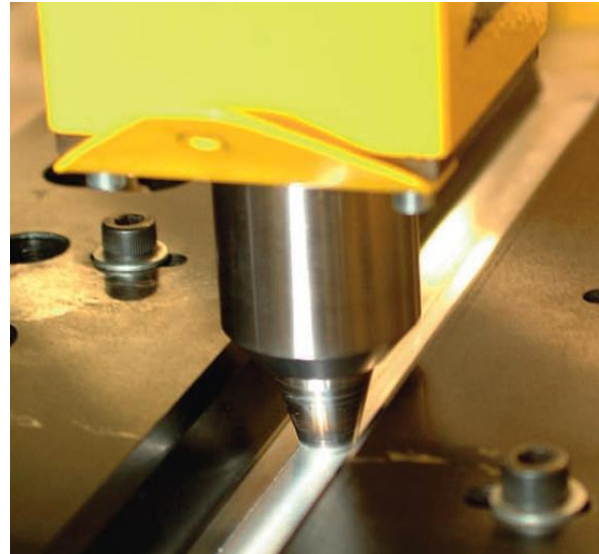
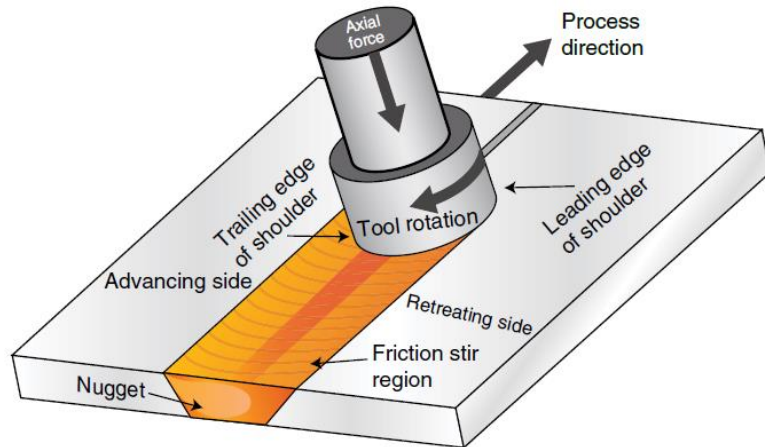
- Simple function
- Motorized rotating tool (single or multi-axis)
- Stationary or traverse motion
- Workpiece support
- Varies, power capacity, length capability, tool customization so material compatibility etc.



FSW – Equipment

– Equipment:

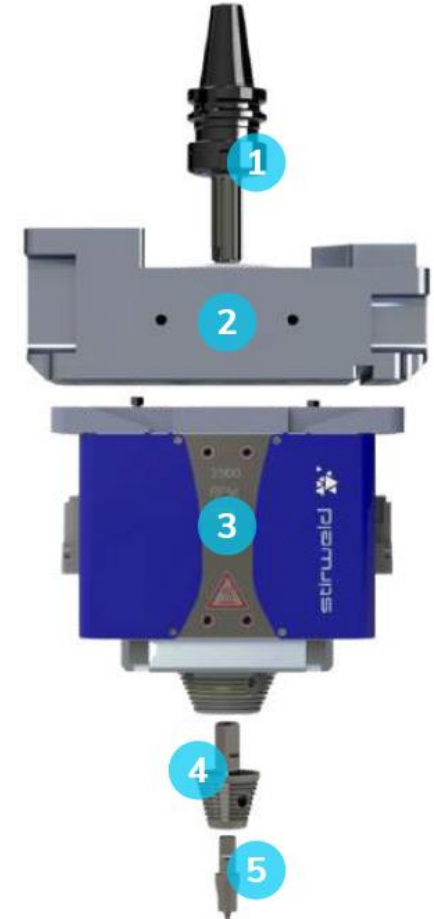
- Simple function
- Motorized rotating tool (single or multi-axis)
- Stationary or traverse motion
- Workpiece support



FSW – Equipment

– Equipment:

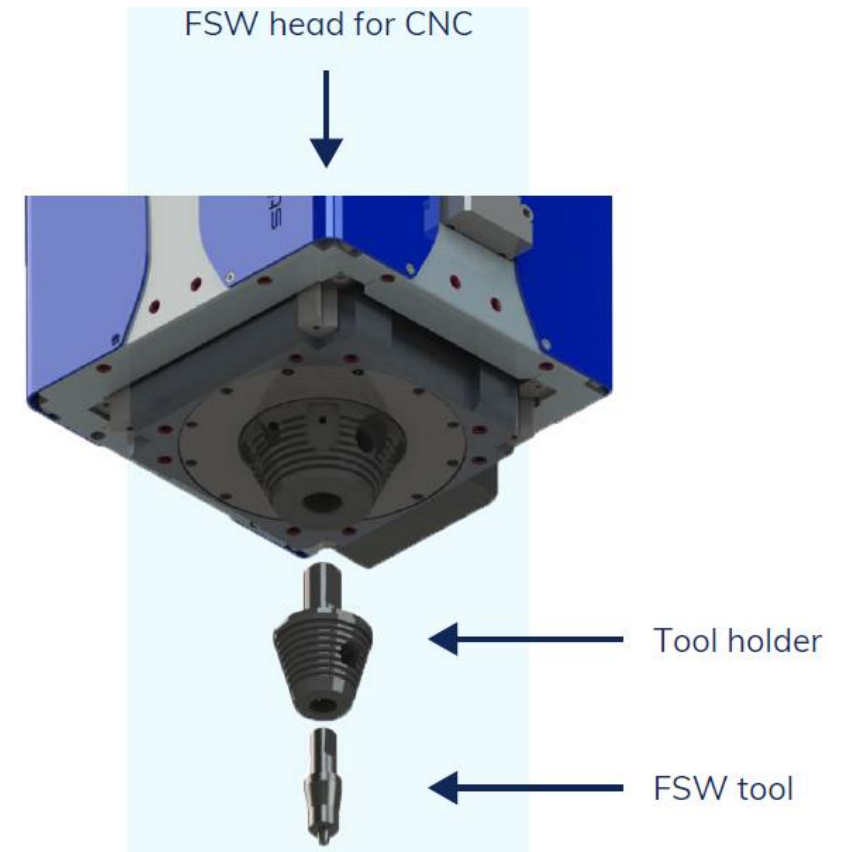
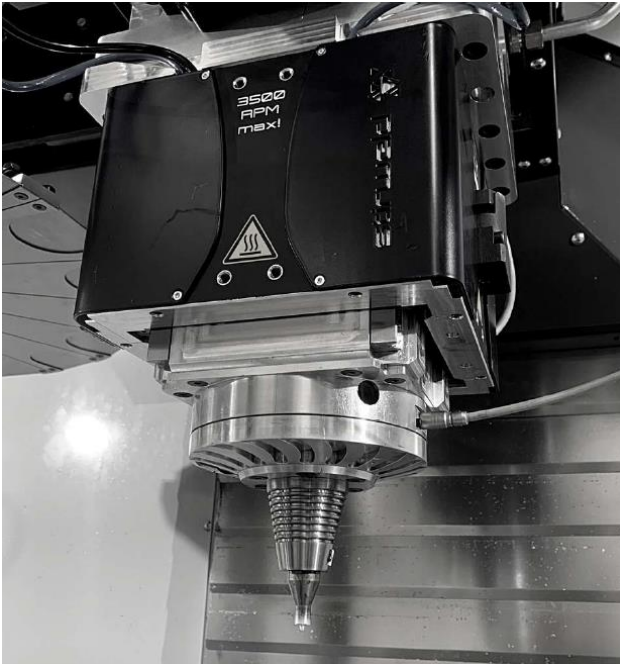
- FSW Tool head
 1. Axis: Shaft fixed with CNC spindle
 2. Adaptor: Fixed to CNC frame, support FSW head weight
 3. Core of the head
 4. Tool holder
 5. Tool
- Same in Robotic FSW



FSW – Equipment

– Equipment:

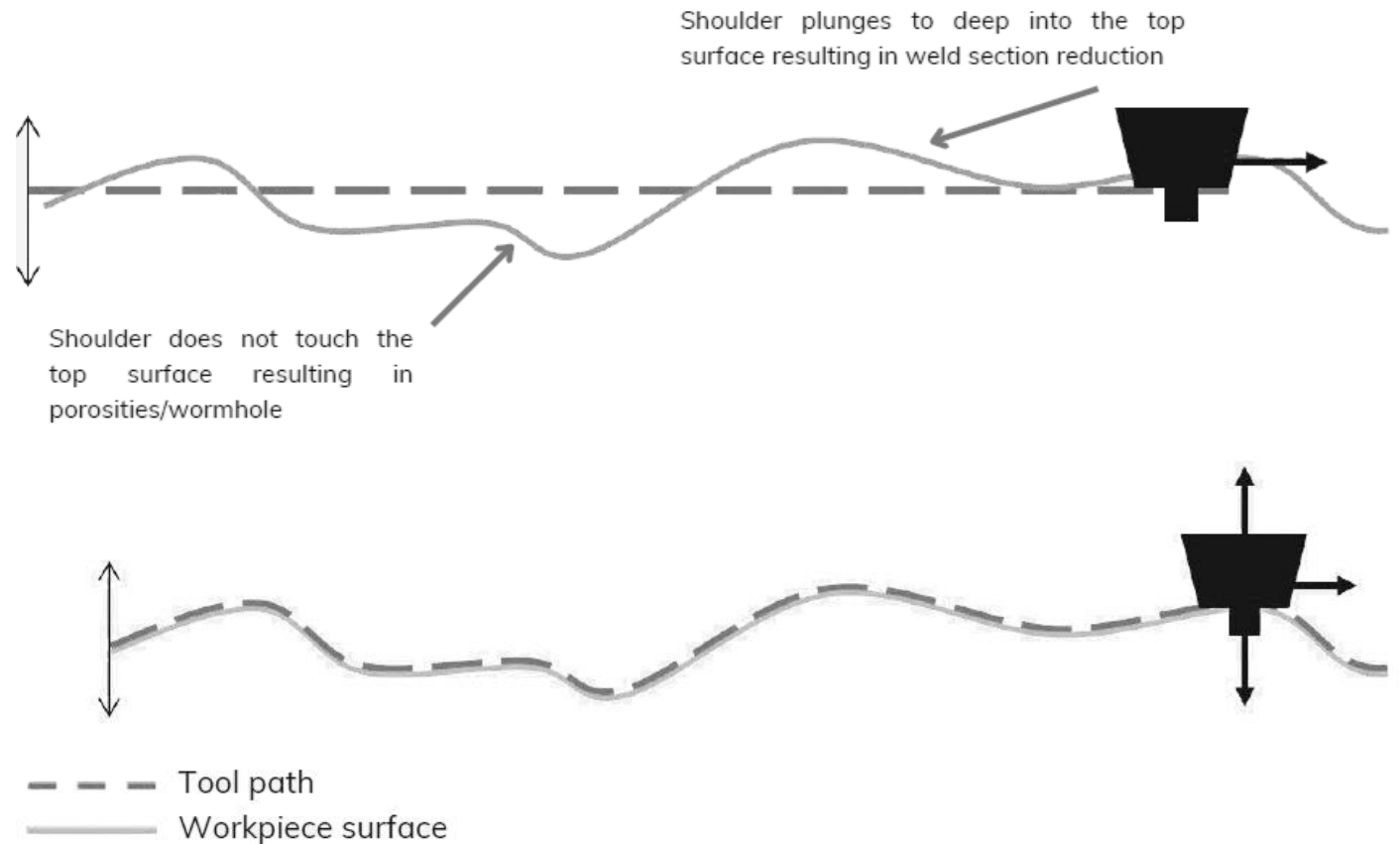
- Tool head: Smart tool head can measure temperature, have liquid cooling, force & vibrations protection



FSW – Equipment

– Equipment:

- Tool head with & without force control feature



FSW – Equipment



AILEEN

– Equipment



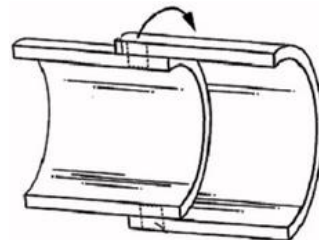
Vertical Longitudinal welding



Horizontal Longitudinal welding



Longitudinal welding



Circumferential welding



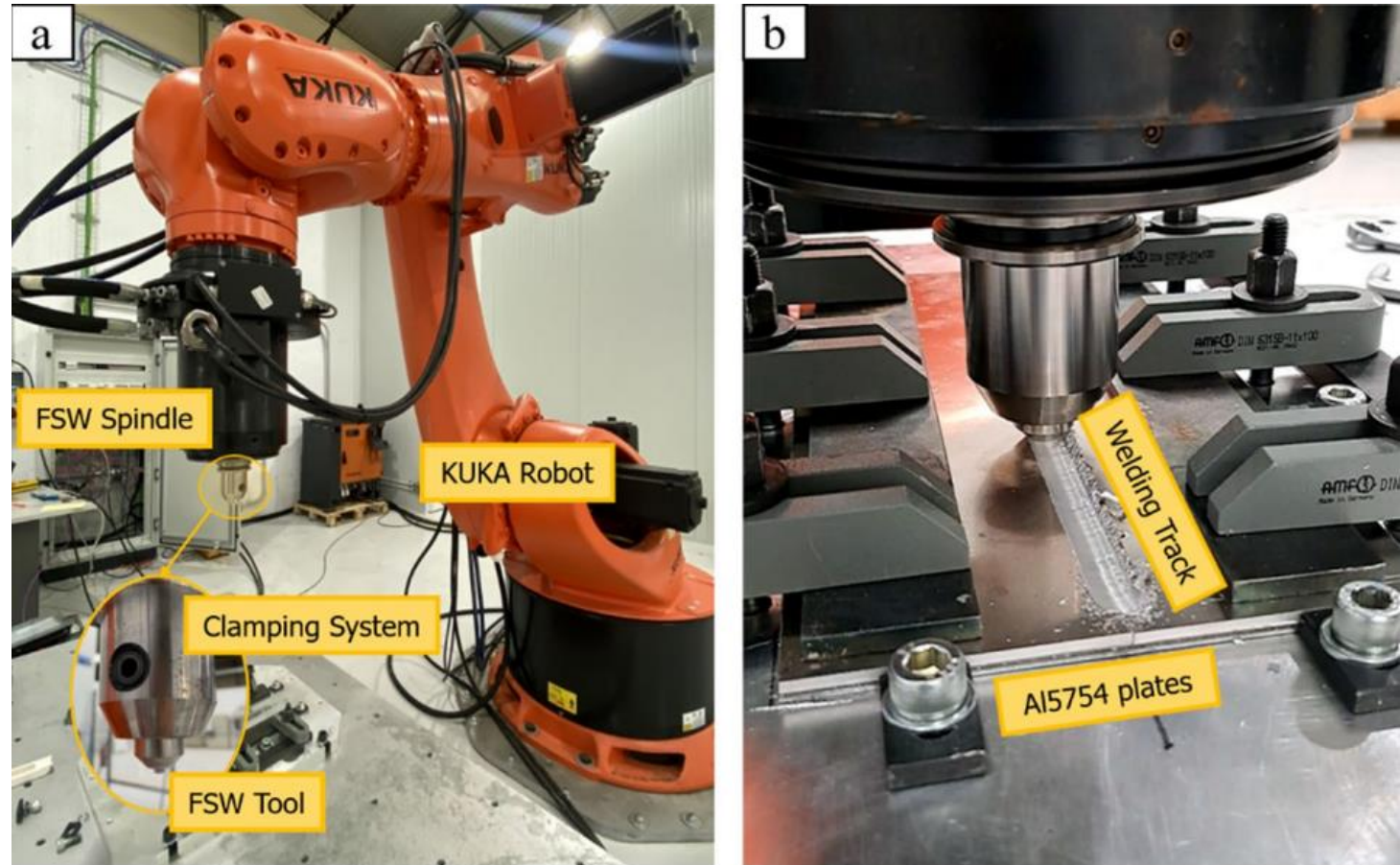
Robotic multi-axis welding

FSW – Equipment

– Equipment



IN718 FSW Tools produced by DED-wire AM technology and machined



CETEMET R-FSW setup and Al plates welding in process

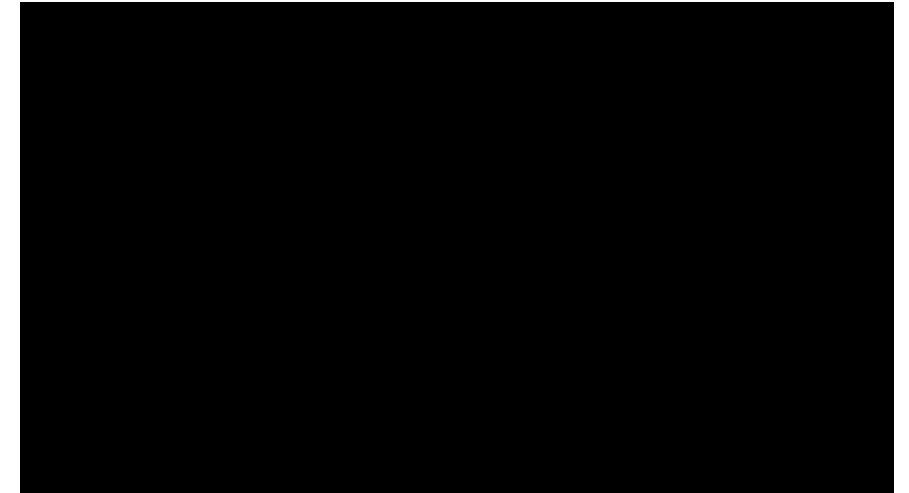
Credit: MULTHEM

FSW – Process and parameters



AILEEN

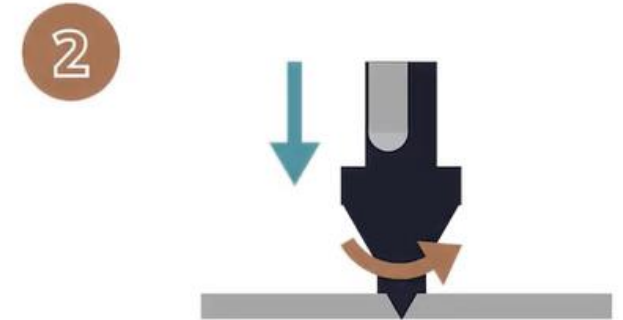
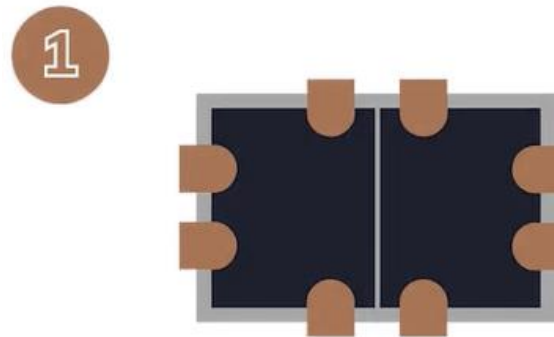
- Friction stir welding is a joining method of materials using the heat produced under a rotating tool which is not consumable.
- When the tool is rotated in relation to the work piece touching on their surfaces, heat is produced by friction between the work piece and the tool.
- Due to the generated heat, the work-piece material becomes soft before reaching the melting temperature and providing strong bonding in that soft state.



FSW – Process and parameters

– FSW weld in four steps

1. Clamping of the parts
2. Tool rotates & plunges into the material
3. Welding process
4. Tool rises or disengages from the parts



Credit: Stirweld

FSW – Process and parameters



- FSW weld in four steps
 1. Clamping of the parts
 2. Tool rotates & plunges into the material
 3. Welding process
 4. Tool rises or disengages from the parts



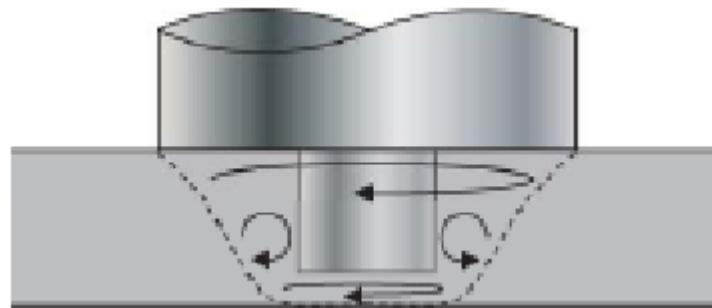
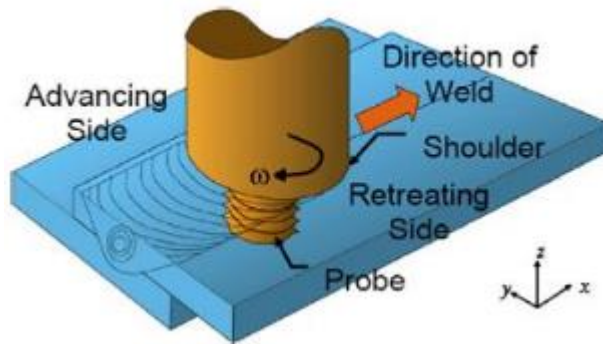
CNC FSW

Credit: Stirweld

FSW – Process and parameters

– FSW weld simply,

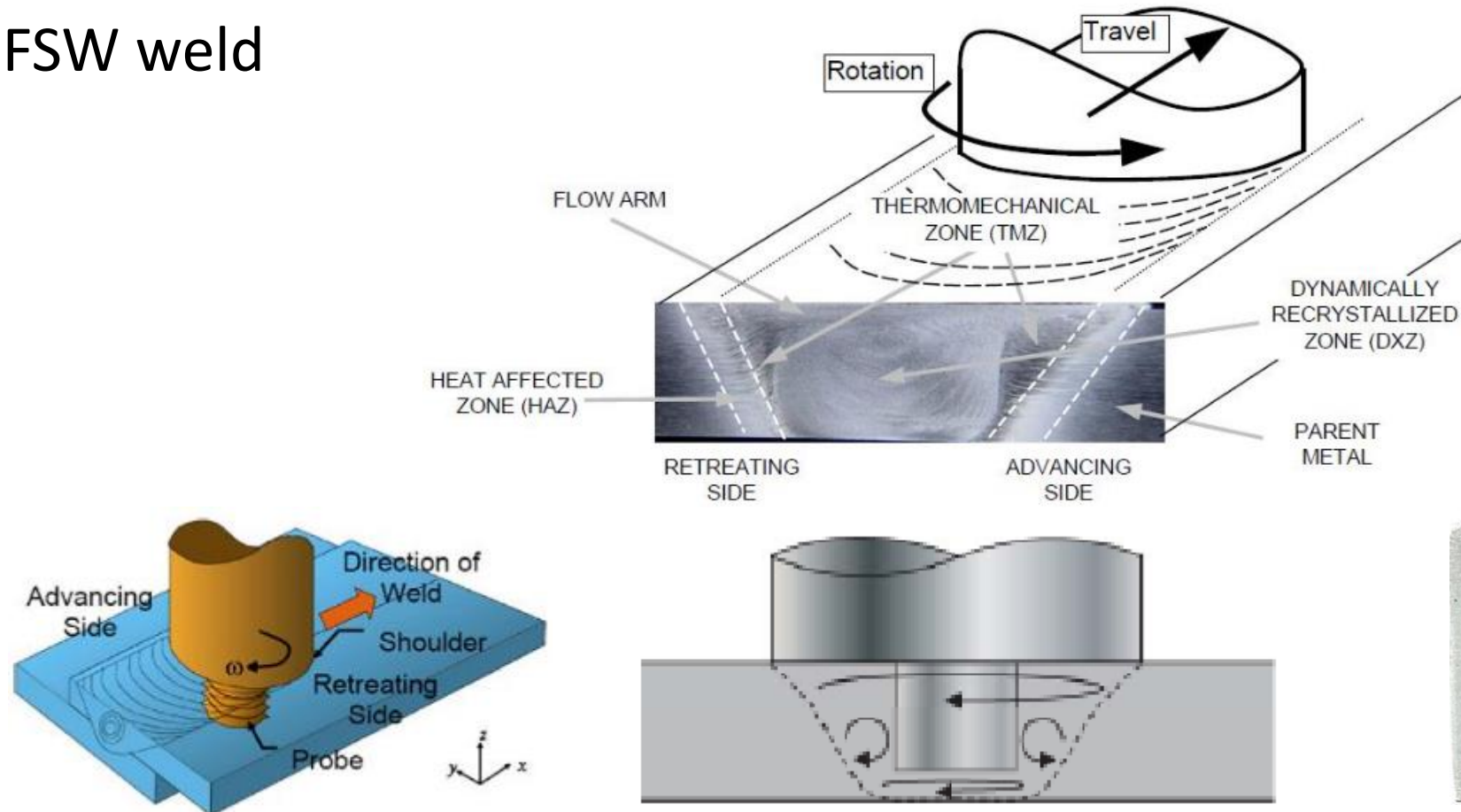
- Heat is generated by friction between the tool and workpiece material
- Material adjacent to the tool softens
- The softened material is mechanically mixed by the tool
- The softened material is joined using mechanical pressure supplied by the tool shoulder



A FSW weld

FSW – Process and parameters

– FSW weld

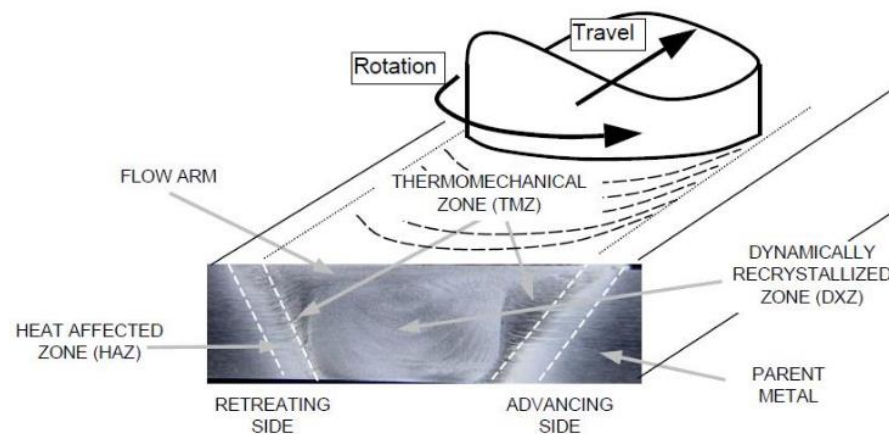
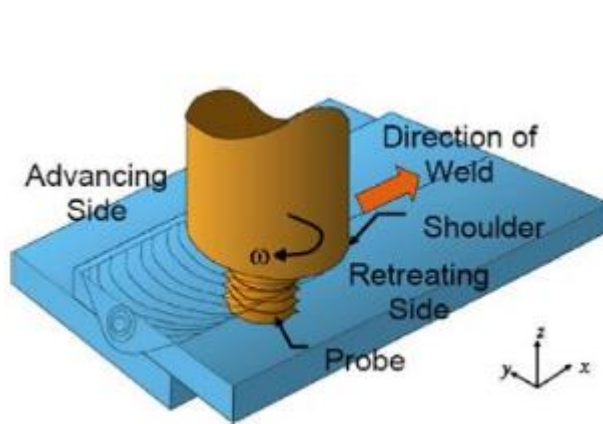
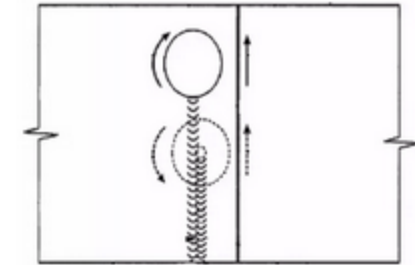


A FSW weld

FSW – Process and parameters

– Multi-pass FSW weld

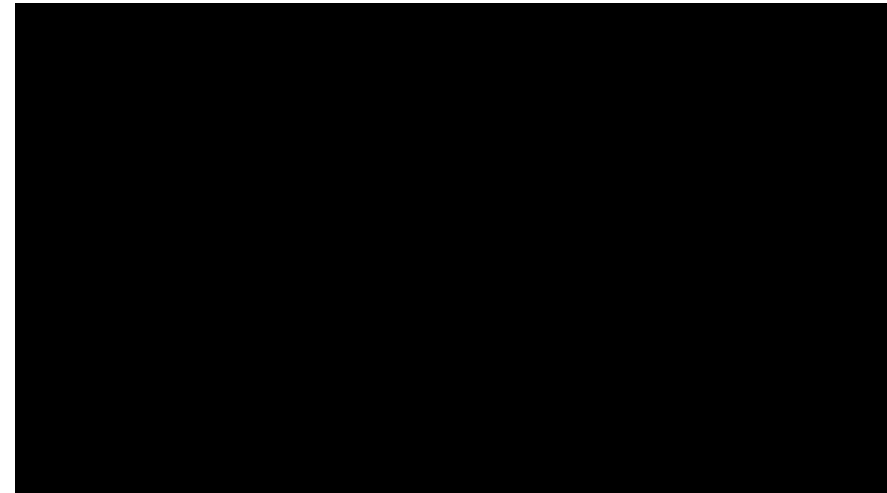
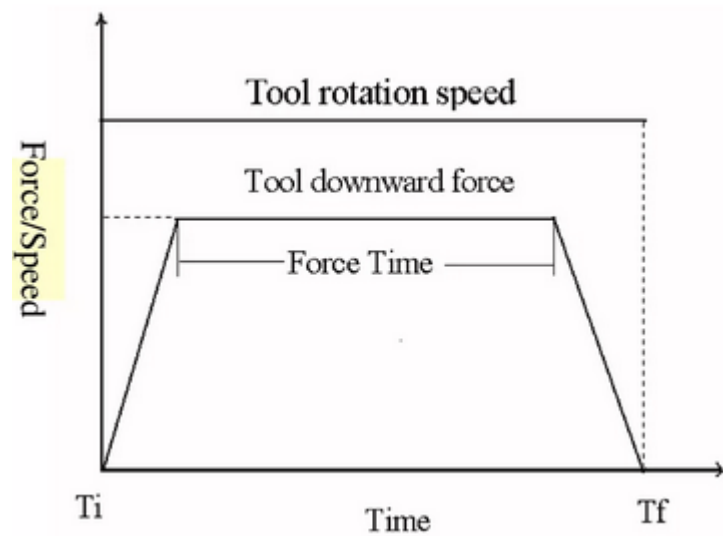
- Material on the advancing side is mixed vigorously
- So, for uniformity second pass is done
- Sides become opposite



A FSW weld

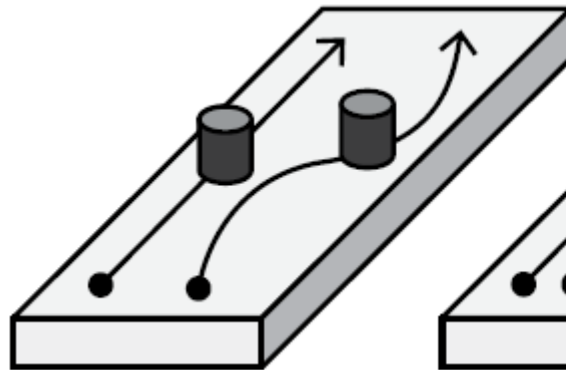
FSW – Process and parameters

- FSW weld
 - Cycle representation, typical FSW process

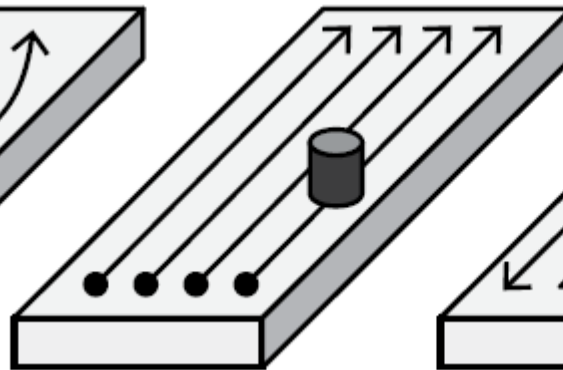


FSW – Process and parameters

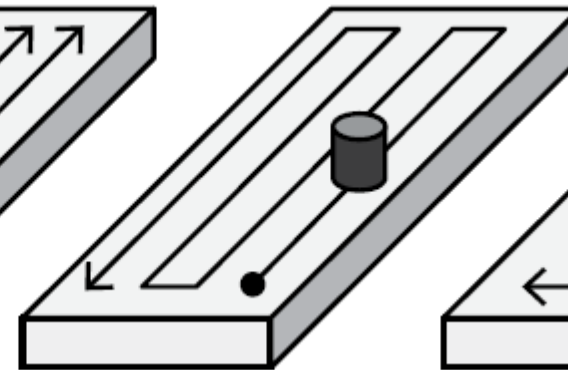
- FSW weld
 - Various tool paths



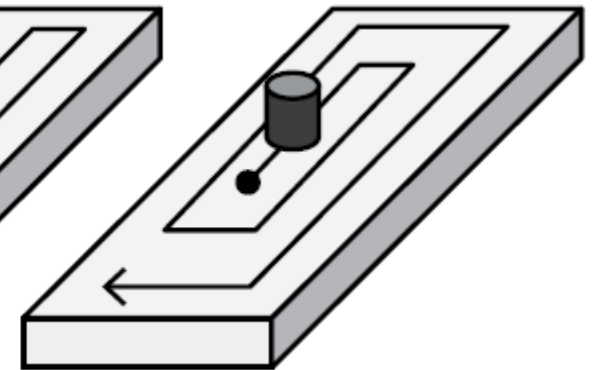
Linear & Curve



Multiple equal distance parallel pass



Raster path



Spiral path



Large cold plate



Thin cold plate



Copper



Standard

FSW – Process and parameters



– FSW simple weld test

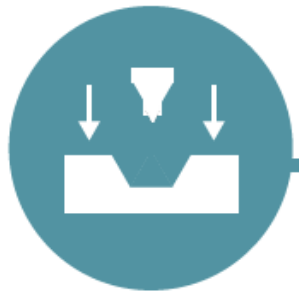


A Simple Weld Test

Credit: Stirweld

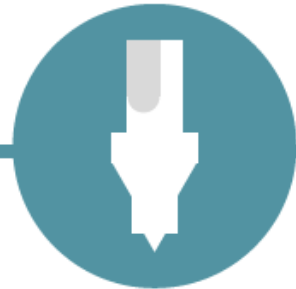
FSW – Process and parameters

– FSW quality weld



CLAMPING SYSTEM

Backing, Z-clamping,
XY-clamping



TOOL GEOMETRY

The shoulder and the pin
of the FSW tool



WELDING PARAMETERS

Rotational speed, welding
speed, Z-force



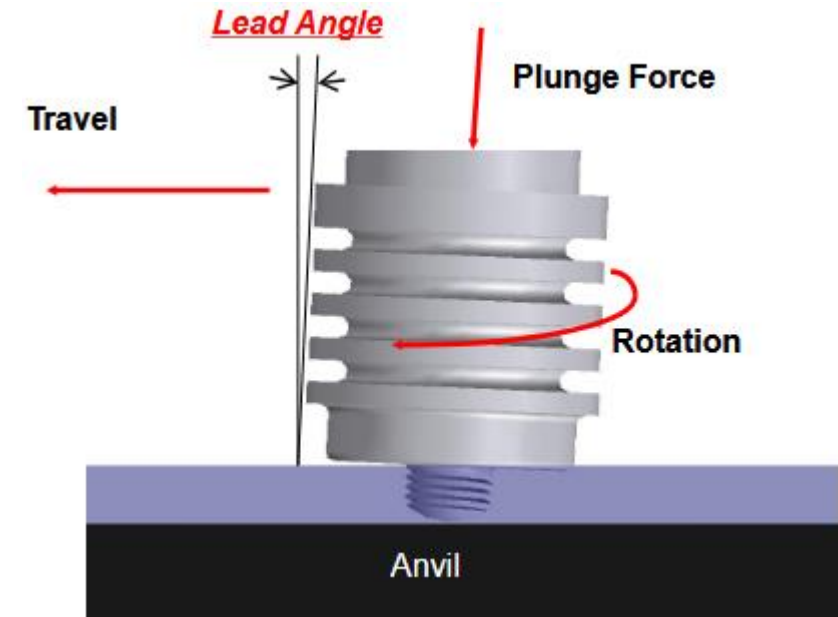
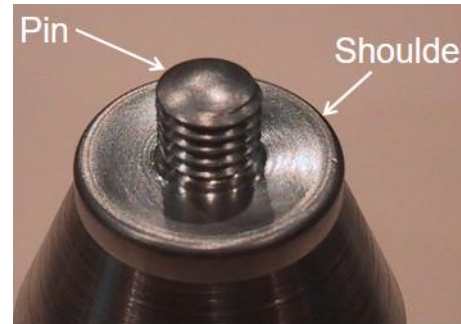
FORCE CONTROL

The penetration of the
tool must be constant

FSW – Process parameters

– Basic Parameters

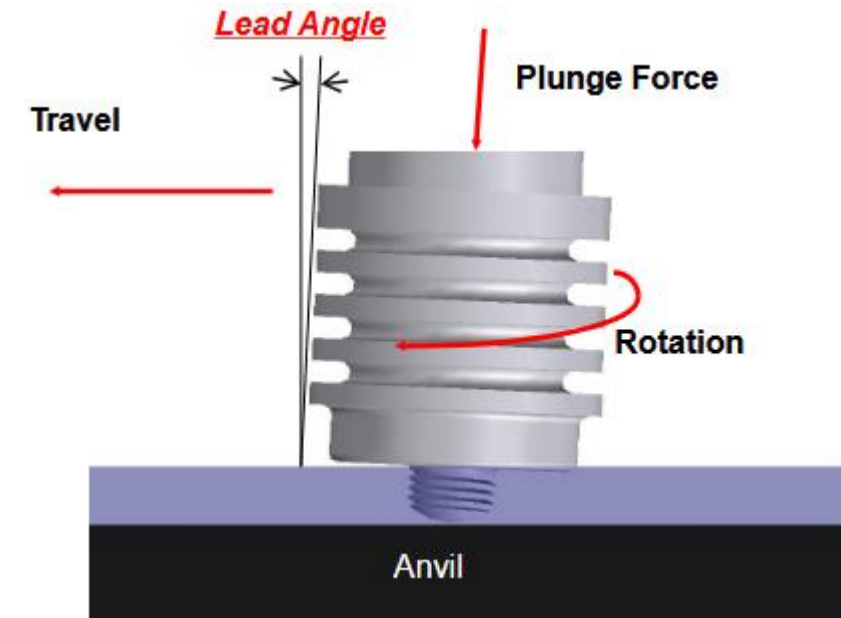
- Down plunge force
 - Travel / welding speed
 - Tool rotation speed
 - Tilt / lead angle
-
- Ensuring a high quality weld, the most important control feature is down force (Z-axis)
 - The heat generated in the joint area is typically about 80-90% of the melting temperature.



FSW – Process parameters

– Basic Parameters

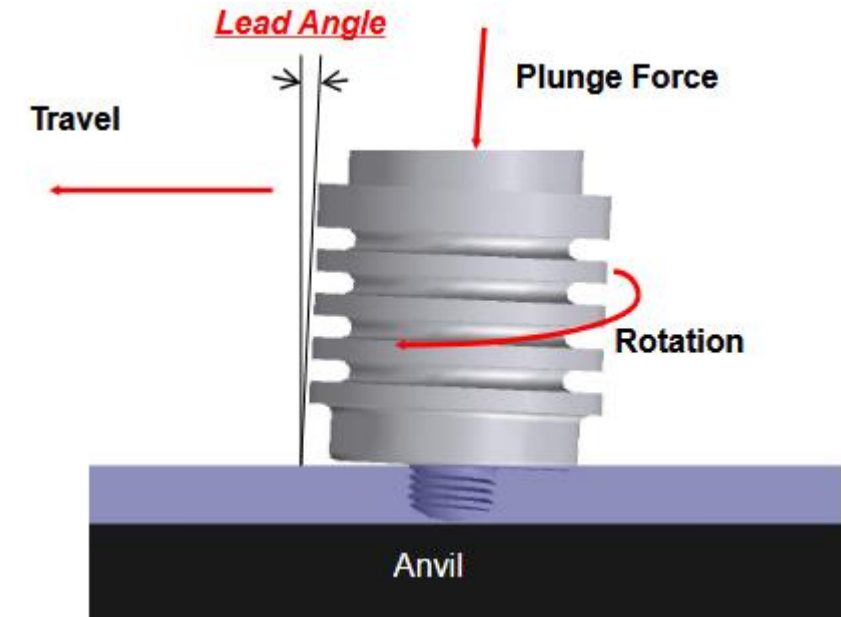
- Down plunge force or Axial force
 - The axial force is the force applied to the workpiece along the axis of tool rotation
 - The downward force applied ensures the continuous contact between the shoulder and the workpiece surface, in order to generate heat from the friction of these two surfaces.
 - 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



FSW – Process parameters

– Basic Parameters

- Travel / Traverse or welding speed
 - Direct relation with peak process temperature
 - Temperature increases with decrease in weld travel speed
 - Temperature increases with increase in tool rotation speed
 - Heat input inversely proportional to welding speed
 - To increase the welding speed, it's needed to increase rotation speed to keep the temperature needed for the operation.
 - High welding speed causes increase in stresses and wear on the tool. These can lead to an increased incidence of defects and require repairs



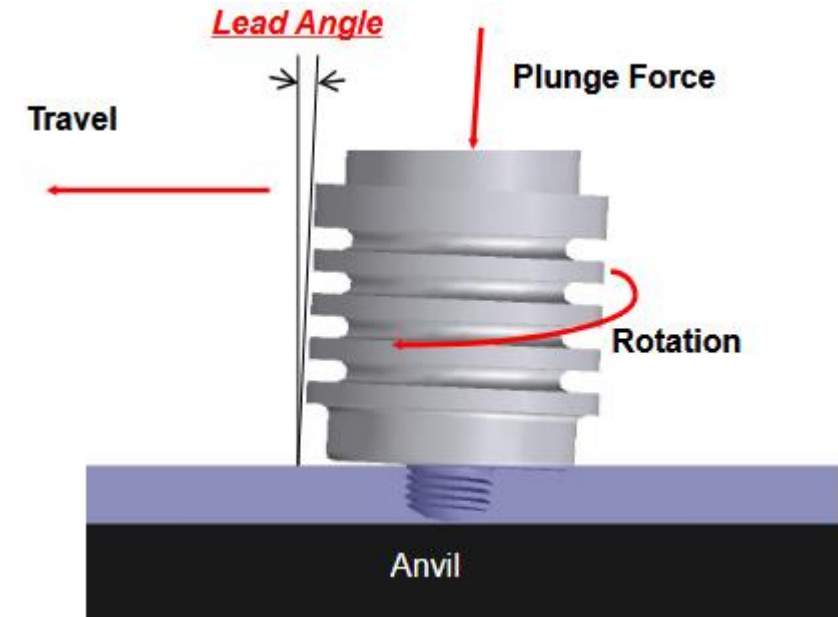
FSW – Process parameters



AILEEN

– Basic Parameters

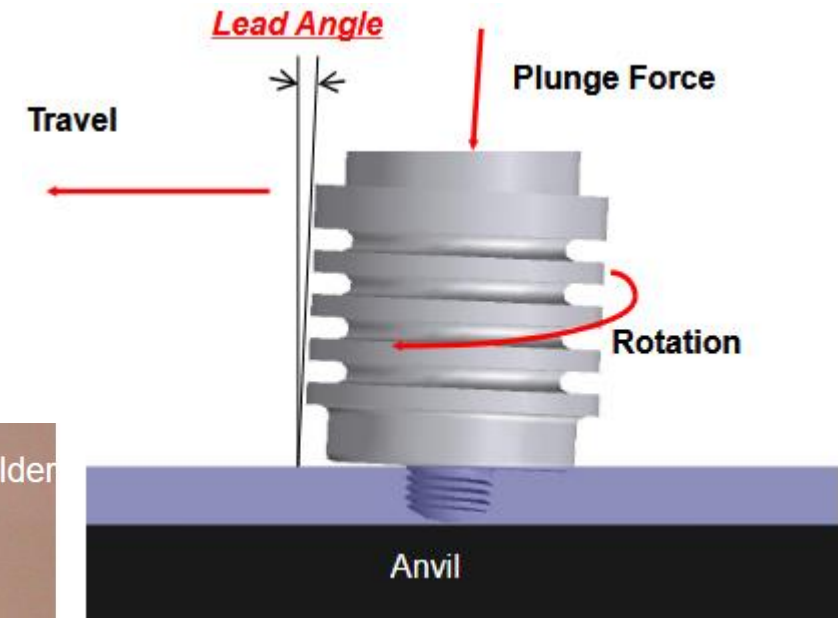
- Tool rotational speed
 - Process temperature increases with increase in tool rotation speed
 - Can be manipulated to increase welding travel speed for faster welding
 - Lead to high heat input & so higher cooling rates



FSW – Process parameters

– Basic Parameters

- Tilt / Lead Angle
 - Very minimum
 - Tilt angle is the angle between the centreline of the tool (axis) and a line perpendicular to the surface of the work piece, opposite to the direction of welding.
 - A featureless shoulder usually employs a tilt angle
 - Tool leans backward relative to welding path, to open room in front of the tool
 - The back of the tool does the forging of material behind the pin
- Typical values = 0° to 3°

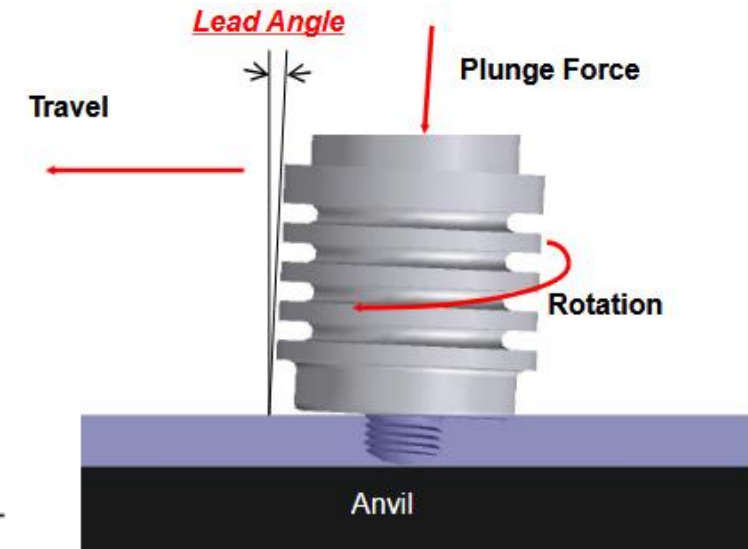
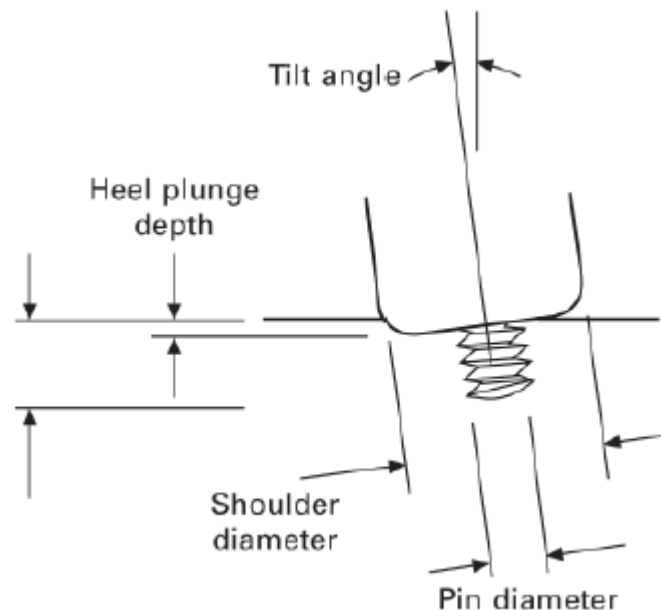


FSW – Process parameters

– Basic Parameters

• Plunge Depth

- ‘Heel plunge depth’ corresponds to the distance the heel extends into the weld or base metal
- Axial force is transferred via this depth due to tilt
- Higher depth means high axial force from the tool
- Constant force means constant depth & so the quality of the weld



FSW – Process parameters

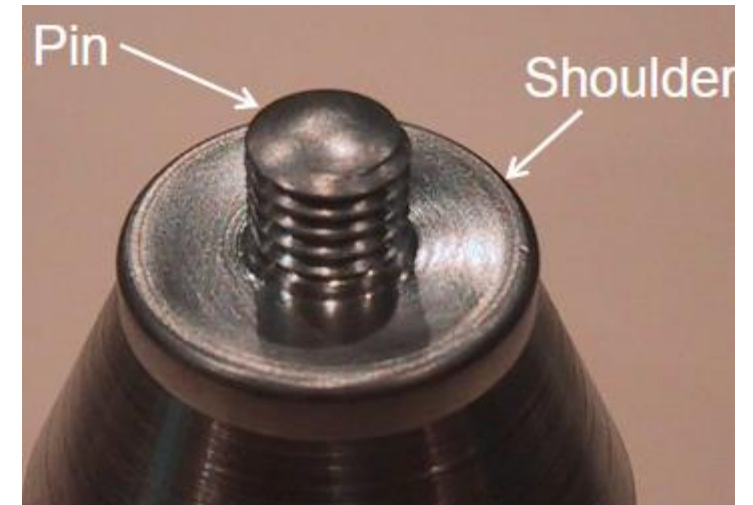


– Basic Parameters

- Dwell Time
 - Preheating time by a stationary, rotating tool in order to achieve a sufficient temperature ahead of the tool plunging and advancement. Just on surface.
 - May also include the time the tool remains plunged into the workpiece
 - E.g., Steel vs Aluminium

FSW – Process parameters

- FSW Tool Design (another parameter)
 - Standard Tool Geometry
 - Concave shoulder and threaded pin.
 - Pin thread drives material toward the root during welding. More effective mixing by threads (clockwise rotation with left hand thread)
 - Pin/Probe establishes the stirring action
 - Special tools widen material compatibility (just like 3D printers)

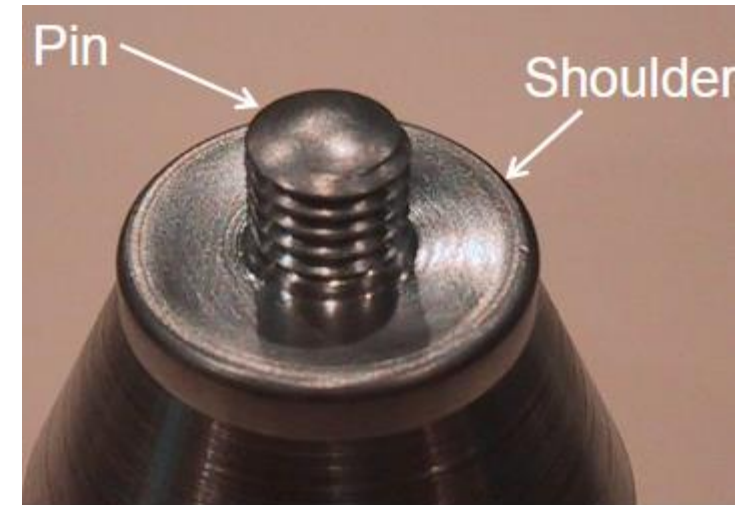


FSW – Process parameters



– FSW Tool Design

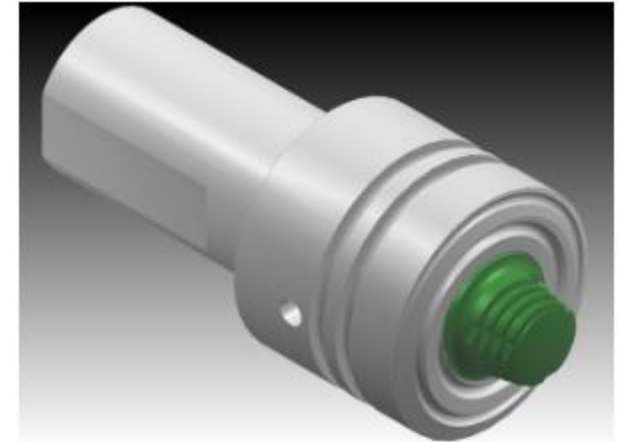
- Role of the Shoulder
- Biggest component of heat generation
- Plunged below the surface of the material to generate a high pressure forging action
- Confines the plasticized material



FSW – Process parameters

– FSW Tool Design

- Tool variants
- Tapered pin
- Fluted pin
- Scrolled shoulders
- Advantage: To reduce load, improve material flow, increase travel speed

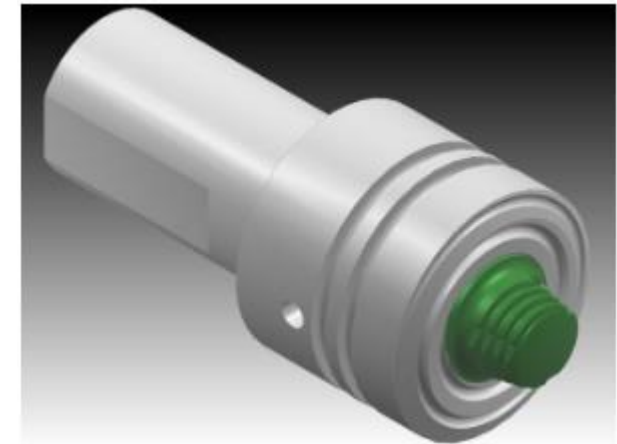
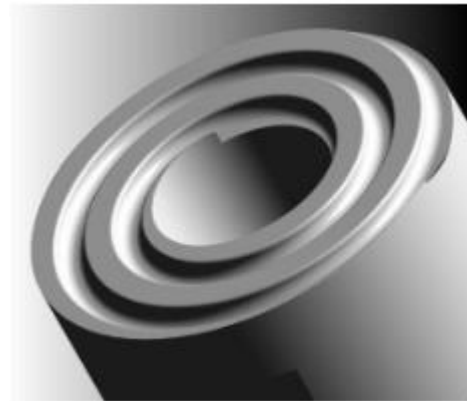
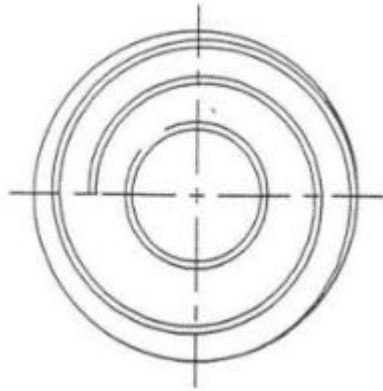


FSW – Process parameters



– FSW Tool Design

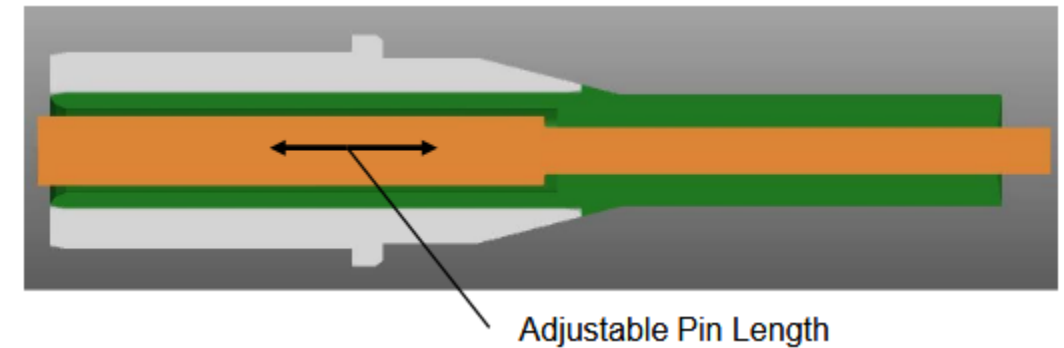
- Scrolled shoulders
 - The development of the scroll-type shoulder geometry eliminates the need for a lead angle



FSW – Process parameters

– FSW Tool Design

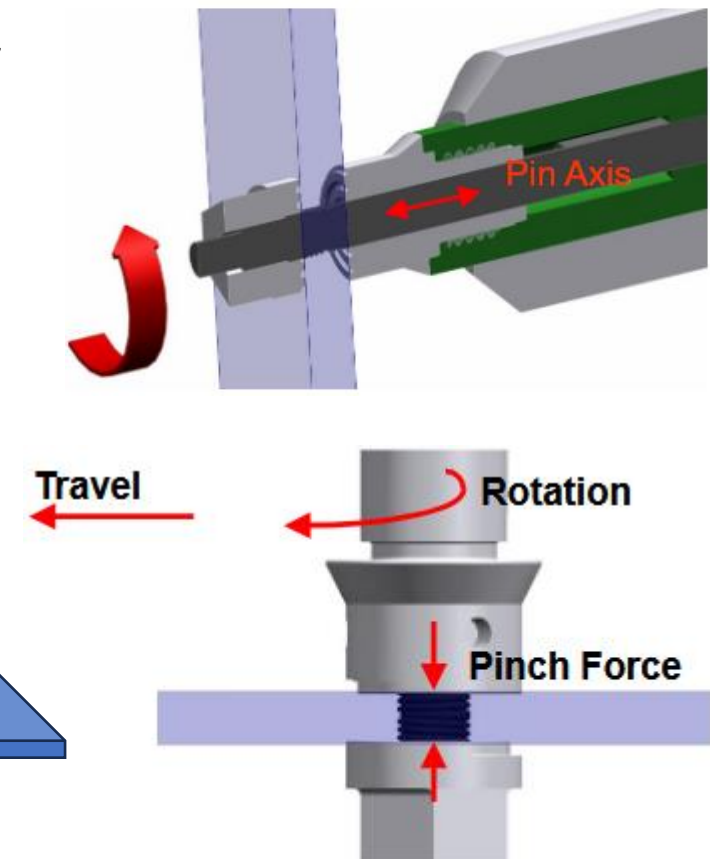
- Retractable pin tool
 - NASA Patented
 - Feature in which the pin of the FSW tool may be moved independently of the tool's shoulder.
 - This permits adjustments of the pin length to be made during welding, to compensate for known material thickness variations
 - To close the exit hole of the weld.
- Improves weld joint quality
- Aids in avoiding lack of penetration defects



FSW – Process parameters

– FSW Tool Design

- Retractable pin tool + Scrolled shoulder = Self reacting FSW (also called Bobbin tool FSW)
 - No anvil required
 - Rotating tool “pinches” the work piece between two shoulders and traverses along the weld joint.
 - Advantage, simplifies Tooling, eliminates lack of penetration defects
 - Disadvantage, hole left at end of weld
- If non-retractable pin, it is called ‘fixed bobbin tool’

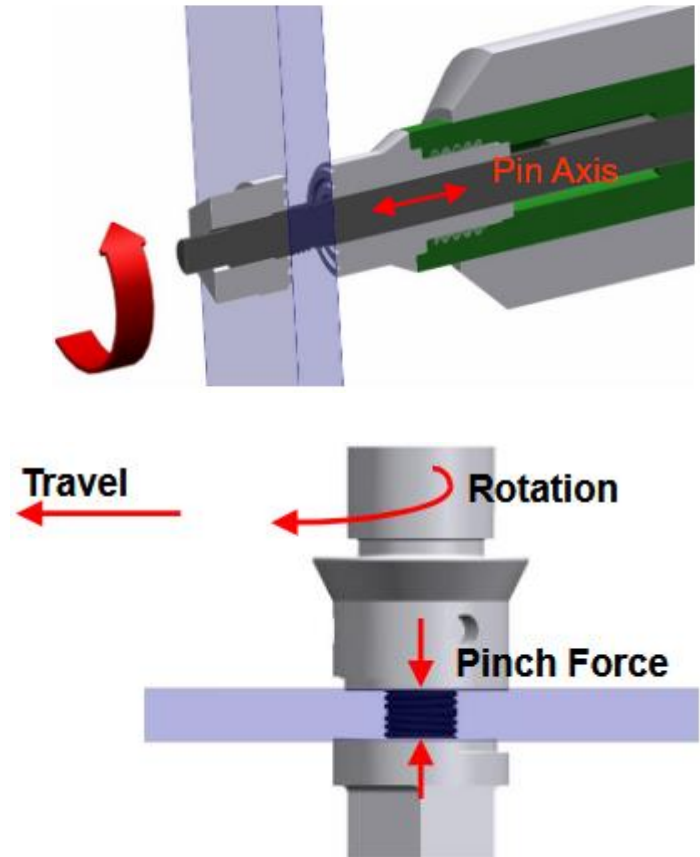
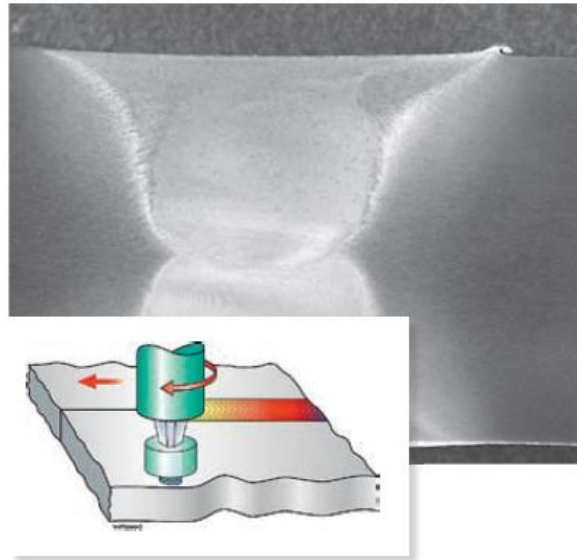


FSW – Process parameters

– FSW Tool Design

- Bobbin tool FSW

- If fixed, distance between shoulders in fixed, just like typical FSW
- If retractable, allows us to control the contact conditions for the two shoulders independently, to compensate for variations in material thickness.

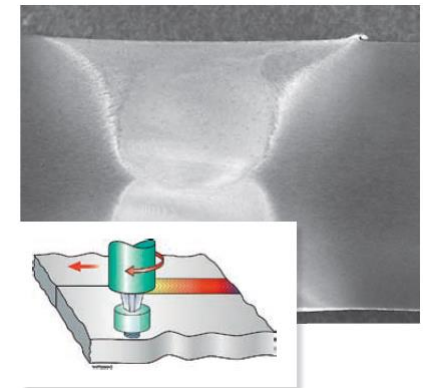
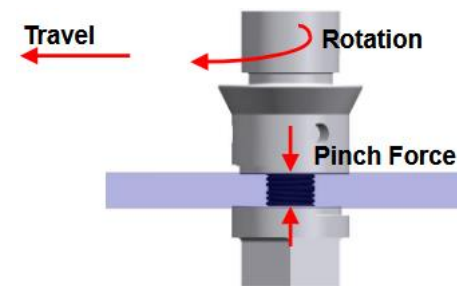
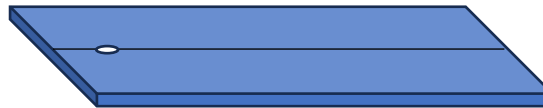


FSW – Process parameters

– FSW Tool Design

• Bobbin tool FSW

- Initiating a bobbin weld either involves first drilling a hole in the material in which the tool is inserted, or by employing a run-on preparation of the material. The end of the weld is normally welded through, leaving the exit un-bounded, for removal at a later stage.
- The bobbin tool is typically used to join extruded profiles, where the technique eliminates the need for a backing bar or advanced fixtures.
- To summarize,
 - No backing bar needed.
 - Less complex fixtures.
 - No root flaws from incomplete penetration.
 - Less (or zero) down force needed.



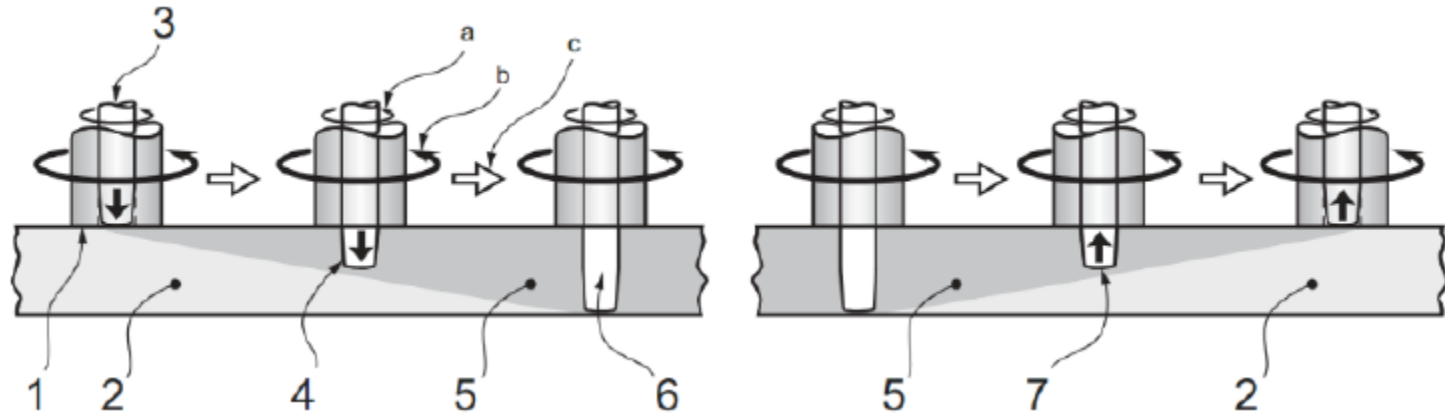
FSW – Process parameters

– FSW Tool Design

- Bobbin tool FSW

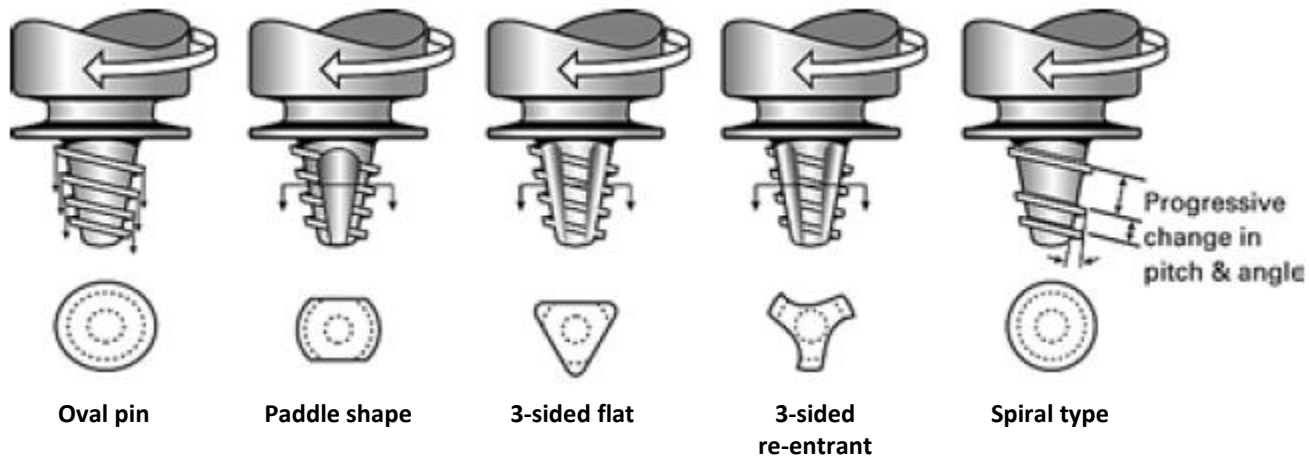
Illustrative process of a Retractive tool FSW.

- 1-Shoulder;
- 2-Unwelded Workpiece;
- 3-Pin;
- 4-Pin moving downward;
- 5-Welded Workpiece;
- 6-Probe/pin at Required Position for Welding;
- 7-Probe/pin moving upward



FSW – Process parameters

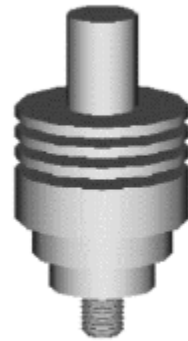
- Some other FSW Tool Designs
 - For particular applications and welding needs



FSW – Process parameters

– Some other FSW Tool Designs

- For particular applications and welding needs
- For thicknesses ≤ 12 mm, the recommended pins are the cylindrical pins,
- For thicknesses > 12 mm tapered or flared-triflute are more suited.
- Also, material dependent



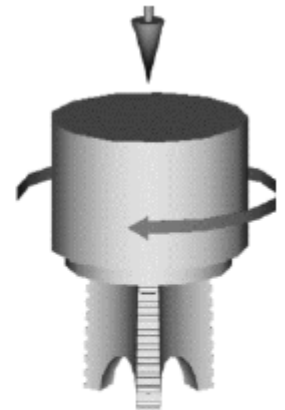
Stepped shoulder with
cylindrical threaded pin



Flat shoulder with
cylindrical threaded pin



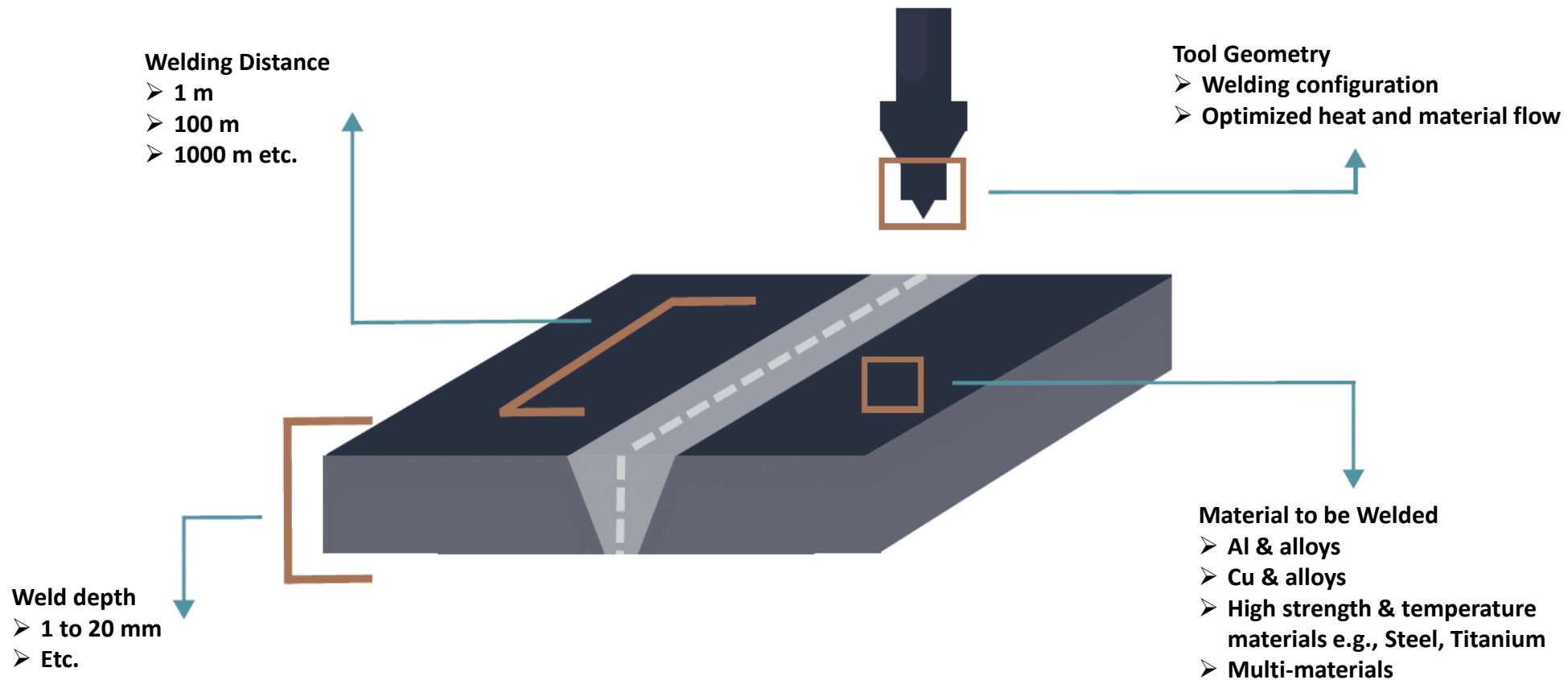
Flat shoulder with tapered
pin



Flared Triflute pin

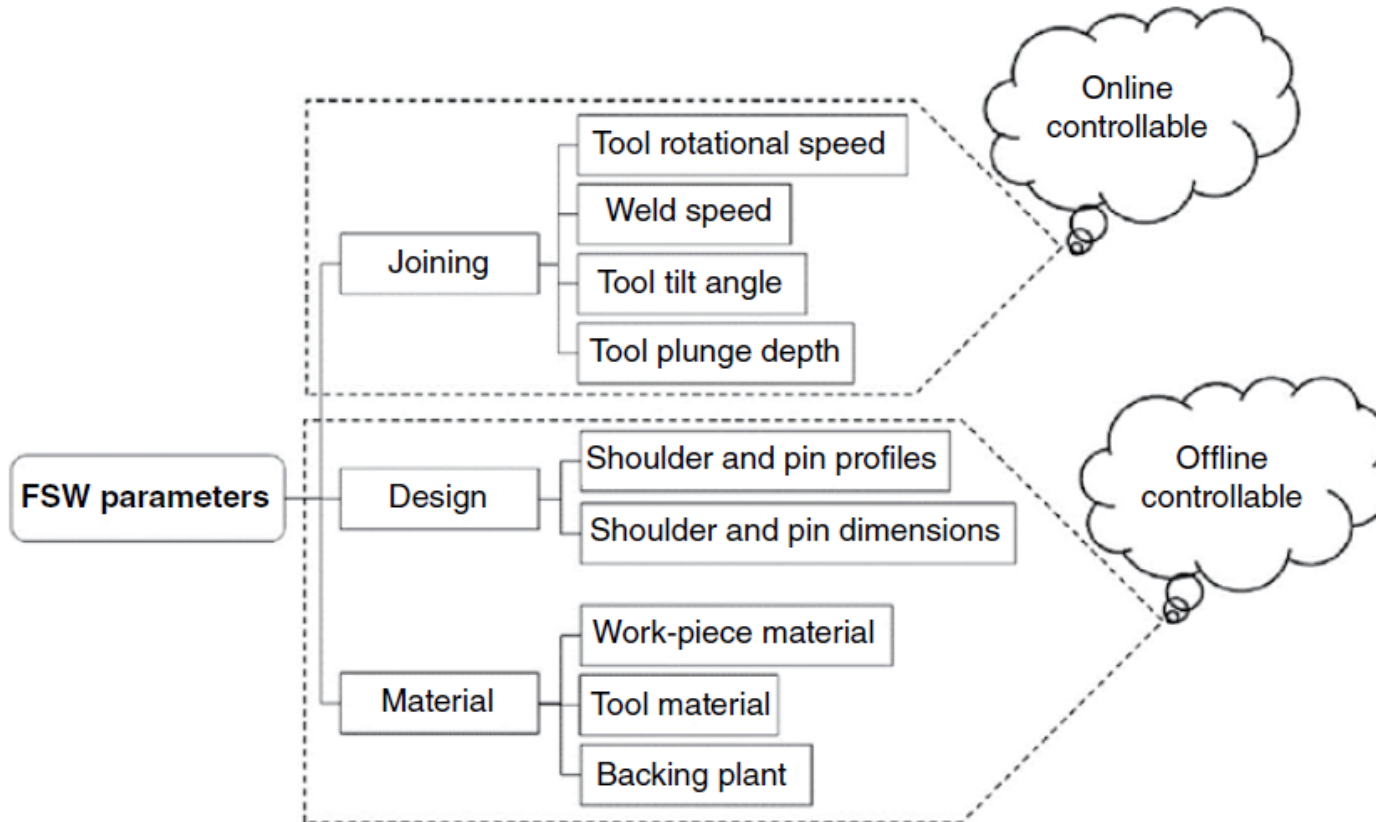
FSW – Process parameters

– How to choose a FSW tool



FSW – Process parameters

– Parameters affecting weld quality

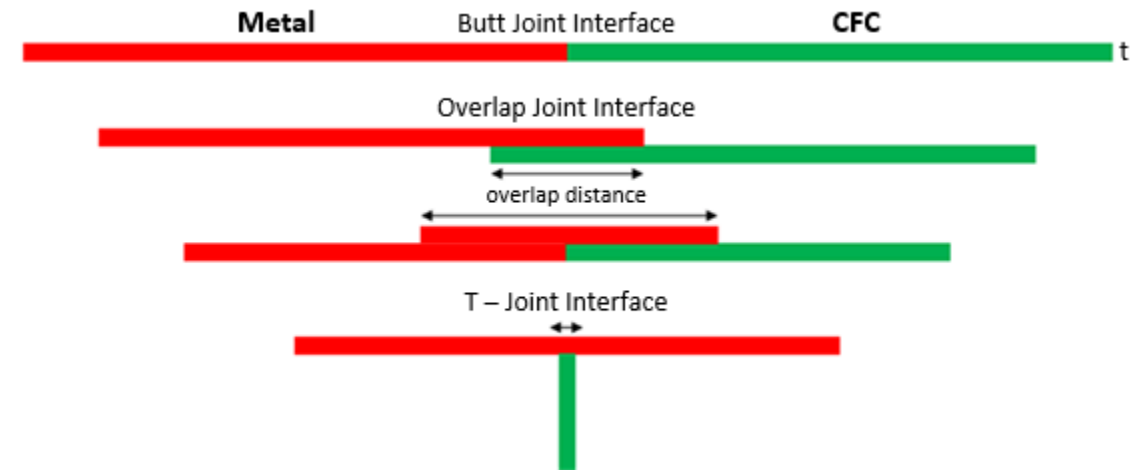


FSW – Process parameters



– Joint preparation & types

- Cleaning
- Measuring devices
- Positioners (fixing)
- Setup FSW program



Credit: MULTHEM

FSW – Process parameters



– Joint preparation & types

- Cleaning
 - Any dust, grease or moisture must be removed as to avoid adverse affects on joint quality
 - Fallouts: poor fatigue performance, low ductility, volumetric defects
- Normally, use degreasing solvents, paper towel wiping
- Special methods include grinding, wire brushing, paint removal, pickling (acidic solution)

FSW – Process parameters

– Joint preparation & types

- Measuring devices
 - Employed for plate thickness variations check
 - Irregular thickness causes tensile residual stresses
- Otherwise,
- Workpiece gap
- Incorrect pin length vs material thickness



Dial thickness gauge



Vernier calliper

FSW – Process parameters



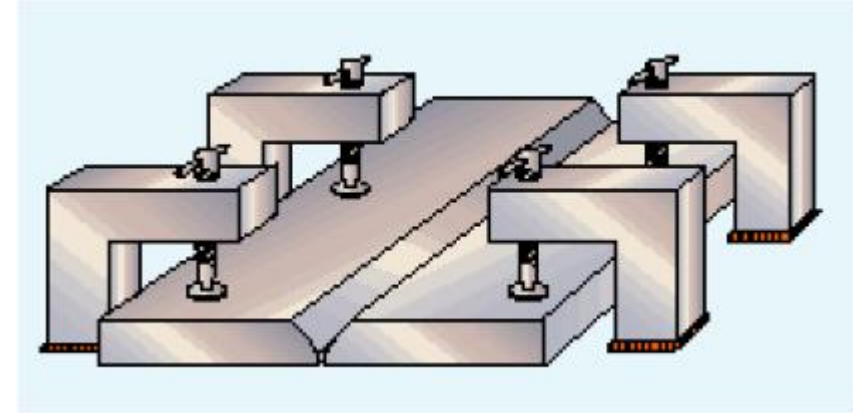
– Joint preparation & types

- Clamping
 - Proper firm fixing affect weld quality, welding cost and completion time
 - Improper fixing can be dangerous
 - Anvil must not deflect under process plunge loads and clamping loads.
 - High clamping loads are often required to keep the joint from separating.
- Jigs
- Fixtures

FSW – Process parameters

– Joint preparation & types

- Clamping:
 - Jigs
- A jig is a device designed to keep a welding project stable in face of pressure, heat, motion and force
- Can be a drill jig if drilling required



FSW – Process parameters

– Joint preparation & types

- Clamping:
 - Fixtures
 - A fixture allows movement of both tool and workpiece together while a jig stays still and may allow the work piece to move



Frame railing

FSW – Process parameters

– Joint preparation & types

- Clamping:
 - Some other types include;
 - Mechanical actuation clamps
 - Pneumatic and Hydraulic clamps
 - Magnetic clamping
 - Electrostatic clamping

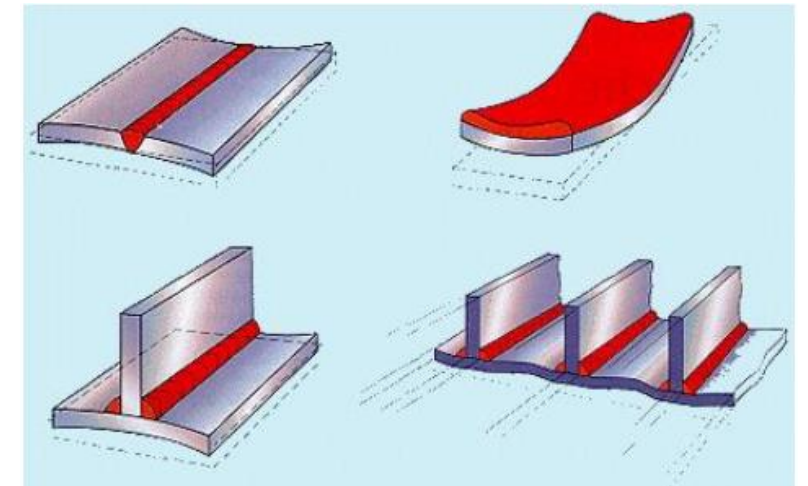


Vacuum clamping

FSW – Process parameters

– Joint preparation & types

- Clamping:
 - Clamping force should be directed to a robust area of the workpiece
 - Enough to secure hold of the parts without causing damage
 - Fibre pads could be used to avoid damage to fragile workpieces
 - Use of knobs and handles to reduce clamping time rather than fasteners
- Causes bulging or buckling or bending
- Affected by,
 - Pre-heating clamps = homogenous deformation
 - Clamps close to weld area = less distortion
 - Longer release time = reduce bending or angular distortions



Common weld distortion forms

FSW – Process parameters

– Joint preparation & types

- FSW program
 - Set Pre / In-process / Post welding parameters
 - E.g., welding path, clamping fixtures control, welding parameters (depth, speed, travel, angle) etc.
 - Can record and analyze weld data as well



FSW machine and Control Unit

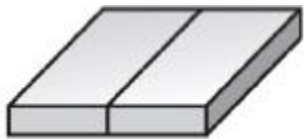
FSW – Process parameters



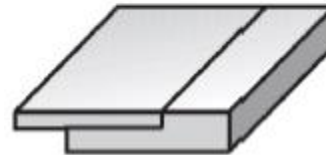
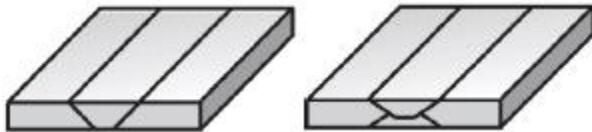
AILEEN

– Joint preparation & types

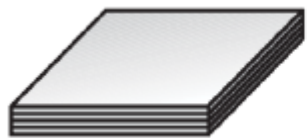
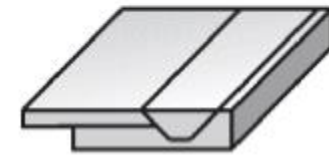
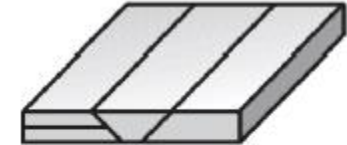
- Joint types



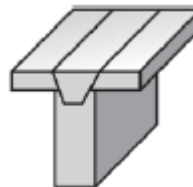
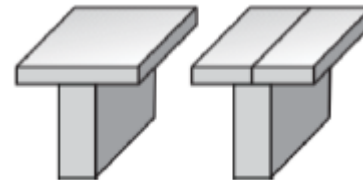
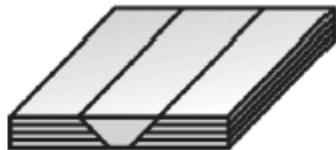
Butt Joints before and after FSW



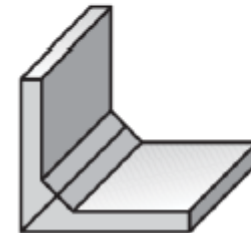
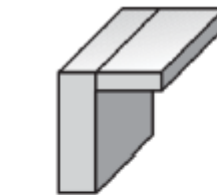
Lap and Butt joint before and after FSW



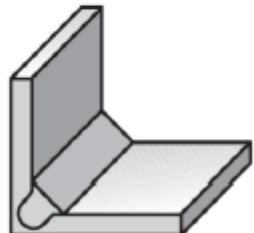
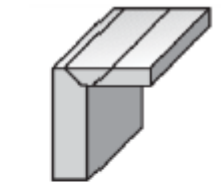
Lap joint before and after FSW



T-joint before and after FSW



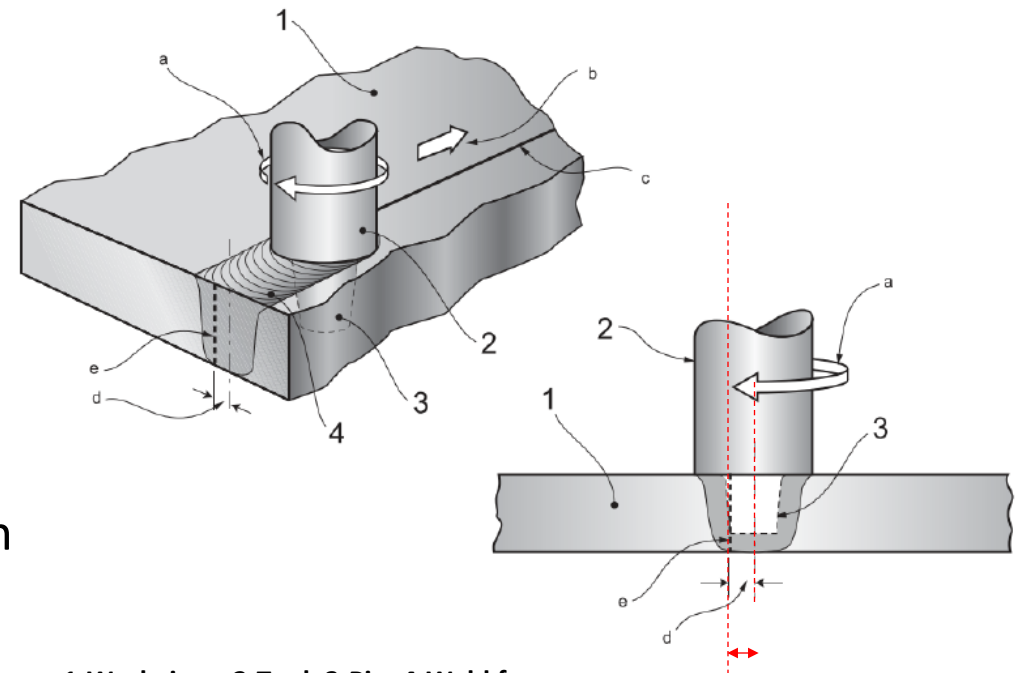
Corner joint before and after FSW



FSW – Process parameters

– Joint preparation & types

- Dissimilar Joint
 - Use of offset position
- Recommendation:
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



1-Workpiece; 2-Tool; 3-Pin; 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

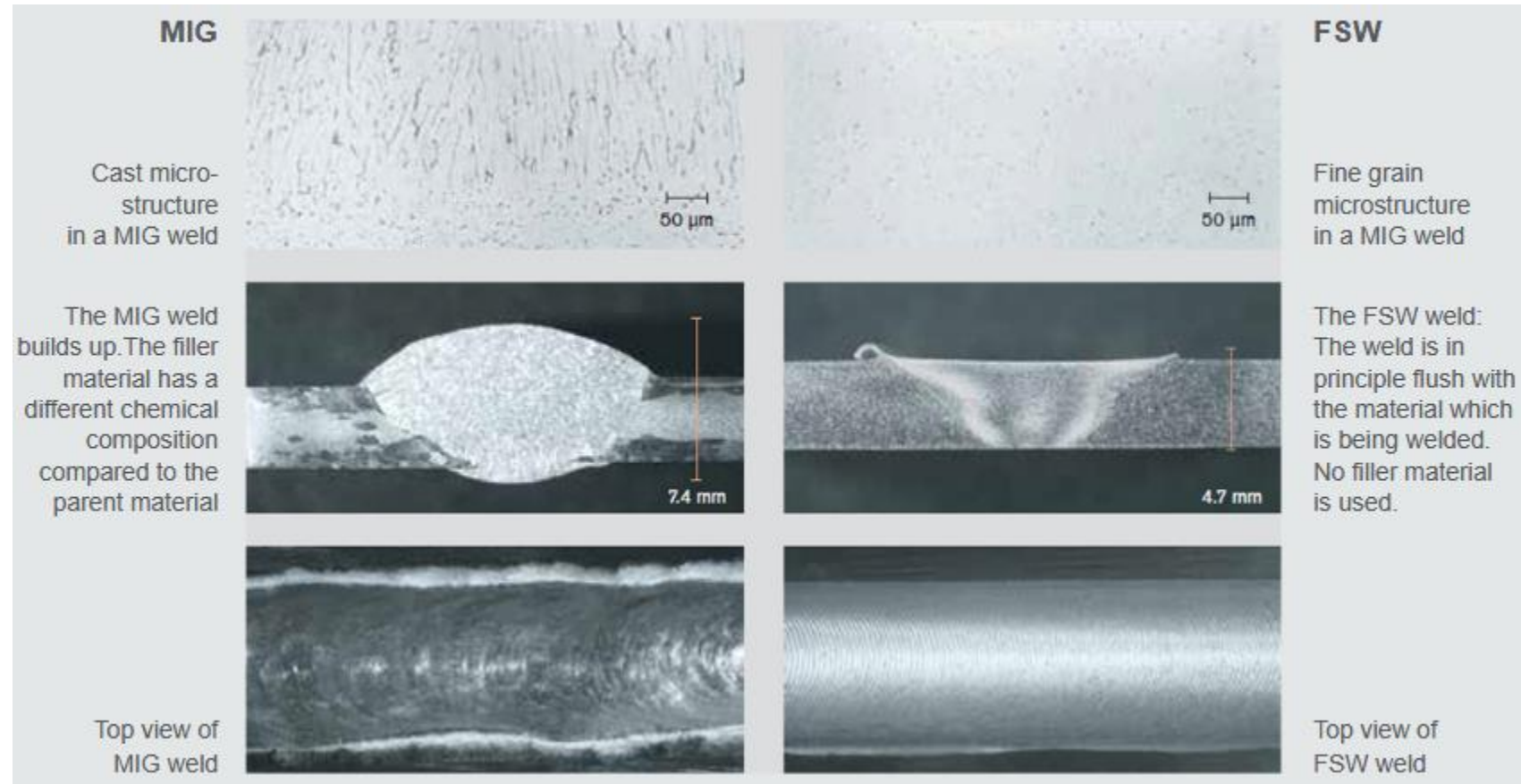
– Advantages

- FSW, being a solid-state (eliminates fusion processes defects, distortion, shrinkage, solidification hot cracking and porosity)
- Low-energy-input
- Repeatable mechanical process capable of producing very high-strength welds in a wide range of materials
- Wide range of material thicknesses and lengths.
- Offers a potentially lower-cost
- High-strength joints with low distortion (either butt or lap joints)

FSW – Applications

– Advantages

Weld Comparison

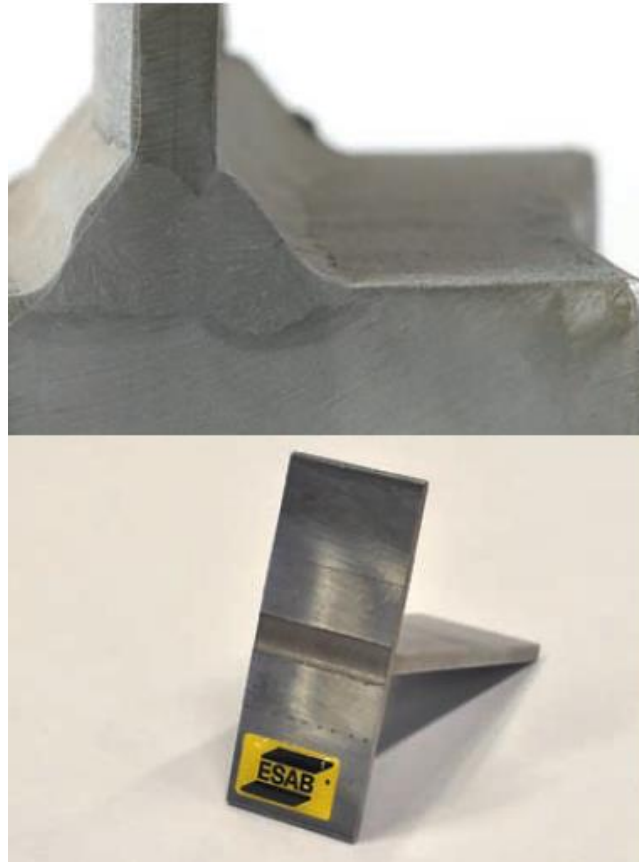


FSW – Applications

– Advantages



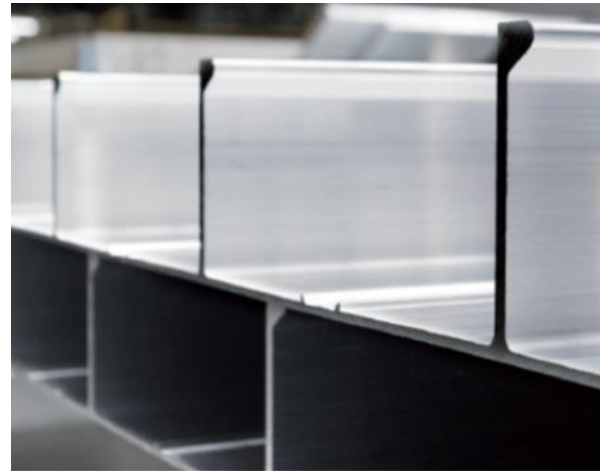
Traditional fillet joint vs FSW T-joint



FSW – Applications

– Ship building and Marine

- Two of the first sectors that have adopted the process for commercial applications.
- The process is suitable for the following applications:
- Panels for decks, sides, bulkheads and floors.
- Hulls and superstructures
- Helicopter landing platforms
- Marine & transport structures
- Masts and booms, e.g. for sailing boats
- Refrigeration plant



FSW on Single Skin Deck Panel



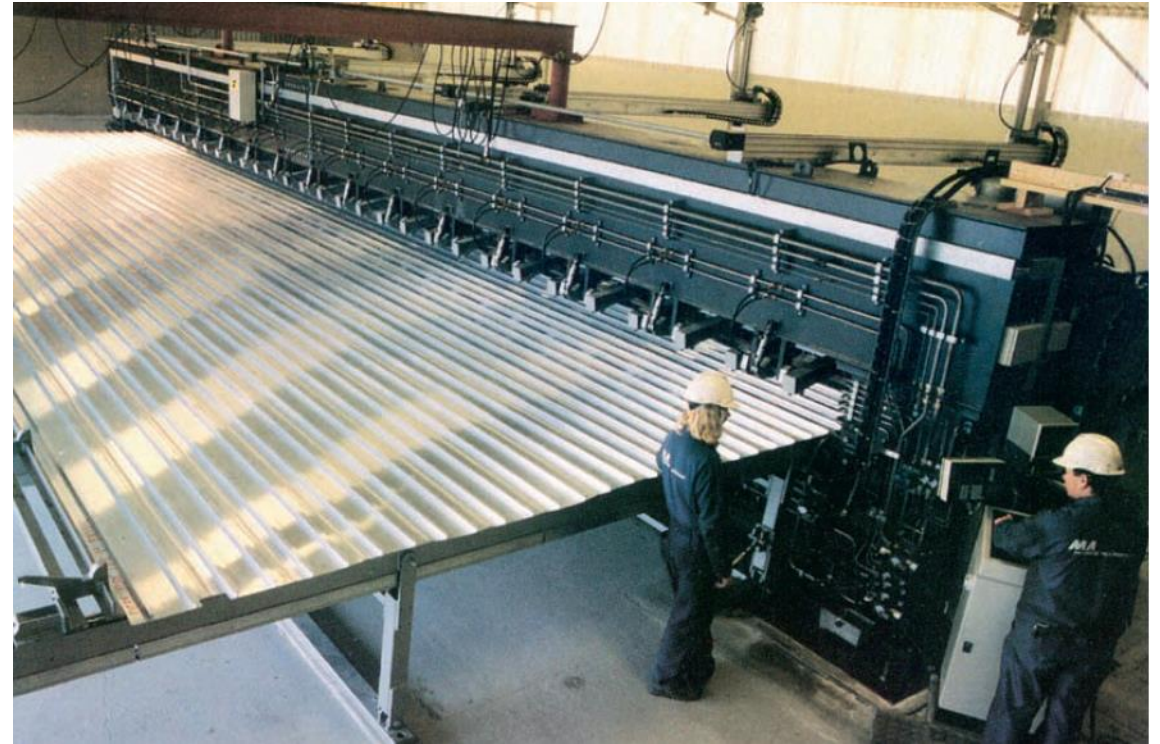
Prefabricated Deck Panels

FSW – Applications

– Ship building and Marine



An over-hull structure at Marine Aluminium



FSW equipment installed at Marine Aluminium for welding panels.

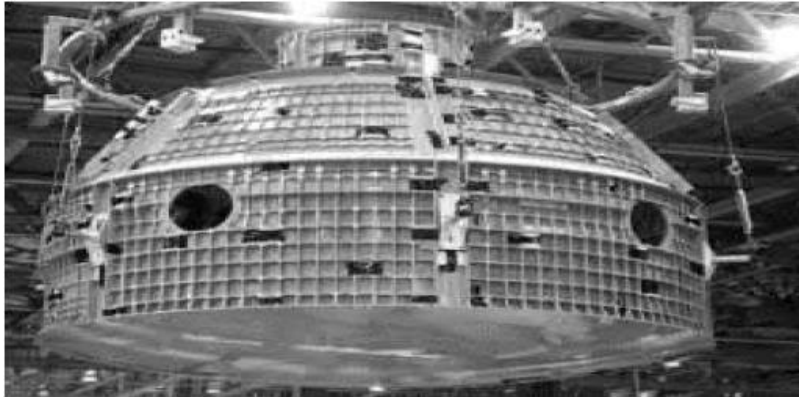
– Aerospace industry

- Prototypes or production parts
- Eliminates costly riveting or machining from solid
- Space vehicles fuel tanks (Al alloy)
- Wings, fuselages, turbine components
- Cryogenic fuel tanks for space vehicles
- Aviation fuel tanks
- External throw away tanks for military aircraft
- Military and scientific rockets
- Repair of faulty MIG welds

FSW – Applications



– Aerospace industry



Space Craft module – use with FSW

FSW at NASA since 2000's to Present:

- Aluminum-Lithium alloy 2195 implemented on External Tank
- 2195 has a propensity for hot cracking, particularly in repair welds
- This drove NASA's to look into FSW supported by TWI
- First production of External Tank were made in 2001
- Friction Stir Welding implemented for assembly of the Space Launch System, and on all elements of NASA's exploration program

NASA Space Shuttle External Tank



NASA SLS Spacecraft



Welding of Space Shuttle External Tank Barrel Sections



NASA SLS Spacecraft Adaptor



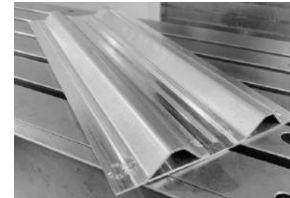
NASA Orion Capsule being welded



FSW – Applications

– Aerospace industry

- Rocket Fuel Tanks – Primarily square butt welds in 2XXX series Aluminum.
 - Space Shuttle External Tank
 - United Launch Alliance Delta II, Delta IV, and Atlas V
 - Space X Falcon and Falcon 9
 - Japan – JAXA H-IIB
 - NASA – Space Launch System Core Stage
- Aircraft Primary Structure
 - Eclipse 550 wing and fuselage – Skin to Stringer
 - Embrarer Legacy 450 and 500



Embrarer legacy



Eclipse 550

– Railway industry

- High speed trains bogies, sheets made with Al extrusion (more than a decade)
- Floors, body sides, roofs
- Rolling stock of railways, underground carriages, trams
- Railway tankers and goods wagons
- Container bodies



Stiffened panels

FSW – Applications

– Railway industry

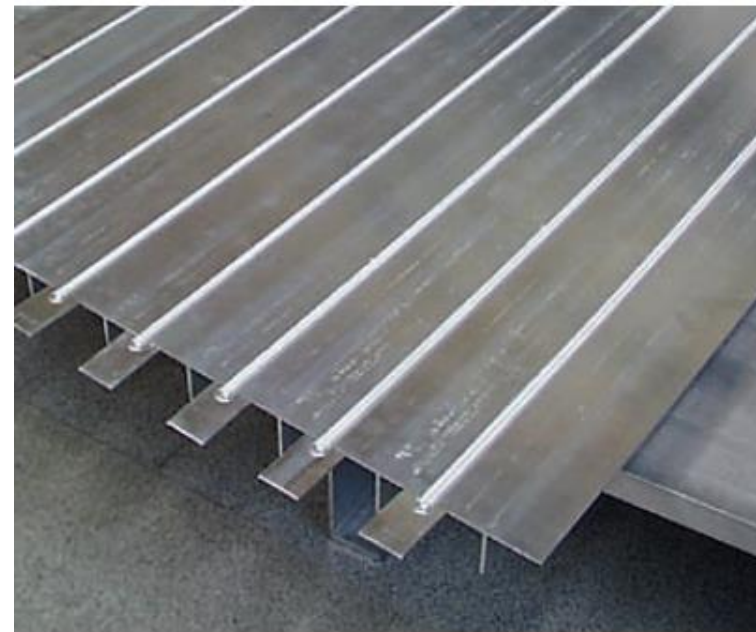
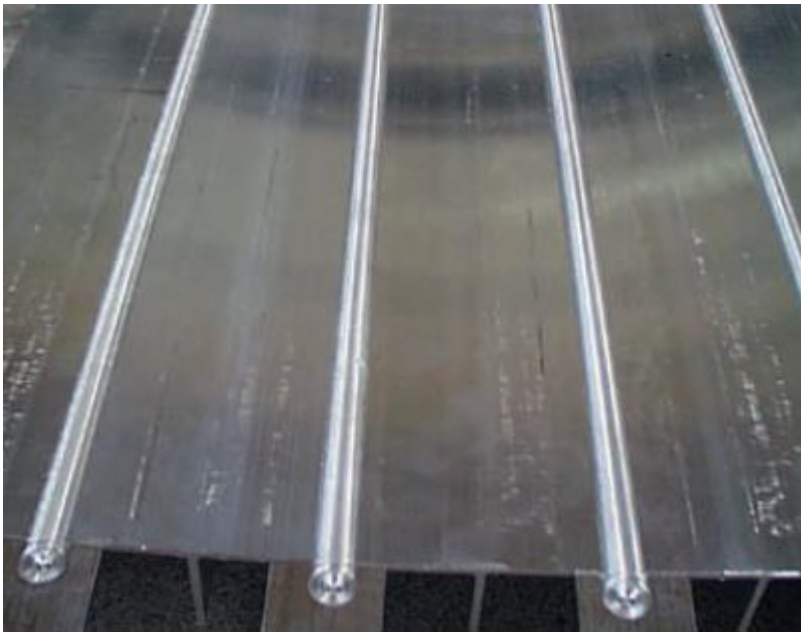


FSW double skin train coach panel



FSW – Applications

– Railway industry



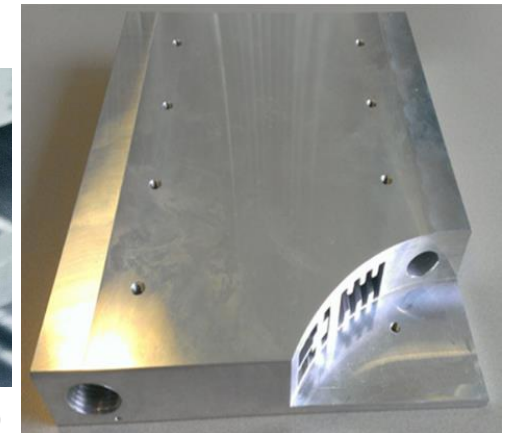
Floor panels

FSW – Applications

- Automotive (locomotive) industry
 - Existing and potential applications include:
 - Engine and chassis cradles, panels, heat sinks
 - Wheel rims, suspension arms, fuel tank, motor housings
 - Pipelines and heat exchangers
 - Attachments to hydroformed tubes
 - Space frames, e.g. welding extruded tubes to cast nodes
 - Truck bodies & tail lifts for lorries
 - Mobile cranes
 - Armour plate vehicles
 - Fuel tankers, Caravans, Buses and Airfield transportation vehicles



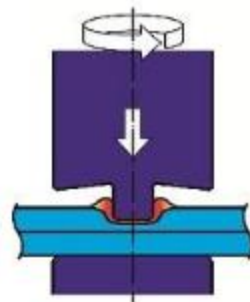
Liquid Coolers (Heat Exchangers)



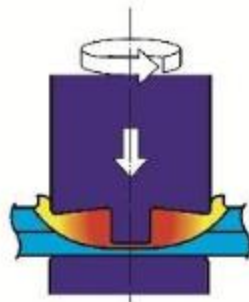
FSW – Applications

– Automotive (locomotive) industry

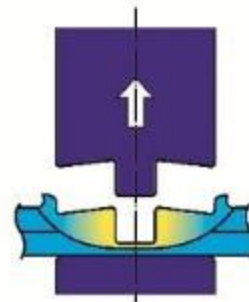
- Ford GT center tunnel
- Lincoln Towncar engine cradle and suspension struts
- Mazda RX5 – Spot weld aluminum to galvanized steel
- Mazda RX8 and Toyota Prius trunk lids
- Volvo V70 seats



Plunging



Bonding



Drawing out



Mazda Friction Spot Welding

FSW – Applications

– Automotive (locomotive) industry

- RX-8 2003
- Ford GT



AI Extrusion

AI sub-frame welded by FSW in Ford GT

AI Stamping

FSW



Entire doors were welded by FSW

FSW – Applications

– Automotive (locomotive) industry



Motor stator carrier



Engine cradle



Battery casing

FSW – Applications

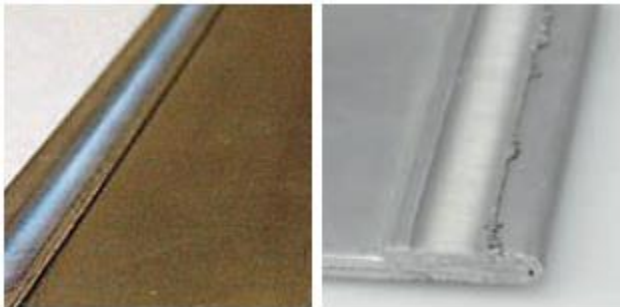
– Automotive (locomotive) industry



Suspension links



Piston head resurfacing



Overlap folded seal weld by FSW



Mixed joint between two thickness (2+1 mm)



Numerous FSW joints in this car frame body

FSW – Applications

– Other items



The front and back case parts of the 2012 version of the 21.5" Apple iMac are made from aluminium and joined together in large-scale production by friction stir welding

FSW – Applications

– FSW Materials

Material	Sample Thickness						
	Sub 1 mm	1-4 mm	4-8 mm	8-12 mm	Up to 25 mm	Up to 50 mm	Up to 75 mm
Al – Pure		D	D				
Al – 2xxx series		P	P	P	R	R	
Al – 5xxx series	R	P	P	P	P	R	R
Al – 6xxx series	R	P	P	P	P	R	R
Al – 7xxx series		P	P	P	R	R	
Al – Castings		R	R	R	R		
Mg – AM series		R	R	D			
Mg – AZ series		R	R	D			
Cu – Pure	D	D	R	R	D	R	
Cu – Brasses		D	D	D			
Ti – Pure		D	R	D			
Ti – α - β alloys		R	R	D			
Ni – Pure		R	R				
Steels – mild		D	D				
Steels – C-Mn		R	R	R	D		
Steels – Stainless		R	R	R			
Pb – Pure		D	D				
Zn – Pure	D	D					

- Area of Current FSW Production Use
- Area of Current FSW Research
- Area where FSW has been Demonstrated

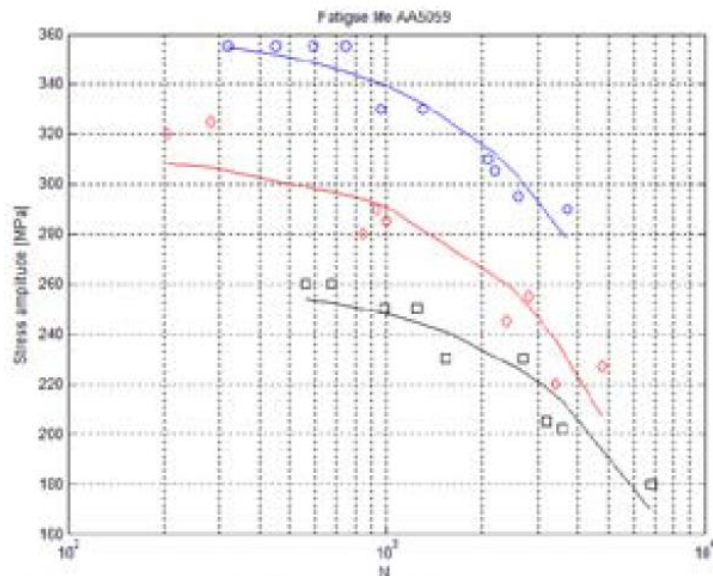
– Materials: Aluminium

- Originally invented for Al
- Very high-strength 2XXX and 7XXX series of alloys, unweldable by arc techniques.
 - Issue:
 - volatility of many of the alloying elements e.g., Li easily oxidised or even burned off during fusion. Upon solidification, alloy does not remain that alloy or as same grade
 - Up to 4% volume changes Al & alloy in arc welding during melting and resolidification, causing cracking
- FSW eliminates issues with low distortion, in all aluminium alloys, wrought and cast.

FSW – Applications

– Materials: Aluminium

- Different Al grades possible by FSW vs Fusion welding

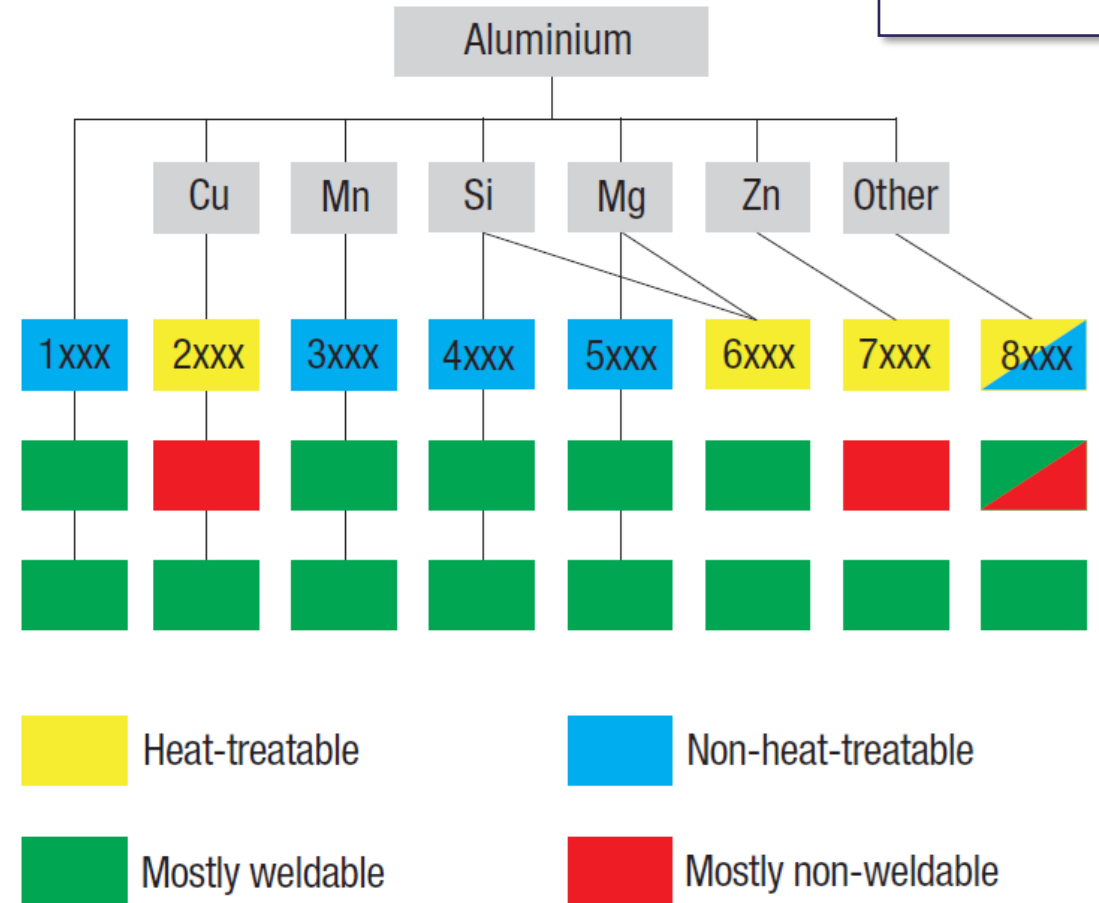


Blue = base material Red = FSW Black = MIG

Fatigue life of an Al alloy by FSW vs MIG

Fusion welding

FSW



FSW – Applications

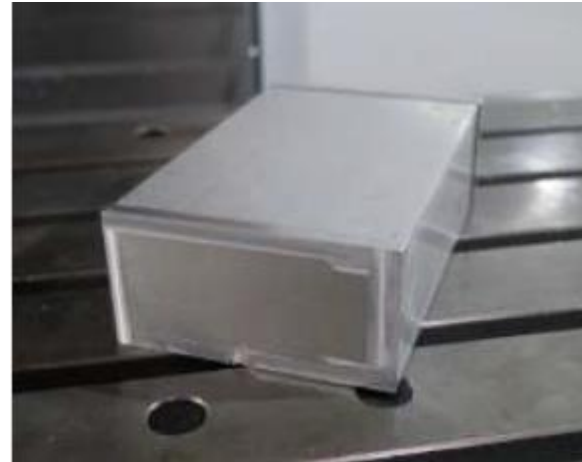
- Materials: Aluminium
 - Numerous previously shown



Mounting brackets



Al tanks under & over 300mm diameter



Flat type tanks



Vacuum flanges

FSW – Applications



– Materials: Magnesium

- Similarly, magnesium is difficult to weld using fusion techniques
- No issues with FSW in both wrought and cast forms
- TWI has developed the welding of 75mm-thick magnesium plates, 1.3m by 3m, to form the slip bed of large vibration test machines

FSW – Applications

– Materials: Copper and alloys

- High thermal and electrical conductivity of copper have long made it a difficult material to weld, particularly in thick sections.
- FSW does not melt, so adopted perfectly
- SKB – TWI, demonstrated 5m long, 1m diameter, 50mm wall thickness canisters for nuclear waste.
- Welding of copper cooling plates for X-ray sputter targets by Hitachi



FSW – Applications

- Materials: Copper and alloys
 - Brass (alloy of Cu and Zinc)

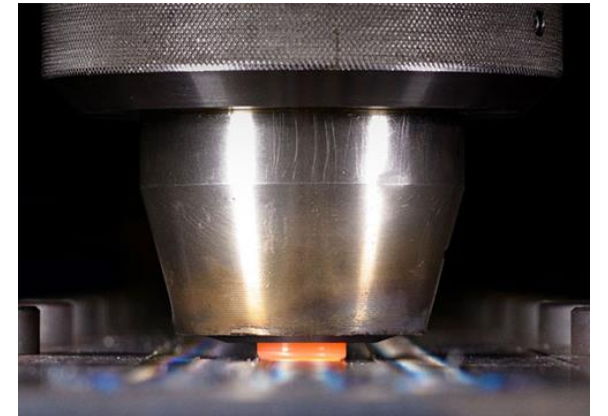


FSW – Applications



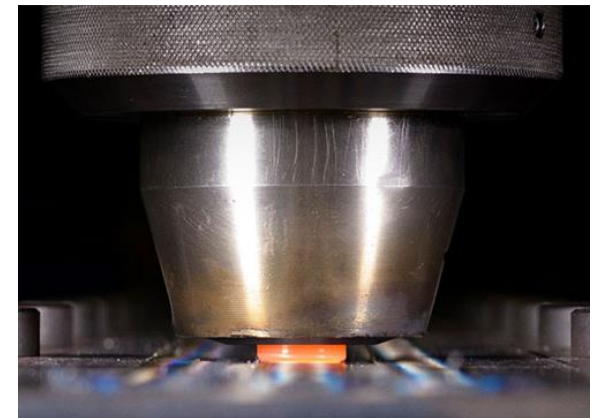
– Materials: Steel and ferrous alloys

- Weld lengths up to 30m can be attained in a wide range of engineering steels
- Weld with excellent mechanical properties (corrosion, fatigue) than fusion welds
- Requires tools strong and stiff at temperatures of over 1,000°C, whilst simultaneously being resistant to oxidation, inert to hot iron and resistant to the high bending and fatigue loads during traverse through steel.
- E.g., TWI – Element Six developed tool for 6mm carbon steel
- Being researched. Tool life capable up to 60m with 6mm tool



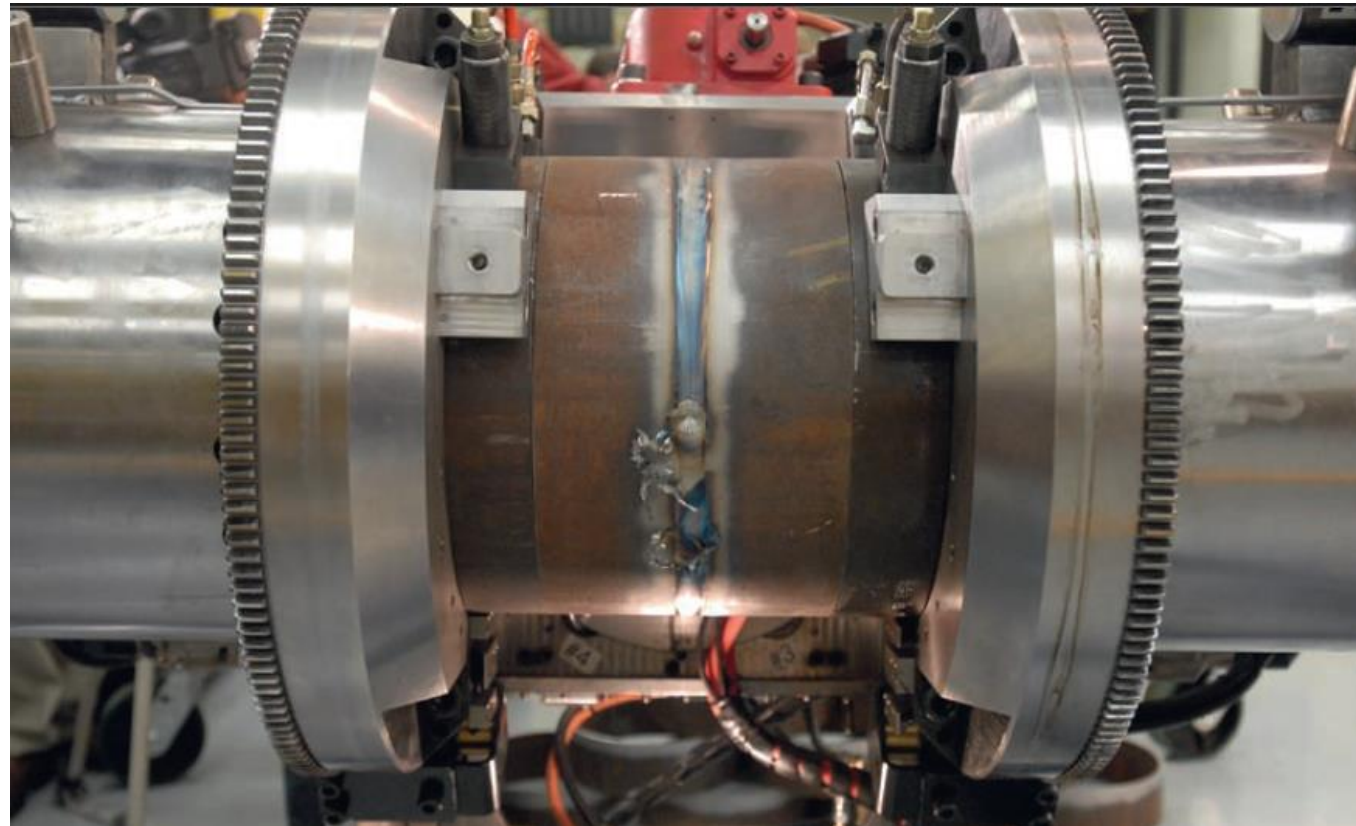
FSW – Applications

- Materials: Steel and ferrous alloys
 - Specialized tools
 - E.g., ESAB tool tip material is polycrystalline cubic boron nitride (PCBN).



FSW – Applications

- Materials: Steel and ferrous alloys



Orbital FSW of steel pipe

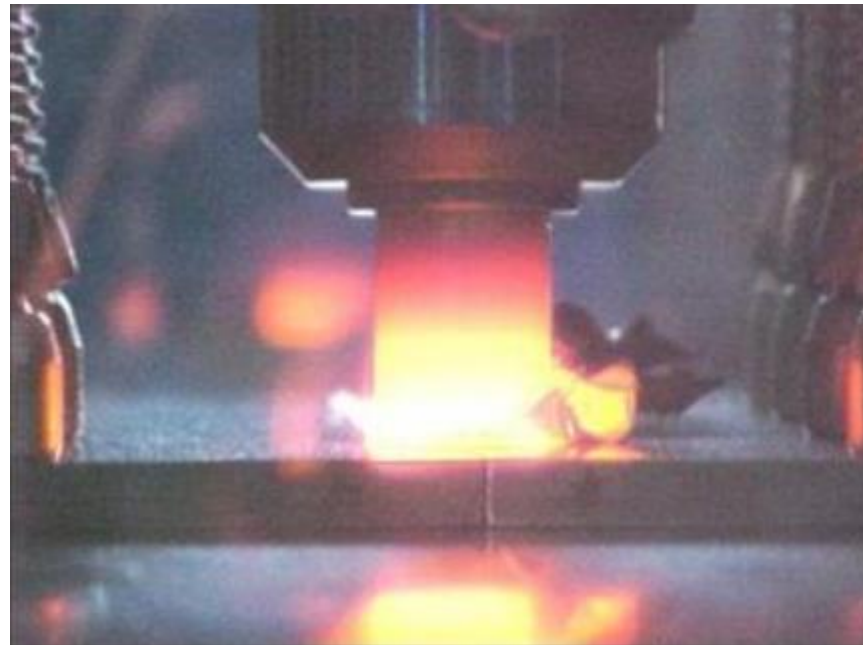
– Materials: Titanium

- Ti alloys are generally weldable by conventional fusion means but some adv. alloys such as Ti-6246 and Ti-17 are difficult
- Ti, Ti-6Al-4V, and Ti-15V-3Al-3Cr-3Sn have been welded by TWI using adv. tool.
- Weld tensile strengths similar to those of the parent alloy have been achieved in 6.35mm thickness Ti-6Al-4V.
- FSW for Ti is an emerging technology, not fully optimized and is being developed.
- The advanced tool technology and supporting systems required for FSW of Ti are currently relatively expensive.
- Problem: Poor thermal conductivity ($\sim 10 - 12$ times less than Al)

FSW – Applications



– Materials: Titanium



Welding of Ti-6-4 using Tungsten tool

– Other Materials:

- Hafnium and zirconium (petro-chemical, oil refinery, power generation industry)
- Brass components, including propellers and impellers, for marine applications
- Nickel aluminium bronze propellers for naval applications (surfacing to avoid cavitation and noise)
- Inconel and superalloys (welding is difficult due to cracking & microstructural changes in HAZ, FSW overcomes this). Research still under progress due to its high plasticisation point.

– Other Materials:

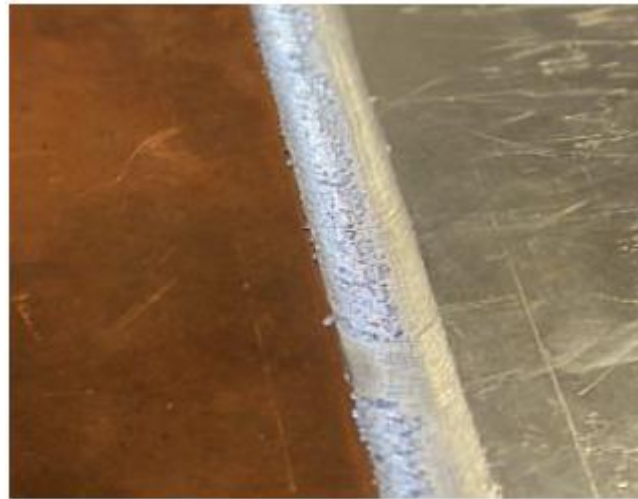
- Thermoplastics soften and flow as these are heated, and then regain their stiffness on cooling.
- Therefore can be friction stir welded.
- Friction stir welding of thermoplastics is more complex than the FSW of metals as thermoplastics comprise long chain molecules rather than individual atoms and so have very different flow characteristics.
- Process parameters and tool designs for the FSW of thermoplastics are therefore quite different from those required for metals.

– Dissimilar welds

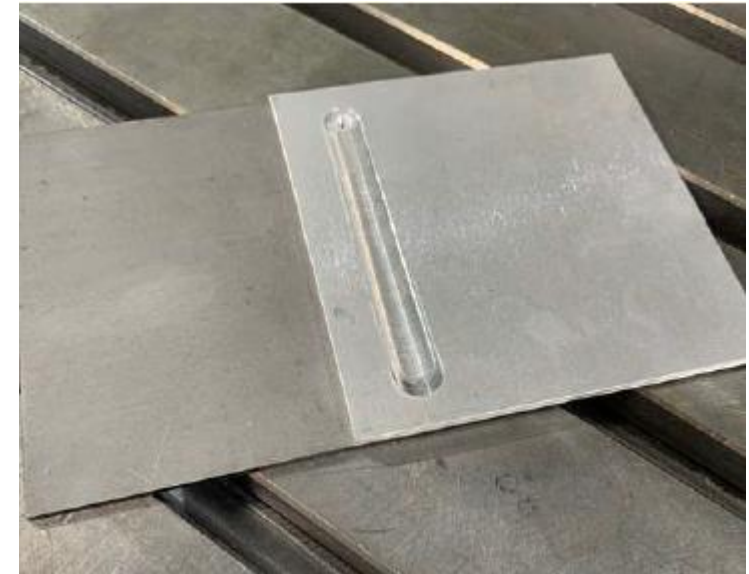
- Compatible same of different melting temperatures
- Most easily achieved when the metals to be joined have similar thermal properties and plasticisation temperatures
- As Al-Mg, Cu– Al, Al– Al alloys Mg– Mg alloys
- FSW is capable of welding of magnesium, titanium, copper, zinc and other refractory materials (resistant to heat or chemical contact).
- TWI has successfully joined copper, silver and gold (producing far less waste than handcraft traditional method)

FSW – Applications

– Examples



Copper and Aluminium Joints



Al with Fe

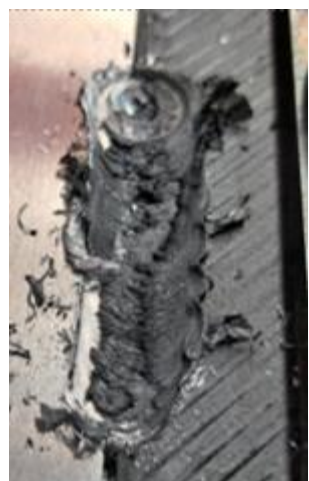
Credit: MULTHEM

FSW – Applications



AILEEN

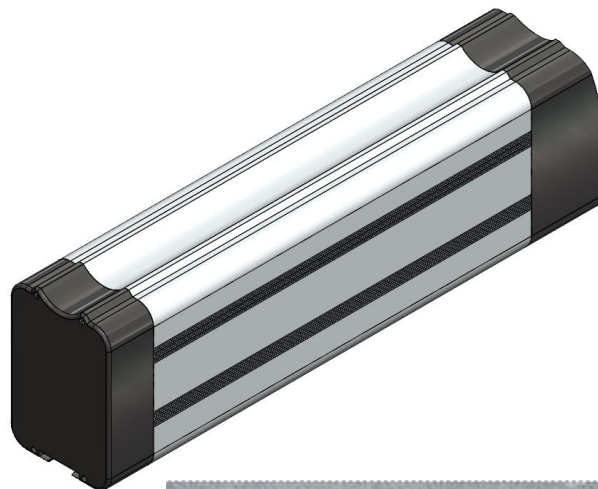
– Examples



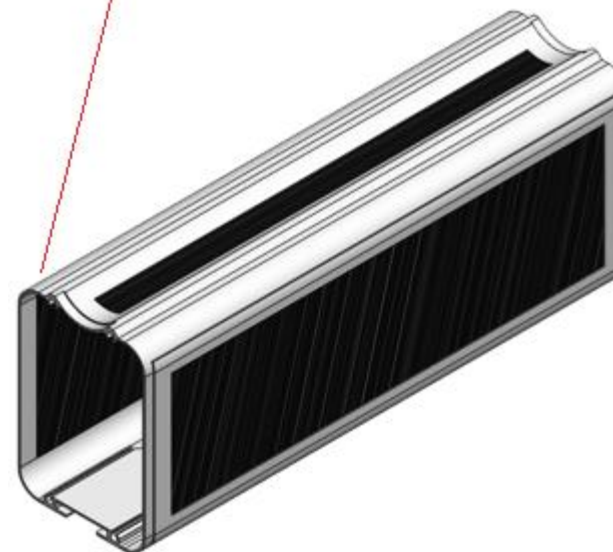
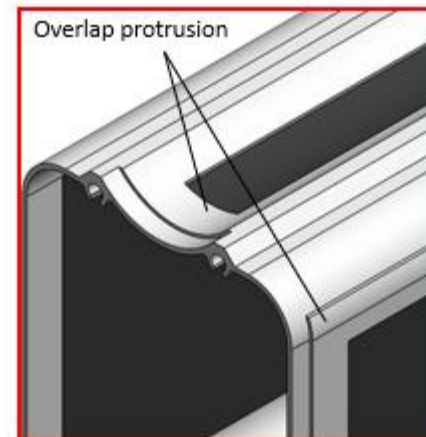
BUTT JOINT



BUTT JOINT with interlocks



PA6 and AL



Credit: CETEMET
MULTHEM

FSW – Applications

– Microsector

- Micro-FSW
- Evolving field
- Al-SiC <0.5mm



FSP welded 0.5 mm Al sheet

FSW – Limitations

- High initial investment in tooling and equipment
- Sensitive to joint tolerances
 - Typically not for mismatch or gap joints (if not specialized tool & machine)
 - Mismatch can lead to excessive flash
- Work piece must be rigidly clamped
- Backing bar or anvil required for typical FSW if not self-reacting
- Keyhole at ends if not used specialized tool
- Cannot make joints which require material deposition
- Typically require flat surfaces or simplistic joint geometries
- Corrosion protection is needed
- License is required from TWI...
- Tool material limitations and so limitation for wider range of materials to be welded



Excessive Flash

- Problems which may arise during FSW
 - Insufficient heat supply or generation due to incorrect parameters to cause material plasticization
 - Mainly tool rotational speed and welding speed
 - Can cause voids or cracks with high welding speeds
 - Insufficient stirring in the plasticized area resulting improper weaker weld joint
 - Excessive flash due to too much tool depth, can be mitigated by suitable tilt angle
 - Excessive flash can require milling process for removal
 - Larger diameter of tool shoulder can prevent improper plasticization and thus voids or cracks
 - Insufficient pin length can cause lack of root fusion therefore weaker joint
 - Optimized parameters should be set to avoid defects in the weld

FSW – Health and Safety Aspects



- FSW one of the most operator friendly processes (no radiation IR, UV, no toxic smoke) for eye and skin protection.
- Discards exhaust systems in some cases
- Most hazards are electrical or mechanical-human interface related i.e., during setup, handling, adjustments need while the process is running
- Cautions should be taken by using ergonomics in material/human interaction
- Emergency stop button while pin is plunged in the weld (e.g., in case of specialized or threaded tool). Deal this with careful measures. Cooldown, unclamping and disconnecting the tool.

FSW – Health and Safety Aspects

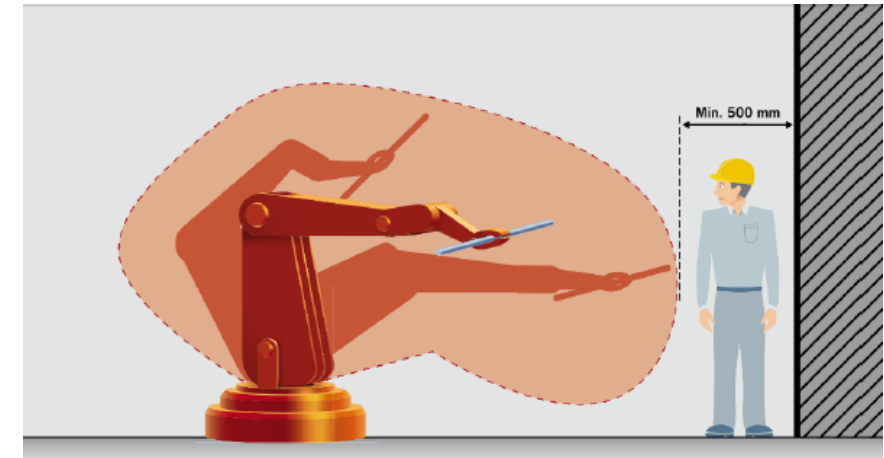


- Common FSW hazards: Electrical, mechanical, noise
 - Physical hazards (skin burns from hot tool, cuts from metal debris or sharp edges e.g., excessive flash)
 - Appropriate protective gear (PPE – protective glasses, hearing protection, safety boots and heat-resistant gloves)
 - Qualified personal to use
 - Equipment remains off in-use
 - Accidental machine start can cause a hazard
 - Heavy workpiece or material or equipment handling
 - Bare cables inspection should be carried out (avoid shock, or short-circuit fire)
 - Proper insulation and grounding required. Specially areas involving sinks or water
 - Disconnect power supply if coolants gets into electrical components

FSW – Health and Safety Aspects



- Common FSW hazards: Electrical, mechanical, noise
 - Tipping off heavy objects can fall from the machine table
 - Distance should be maintained from rotating components or approach of the machine
 - Daily check for machine covers and guards on rotating shafts, belts and pulleys
 - Health & safety manual with the machine for associated hazards
 - High strength tool operation can cause uncovered tool to fracture and violently eject itself, or damage the workpiece causing chips blast or blow
 - Avoid mess (loose hairs, dust, clothing, papers)
 - Care for closing parts for closure (fingers trapping)



Robot envelope

FSW – Health and Safety Aspects



AILEEN

- Common FSW hazards: Electrical, mechanical, noise
 - Routine servicing of the machine (e.g., ECUs, PCBs) either through manual, suppliers or contractors.
 - Daily checks be performed for normal operation by operator before actual work
 - Noise levels in FSW can be very high (depends on design, material of tool, parameters, welding materials)
 - Repetitive levels >85 dB can cause damage to inner ear cells. High impact noise can cause eardrum perforation and scarring leading to less sensitiveness to sound
 - Heat can reach 0.8 of melting temperature in workpiece. Can cause fire spits. Heat resistant gloves should always be worn while adjusting the tool or workpiece
 - Proper cool down time should be maintained (tool & workpiece).
 - Use pyrometer for non-contact temperature measurements

FSW – Health and Safety Aspects



AILEEN

– Common FSW hazards: Material particles solid emissions

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

FSW – Applicable standards



- The FSW method is standardized according to ISO 25239
- ISO/FDIS 2553:2013-Welding and allied processes-Symbolic representation on drawing-Welded joints (joints information)
- ISO 13857:2008 - Safety of machinery
- ISO 14001 and OHSAS 18001 standards in Environmental, Health & Safety Management Systems

Thank You



AILEEN

