Friction Stir Welding European Qualifications

CU1 – FSW Fundamentals

FSW Specialist and Engineer

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1. FSW Fundamentals

1.1 - Introduction to FSW

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1.1 - Introduction to FSW

Friction Stir Welding (FSW)

– 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 non-consumable rotating tool that traverses along the weld.

Friction Stir Processing (FSP)

– Is a variation on the FSW operatio n. The FSW process locally changes the microstructure and properties of the weld region. Friction stir processing applies the FSW process to whole pieces of material. The tool is inserted and traversed back and forth changing the properties of the material.

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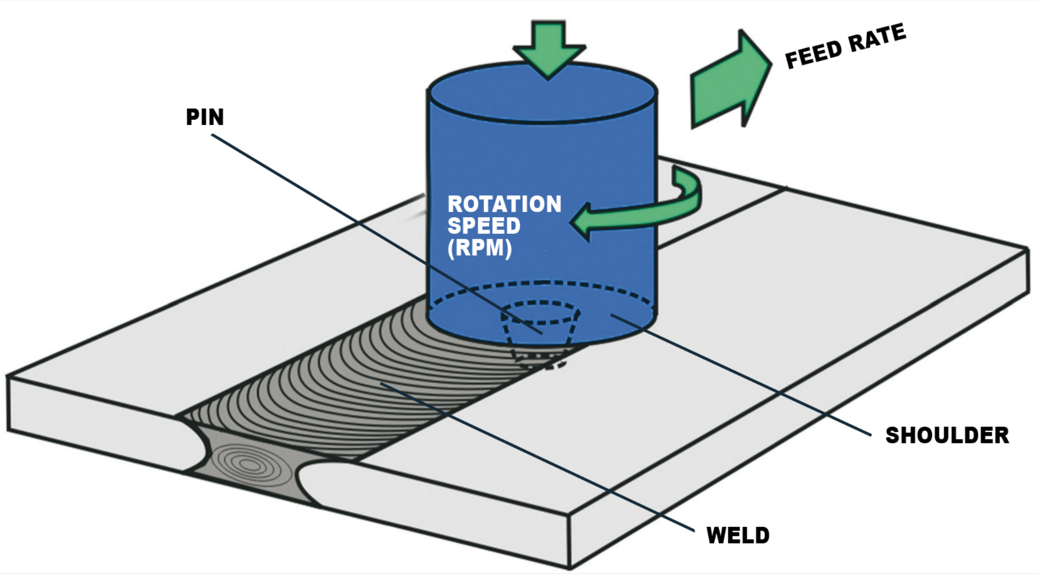
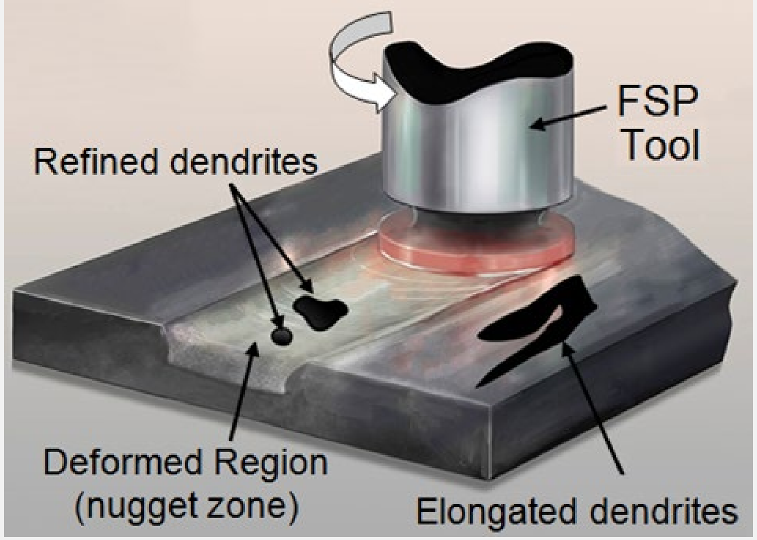
1.1 - Introduction to FSW



Friction Stir Welding (FSW)



Friction Stir Processing (FSP)

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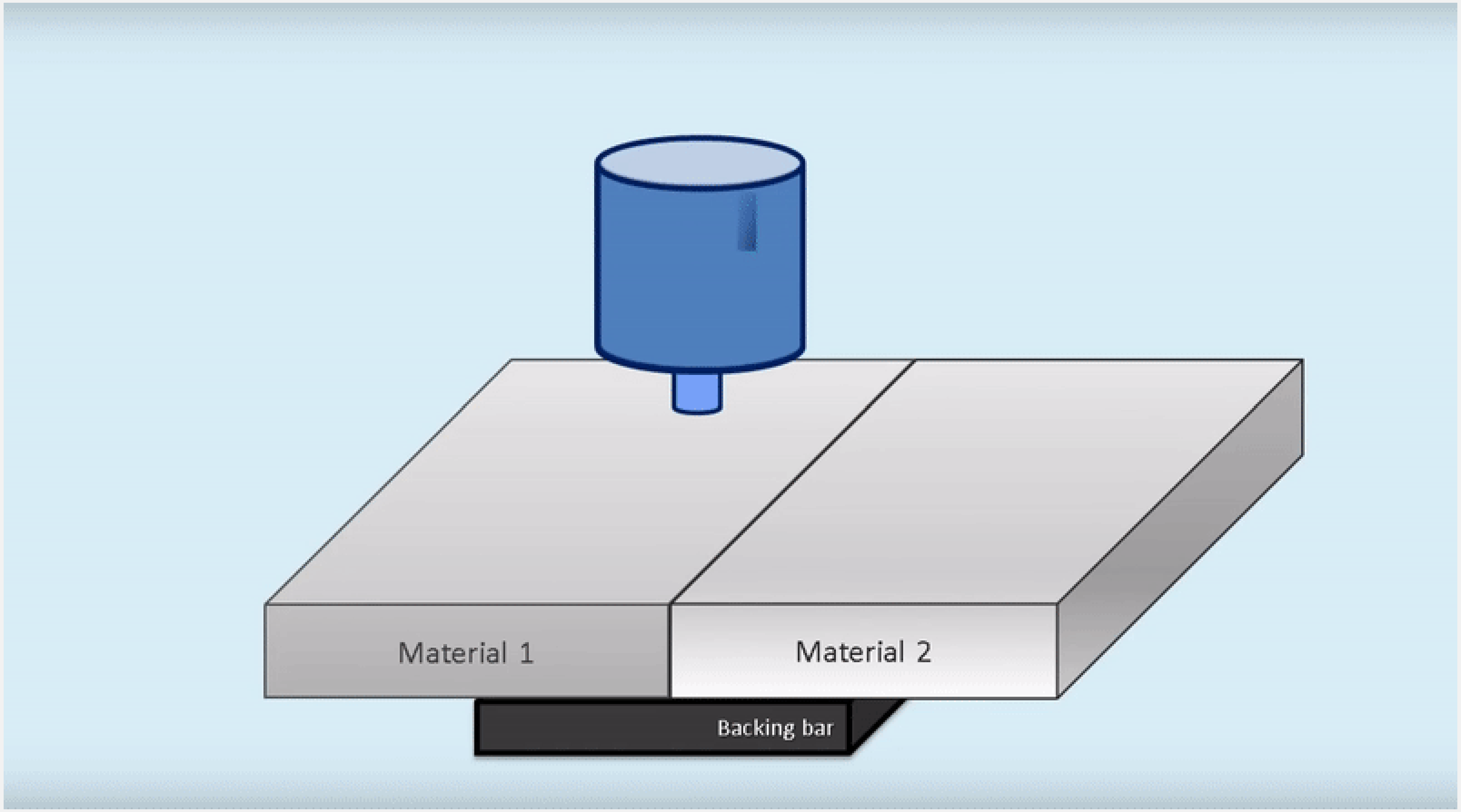

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1.1 - Introduction to FSW

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.

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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.

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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.

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Disadvantages of FSW process:

- A great amount of tool wear takes place during the plunging stage
- Single pass welding speeds in some alloys are slower than for some arc welding techniques
- 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

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FSW can be used in following industries:

- Shipbuilding and Off-shore
- Automotive
- Railways
- Aerospace
- Fabrication
- Others (electrical, oil and gas, nuclear industry, construction)

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The Friction Stir Welding Process for the **Railway** can be mainly utilized for aluminum panels for railway rolling stock

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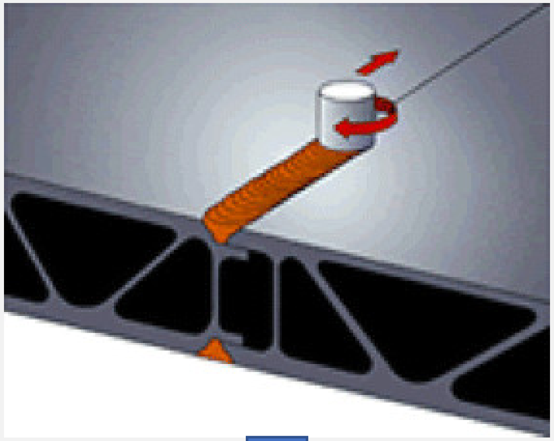
Railway – fully automatic extruded profile panels welding



Extruded profile welding

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The Friction Stir Welding Process for the **Automotive** can be utilized for:

- closures,
- tanks,
- suspensions,
- pistons,
- wheel rims,
- trailers

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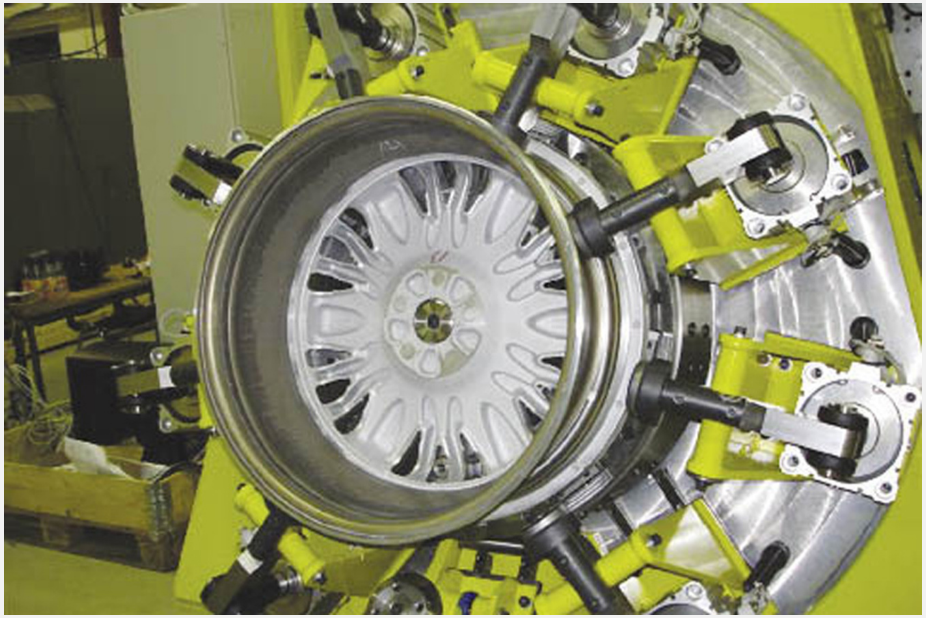
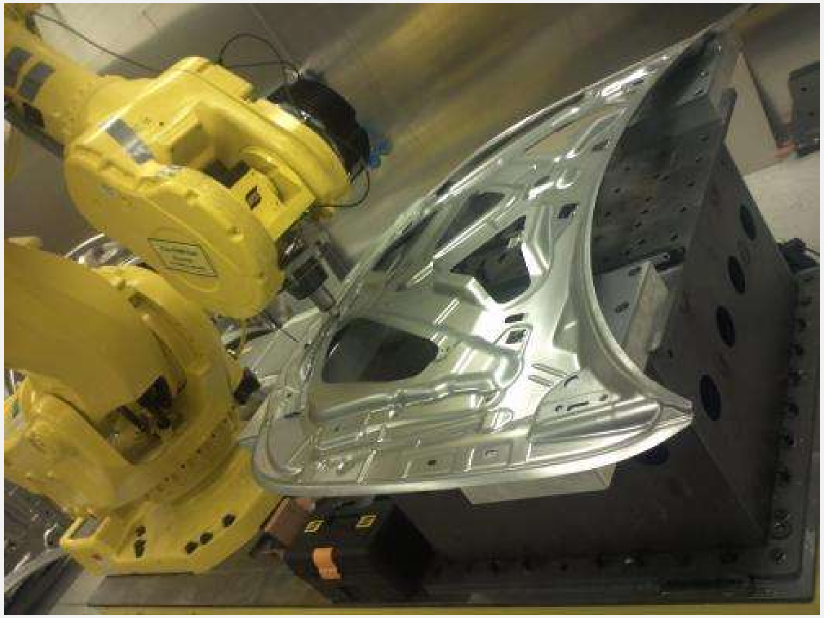


Automotive - manufacturing of wheel rims.



Robotic FSW of car body panel

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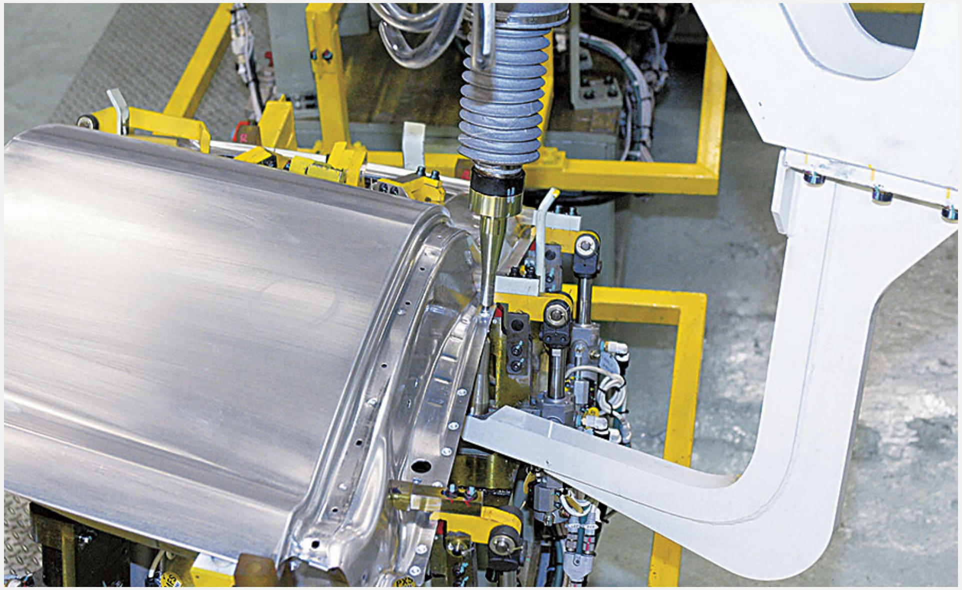

Friction stir spot welding

Dissimilar metals joining

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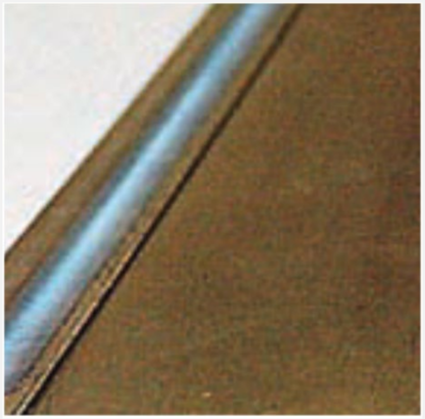

Possible automotive applications for friction stir welding: mixed joint between two thickness, folded seal weld and overlap joint.

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The Friction Stir Welding Process for the **Shipbuilding** can be utilized for:

- aluminum panels for deep freezing of fish on fishing boats,
- joining extrusions to create panels for decks and bulkheads,
- honeycomb panels,
- sea water resistant panels

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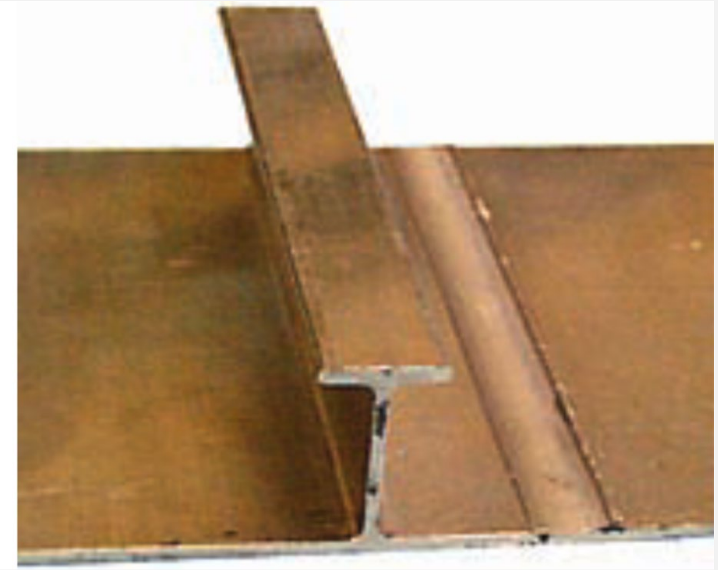
Shipbuilding – large panel FSW



Panel welded with FSW

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The Friction Stir Welding Process for the **Architecture and Construction Industry** can be utilized for:

- Flooring
- Decks
- Walkways
- Gangways
- Walls
- Awnings
- Weather Shields
- Suspended Systems
- Brackets

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Construction – canopy manufactured with FSW

Gangway and weather shield

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The Friction Stir Welding Process for the **Aerospace** can be utilized for:

- Fuel tanks for spacecrafts
- Toe nails of cargo ramp
- Aluminum panels
- Sandwich assemblies
- Landing gear doors
- Aircraft fuselages
- Wings

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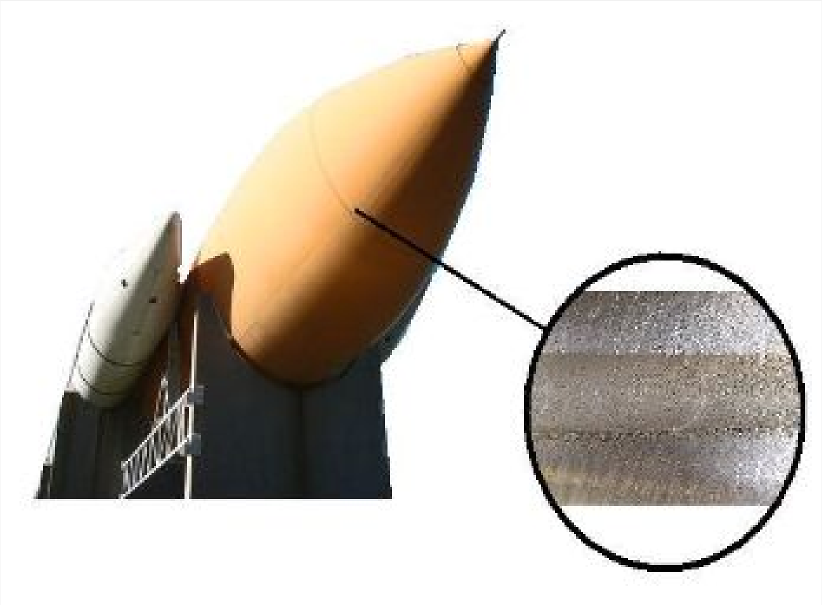
Aerospace industry - aircraft panelling



Rocket fuel tank

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The Friction Stir Welding Process can be also utilized for:

- Motor and loudspeaker housings
- Heat sinks
- Heating, ventilating and air conditioning unit
- Vacuum vessels
- Drying trays – food industry
- Copper canisters for nuclear waste

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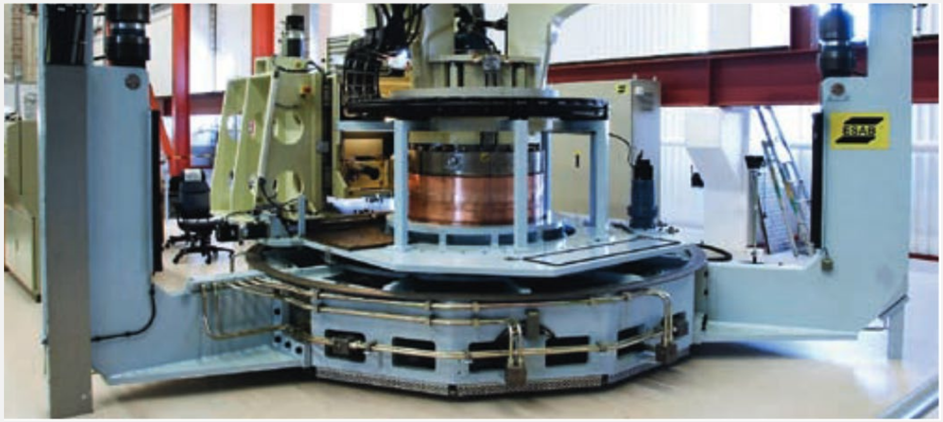

Nuclear industry – Copper canister with cast iron insert for nuclear fuel welded with FSW

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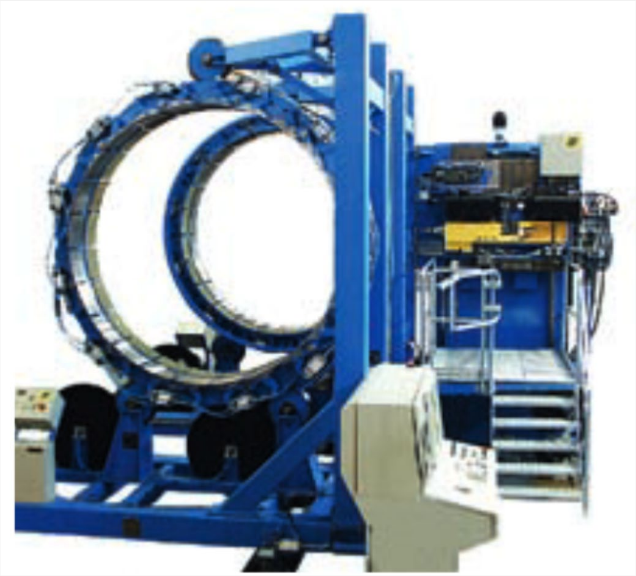

Circumferential welding machine

Orbital friction stir welding of steel pipe

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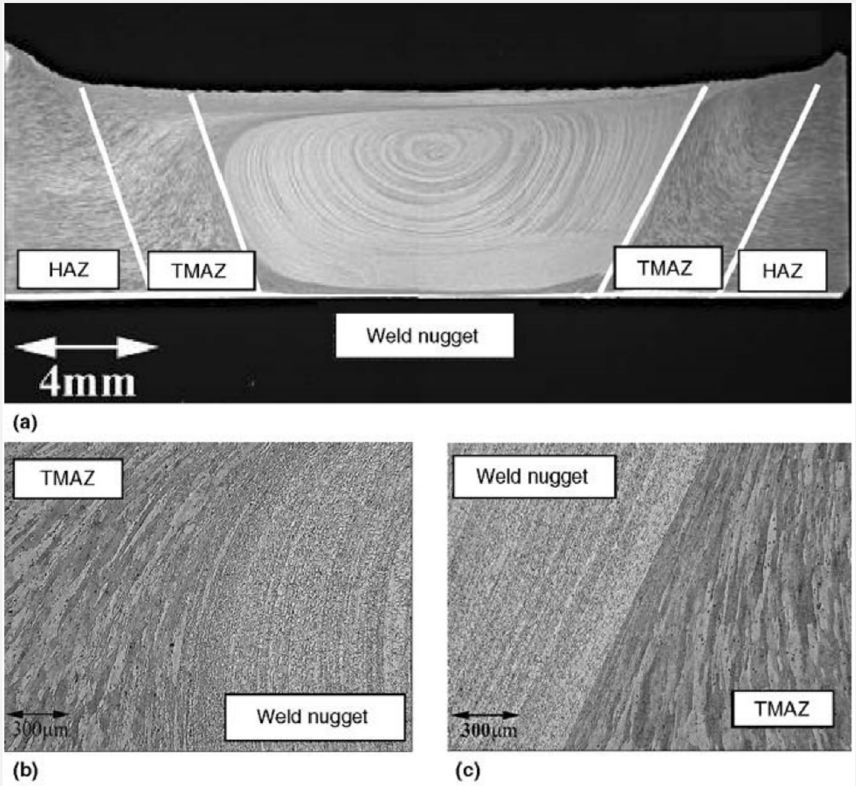

(a) Micrograph illustrating different zones in a friction stir welded aluminum alloy. (b) Retreating side. (c) Advancing side.

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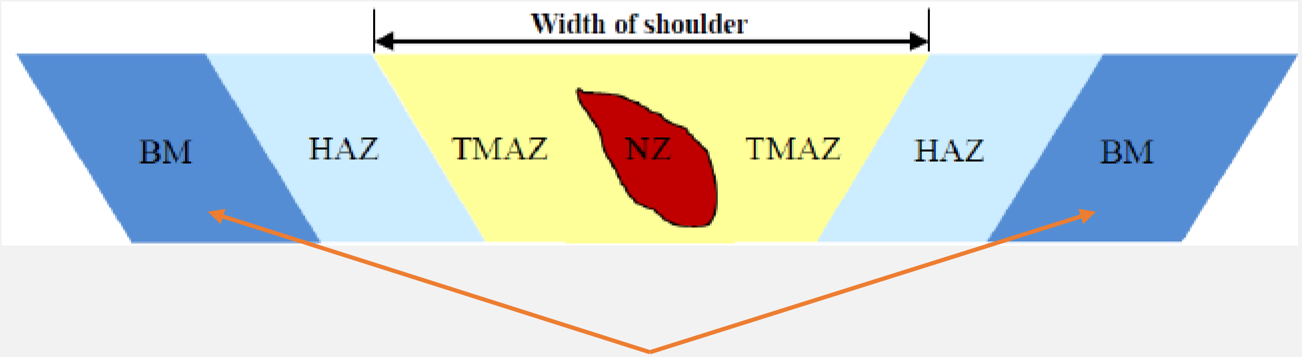

Base material (BM) zone

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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. 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.

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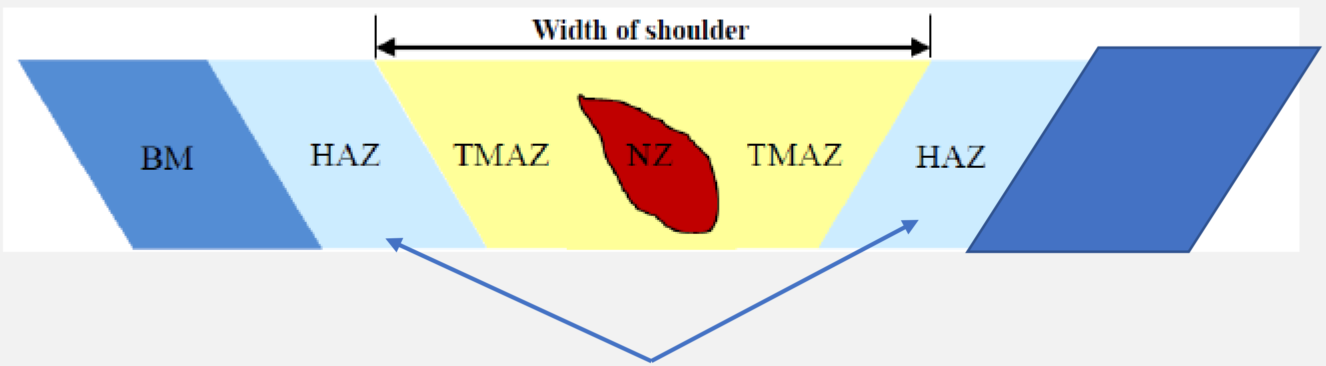

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1.1 - Introduction to FSW

Heat affected zone (HAZ)

- Moving towards the weld center, 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.

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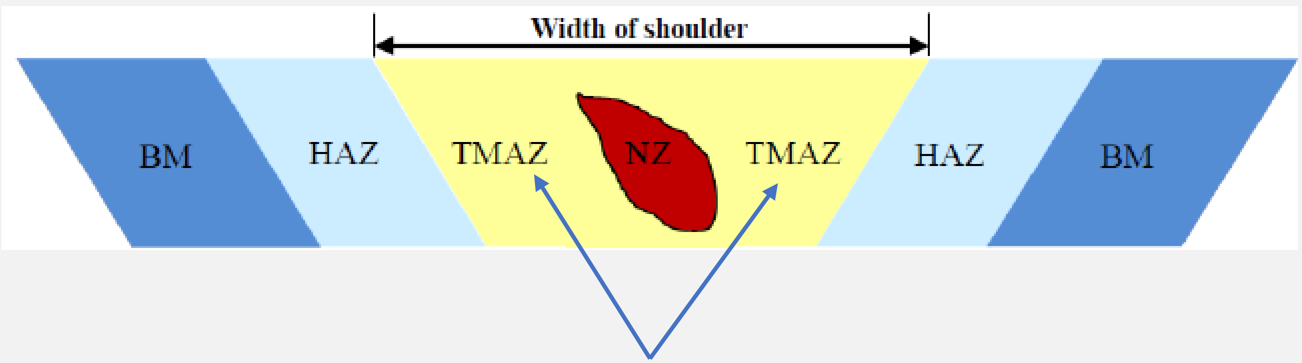

Thermo-mechanically affected zone (TMAZ)

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Thermo-mechanically affected zone (TMAZ)

- Zone that undergoes mechanical deformation
- In this zone the material is plastically deformed and the process is comparable to hot-working of metallic material
- Often defined to be without recrystallization. This is true for aluminum, 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 distinct boundary between weld nugget and TMAZ.

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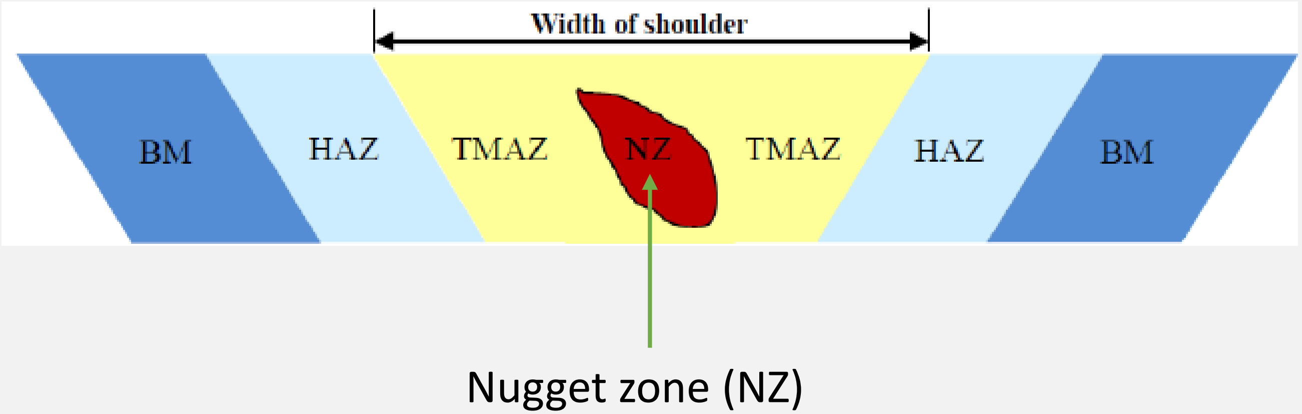

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1.1 - Introduction to FSW

Stir zone (SZ) or weld nugget

- Region with intense plastic deformation and frictional heating during the FSW process, lead to recrystallized fine-grained microstructure.
- This was the zone 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.

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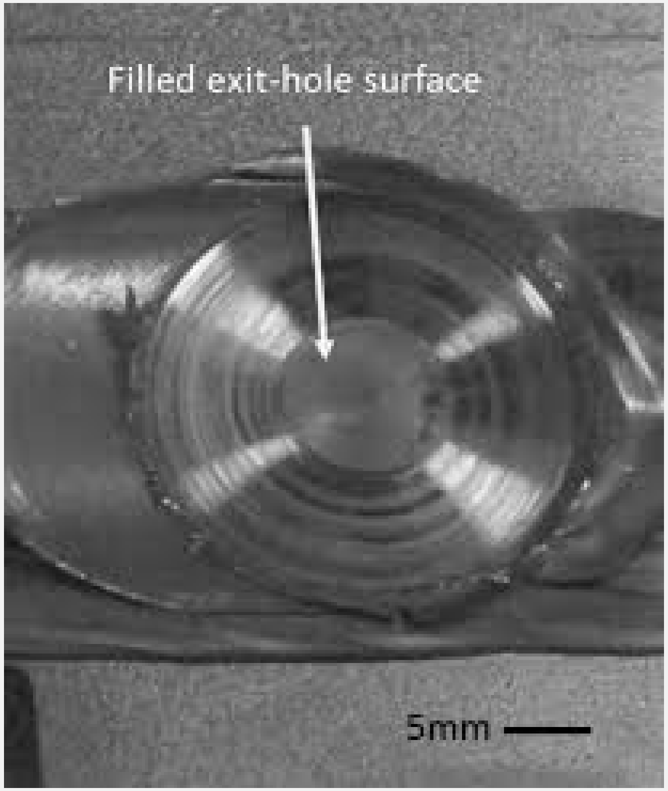

Filled exit-hole surface

Tandem FSW exit holes

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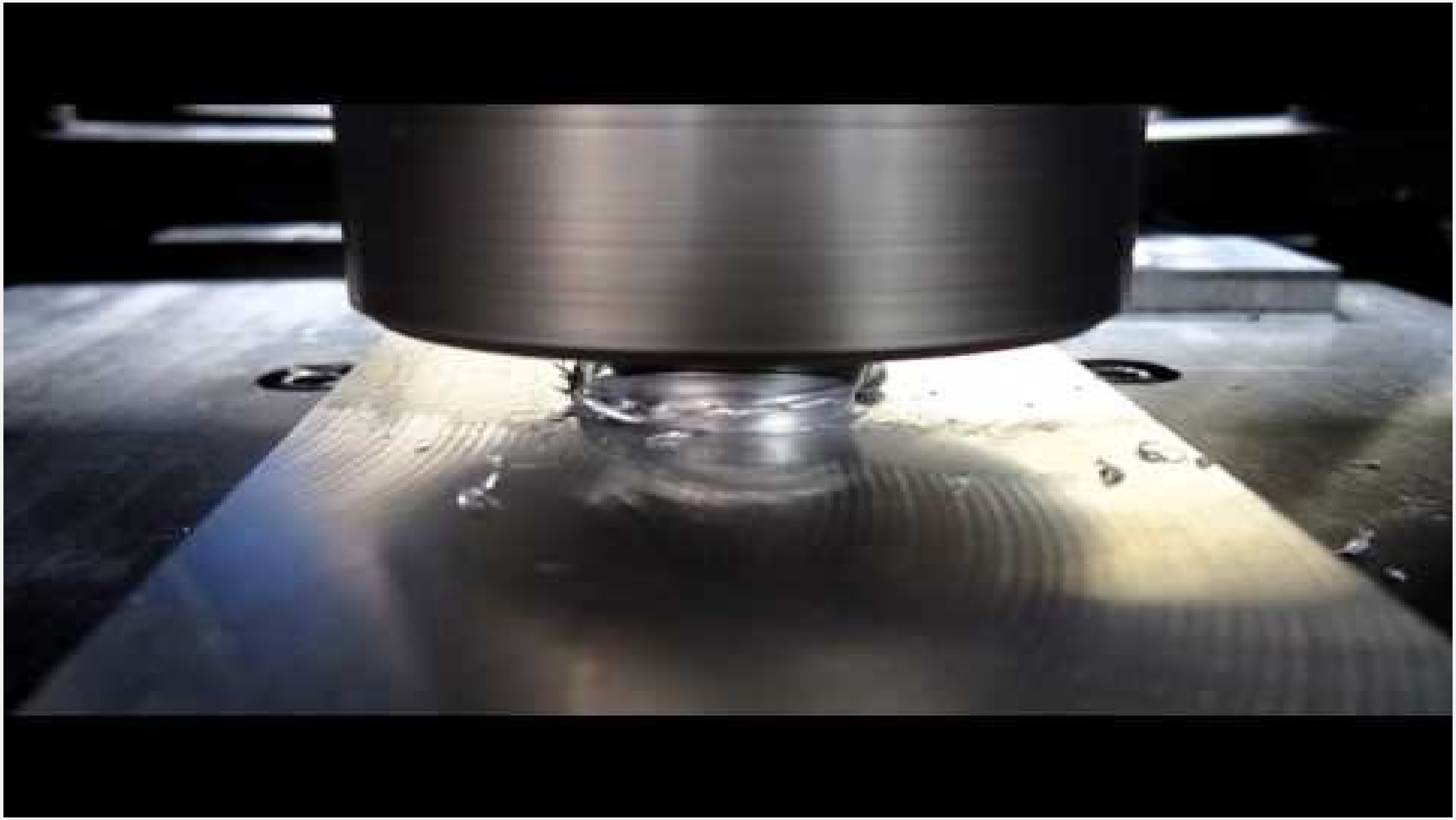

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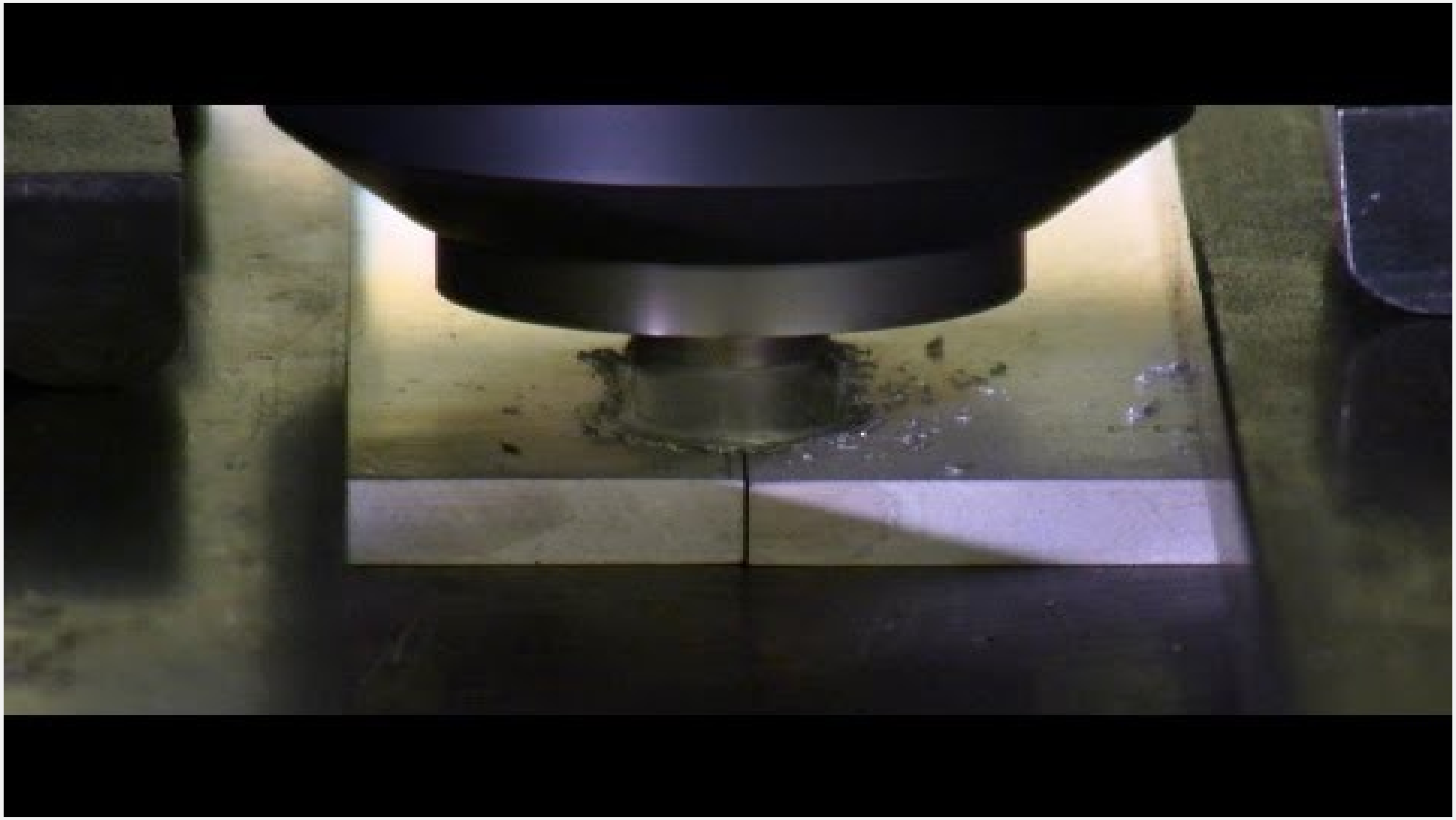

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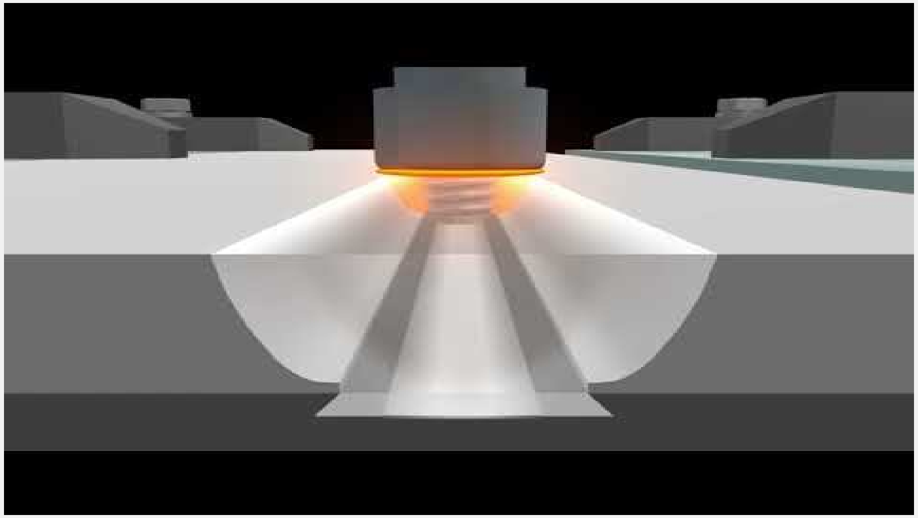
Developed on the base of friction stir welding

Friction Crush Welding (ger. Reibquetschschweißen)

Friction Stir Dovetailing



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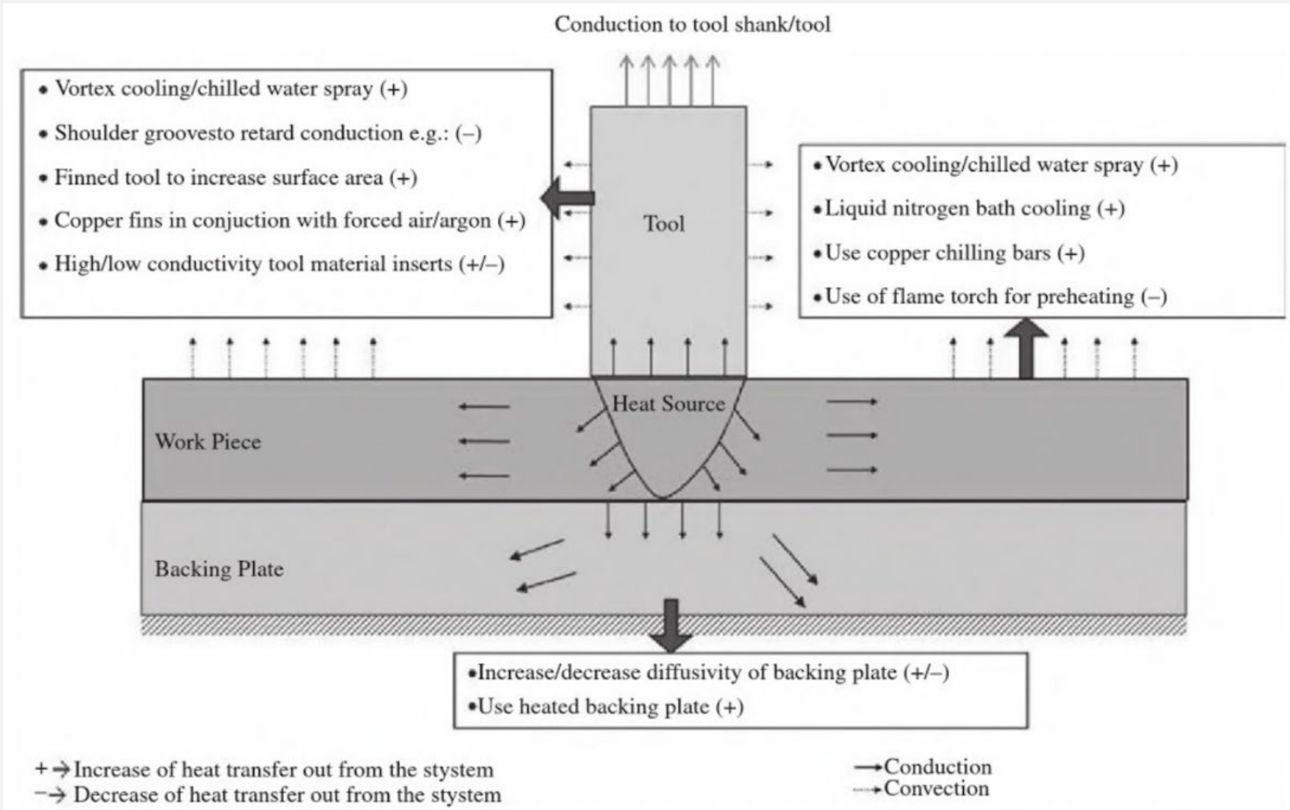

Thermal management methods that can be used in friction stir welding process. Arrows indicate heat transfer.

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1.1 - Introduction to FSW

1. FSW Fundamentals

1.2 - Welding equipment

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1.2 - Welding equipment

Basic system components include:

- spindle,
- motors,
- motor drive mechanism,
- FSW tool.

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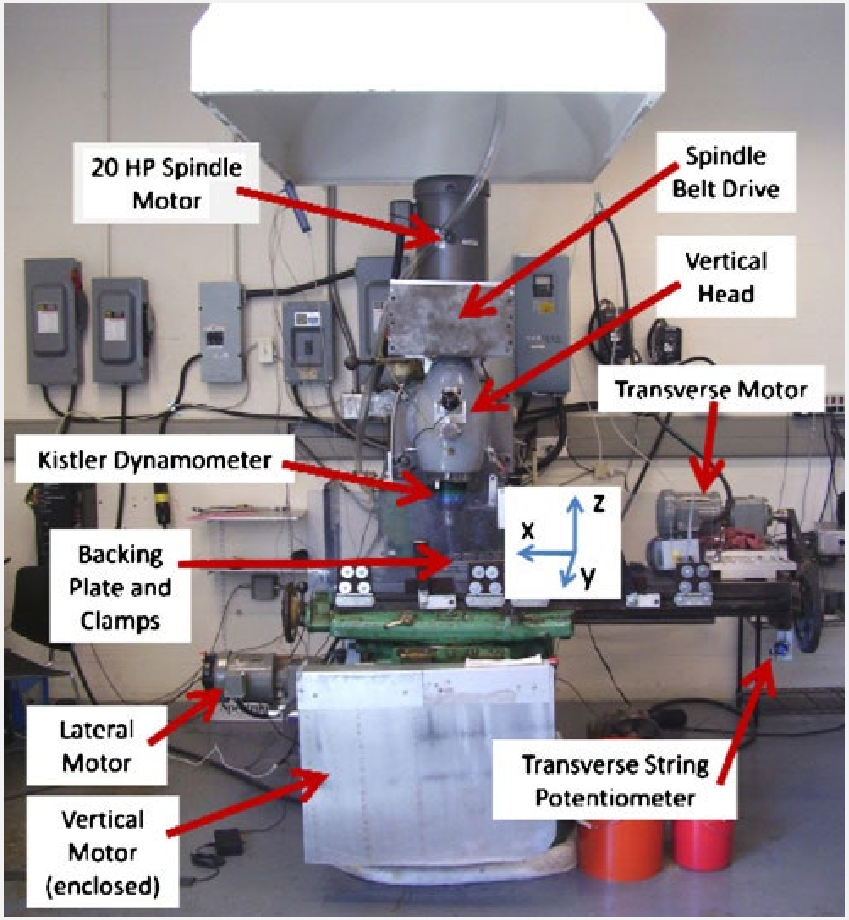

Example of FSW system configuration

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1.2 - Welding equipment

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

- CNC control,
- Production monitoring,
- Weld temperature monitoring,
- Joint tracking,
- Gas shielding,
- Machine Fixturing,
- Data Acquisition System,
- Height Sensing.

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1.2 - Welding equipment

Conventional machine tools

- low initial cost
- flexibility can be improved by the introduction of additional motors (additional DOF)
- stiffness of the machine – need to be strengthened
- force control solutions are needed to prevent equipment damage, ensure human safety and to achieve good weld quality

Adapted milling machine for FSW

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1.2 - Welding equipment

Robotic FSW machines

- high repeatability and flexibility
- relative low cost
- 3D paths welding
- process automation

- low accuracy that worsens when they are subjected to high loads
- relatively low stiffness and moderate load capability

Articulated arm robots

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1.2 - Welding equipment

Robotic FSW machines

- support higher loads
- significantly higher stiffness than articulated arm robot
- 3D paths welding
- process automation

- their cost can be notably higher and their volume is significantly lesser than the articulated arm robot

Parallel-kinematic robot

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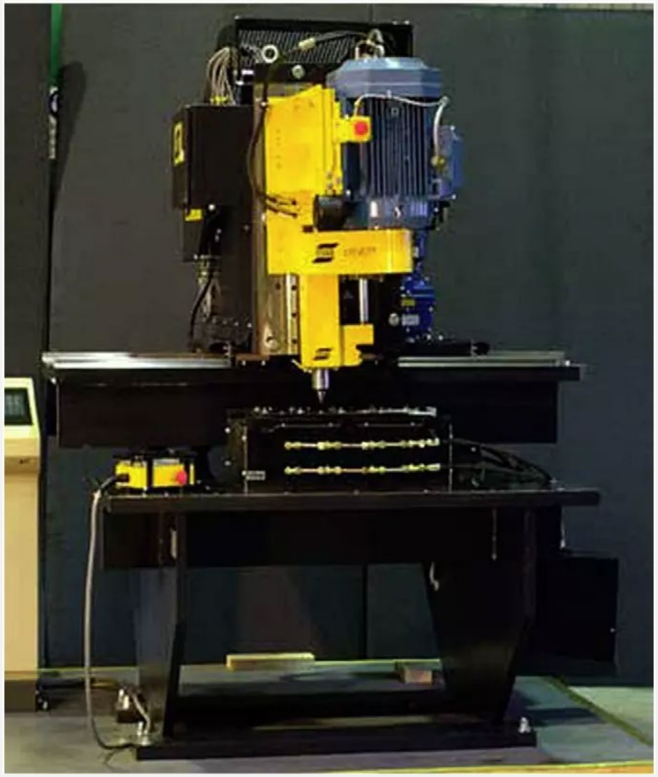
1.2 - Welding equipment

Dedicated FSW machines

- high load capability, stiffness, accuracy and availability
- possible different configurations thus presenting levels of flexibility
- the dedicated FSW machines are most robust and structurally stiff machines (welding of high temperature materials)
- rather expensive and their cost increase with increase in flexibility

Dedicated FSW machine



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1.2 - Welding equipment

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

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1.2 - Welding equipment

Example of tool geometry

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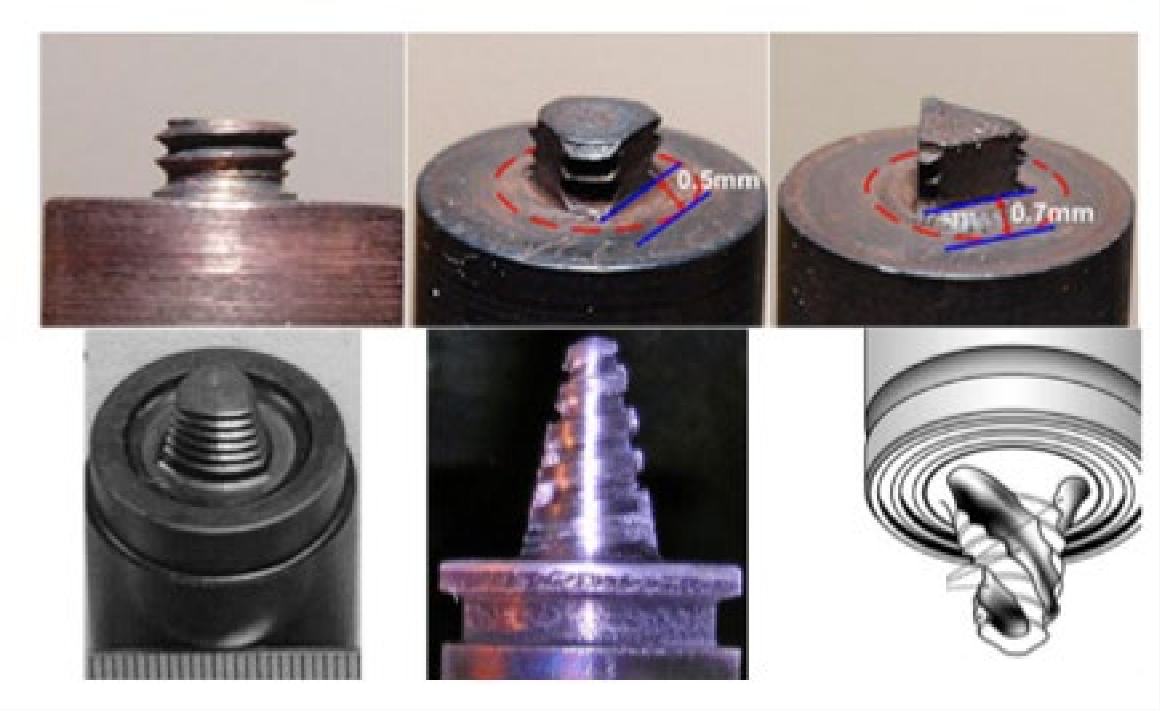

Different types of pin geometries

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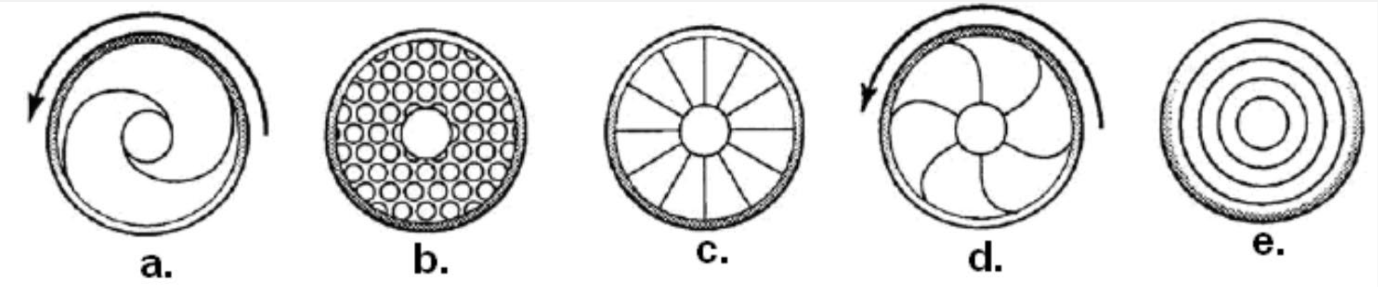

Different shoulder features (top) and example of convex and scrolled shoulder (bottom)

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1.2 - Welding equipment

Possible clamping systems include:

- Clamping claws,
- Hydraulic and pneumatic systems,
- Vacuum clamping systems.

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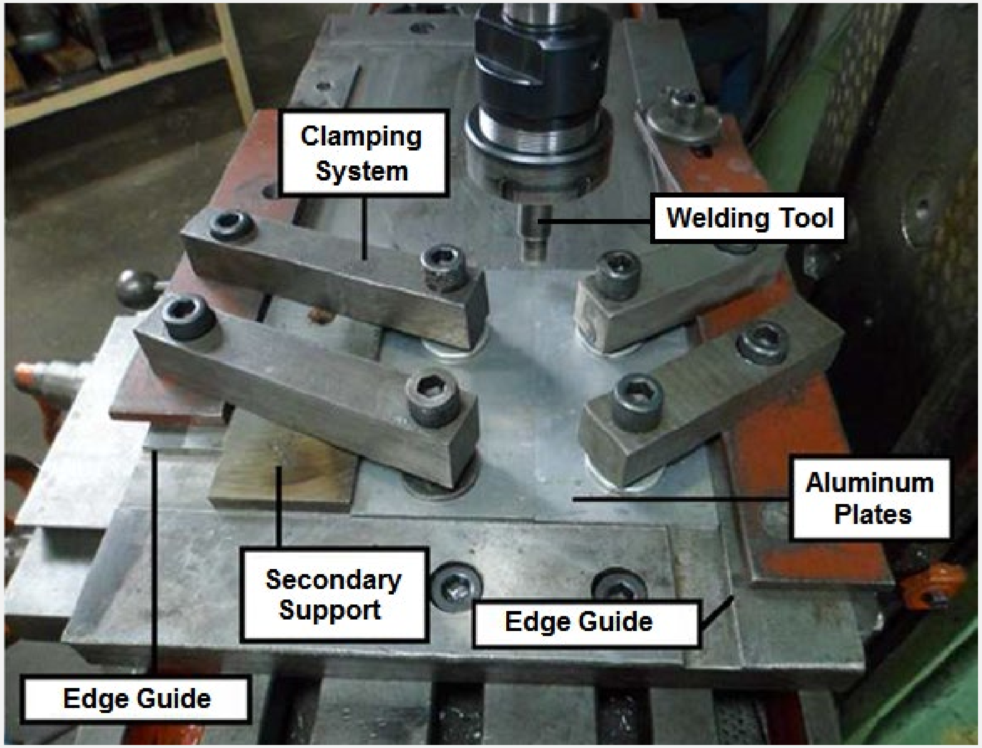

Clamping system

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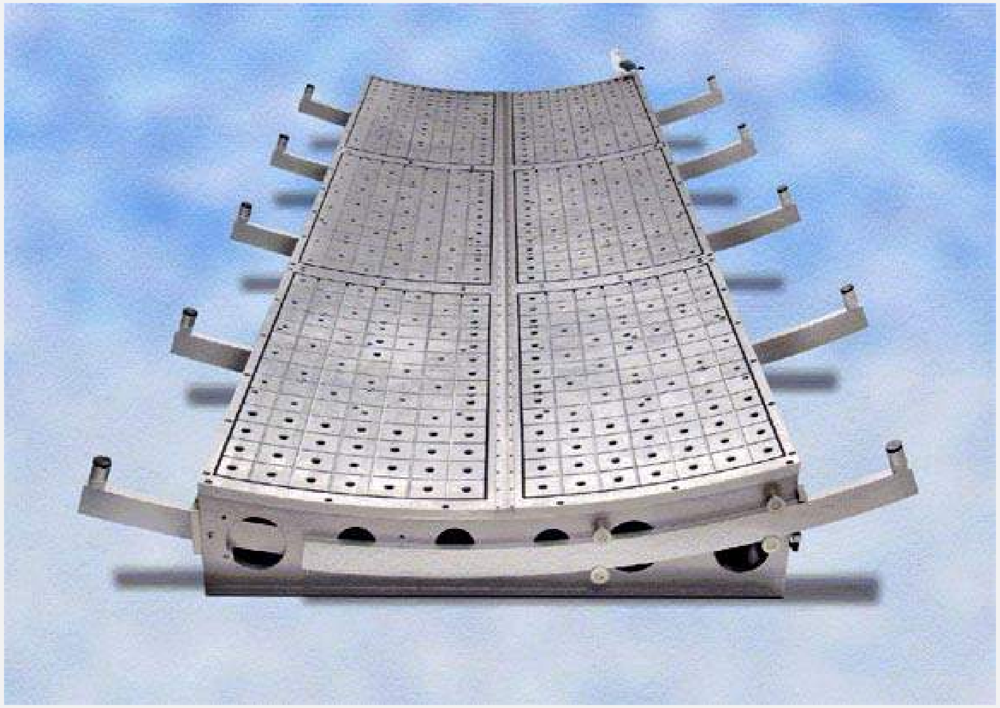

Vacuum clamping system

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1.2 - Welding equipment

Cooling enhanced FSW

- Water
- Liquid CO2
- Liquid nitrogen

- Steel, titanium, stainless steel and higher-temperature alloys are friction stir welded with coolant-cooled tools

Heating

- Electrically assisted FSW
- Laser assisted FSW
- Arc assisted FSW
- Ultrasonic energy assisted FSW

- The heating can minimize tool wear (especially the plunge) and increase the tool travel speed

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1.2 - Welding equipment

The key components of FSW machine include:

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

- Maintenance plans, inspections and complete documentation should ensure long term and trouble-free operation

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1. FSW Fundamentals

1.3 - Welding processes

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1.3 - Welding processes

Design implications of FSW:

- Mechanical limitations
- Fixture limitations
- Joint design limitations
- Keyhole limitations
- Workpiece and base material thickness limitations
- Material

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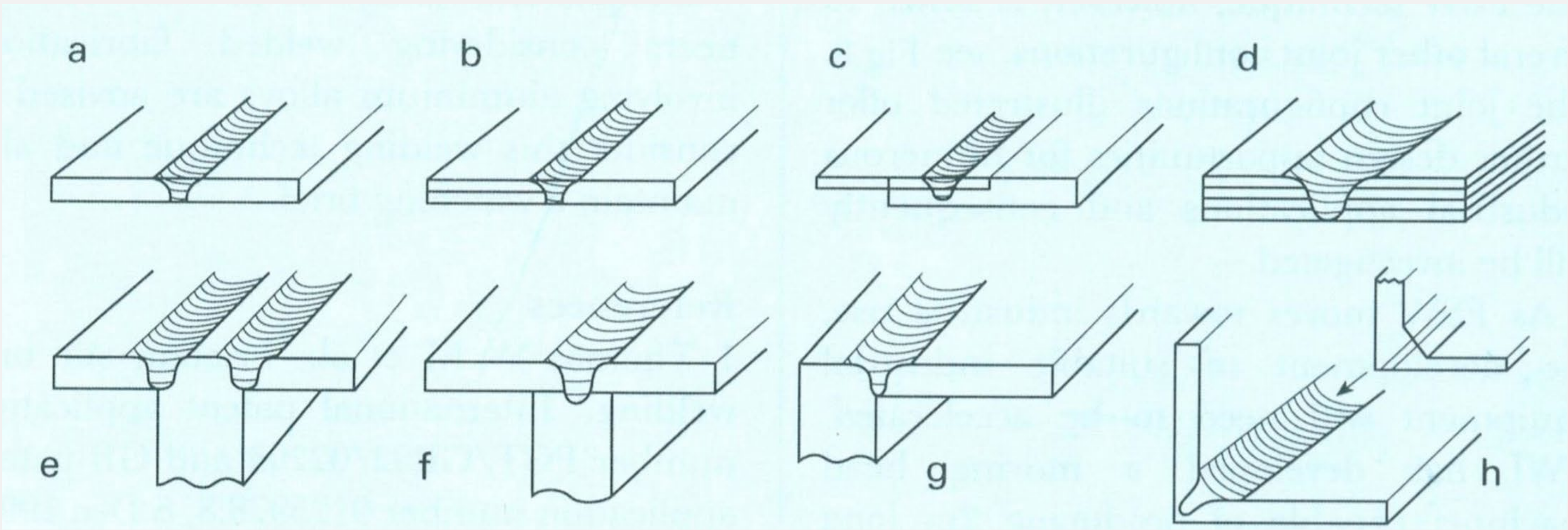
1.3 - Welding processes



Possible joint configurations: square butt ; (b) and (c) lap joint; (d) multiple lap joint; (e) T butt joint (f) T lap joint (g) edge butt (h) fillet joint

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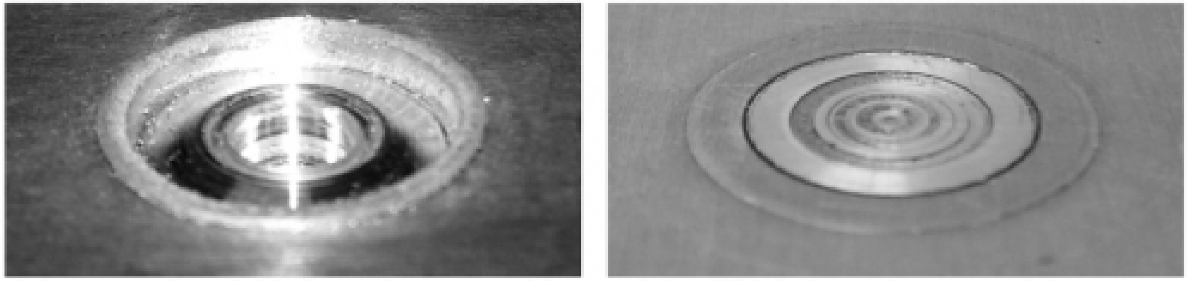
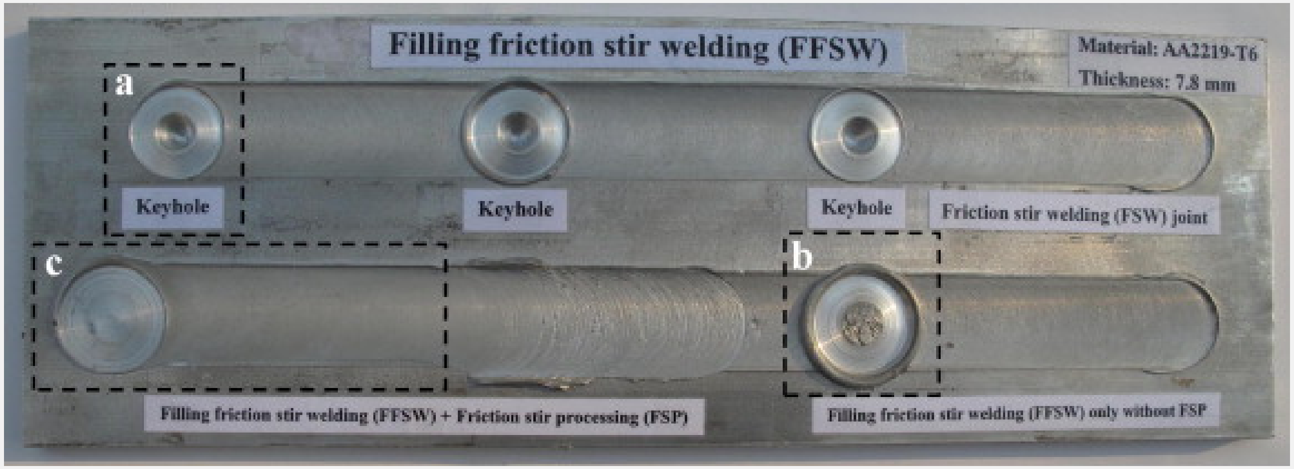
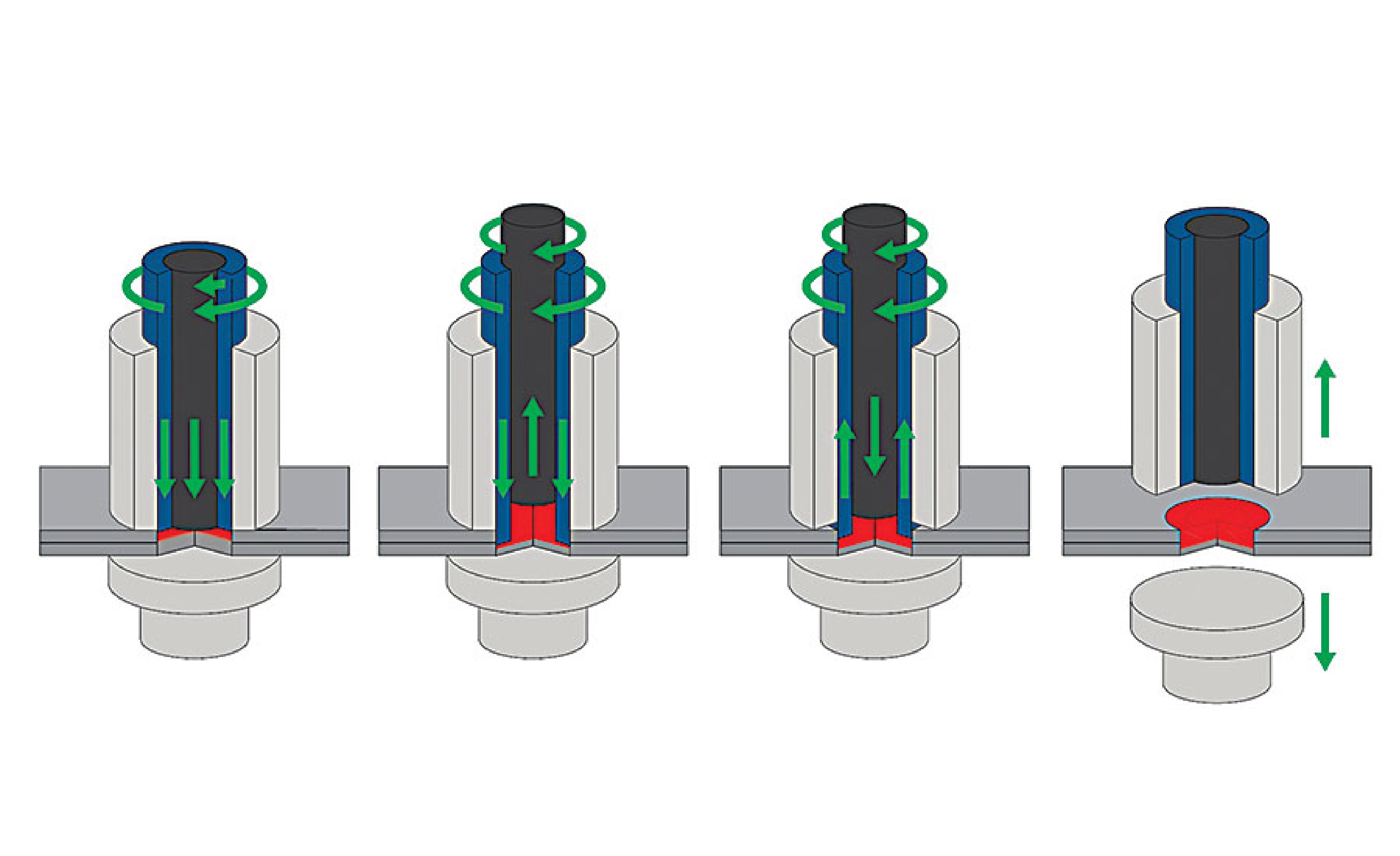

(a) conventional friction stir spot weld (b) refill friction stir spot weld.



Filling of keyhole

1.3 - Welding processes



Refill FSW process

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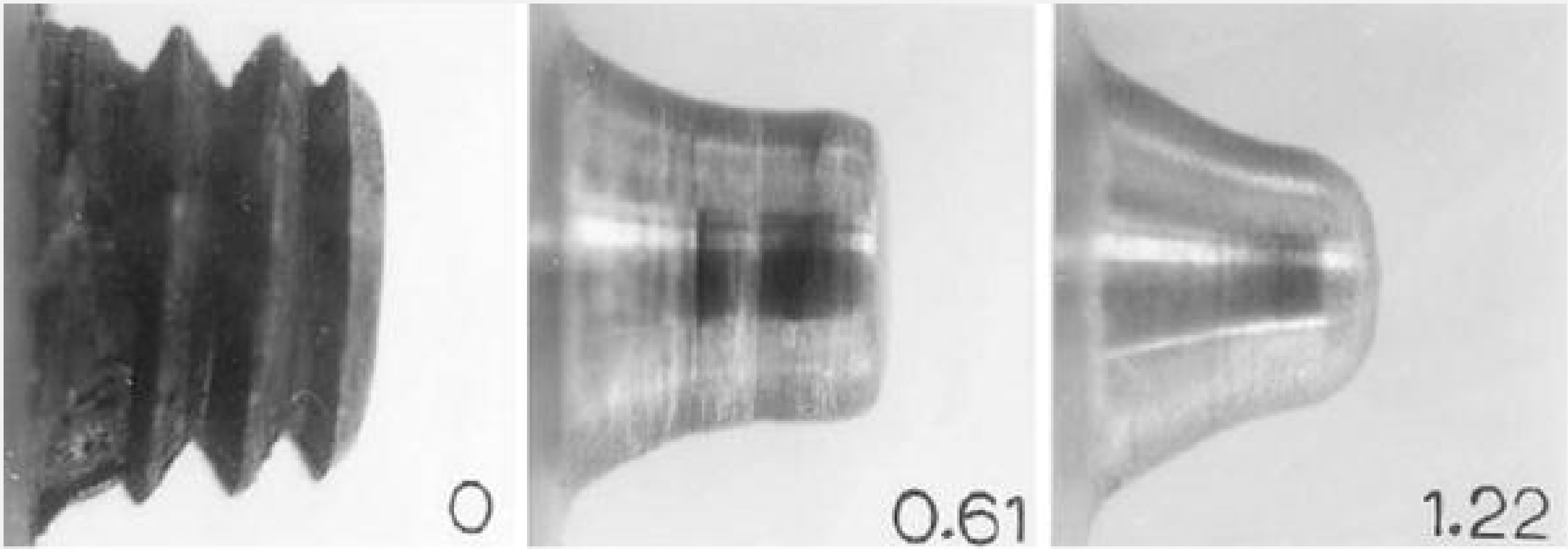

Tool wear (the number in the image correspond to the loss of thickness in the pin)

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1. FSW Fundamentals

1.4 - Parent Materials

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1.4 - Parent Materials

- FSW can be used in joining materials like aluminium, copper, magnesium, steel, thermoplastics and titanium.
- It is also possible to perform dissimilar material welding.
- Welding of high melting point materials is more difficult, because the welding tool material is working in harsh operating conditions.

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1.4 - Parent Materials

- 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.

Alloy	Thickness, mm	Tool material
Aluminum 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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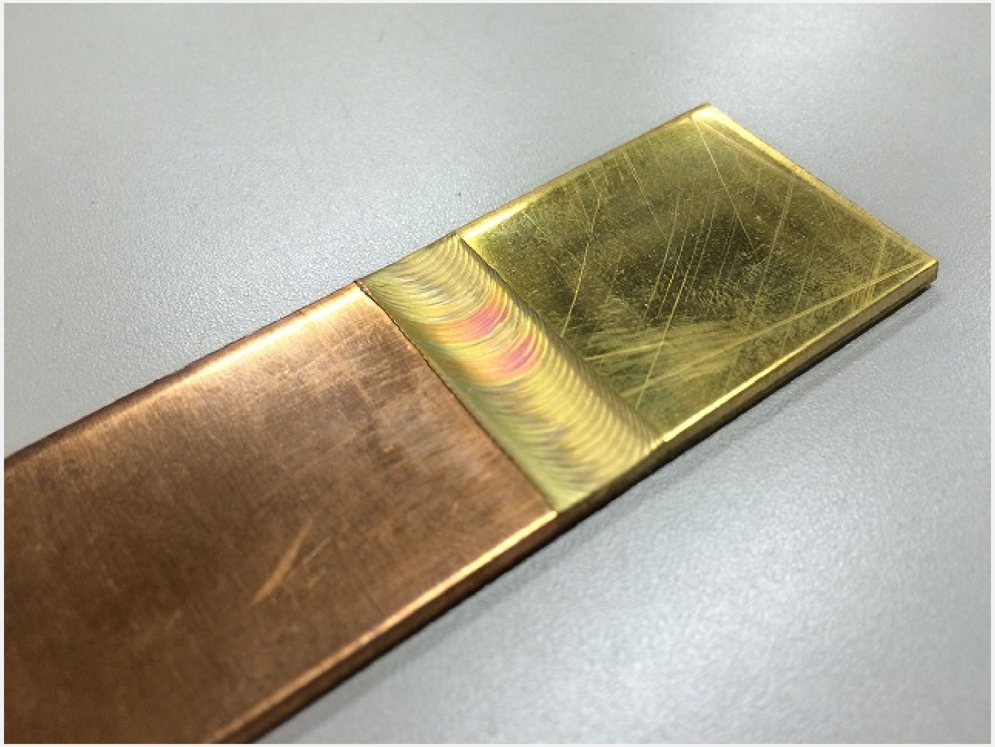

Dissimilar metals

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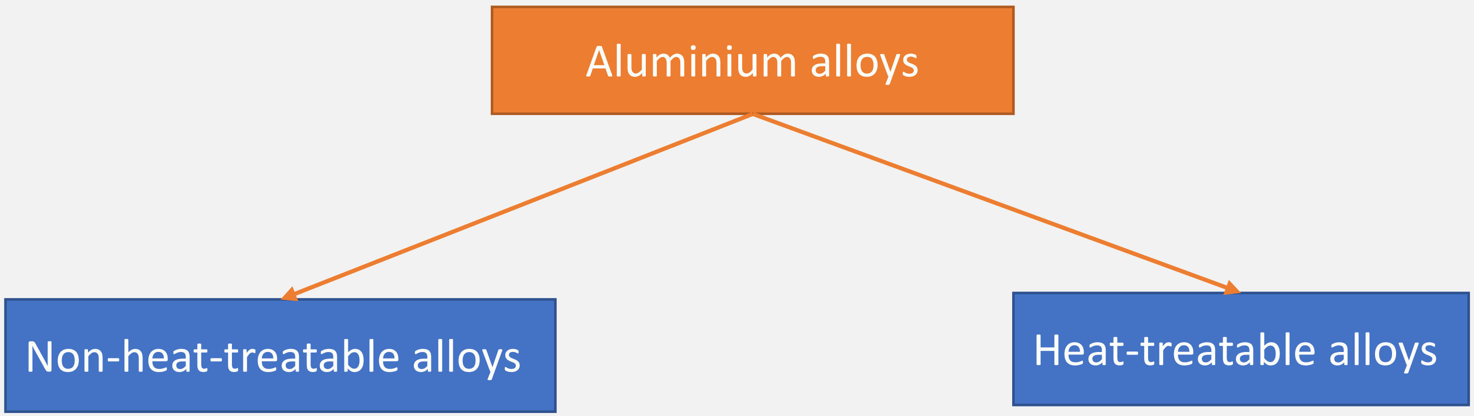

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1.4 - Parent Materials

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).

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1.4 - Parent Materials

Non-heat-treatable alloys have following properties:

- Softened weld zone is not verified in this 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.

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1.4 - Parent Materials

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.

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1.4 - Parent Materials

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.

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1.4 - Parent Materials

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.

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1.4 - Parent Materials

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.

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References

Slide:

[4] https://en.wikipedia.org/wiki/Friction_stir_processing

[4] http://www.uqac.ca/ceeuqac/index/csfm_english

[5] https://www.youtube.com/watch?v=ZpGfjg6BI5o

[12] http://assets.esab.com/asset-bank/assetfile/12296.pdf

[12] Cam, G., & Mistikoglu, S. (2014). Recent developments in friction stir welding of Al-alloys. *Journal of Materials Engineering and Performance*, *23*(6), 1936-1953.

[14] https://spinoff.nasa.gov/Spinoff2008/ip_4.html

[14] https://phys.org/news/2014-06-lighter-cars-robotic-welding-method.html

[15] https://www.assemblymag.com/articles/93337-friction-stir-spot-welding

[15] http://www.ftech.co.jp/en/development/

[16] http://assets.esab.com/asset-bank/assetfile/12296.pdf

[18] http://assets.esab.com/asset-bank/assetfile/12296.pdf

[20] http://assets.esab.com/asset-bank/assetfile/12296.pdf

[20] https://www.productionfrictionstirwelding.com/architecture-and-construction-products

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References

Slide:

[22] http://www.gatwicktechnologies.com/applications/body-panels

[25] http://assets.esab.com/asset-bank/assetfile/12296.pdf

[26] http://assets.esab.com/asset-bank/assetfile/12296.pdf

[27] Rajiv S. Mishra, Murray W. Mahoney, Friction Stir Welding and Processing, ASM International, 2007

[28] [30] [32] [34] Dawood, Hasan & Mohammed, Kahtan & Rahmat, Azmi & Basheer, Uday. (2015). Microstructural Characterizations and Mechanical Properties in Friction Stir Welding Technique of Dissimilar (Al-Cu) Sheet. JOURNAL OF APPLIED SCIENCE AND AGRICULTURE. 10. 149-158.

[37] Behmand, S. A., Mirsalehi, S. E., Omidvar, H., & Safarkhanian, M. A. (2015). Filling exit holes of friction stir welding lap joints using consumable pin tools. Science and Technology of Welding and Joining, 20(4), 330-336.

[37] https://www.researchgate.net/figure/Tandem-twin-stirTM-lead-and-follow-exit-holes_fig4_228600743

[43] Rajiv S. Mishra (Author), Harpreet Sidhar, Friction Stir Welding of 2XXX Aluminum Alloys including Al-Li Alloys, Butterworth-Heinemann, 2016

[38] Longhurst, W. R., Strauss, A. M., Cook, G. E., & Fleming, P. A. (2010). Torque control of friction stir welding for manufacturing and automation. *The International Journal of Advanced Manufacturing Technology*, *51*(9-12), 905-913.

[47] http://www.bil-ibs.be/en/friction-stir-welding

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References

Slide:

[50] https://www.asiamachinery.net/supplier/product_details.asp?ProID=13282&SupID=7312

[51] Mendes, N., Neto, P., Loureiro, A., & Moreira, A. P. (2016). Machines and control systems for friction stir welding: a review. Materials & Design, 90, 256-265.

[52] http://www.directindustry.com/prod/esab/product-18224-981963.html

[53] [40] Mendes, N., Neto, P., Loureiro, A., & Moreira, A. P. (2016). Machines and control systems for friction stir welding: a review. Materials & Design, 90, 256-265.

[54] Maria Asli Sicilan and S. Senthil Kumar"Analysis of Surface Quality of Friction Stir Welding Joints using Image Processing Techniques "International Conference on Emerging Trends in Engineering & Technology, Travancore Engineering College,Kollam, Kerela, India. 03/2014

[55] http://www.phase-trans.msm.cam.ac.uk/2011/tools.html

[56] Pasha, A., Reddy, R., Laxminarayana, P., & Khan, I. A. (2014). INFLUENCE OF PROCESS AND TOOL PARAMETERS ON FRICTION STIR WELDING–OVER VIEW. *Int J App Eng Technol*, *4*(3), 54-69.

[58] Pastor, A., & Svoboda, H. G. (2013). Time-evolution of heat affected zone (HAZ) of friction stir welds of AA7075-T651.

References

Slide:

[59] https://www.aerospace-technology.com/contractors/sub_contract/horst/attachment/horst3/

[65] Han, B., Huang, Y., Lv, S., Wan, L., Feng, J., & Fu, G. (2013). AA7075 bit for repairing AA2219 keyhole by filling friction stir welding. *Materials & Design*, *51*, 25-33.

[65] https://uwaterloo.ca/centre-advanced-materials-joining/laboratory-facilities-and-equipment/production-equipment/friction-stir-welding-equipment

[66] https://www.assemblymag.com/articles/93337-friction-stir-spot-welding

[67] Wang, D., Xiao, B. L., Ni, D. R., & Ma, Z. Y. (2014). Friction stir welding of discontinuously reinforced aluminum matrix composites: a review. *Acta Metallurgica Sinica (English Letters)*, *27*(5), 816-824.

[70] Rajiv S. Mishra, Murray W. Mahoney, Friction Stir Welding and Processing, ASM International, 2007

[71] https://www.kikukawa.com/en/technology/friction-stir-welding/

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