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State of the art of continuous friction stir welding

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Modern industries are constantly looking for better solutions to produce strong, reliable joints in their products. The ever-evolving need for more lightweight structures alongside with environmentally sustainable methods sets limitations for the processes to be used. So far, fusion-based welding methods have been widely used to join similar materials. However, those methods cannot effectively create sufficient bonding between dissimilar materials, as the requirement of lightweight structures is often met with hybrid material joints. Friction stir welding (FSW), in contrast to fusion welding, is ideal for hybrid joints. The method was developed in 1991, and various modified methods have been invented since then. FSW has great potential to become more widely used in multiple industrial applications and therefore it is necessary to understand the current advantages and limitations of the process.

The purpose of this thesis is to conduct a literature review of the state of the art of continuous friction stir welding. This thesis focuses on presenting multiple current available FSW processes and applications, discusses the most important welding parameters in FSW processes, introduces the future potential of FSW and reports the current market situation of FSW.

The author declares that Microsoft Copilot AI-tool has been used to check and refine the language of this thesis.

Key words: friction stir welding, FSW, state of the art, solid-state welding, FSW applications

List of used abbreviations:

FSW	friction stir welding
TWI	The Welding Institute
AS	advancing side
RS	retreating side
SZ	stir zone
TMAZ	thermo-mechanically affected zone
HAZ	heat affected zone
BM	base material
SSFSW	stationary shoulder friction stir welding
RDR-FSW	reverse dual rotation friction stir welding
BT-FSW	bobbin tool friction stir welding
SSUBTFSW	stationary shoulder bobbin tool friction stir welding
FLW	friction lap welding
FSLW	friction stir lap welding
FSSW	friction stir spot welding
Refill FSSW	refill friction stir spot welding
FSpW	friction spot welding
PCBN	polycrystalline cubic boron nitride
WRe	tungsten rhenium
HfC	hafnium carbide
WC	tungsten carbide
WC-Co	tungsten carbide-cobalt

HWTS	hot work tool steel
HSS	high-speed steel
TRS	tool rotational speed
WS	welding speed
PD	plunge depth
IMC	intermetallic compound
AM	additive manufacturing
LPBF	laser powder bed fusion
FSAM	friction stir additive manufacturing
M-FSAM	modified friction stir additive manufacturing
AFSD	additive friction stir deposition
AFED	additive friction extrusion deposition

Table of contents

1 Introduction

Friction stir welding, often called FSW, is a solid-state joining process that was originally developed for strong, high-quality welds, especially for high-strength aluminium alloys by Wayne Thomas at The Welding Institute (TWI) in 1991. The process enhances the properties of welded materials compared to traditional fusion welding methods. The advantages are produced by the plastic deformation experienced at high temperatures, but below the melting point. This results to a wrought microstructure instead of a solidification microstructure, usually found in welds produced by fusion methods. [1–3]

Friction stir welding has multiple advantages. The process can be used to join various metals and composites, either similar or dissimilar materials. Producing strong multi-material structures creates new opportunities for manufacturing applications. One of the greatest advantages is that FSW is an environmentally friendly manufacturing method. It requires less energy, produces no harmful emissions such as UV radiation or fumes and causes significantly less waste compared to other welding technologies. FSW has potential and can be developed into automated processes, increasing productivity and adapting to the needs of modern industries. [2] Because FSW is a solid-state process, it produces nearly defect-free welds. Avoiding hot cracking, porosity and solidification cracking leads to good mechanical properties in the weld. As the temperature in the process stays low, the material dimensions do not significantly change compared to fusion welding technologies. [4]

Even though friction stir welding has a lot of advantages, the method has also its own limitations. Metals with high melting points are hard to process cost-effectively with FSW. [2] Due to the movement of the tool, an exit hole or a keyhole is often formed at the end of the weld. A strong downward force and traverse forces are needed to produce the required heat for softening the material and creating the weld. This leads to the need for clamping the workpieces, which is more significant compared to arc welds. Also, the positioning of the parts to be joined is substantial, because there is no filler material used. However, the limiting effects related to FSW can be partly reduced. The formation of an exit hole can be taken into account while designing the part. [4] The need for fixing the parts can be avoided by using developed FSW methods, that do not require the clamping, such as bobbin tool friction stir welding. Choosing the correct FSW-method might also delete the problem related to the exit hole (refill friction stir spot welding).

2 Friction stir welding

2.1 FSW methods

2.1.1 Standard FSW

There are multiple variations of friction stir welding. The standard, conventional method of FSW originally relies on the principle of joining two workpieces with a rotating tool. The tool is made of non-degradable materials and consists of two parts: a shoulder and a probe. The material of the tool depends on the processed materials. In the standard method, the FSW tool rotates at high rotational speed and is inserted between the tightly fastened workpieces. The probe bores into the material until the shoulder touches the top of the workpieces. After the shoulder contact and a short dwell at the start, the tool follows the interface of the workpieces. The rotation of both the probe and the shoulder causes the material to soften, while the downward force extrudes the softened, flowing material to form a weld. After reaching the end of the weld, the tool is retracted away from the workpieces. [2] Figure 1 illustrates the working principle of standard FSW, with AS denoting the advancing side of the base material and RS denoting the retreating side.

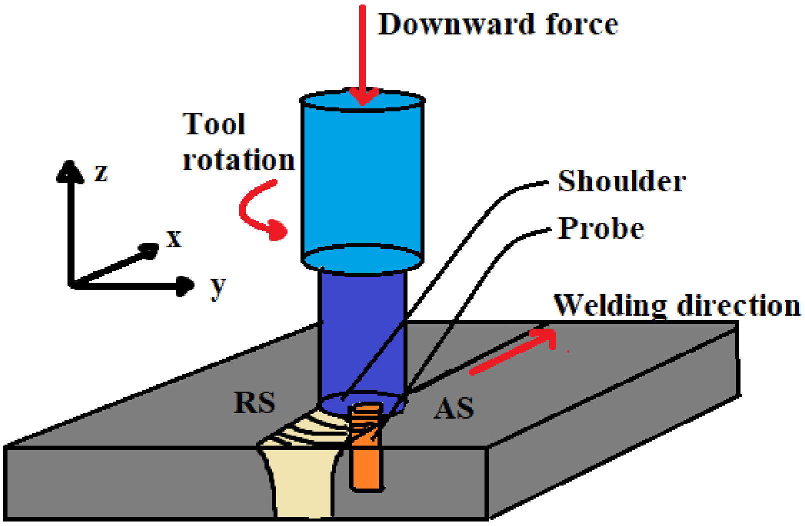

Figure 1. The standard friction stir welding (FSW) process

The welding process forms four different zones in the processed material. In the middle of the weld is the stir zone (SZ), where the highest temperature and deformation levels are located. In the SZ, the significant plastic deformation results in a fine and complex microstructure. The next zone from the middle is the thermo-mechanically affected zone (TMAZ), where plastic deformation occurs with coarser grain structure compared to SZ. TMAZ is surrounded by heat-affected zone (HAZ), where the grains are even coarser. The base material (BM) zone represents the unchanged material. [5] The formed zones are illustrated in figure 2 as a cross-section of a weld.

Figure 2. Formed material zones in FSW

2.1.2 Stationary shoulder FSW

Stationary shoulder friction stir welding (SSFSW) is one application of friction stir welding. The difference between standard FSW and SSFSW is the tool. Instead of rotating in the same direction as the probe, the tool shoulder stays fixed. Overheating is often a problem when welding thick materials with low thermal conductivity. Fixing the shoulder reduces the heat input into the weld, reducing the chance of overheating at the top of the weld zone. [2,6]

2.1.3 Reverse dual rotation FSW

Reverse dual rotation FSW (RDR-FSW) is a FSW variant, in which the shoulder and probe rotate in opposite directions and independently. The rotating speeds are different, with the probe having significantly higher rotation speed, whereas the shoulder rotates at lower speed. This type of configuration is advantageous in reducing overheating and preventing the melting of the material. The net torque on the workpieces is lower because the reverse rotation of the shoulder partially offsets the torque created by the probe. Therefore, the variant is useful in cases where clamping the workpiece is difficult. Considering the produced weld, using RDR-FSW leads to a more uniform temperature distribution compared to the conventional FSW. Despite the advantages, RDR-FSW still needs to be investigated to optimize and understand the relationship between the welding parameters and joint properties. With the more complicated design of the tool, RDR-FSW is a more complex process and must be developed further to implement it in industrial use. [2]

2.1.4 Bobbin tool FSW

Bobbin tool friction stir welding (BT-FSW) is a method, in which the materials are welded together by a tool that has two shoulders instead of one. The shoulders are connected to the probe in between them. As a method, BT-FSW is more flexible compared to standard FSW. Because the tool consists of a pair of shoulders, no rigid backing support plate is needed, as the tool supports the workpiece from behind. This allows the welding of hollow structures like pipes. [2,7]

With the tool being in contact with the upper and lower surfaces of the workpieces, the created stir zone is hourglass-shaped between the tool shoulders. Root defects are less likely to occur due to more uniform heat input. The conventional BT-FSW tool shoulders have a predetermined distance between each other, and the tool is tightly fastened to the rotating spindle. An improved version of the tool allows the bobbin tool to move axially in the connecting sleeve. A pair of shoulders installed this way is advantageous in balancing the axial forces applied to the workpieces, since the lower shoulder can be used to either partially decrease or fully cancel out the downward force. [2,7] The conventional and axially floating BT-FSW tools are presented in figure 3, where A is the conventional and B the floating tool.

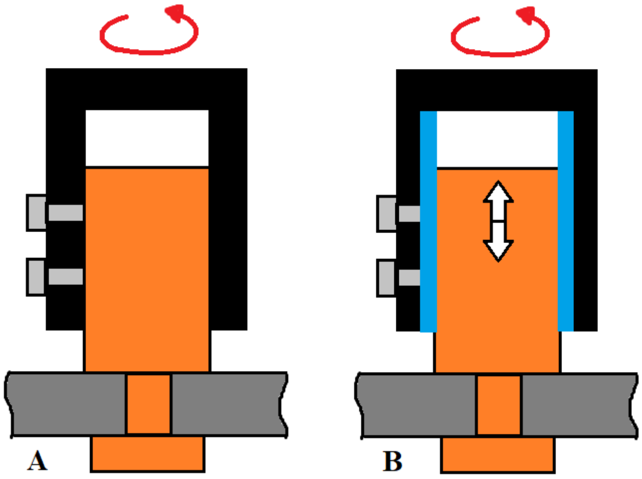

Figure 3. Bobbin tool FSW tools. (Modified from [2]). A: conventional BT-FSW tool, B: floating BT-FSW tool

Due to having two shoulders creating frictional heat, the heat input into the workpieces is much higher in BT-FSW compared to standard FSW. Excessive heat input deteriorates the material’s mechanical properties such as tensile strength. An application of BT-FSW, the stationary shoulder BT-FSW (SSUBTFSW) has been developed to reduce the heat input. With the lower heat input, there are other improvements over conventional BT-FSW, as

SSuBTFSW increases joint strength and gives the weld an excellent, smooth surface finish. The working principle is similar compared to SSFSW, as the upper tool shoulder stays fixed. [8] Fixing both shoulders has been investigated too, but the even lower heat input was found to more likely cause void defects. Both shoulders being stationary also leads to broken tools. [2] Figure 4A shows the tool design for SSuBTFSW.

Reverse dual rotation BT-FSW is an application of BT-FSW with two shoulders, the upper and lower ones, rotating at different directions. The advantage gained from this setup is the reduced risk of tool fractures due to torque offsetting and significantly lower net torque on the workpiece. [2] The tool for reverse dual rotation BT-FSW is illustrated in figure 4B.

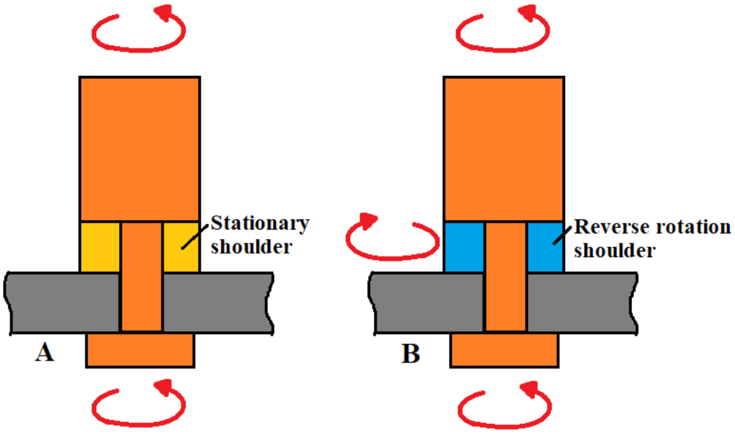

Figure 4. Bobbin tool FSW tools. (Modified from [2]). A: stationary shoulder BT-FSW tool, B: reverse dual-rotation BT-FSW tool

2.1.5 Friction lap welding FLW and Friction stir lap welding FSLW

Friction lap welding (FLW) is a method developed for joining metals and polymers. The working principle is simple, relying on the frictional heat created by a rotating tool. However, the workpiece setup is different. The materials to be joined are overlapped or stacked so that the metal is on top of the polymer-based material. In FLW, the tool does not have a probe. It is rotated and pressed against the surface of the metal layer, creating frictional heat until the wanted temperature is reached. The tool is then moved along the desired welding direction, causing local melting of the polymer under the metal layer. A strong bond between the materials is achieved under compression pressure during the solidification. [2]

Friction stir lap welding (FSLW) is a joining method especially for metals. It has been developed for lap welding configurations and can be used to join either similar or dissimilar materials. The workpiece configuration is similar to FLW, but the tool is different since it often has a pin for the stirring. In the FSLW process, the pin can be plunged into the lower sheet or be just driven on the top surface of the lower sheet. FSLW has potential engineering applications in various areas such as shipbuilding, vehicles and aircraft, but finding the correct parameters for each application is challenging. [9]

2.1.6 Friction stir spot welding FSSW

Friction stir spot welding is a derivative of the standard FSW in which there is no linear movement of the tool. The process consists of three stages: plunging, stirring and extraction. In the conventional FSSW, the rotating tool plunges into the materials to be joined and stirs them, causing friction and softening the material. After the stirring, the tool is extracted from the workpiece. Due to the lack of linear motion, extracting the tool produces an exit hole and only a small welded area. [10]

Refill friction stir spot welding, otherwise known as Refill FSSW or friction spot welding (FSpW) is an improved method of the previously described FSSW. In this process, the probe and shoulder are assembled with a concentric clamp in a way that allows them to move independently along the vertical axis. That makes it possible to produce spot welds without an exit hole. There are two variants of refill FSSW, the shoulder-plunge and probe-plunge. In the shoulder-plunge refill FSSW the shoulder plunges into the material, setting the depth of the weld while the probe retracts creating a hollow chamber for the melted material to be stirred. The probe-plunge method is similar to the shoulder-plunge method, but the plunging and retracting roles are reversed, with the probe being the plunging part as the shoulder retracts. After plunging and stirring, the rotating tool is raised to the top surface of the base material, allowing the softened material to fill the exit hole while the retracted tool component offsets the positions from the plunging stage. [10]

2.2 Tools

In friction stir welding, the tool has a significant impact on the resulting weld. Depending on the welded material, the tool must exhibit excellent properties across a large temperature scale. Soft materials, like aluminium and magnesium can be easily welded in lower temperatures due to their relatively low melting points, whereas high temperature softening materials such as steels must be processed at more than 900°C. The applied forces in FSW are high, requiring the tool to have high strength, fatigue and fracture toughness, while operating in high temperatures. At the same time the tool must be robust and non-consumable against mechanical wear, and resist chemical wear. [3]

Tool profile and features vary depending on the uses of the tool. Different materials require different characteristics from the tool, making the tool selection to be extremely significant for getting the best results in the welding process.

2.2.1 FSW tools for steels

As described before, the FSW process for steels is performed at high temperatures, mostly over 800°C. Multiple tool materials have been tested for welding steels. The most successful ones have been refractory metals and polycrystalline cubic boron nitride tools (PCBN). Another notable category of tool materials includes superalloys. [3]

PCBN is an extremely hard, super abrasive material manufactured at elevated temperatures and under ultra-high pressure. The only tool material having higher hardness than PCBN is diamond. PCBN also exceeds the chemical and thermal resistances of diamond. The disadvantage of PCBN is the brittleness of the material. This unwanted feature has been compensated by adding tungsten-rhenium WRe into the tool material, leading to improved fracture toughness. However, the wear resistance is decreased by the addition of WRe. [3]

The shape of the original PCBN tools was simple and featureless. However, the design has been improved over the years. After introducing spiral threaded probes and convex shoulders into the tools, the process productivity has been improved. It has been proposed that PCBN-WRe tools should not experience tool temperatures over 900°C, because the wear rate will be high, and the features are then easily worn. However, PCBN-WRe tools can be reprofiled multiple times. The PCBN-based tools have been successfully used to produce welds in between high-temperature softening materials like duplex stainless steels, austenitic and super martensitic stainless steels and tool steels. [3]

Refractory metal tools have been successfully joining different types of steel. Metals such as tungsten and molybdenum are used as the base material in refractory metal tools. These materials tend to deform and fracture during plunging into the workpiece. Experiencing the high loads and high ductile-to-brittle transition temperature causes the tool material to fail at this stage.

Alloying rhenium into tungsten (W-25%Re) has improved the features of the refractory metal tools, making this type of tool to become a considerable option alongside the PCBN-WRe tools. The added rhenium lowered the ductile-to-brittle transition temperature, reducing the risk of fractures while improving the hot strength and wear resistance as well. Despite the lowered wear rate, the refractory metal tools are often designed without features, because the wear rate is still relatively high causing them to degrade quickly. In addition to W-Re tools, other refractory metal tools have been used in FSW as well. Hafnium carbide (HfC) has been added to W-Re tools to improve wear resistance. Tungsten carbide (WC) and tungsten carbide-cobalt alloys (WC-Co) have been used too. [3,11]

Superalloy tools based on nickel or cobalt have been investigated and used to weld steels by FSW. The tool wear resistance of these tools has been good for relatively short welds up to 500 mm, depending on the base material and alloyed metal. The impact of tool features on the wear resistance of superalloy tools has not been investigated widely, apparently due to the tools not being able to produce commercially competitive weld lengths of hundreds of meters. [3]

2.2.2 FSW tools for aluminium

Aluminium alloys are generally easier to process by FSW compared to steels due to their lower melting temperatures. Lower temperatures are less demanding for the FSW tool. However, the fracture toughness is still an important parameter to consider because of the high forces in the process.

The most suitable tool materials to be used in FSW for aluminium alloys have been investigated. Based on the perspective of easy manufacturing, the most widely used materials are hot work tool steels (HWTS) such as AISI H13, high-speed steels (HSS), superalloys and tungsten carbide-cobalt alloys (WC-Co). According to TWI, the best tool material for FSW is the cobalt-based MP159 high-strength alloy due to its good properties. The alloy consists of 35,7 Wt% cobalt, 25,5 Wt% nickel, 19 Wt% chromium, 9 Wt% iron, 7 Wt% molybdenum, 3 Wt% titanium, 0,6 Wt% niobium and 0,2 Wt% aluminium. MP159 has high strength, ductility and toughness, as well as high operating temperatures and good creep strength up to 590°C. The material can be forged or machined into complex shapes and has a relatively appropriate price commercially. [12]

2.3 Parameters

In friction stir welding, there are numerous parameters, each of which has a significant impact on the outcome of the produced weld. Different parameters cause different effects, and some of them might even overlap with each other. Because the variety of materials that can be processed with FSW is so broad, the process parameters must be defined for each process separately. However, there are still some basic guidelines and discovered patterns regarding the impacts of single parameters on the welding results. In the following section, the key parameters of the FSW process are presented.

2.3.1 Tool speeds

Tool speeds are highly important in the FSW process efficiency. The tool rotational speed (TRS), usually measured in revolutions per minute (rpm) and welding speed (WS), also denoted as traverse speed, are parameters that strongly affect the weld quality via heat input. The relationship between tool speeds and heat input is not straightforward to model, but it has been discovered that higher tool rotation speeds as well as lower welding speeds create a hotter weld. Excessive heat input deteriorates the weld quality, decreasing the mechanical properties such as tensile strength. [13]

2.3.2 Tool dimensions

Since the joining of workpieces in FSW relies on the heat generated by the tool, the dimensions of the tool have a significant effect on the process. As the working principle of welding depends on the frictional heat, the tool diameters are obviously the main parameters related to the generated heat since the area impacts the amount of frictional heat to be created. Tool geometry is the defining factor regulating the heat input and material flow during the process.

Larger tool pin and shoulder diameters result in higher temperatures due to the larger contact area with the base material and the tool. The pin or probe length of the tool and plunge depth (PD) are also parameters affecting the properties of the weld joints. Larger tool diameters as well as longer probes lead to greater frictional heat due to the increase in base material resistance. This then results in greater forces, both in axial and in longitudinal directions. [13]

The tool probe geometry is the main factor affecting the material flow in the FSW process, influencing the weld strength properties and characteristics. There are multiple probe profiles that can be used in FSW. With the most common shape being circular, there are also square and conical probe profiles. Finding the optimal probe profile is not straightforward, and the developed profiles are often improved with features such as threads or flutes instead of the tool surface being just flat. Different features can also be present at the same time. The tool shoulder geometry is often designed for the needed amount of heat so that the shoulder causes maximum deformation on the base material. Features are designed on the shoulder surface, making it either concave, convex or scrolled. [14,15]

2.3.3 Other parameters

Despite the previously described welding parameters being the most dominant ones in the FSW, other parameters also affect the process. The tool tilt angle, denoting the angle between the tool spindle's axis and the workpiece, is a parameter that has a significant effect on the plunging stage. The tilt angle impacts the material flow and transportation during the plunging of the probe. [13] During the traverse motion of the tool, a suitable tilt angle must be maintained to improve the effective movement of the material flow from the front of the tool to the rear of the tool. [15]

Axial welding force is one of the primary FSW parameters, influencing heat generation and forging pressure throughout the process. The axial force has not been extensively considered as a variable FSW welding parameter in the literature, but because FSW is compatible with joining dissimilar materials, its influence should be considered. The axial force determines the thickness and composition of intermetallic compound (IMC) at the interface, affecting the joint strength. Studies show that decreasing the axial force results in lower metallic bonding due to lower heat input and forging pressure, most likely causing weaker joint strengths. However, higher axial forces result in the formation of a thick IMC layer. The increased thickness causes increased brittleness and is therefore resulting in a lower quality weld. [16] Even though the axial force is not widely considered as a welding parameter, it seems to have a significant influence in the FSW process of dissimilar materials.

3 Industrial applications

3.1 Marine applications

Friction stir welding has many advantages that make it a potential joining method in marine applications. Exposure to harsh environmental conditions such as saltwater and fluctuating, demanding weather conditions require a lot of durability and resistance from the welds. Structural integrity, corrosion resistance of the welds, and reduced distortion due to the lower heat input in the process are the main benefits gained with FSW in marine sector. Fabrication and welding of ship hulls and bulkheads are therefore applications that could especially benefit from FSW. High-quality welds without weld defects minimize the need for large-scale investigations after the welding. Dimensional control is also easier to maintain with FSW compared to traditional arc-welding methods, resulting in better alignment of parts. Because of the ability to join dissimilar materials like aluminium and steel, FSW can be utilized in weight optimization, increasing the strength of the parts and improving the corrosion resistance. [17]

FSW application areas in marine engineering can include shipbuilding, underwater repairs, submersible vehicles, propeller manufacturing, offshore structures, retrofitting and marine components. [17] Particularly shipbuilding has applications, where FSW is a suitable manufacturing method. Aluminium extrusions, panels for decks, helicopter landing platforms, flooring, superstructures and transport structures are examples of possible uses for the method. Figure 5 [18] presents a honeycomb structure, that can be widely used in different marine applications. Considering smaller scale applications for sailing boat parts such as masts and booms, the overall variety of different items manufactured is extremely wide. [19] In addition to mostly structural components, FSW can also be used to manufacture cryogenic tanks for liquefied gases. Figure 6 [20] presents a friction stir welded rocket tank, but the principle is same for other tanks as well. [21] Overall, the opportunity to use aluminium as the manufacturing material has made the FSW widely adopted among most of the major shipbuilding companies all over the world. [2]

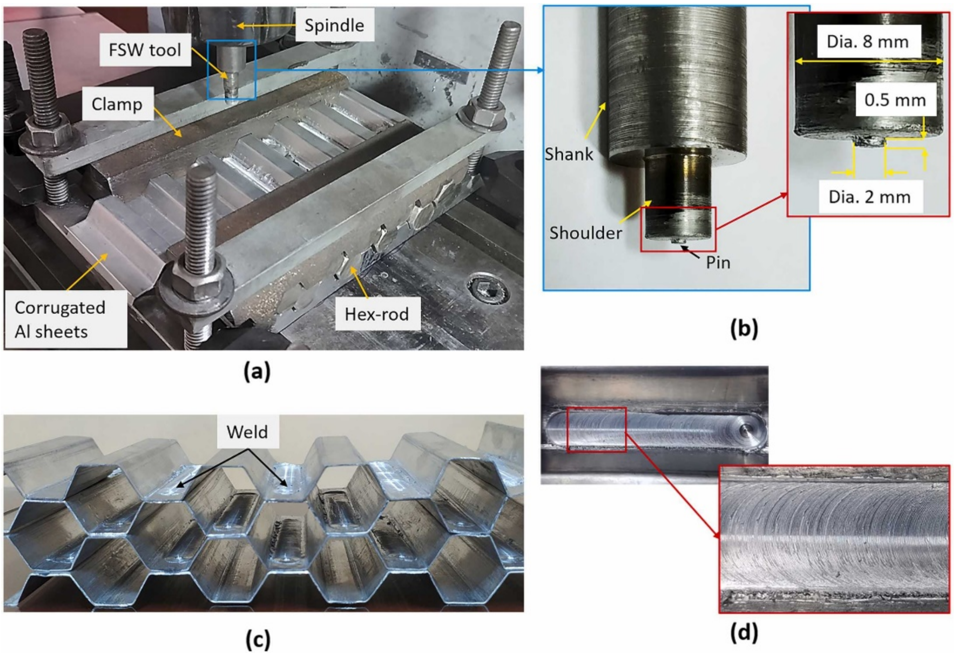

Figure 5. Honeycomb structure manufactured by FSW. Reprinted from Journal of Materials Processing Technology, Vol 330, Ananta Dutta,Surjya K. Pal,Sushanta K. Panda, *Friction stir seam- and spot-welded aluminium honeycombs: Enhanced structural integrity eliminating adhesive bonding challenges*, pages 118449., Copyright 2024, with permission from Elsevier. [18]

3.2 Automotive applications

In the automotive sector, FSW has shown its potential since the challenge of weight reduction and safety improvement for passengers have led to the use of aluminium instead of more traditional steels. However, using aluminium is not straightforward, due to it being a relatively difficult metal to weld with conventional welding methods. With friction stir welding being successfully optimized for joining similar and dissimilar aluminium alloys, it is one solution to this problem. [19]

The automotive industry is an ideal application area for FSW, because generally almost all needed aluminium parts can be welded by FSW including components starting from the outer body structure to the engine blocks or intake manifolds. Considering other automotive applications, besides the body structures and frames, FSW can be used in manufacturing large vehicles and their accessories such as tail lifts or fuel tankers. [19]

As in shipbuilding applications, automotive sector has also utilized FSW in joining aluminium extrusions. Large extrusions are expensive to fabricate. By joining smaller extrusions by FSW, the expenses decrease. Besides economic benefits, the quality of the products manufactured with FSW is better. Larger extrusions have worse dimensional tolerances, often causing them to be useless. Joining smaller extrusions by FSW, the dimensional tolerances remain better. Tailor welded blank have the same idea of manufacturing the needed part with smaller parts. Flat metal sheets are welded together by FSW, after which the large blank is formed into the desired shape. Manufacturing complex shapes out of flat metal sheets improves material consumption and enables lower weight of the product. [19]

3.3 Aerospace and aviation applications

Friction stir welding has high potential in aerospace and aviation applications. Due to high-quality welds and suitability for welding different lightweight alloys, FSW is beneficial for these industries since they require excellent mechanical properties and lightweight structures. Compared to fusion welding methods, the joints created by FSW are stronger. Also, because FSW has fewer process parameters, it is easier to control. [19]

Due to the flexibility of friction stir welding in terms of different welding configurations, aerospace and aviation applications by FSW include for example tanks (Fig. 6 [20]), ribs, wings, and fuselage of the aircraft. Compared to the traditional use of riveting, FSW has significant advantages such as weight reduction and lower manufacturing costs. Riveting is very time-consuming due to the need for holes being drilled and the additional weight of the used rivets has a negative effect on the fuel economy. [19]

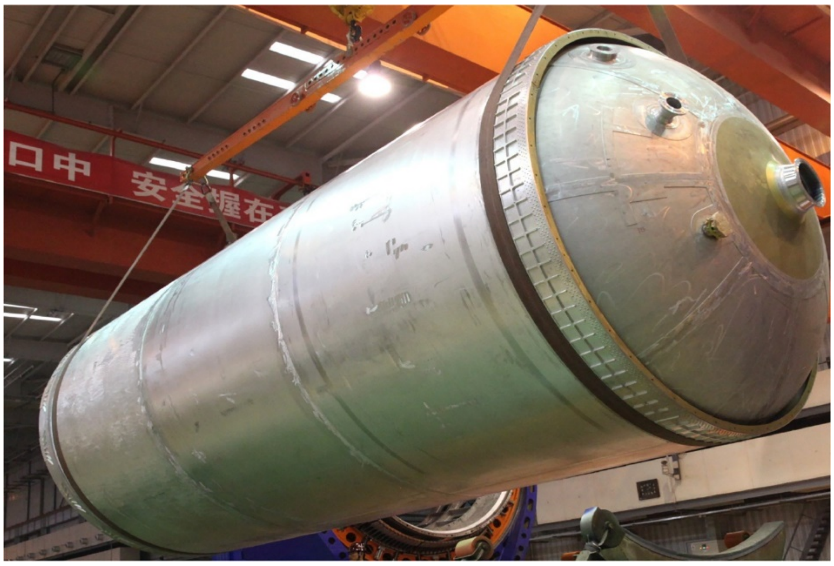

Figure 6. Application of FSW on a rocket tank. Reprinted from Journal of Materials Science & Technology , Vol 34/1, Guoqing Wang,Yanhua Zhao,Yunfei Hao, *Friction stir welding of high-strength aerospace aluminum alloy and application in rocket tank manufacturing*, pages 73-91, Copyright 2018, with permission from Elsevier. [20]

3.4 Other applications

Marine, automotive, and aerospace and aviation industries have been the most significant ones adopting FSW. With evolving technologies, the variety of possible applications for FSW is continuously expanding.

The demand for weight reduction and better performance has been the driving force for implementing FSW also in railway sector. Friction stir welded aluminium extrusions are used to manufacture train bodies either by single-wall or hollow double-wall structures. These configurations have demonstrated enhanced crashworthiness due to high buckling strength under longitudinal compressive load. [2]

Energy industries have adopted FSW in different applications. Finnish and Swedish companies have developed a friction stir system for copper canisters that store used nuclear fuel rods. FSW is used to seal the waste canisters in a reliable, proper way to ensure the safe disposal of the used nuclear fuel. [2] Pipelines for oil and gases, wind turbine parts such as blades, and battery cases for electrical components can also be fabricated with FSW technologies due to the excellent weld quality. [22]

4 Friction stir based additive manufacturing methods

Relying on the same frictional principle of heat generation as FSW, friction stir based additive manufacturing (AM) processes are interesting manufacturing methods that have several potential applications. These methods utilize the advantages of solid-state methods, including improved microstructure and mechanical properties, lack of harmful emissions, and multi-material structures.

Friction stir AM methods have multiple advantages over conventional fusion-based AM methods. The low temperatures in solid-state processing prevent shrinkage and hot cracking at the layer interfaces. Products manufactured with friction stir based additive manufacturing methods possess better mechanical properties resulting from the more refined microstructure. With the lower energy consumption, friction stir AM methods are more environmentally friendly methods compared to fusion AM. Also, the amount of waste generated is significantly smaller, since friction stir AM does not require any support structures for the products. Multi-material structures can be manufactured by friction stir AM, however processing materials with high melting point is challenging.

Despite having advantages over conventional fusion AM, friction stir AM has some limitations. As FSW processes, friction stir AM relies on the frictional heat generated by a tool. The tool wear must be considered, as it increases the already high equipment costs, especially when processing high temperature alloys. Also, the geometries to be manufactured by friction stir AM are limited, since complex and fine 3D shapes are difficult to achieve with the tools. Since the layer thickness in friction stir AM methods is relatively high, (in the range of mm) compared to, for example laser powder bed fusion (LPBF, powder diameter in the range of µm), the dimensional precision of friction stir AM is not very high.

Having its own advantages, friction stir additive manufacturing is a promising manufacturing method for applications requiring excellent mechanical properties. There are some limitations to be understood, but friction stir additive manufacturing is an alternative to fusion-based AM that should be considered. In the past years, multiple additive manufacturing methods that are based on friction stir process have been developed, either using feedstock or relying on the deposition of the base material.

4.1 Friction stir additive manufacturing FSAM

Maybe the most generally referred friction stir based additive manufacturing method is the FSAM, which was originally developed by using a conventional FSW tool to join sheets of metal on top of each other, layer by layer, just like in FSLW. Due to achieving faster build rates and less material waste, Airbus and Boeing have been the initial commercial companies proposing the FSAM method, since aerospace applications, such as stiffened structures are the most potential ones for FSAM. [2]

During FSAM, the metal sheets are stacked on top of each other. The rotating tool probe penetrates the top layer and is driven multiple passes on the interface of the metal sheets, producing inter-laminar bonding between them. Depending on the materials to be joined, expensive friction stir tools may be needed, for example, when joining steel and aluminium. Due to steel causing rapid tool wear and cracking, the tool must be replaced frequently, increasing the costs significantly. [2] The FSAM method is represented in figure 7.

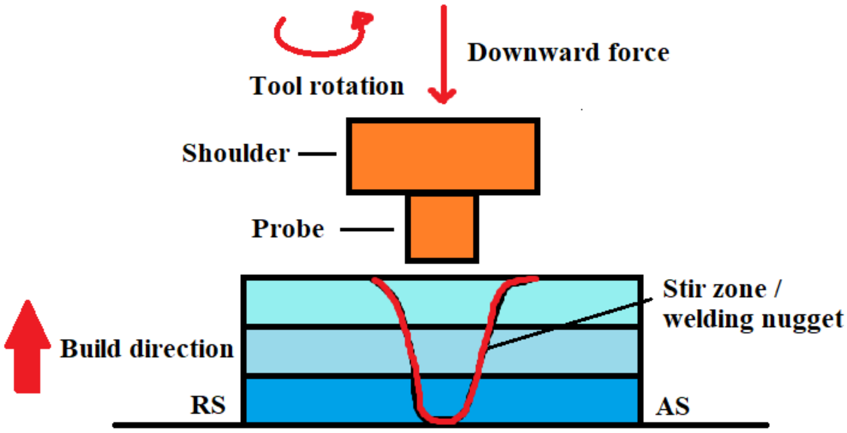

Figure 7. Schematic representation of FSAM.

The formation of detrimental intermetallic components cannot be avoided at the steel-aluminium interface, which leads to weaker bonding strength between the dissimilar materials. A modified version of FSAM, the M-FSAM, was developed to solve the problem with high tool costs and low bonding strength. In the M-FSAM, the tool probe is positioned so, that there is a fixed gap between the tool and the steel surface. This different configuration avoids the interaction between the tool and steel, reducing high tool costs while also producing a nanoscale amorphous metal layer between steel and deposited aluminium. It has been discovered that in tensile tests the amorphous metal leads to a ductile fracture instead of a brittle one. The produced aluminium-steel structure has exceptional stability up to 500°C and higher bonding strength. With the promising results, M-FSAM can be considered as a desirable additive manufacturing method for creating bimetallic structures between aluminium and steel. [2]

4.2 Friction stir AM methods with feedstock

4.2.1 Additive friction stir deposition AFSD

Additive friction stir deposition is an AM method that uses either rods, powder, or even waste machine chips as a feedstock. The method has been patented by MELD Corporation. The additive is delivered to the process through a hollow rotating tool. It is softened by frictional and adiabatic heating while being simultaneously deformed. The additive generates a plasticized film on the substrate, and after a short dwell, the shoulder is subjected to traverse motion, causing the deposition of a layer of the material. The process is repeated selectively layer by layer to achieve the desired thickness or shape of a three-dimensional product. The layer thickness can vary, but the deposited layer of feedstock can for example be in the range of 0,5-1,5 mm. [23] Being suitable for multiple materials, such as aluminium alloys, copper, Inconel 718, and Ti-6Al-4V, AFSD has been promising in creating complex, microstructurally refined parts with minimal defects. [2,24] Compared to conventional AM methods, such as laser powder bed fusion (LPBF), AFSD is advantageous for avoiding shrinkage and hot cracking at the layer interfaces. [23] The working principle of AFSD is presented in figure 8.

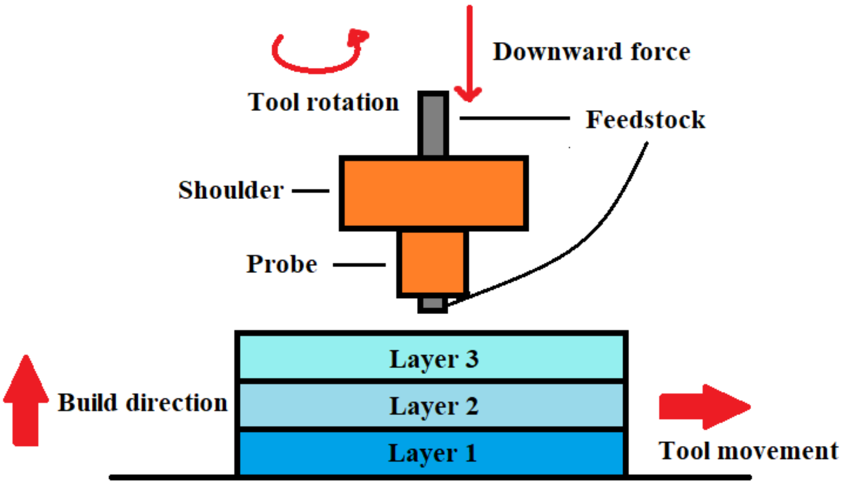

Figure 8. Schematic representation of AFSD.

The ability to produce equiaxed grain structures is the main advantage of AFSD, enhancing the mechanical properties of the deposited material, increasing the tensile strength, ductility, and corrosion resistance. Lower residual stresses and minimal defects in the deposited material are due to the method operating at low temperatures. AFSD has good scalability and a high deposition rate, making it beneficial for larger-scale production, considering also the low energy consumption due to low operating temperatures. [24]

4.2.2 Additive friction extrusion deposition AFED

Additive friction extrusion deposition is also an AM method, that uses metal feedstock. The difference between AFED and AFSD is the softening mechanism for the additive. AFSD requires direct contact between the feedstock and previously deposited material to soften the feedstock by friction. In AFED, the feedstock is processed into a malleable form by rapid friction between the feedstock and rotating die before being deposited onto the previous layer in the form of a paste. The advantage of AFED compared to AFSD is the lack of extremely high pressure needed on the previously deposited layer. Because the previous layer must become stiff before applying extremely high pressure on it, AFSD is more time-consuming and limited compared to AFED, which requires significantly less pressure. [2]

AFED can use metal rods off-the-shelf as a feedstock, so there is no need for expensive metal powders. There is no need for vacuum conditions or inert gas either, which makes the process flexible. Being an extrusion-based process, AFED can be used to for example repairing damaged surfaces or adding features to existing products besides creating completely new products from scratch. The layer thickness of 4 mm has been discovered to be the limiting factor in AFED, after which interfacial defects start to occur. Thinner layers require significantly higher compressive pressure compared to thicker ones, with the applied pressure on a 1 mm layer being around 21 MPa. The needed pressure is decreased to 10 MPa for the 4 mm limiting layer thickness. Even though AFED has good potential, more investigations are necessary to understand the process physics and relationship between process parameters to implement the process into practice. [2]

5 Future prospects

Friction stir welding has been proved to be a suitable method for joining multiple materials. However, materials with high tensile properties or high melting points, such as high-strength aluminium alloys, titanium, and ferrous metals, are still difficult to process with FSW. These materials require a significant amount of heat to be softened. Hybrid FSW processes were developed to overcome the challenge. These processes use external energy, generated either mechanically or thermally, to pre-heat or soften the material. Thermal energy sources, including for example laser, arc or induction, heat and soften the material before or during the welding, whereas mechanical energy sources such as ultrasonic vibration enhance the material flow during the process. [5]

The hybrid FSW processes are showing promising results in improving the efficiency and mechanical properties, but the risk of overheating must be considered. Expanding research on hybrid FSW techniques and studying their impact on quality and efficiency should be part of the development. Knowledge of defects not only in hybrid FSW processes, but also in other FSW processes, should be collected into a database to help troubleshooting and developing the current methods. [5]

Despite the promising innovations, FSW processes possess challenges that must be overcome. Still, after decades of investigation, some fundamentals are not widely understood. One example is the location and temperature dependency of the friction coefficient at the workpiece-tool interface. Modelling methods for new friction-based AM processes are also needed to understand the process physics, linking the microstructural evolution to the performance of the manufactured product and making the processes predictable via parameters. At the same time, more studies must be conducted with proper effort to overcome the challenges related to high-temperature tools. [2]

6 Market trend

The possible application areas for friction stir welding are continuously expanding. New applications and technological advancements create opportunities for using FSW technologies more efficiently.

In 2023, the aerospace sector was the largest end-use segment in the global FSW equipment market with 29,9% of the market revenue, since FSW is widely used to manufacture aircraft components such as fuselages and fuel tanks. However, the automotive and shipbuilding industries were also significant end users. [25]

Globally, the friction stir welding equipment market size has been estimated having been 232.7 million USD in 2023 and it is projected to grow up to 320 million USD by 2030. The development of technologically advanced equipment, such as robotics, is one significant driver for growth while enhancing the flexibility and productivity of FSW processes. Increasing demand for more environmentally friendly methods, high-quality products and lightweight structures also positively impacts on the market growth of FSW equipment, since FSW-methods meet those needs. [25,26]

Even though constant market growth seems likely, the high cost of FSW equipment and complex process can restrain the market growth. Small and medium-sized companies may have difficulties finding budget for large investments as the average cost of an FSW machine is around 600 000 USD. [25,26]

7 Discussion and conclusions

Friction stir welding has multiple advantages that make it a considerable manufacturing method for various industries and applications. Enhanced properties of the processed materials are one of the most significant advantages of FSW. Lack of defects and great tolerances make FSW suitable for even the most demanding applications. Excellent processability of soft materials and the ability to join dissimilar materials make FSW an appealing alternative for current and future welding needs. However, the difficulty in processing high-temperature alloys is still an issue that must be solved. Hybrid FSW processes are showing promising potential and might be the solution to the problem.

The development of robotics and technological innovations is making FSW more effective, and therefore it is a considerable option over fusion welding. Simultaneously, additive manufacturing is one of the future possibilities for friction stir based processing, being developed from the FSW. The variety of application areas for FSW is therefore not limited to only joining materials.

Considering the economic point of view, FSW is showing constant growth in various industrial fields. Automation and increasing use of robotics are driving the growth since new technologies promote the implementation of FSW for many novel applications. Despite showing great potential to be an alternative to traditional joining methods, the cost level of FSW equipment is still quite high for smaller companies. High costs will slow down the economic growth in FSW market, but as the increasing use of FSW is likely to bring down the prices, more companies will be able to invest in FSW.

Environmental perspective is significant nowadays and must be considered, when a manufacturing process is evaluated. Friction stir welding is an environmentally friendly joining method that produces no harmful emissions. Solid-state processing does not create any fumes or UV radiation, as the material is not melted. Low heat input decreases the needed amount of energy in the process, allowing major energy savings compared to traditional fusion welding. Based on the advantages mentioned, FSW can be considered an environmentally friendly alternative.

There are numerous different FSW methods available, each of which can be modified even further to suit the requirements of the desired application. It is essential to understand that despite being developed over thirty years ago, the FSW process still has some limitations.

However, for many applications, especially for aluminium alloys, the development of the FSW process has been successful and it is widely implemented in industrial applications.

The topic of this bachelor's thesis was proposed by Wärtsilä Oyj.

References

[1] Friction Stir Welding, FSW, Wayne Thomas and Solid State Welding n.d. https://www.twi-global.com/what-we-do/research-and-technology/technologies/welding-joining-and-cutting/friction-welding/friction-stir-welding/home.aspx (accessed February 11, 2025).

[2] Liu FC, Feng AH, Pei X, Hovanski Y, Mishra RS, Ma ZY. Friction stir based welding, processing, extrusion and additive manufacturing. Prog Mater Sci 2024;146:101330. https://doi.org/10.1016/j.pmatsci.2024.101330.

[3] Liu FC, Hovanski Y, Miles MP, Sorensen CD, Nelson TW. A review of friction stir welding of steels: Tool, material flow, microstructure, and properties. J Mater Sci Technol 2018;34:39–57. https://doi.org/10.1016/j.jmst.2017.10.024.

[4] What is Friction Stir Welding (FSW)? - Process and Applications n.d. https://www.twi-global.com/technical-knowledge/faqs/faq-what-is-friction-stir-welding.aspx (accessed February 18, 2025).

[5] El-Zathry NE, Akinlabi S, Woo WL, Patel V, Mahamood RM. Friction Stir-Based Techniques: An Overview. Weld World 2025;69:327–61. https://doi.org/10.1007/s40194-024-01847-w.

[6] Jin T, Miao P, Cui X, Wang J. Intelligent optimization of non-rigidly supported stationary shoulder friction stir welding parameters. Adv Mech Eng 2024;16:16878132241235519. https://doi.org/10.1177/16878132241235519.

[7] Kumar S, Maurya M, Bansal S, Aniruddha. Influence of Bobbin Tool on Microstructure, Residual Stress, Tool and Corrosion Analysis of Al 6063 Alloy Friction Stir Welded Joint. J Mater Eng Perform 2024. https://doi.org/10.1007/s11665-024-10244-9.

[8] Quan W, Wenya L, Xiaogang D, Shouwei R, Jing Z, Benjamin K. Clarify the forming mechanism and affecting factors of defects in semi-stationary shoulder bobbin tool friction stir welding. Weld World 2024;68:1783–90. https://doi.org/10.1007/s40194-024-01707-7.

[9] Zhang Z, Jin Y, Ma L, Ji S, Dong J, Zhao H, et al. A general strategy for achieving high-strength joining of 2024 aluminum alloys via impacting flow friction stir lap welding. J Manuf Process 2025;134:619–32. https://doi.org/10.1016/j.jmapro.2025.01.007.

[10] Refill Friction Stir Spot Welding n.d. https://www.twi-global.com/technical-knowledge/job-knowledge/refill-friction-stir-spot-welding-150.aspx (accessed February 12, 2025).

[11] Mohan DG, Wu C. A Review on Friction Stir Welding of Steels. Chin J Mech Eng 2021;34:137. https://doi.org/10.1186/s10033-021-00655-3.

[12] Functions, Designs and Materials of Friction Stir Welding Tools n.d. https://www.twi-global.com/technical-knowledge/faqs/friction-stir-welding-tools.aspx (accessed February 21, 2025).

[13] Ray A, Pendokhare D, Chakraborty S. A comprehensive review of multi-objective optimization of friction stir welding processes. Weld World 2024. https://doi.org/10.1007/s40194-024-01888-1.

[14] Anand R, Sridhar VG. Studies on process parameters and tool geometry selecting aspects of friction stir welding – A review. Mater Today Proc 2020;27:576–83. https://doi.org/10.1016/j.matpr.2019.12.042.

[15] Gite RA, Loharkar PK, Shimpi R. Friction stir welding parameters and application: A review. Mater Today Proc 2019;19:361–5. https://doi.org/10.1016/j.matpr.2019.07.613.

[16] Ramachandran KK, Murugan N. Influence of Axial Force on Tensile Strength and Microstructural Characteristics of Friction Stir Buttwelded Aluminum Alloy/Steel Joints. Strength Mater 2019;51:300–16. https://doi.org/10.1007/s11223-019-00076-7.

[17] Bharti S, Kumar S, Singh I, Kumar D, Bhurat SS, Abdullah MR, et al. A Review of Recent Developments in Friction Stir Welding for Various Industrial Applications. J Mar Sci Eng 2024;12:71. https://doi.org/10.3390/jmse12010071.

[18] Dutta A, Pal SK, Panda SK. Friction stir seam- and spot-welded aluminium honeycombs: Enhanced structural integrity eliminating adhesive bonding challenges. J Mater Process Technol 2024;330:118449. https://doi.org/10.1016/j.jmatprotec.2024.118449.

[19] Amini A, Asadi P, Zolghadr P. 15. Friction Stir Welding Applications in Industry - Knovel n.d. https://app.knovel.com/web/view/khtml/show.v/rcid:kpAFSWP002/cid:kt00U82FQ3/viewerType:khtml/root_slug:advances-in-friction/url_slug:advances-i-friction-stir-13?&b-toc-cid=kpAFSWP002&b-toc-root-slug=advances-in-friction&b-toc-title=Advances%20in%20Friction-Stir%20Welding%20and%20Processing&b-toc-url-

slug=general-introduction&kpromoter=federation&view=collapsed&zoom=1&page=1 (accessed February 28, 2025).

[20] Wang G, Zhao Y, Hao Y. Friction stir welding of high-strength aerospace aluminum alloy and application in rocket tank manufacturing. J Mater Sci Technol 2018;34:73–91. https://doi.org/10.1016/j.jmst.2017.11.041.

[21] TRA-C industrie. FSW in shipbuilding: challenges and benefits I TRA-C industrie. TRA-C Ind 2024. https://www.tra-c.com/en/article-en/fsw-in-shipbuilding-challenges-and-benefits/ (accessed March 26, 2025).

[22] TRA-C industrie. FSW in the energy sector: interests I TRA-C industrie. TRA-C Ind 2024. https://www.tra-c.com/en/article-en/fsw-in-the-energy-sector-challenges-and-benefits/ (accessed April 10, 2025).

[23] Qiao Q, Zhou M, Gong X, Jiang S, Lin Y, Wang H, et al. In-situ monitoring of additive friction stir deposition of AA6061: Effect of layer thickness on the microstructure and mechanical properties. Addit Manuf 2024;84:104141. https://doi.org/10.1016/j.addma.2024.104141.

[24] S Y, N R, Prakash KB, Raju K R, Saleel CA, Rajendran P, et al. A critical review on the performance and microstructural characteristics of materials fabricated through friction stir additive methods and deposition techniques. J Mater Res Technol 2024;33:8002–24. https://doi.org/10.1016/j.jmrt.2024.11.094.

[25] Grand View Research. Friction Stir Welding Equipment Market Size Report, 2030 n.d. https://www.grandviewresearch.com/industry-analysis/friction-stir-welding-equipment-market-report (accessed March 13, 2025).

[26] Zion Market. Friction Stir Welding (FSW) Machine Market Size, Share and Value 2030. Zion Mark Res n.d. https://www.zionmarketresearch.com/report/friction-stir-welding-fsw-machine-market (accessed March 13, 2025).