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REVIEW ARTICLE

A Review of Recent Improvements, Developments, Influential Parameters and Challenges in the Friction Stir Welding Process

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ABSTRACT - Friction Stir Welding (FSW) is an innovative and reliable welding technique. Since this method is environmentally beneficial, it has received much attention and development over the past few decades. This study aims to revise the conceptual facts of FSW and evaluate the most recent improvements and developments in its applications. This review also assesses the influences of design parameters such as rotational and welding speeds on weld quality and joint efficiency. Existing challenges associated with applying FSW in various contexts, as well as the potential advantages that might lead to further study and broader FSW applications, are addressed. It has been concluded that FSW allows for optimising the rotating speed based on the preferred welding speed to achieve the greatest tensile strength in the welded materials. Despite FSW being established as effective in laboratory and small-scale applications, utilising FSW for large structures poses challenges. These challenges include maintaining consistent weld quality, controlling heat dissipation, and ensuring joint integrity during FSW. Consequently, further research is required to resolve these challenges and make FSW a promising welding method in contemporary production sectors.

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1.0 INTRODUCTION

Friction Stir Welding (FSW) is a solid-state joining technique that utilises the heat produced by friction between a rotating tool and the material of the workpiece to produce strong, flawless welds. In general, the resulting joint is efficient and mostly free of defects [1,2]. Compared to conventional welding methods, it has a number of fundamental benefits, such as the lack of a melting phase and the consequent absence of solidification-related flaws.

Key design factors in FSW have a great impact on how much heat is produced throughout the process. The FSW tool's rotating speed is one important parameter. Due to the higher tool-to-work piece surface area contact at greater rotating speeds, frictional heat generation is enhanced. Lower rotational speeds would result in less heat input [3]. The welding speed, which relates to the linear travel speed of the FSW tool along the joint line, is another crucial design factor. Due to the shorter interaction time between the tool and the workpiece, higher welding speeds typically result in less heat being generated. On the other side, slower welding speeds cause more heat to be generated and longer contact times [4]. The heat input during FSW is affected by the interaction of rotating and welding rates. To accomplish the desired heat input, ensure adequate material flow, mixing, and consolidation while preventing overheating that could cause flaws or structural damage, it is essential to control these parameters as well as possible [5].

Aluminium alloy welding is well known for its low tensile and fatigue strength at the weld zone. Friction Stir Welding (FSW) is currently the only effective method for welding the 2xxx and 7xxx series of Alloys [6]. The idea was originated by Thomas et al. [7] in 1991, and the welding institute was tasked with developing the concept. This marked the beginning of the development and adoption of various conventional joining techniques by businesses worldwide, particularly for aluminium and its alloys. Masithulela [8] reported that some companies and applications fully utilise FSW for their products, especially in ship construction, electrical applications, defence, automotive, and aerospace industries.

In brief, the FSW process involves two rigidly clamped work parts that are rotated along the thickness using a tool with a shoulder and a specially designed pin (probe), as depicted in Figure 1 [6, 9]. FSW consists of four stages, which are plunging off the pin between the two workpieces, dwelling, welding, and retracting (Figure 2). To generate the requisite heat when the pin penetrates the plates, the shoulder must be in contact with the top face of the work parts. Then, a linear movement of the tool across the abutting edges line should be employed. The friction between the tool and the workpieces will cause heat to be produced. Materials will undergo strict plastic deformation due to tool movement, which adds an additional heat source. In most circumstances, heat will weaken the workpiece material without melting it. The second component of the tool, the shoulder, which is positioned centrally at the top of the tool, releases necessary pressure and aids in the majority of the heat production process, after which the tool moves linearly, and the welding is completed. This method can be utilised for variable joint shapes, including lap, butt, and T-joints, among others.

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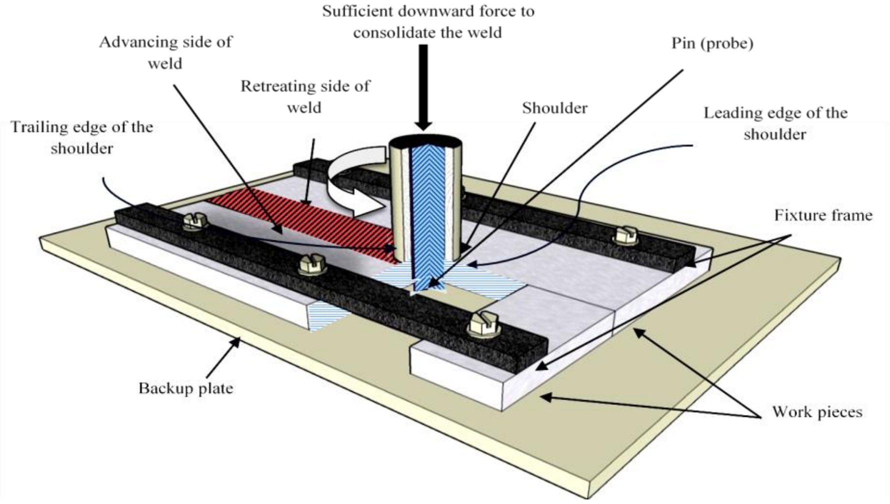

Figure 1. A representation of friction stir welding

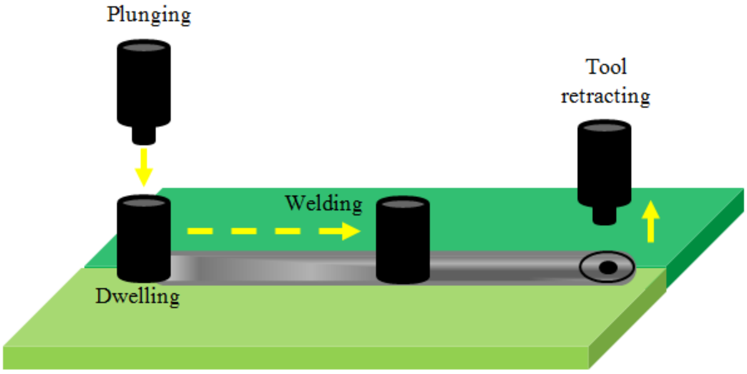

Figure 2. FSW process stages

Over the past 30 years, FSW has significantly improved the technique of metal joining. Firstly, FSW has made outstanding strides toward producing high-quality welds. Compared to conventional welding techniques, it creates joints without flaws and with less deformation, porosity, and defects caused by solidification. As a result, the structural integrity and mechanical qualities of welded components have improved [10, 11]. Second, the joining of materials that were previously thought to be challenging to weld has also been revolutionized by FSW. Combining aluminum alloys, even those with high strength and poor weldability, has proven to be very successful. FSW has also been used to join other difficult materials, including steel, copper alloys, and magnesium alloys. This broadens the spectrum of materials that can be joined successfully [12]. Third, FSW is a solid-state joining procedure; hence, there is no solidification or melting stage. The welding process is simpler and less expensive overall due to the absence of filler materials and shielding gases. Additionally, FSW permits high welding speeds, which boosts output [13]. Fourth, the advantages FSW brings to the environment have drawn attention. Compared to traditional welding techniques, it generates a great deal less fumes, gases, and spatter since it is a solid-state method. As a result, the workplace becomes cleaner and healthier. Additionally, the absence of filler elements encourages sustainability and lowers material waste. It is arguable that FSW is the new “Green Technology” in the welding industry since it is energy-efficient, adaptable, and ecologically beneficial [14, 15]. Besides these advantages, FSW has applications in numerous industries. For example, it has been applied effectively in automotive, aerospace, shipbuilding, and railway contexts. FSW is appropriate for various applications needing lightweight components and structures due to its capacity to combine dissimilar materials and construct complicated shapes [16-18]. Aluminum, titanium, and magnesium are low-weight, high-strength materials that are attractive in many such applications. Artificial intelligence methods were also used to produce factual findings for the industries [19].

A technique that shares some common techniques and equipment with FSW is friction stir processing (FSP), however, it is a dissimilar process with different objectives. While FSW is used to join materials, FSP is used for surface modification and property improvement in a single workpiece. Recently, FSP appeared to be a brand-new production technique employed in addition to FSW [20]. Specifically, FSP was utilised to enhance and change the microstructure of materials and alloys. It was discovered that the welding joint zone's improved grain size and micro-structure result in high efficiency [21–23]. Hence, the FSP technique has been effectively applied to generate not only a fine-grained structure but also new compositions, improved surface finishes, and altered micro-structures of materials [24–28]. This approach has been fully described and makes it possible to create products like fresh, sharp knives with long tool lives [29].

FSW offers the benefits of being able to join thick and thin, similar and dissimilar materials, and alloys that are challenging to join with other welding techniques [30]. The flow of material is significantly impacted by material property discontinuities resulting from different materials used along the welding line [31]. The pin location, the position of the workpieces on the advancing or retreating sides (Fig. 1), and the welding settings all have a significant impact on the welding quality in this situation [32].

This paper aims to review and analyze the developments and applications of FSW for the period between 2007 and 2024 for different types of alloys, besides addressing the challenges and potential advantages associated with this process. The impact of welding settings and the resulting strengths will be discussed. To emphasise the importance of FSW in the fields of joining and manufacturing process research, the latest developments in FSW across various sectors will be reviewed in detail.

2.0 CONTINUOUS DEVELOPMENT IN APPLICATIONS OF FSW

As stated by P. Kah and Marikainen, as well as The Welding Institute (TWI), the progress of the FSW approach has typically become obvious in the domains of shipbuilding, railways, aerospace, and land transportation [18]. Further uses have also been identified [33–40]. FSW can be used to effectively weld panels (sides, bulkheads, decks, and floors), landing pads for helicopters, offshore accommodations, hulls and constructions, and containers for refrigeration plants. In the aerospace sector, it is possible to weld fuel tanks, skin, spars, ribs, and strings for use in both military and commercial aircraft. FSW can be exploited in the land transportation industry as markets require lighter, firmer payloads with attractive appearance, and so on. These pressing needs help create a robust and smart design with custom blanks, truck bodywork, wheel rims, a number of engine parts, and motorbike components. FSW is used to weld tankers, wagons, and container bodies in the railroad industry. It can also be employed in the building industry for such items as aluminum bridges, window frames, and façade panels. In electric power industries, FSW can be applied to the manufacture of bus bars, electrical connectors, electrical motor housings, and electronic encapsulation. Finally, FSW may successfully assemble mechanical parts that are subjected to fatigue stresses [41].

In today's vehicle manufacturing, weight reduction and oxidation reduction are the primary goals. Typically, some light alloy types, such as magnesium and aluminum alloys are employed (for example, by Honda Motors). In some cases, especially for thin plates, friction stir spot welding (FSSW) seems promising [42,43]. This procedure suggests a more advanced FSW/FSSW machine. The Swedish industrial business ESAB has adapted one of the more conservative three-dimensional robotic devices to employ the FSSW in such industry sectors [44]. The target process for the manufacturing of automobiles continues to present unique difficulties because of the relatively high generated FSW forces. Due to their extensive use, articulated arm robots are the preferable option. The FSW machines are still being developed as a result of a significant increase in the complexity of workpiece shapes and greater mass production. Owing to their frequent usage in the automotive sector, three-dimensional path movements, and repetition, machine robots will become the optimum option for executing FSW [45, 46]. Table 1 summarises developments in the machine aspects

FSW was successfully employed by Lammlein et al. [47] to join a length of small-diameter butted pipe or steel pipes [48]. Both friction welding and friex welding were utilised to accomplish the same goal. Similar concepts to those utilised in the FSW process were followed by these two forms of welding. FSW is presently utilized in extremely delicate and risky applications, such as the fuselage of aircraft, a thick-walled pressure tank, and a copper canister with a reliable seal that was created to house Swedish nuclear waste. Indeed, modern welding equipment has helped to solve the problems posed by the curvature of curved work parts. Friction stir additive manufacturing (FSAM) is one of the recent developments in the additive manufacturing sector as well [49, 50]. With this solid-state additive manufacturing, large multi-layered components can be produced in a plate addition fashion.

Table 1. The development of the FSW machines

The machine	The specification of the machine [reference]
Conventional milling machine but can be used for FSW [51]	• First machine used for the FSW. • Not preferred for mass production. • Not computerized and can lack precision; there are limitations during the welding process. • The risk is high for human related accidents. • The machine can be considered as relatively cheap. • The welding speed and the rotational speed may change during the process especially for a machine using a belt drive.

Table 1. (cont.)

The machine	The specification of the machine [reference]
CNC milling machine but can be used for the FSW [52]	• Second machine type used for the FSW. • Not recommended for the FSW because of its high cost of this machine. • Not preferred for mass production. • Computerized and so it can be used for complicated welds. • The risk is low due to the existence of the safety door. • The welding speed and the rotational speed are constant because the machine uses servomotors.
FSW machine (specific) [53]	• Preferred for mass production because it is specific for FSW. • Computerized and easy to use. • The risk is low due the distance between the worker and the welding process area. • The welding speed and the rotational speed are constant because the machine uses servomotors.
Robotic FSW machine [54]	• The most modern FSW machine. • Preferred for mass production because it is specific for FSW. • Computerized and easy to use. • Can weld very complicated mechanical parts. • The risk is low due the distance between the worker and the welding process area. • The welding speed and the rotational speed are constant because the machine uses servomotors.

3.0 INFLUENCES OF PROCESS PARAMETERS ON FSW WELD QUALITY

The quality and strength of the weld are influenced by a number of variables and characteristics. The tool design, plunge length, pin profile, threaded or unthreaded pin, shoulder and tool features are critical, while the welding speed and tool rotational speed are the two other crucial factors.

More specifically, as determinants of welding quality in FSW, shape design parameters like pin profile and shoulder geometry are quite important and denoted as significant influential factors. The material flow, shoulder form, and the tool-workpiece contact area are all affected. Improved weld quality is the result of a shoulder design that supports effective heat transfer and material mixing. The pin profile also affects how the material stirs and how defects occur. A suitable pin profile aids in achieving consistent material flow and fewer flaws, which improves the quality of the welding process [55].

Several researchers investigated the joint and welding quality of FSW under the impact of these parameters. Li and Liu [56] revealed the impact of the shoulder state, whether it was stationary or moving. When they increased the tools' rotational speed from 600 to 900 rpm, they noted that several defects would worsen. They believed that the non-rotating shoulder was to blame for these flaws. However, certain benefits of employing this kind of shoulder include slightly increasing joint efficiency, and using an adequate rotational could lead to a defect-free weld. Regarding similar and dissimilar materials, the impacts of the aforementioned factors are virtually the same. The rotating speed of the tool is the primary factor influencing the welding quality of AA5083 and commercially pure copper sheets in lap joints, as stated by Bisadi et al. [57]. They noticed that many defects were found for low or high-welding temperatures, which are consequences of the friction of the rotational tool with the workpieces.

The tensile test for the joint between the two distinct welds, AA2024 T6 and AA5083, was investigated by Sundarama and Murugan [58]. They used a variety of tool shapes to experimentally show that tapered hexagon tool pin profiles have the greatest degree of tensile strength and elongation while straight cylinder tool pin patterns have the lowest tensile strength and elongation. Referring to Elangovan and Balasubramanian [59,60], the square pin shape outperformed the other pin shape design in a tensile test. In their research, they took into account shoulder diameter size, which demonstrated that the diameter must fall within a specific range to provide good joint effectiveness. Because the shoulder generates a greater quantity of heat as a result of friction and stir existence, various shoulder forms need to be carefully constructed to prevent excessive heat generation [58,61,62].

The amount of heat generated is influenced by the forces created. The torque and amount of sticking and sliding at the interface of the tool and work components were estimated by Arora et al. [62]. The amount of torque is influenced by the heat generated and vice versa. At the targeted interface, which is depicted in Eq. 1, they calculated the heat generation per unit area Q:

$$Q = \left[(1-\delta)\xi\tau + \delta\mu_f P_N\right](\omega r - v sin\theta) \tag{1}$$

ξ is the mechanical efficiency, ω is the rotational speed of the tool in (rad/sec), P_N is the applied axial pressure, τ denotes the shear yield strength, μf and δ denote the friction coefficient and spatially variable fraction slip, respectively. r is the radial distance, while ν is the welding speed. The parameters δ and μ_f are estimated using Eqs. 2 and 3, respectively

$$\delta = 0.31 \exp\left(\frac{\omega r}{1.87}\right) - 0.062 \tag{2}$$

$$\mu_f = 0.5 \exp(-\omega r \ x \ \delta) \tag{3}$$

ωr is measured by m/s. Eqs. 2 and 3 have boundaries within the range between 0.1-1.6 m/s. The heat depends on the shoulder diameter and rotational speed. (ωr-νsinθ) is the significant part of Eq. 1. However, although it might be changed throughout the welding process, ωr must be larger than νsinθ. Thus, neither the heat generation process nor the torque are significantly influenced by pin geometry [63]. However, when considering the same welding parameters, it can be seen that the tool shape design is a significantly relevant parameter for the welding strength and quality [62-65]. At the welding institute, numerous improvements and modifications to the welding tool design have been made. Some of the tool shapes and their uses are displayed in Table 2.

Table 2. Some important developments of tool shape design used in FSW

Descriptions and features of tools	Reference
Bobbin tool • Has an extra backup part instead of the backup plate. • Can be used for welding curved plates by using shoulder and backup parts that have concave or convex shapes.	[33]
Tool with supporting arm • The arm is used to preserve the plates at the welding line. • The arm can also be modified to provide heat for welding materials and alloys with high melting temperatures.	[66]
Retractable tool • This tool can be retracted automatically into the shoulder to avoid hole defects at the end of the welding process. • The tool moves vertically, rotationally, and linearly. • However, additional equipment is needed to control this tool. It is manufactured by the NASA Marshall Space Flight Center.	[67]
Shoe heater tool • The shoe is used to provide additional heat. • It is suitable for welding materials with low-friction coefficients, such as ABS material.	[68]
Twin-stir tool • Reduces the forces required for fixing the workpieces. • Has high-quality joining results. • Unfortunately, it produces two-hole defects. Three different variants of this instrument were produced at the welding institute: parallel, tandem, and staggered twin-stir.	[69]
Stationary shoulder tool • There are two shoulders on this tool; the one closest to the pin rotates while the other remains motionless. • Removes the flash defects • Lessens the required torque • This tool requires a careful selection of the welding parameters to prevent additional defects caused by the stationary shoulder.	[56]
Tungsten carbide tool • It provides a cooling factor that decreases the wear. • Typically used for welding harder alloys and materials. • A cooling bracket at the outside shoulder and an internal heater to raise the temperature at the stir point are features of some models. • It has the ability to protect gases.	[70]

Evidently, careful selection of suitable tool material is necessary for the good quality of the FSW output. In other words, the welding quality of FSW is greatly impacted by the material selection for the tools. To endure the mechanical and thermal loads that occur during welding, the tool materials need to be highly wear-resistant, thermally stable, and strong enough. To effectively remove heat produced by frictional contact, the tool material should also have high thermal conductivity. Consequently, having a tool that loses its specified properties, dimensional stability, or causes fracture is undesirable. Knowing the right tool to use to weld the material in question is necessary for the proper selection of the tool material. A consistent welding quality is ensured by careful tool material selection, which prevents early wear, distortion, and failure. Some of the products are made from a material that is subject to wear, like Metal Matrix Composites or High Melting Point. Accordingly, the tool material has a significant role in the welding because these materials have an impact on tool wear in the FSW; however, it should be noted that tool materials vary depending on the thickness and anticipated tool life, in addition to the material of the workpieces.

The most popular material for friction stir welding, especially with aluminum alloys, is tool steel H13. Table 3 is a list of some of the necessary tool materials [58, 71]. An essential component of the weld quality is the material's flow paths [72, 73]. It is certain that there will be imperfect knowledge regarding the flow of the stirred material throughout the FSW process because it cannot be noticed immediately, particularly when the work pieces' materials are various. Morisada et al. [73] individually portrayed the flow of aluminum and steel along the transverse direction (TD) and welding direction (WD). Compared to aluminum, the flow of the steel materials was greater even at a slow rotational speed (400 rpm). When there is a stir, the flow of steel material at the advancing side can become stagnant, which leads to the establishment of flaws in the stir zone. The authors explained the differences in material flow as a result of variances in the welding process's deformation resistance in both aluminum and steel.

Replicating the flow modeling using FLUENT or CFD tools is difficult since the material flow is neither linear nor uniform along the thickness of the plates. Therefore, it is easiest to choose the 2D solution. However, this simulation type can aid in modeling the forces and/or torque produced as a result of this material movement [32, 74, 75]. The amount of generated moment and force depends on the values of the rotation and welding speeds, the pin size, the shoulder size, and the overall tool design. The primary sources of the generated forces are the tangential friction forces at the area where the tool and workpieces make contact, in addition to the flow of metal. At the intersection of the metal flow streamlines, there is a greater concentration of force [75].

The weld formation is influenced by the tool's rotational orientation, according to Fu et al. [76]. When welding, tools should be rotated counter clockwise to produce better-quality joints than when rotating them clockwise. This point was verified for underwater FSW, regardless of other welding settings and conditions. These results were previously confirmed by Chowdhury et al. [77] using a comparable tool form. These authors also found that the fatigue strength was roughly 80% of the original material. This percentage was decreased by using the right-hand screw threaded to 60% of the parent material's fatigue strength.

Other factors, such as the offset between the welding line and the vertical tool penetration line, can affect the welding efficiency. The layout of the hard and soft materials could indicate another parameter in welding situations involving different materials. Gou et al. [78] examined the effectiveness of welding joints between the dissimilar metal matrix composite materials AA6063 and AA1100-B4C. To achieve a higher quality weld joint, the AA6063 plate must be on the advancing side. Additionally, an acceptable tool axis line offset in the direction of the AA6063 side will strengthen the joint even more; however, the offset distance should not exceed 0.8 mm.

Table 3. Appropriate tool design materials in FSW [58, 71]

Type of alloy	Thickness (inch)	Tool material
Al Alloys	<0.50	Tool Steel, WC-Co
	<1.02	MP159
Magnesium Alloys	<0.24	Tool Steel, WC
Copper and Copper Alloys	<2.00	Nickel alloy, PCEN[(a)], Tungsten alloys
	<0.40	Tool Steel
Titanium Alloys	<0.24	Tungsten Alloys
Stainless Steel	<0.24	PCBN, Tungsten Alloys
Low-alloy Steel	<0.40	WC, PCBN
Nickel Alloys	<0.24	PCBN

(a) Polycrystalline Cubic Boron Nitride

4.0 VARIOUS MATERIALS TO BE PROCESSED BY FSW AND FSP

FSW is increasingly being used in mass production across diverse sectors, further implying a great variety of materials that must be welded. Roughly, Al Alloys materials are prime candidate materials, while the potential to weld other materials and alloys is provided by the ongoing improvements in tool material and geometry. Recently, the FSW welding practice was utilised to join copper, lead, magnesium and their alloys, steel materials such as AISI 304L Stainless Steel [6], and other high melting temperature materials like Titanium, Nickel, and associated alloys. As stated in Table 2, some welding tools are offered with a supplementary cooling/heating technique and gas shielding in other situations because welding these materials requires highly thermal and wear-resistant welding tools. As indicated by Aissani et al. [79], a high workpiece gripping force, and occasionally the use of an absorber in the tool, is required to combat the vibration of the work parts during the use of an absorber. In addition to high-strength materials, this kind of tool is also employed in aluminum alloys.

Some composite materials are produced using FSP, particularly metal matrix composites [20]. To create an AZ31/Al_2O_3 nanocomposite on a surface, Azizieh et al. [20] inserted a Nano-powder into a surface groove. After multiple FSP runs, the nanoparticles had a better distribution. The best microstructural data are obtained with a high rotational speed (1200 rpm) and four FSP passes. FSP can also be used to create Functionally Graded Material (FGM) [80]. On the other hand, Marode et al. used nanoparticles of Silicon Carbide (SiC) and Graphite (Gr) as reinforcements to modify the properties of AZ91 Mg alloy composites [81]. Multi-layered laminates can also be produced by FSP with freedom from defects; Hassan et al. explain the FSAM method to manufacture metal (AA7075-T651) laminates [82]. The same method, FSAM, was exploited by Hassan and Pedapati to produce laminate structures of AA5083 [83].

An assortment of studies on welding settings and joint effectiveness for various materials are outlined in Table A.1 of Appendix A. More significantly, Table A.1 of Appendix A illustrates the extensive growth in alloys and materials that use FSW joining procedures.

The values of joint efficiencies vary, and it can be seen that pure materials have higher joint efficiencies than alloys. This is not the case for Metal Matrix Composites (MMC). Al alloys generally have melting points that range from 463-671 °C, while Mg alloy has a lower melting point. Additionally, Table A1 of Appendix A demonstrates that, when compared to the other materials, the melting point temperature and efficiency are varied. This can be attributed to the welding/processing parameters employed. Furthermore, it might be related to the dissolution of certain existing alloyments, as some of these alloys' components disintegrate at temperatures lower than those at which the main alloy melts [84]. Indeed, as the material dissolves and the grain size increases, the material will soften in this zone.

The grains of material benefit from the preservation of heat throughout the process of recrystallization, which takes place after the tool passes the direct welding point. Currently, certain approaches can be used to decrease the grain size and improve joint performance. For instance, heat reduction can be achieved by injecting water inside the fixture, while the backup plate and fittings frame could benefit from the addition of a cooling water line [85]. In FSW, the tangential speed is anticipated to range from zero at the pin's center to its highest value at the shoulder edge's tip. When the shoulder diameter is big, as shown in Eq. 1, it is expected that the speed variance causes some materials and/or alloys with a low melting point to begin to melt. The mechanical and microstructural qualities are impacted by this phenomenon. Li and Liu [86], therefore, suggested a dual rotational tool to prevent such an incidence. The dual tool allows for a difference in speed between the tool pin and the shoulder so that the pin will revolve at a sufficient pace without affecting the speed of the outlying shoulder. Weldment findings outperformed standard FSW procedures in terms of joint efficiency.

The particles of MMC, a high-melting temperature composite material, are specifically and intensely combined when they are perfectly welded with Al Alloys. This process results in a new, progressively evolving grain size and structure. Additionally, this is the driving force towards MMC production employing FSP. In light of the FSP results shown in Table A.1 of Appendix A, welding might not completely fill the thickness along the plate's faying line at the welding joint line. When used to Al Alloy in certain related experiments, FSP did not yield a superior performance than FSW [57]. Therefore, this statement should not be taken as a given.

5.0 MANIPULATING THE WELDING PARAMETERS

The influence of rotation numbers per millimeter along the weld line and its effect on joint efficiency is explicitly found using the N parameter indicated in Table 4 and expressed in Eq. 4.

$$N = \frac{w}{v} \tag{4}$$

v is the welding speed (feed rate) and w is the rotational speed.

The N factor (one factor) will be used instead of rotating speed and welding speed (two factors). To put it another way, if N was employed in the Design of Experiment (DoE), one factor could be removed as an input factor, allowing for the inclusion of new parameters like tilt angle, shoulder concave, etc. This will produce a variety of response optimization. The rotational and welding speeds must be specifically selected for this procedure, and occasionally trial and error under the same amount of N is required. In contrast to conventional procedures, this will provide a wide variety of optimization aspects that are greater than those of the classical context in a short amount of time. Many studies agree on the role of DoE in their experiments to attain excellent results. For instance, integrating Taguchi and grey relational analysis was a useful technique to enhance the microhardness and corrosion resistance by Marode et al. [81].

Due to the high friction between the tool and the work parts, increasing the N factor will result in a surge in heat. Due to the ABS material's minimal friction, high N was selected. As a result, it was accomplished by using a tool known as shoe shoulder geometry to increase the heat [64]. When applied to different alloys like Al, this technique might not produce satisfactory results. For alloys like Al Alloys, raising the N factor and, subsequently, the heat is not always enough. Lakshminarayanan and Balasubramanian [80] investigated the relationship between joint efficiency and the welding speed (v), rotating speed (ω), and applied force (F). The selection range is depicted in Table 4. To ensure all data is within the optimisation window, if N is utilised, the parameters will be two, and the levels should be modified by adding the outside points (-2 and +2). Since the highest joint efficiency may be associated with the lowest value of ν and the highest value of ω, and vice versa, it is recommended to employ these two points, which must be included in the new DoE. Thus, the experiment can be expanded to include two additional force levels. It is important to understand that adding levels improves response accuracy. The table will look similar to Table 5.

Table 4. Welding parameters [87]

Parameter	Level		
	-1	0	1
Rotational speed, ω (r 1/min)	1200	1400	1600
Welding speed, ν (mm/min)	22	45	75
Axial force, F (kN)	4	6	8

Table 5. New factors and levels [87]

Factors	Out point (-2)	(-1)	0	(+1)	Out point (+2)
ω (r 1/min)	1600	1200	1400	1600	1200
ν (mm/min)	22	22	45	75	75
N (r 1/mm)	72.7	54.5	31.1	21.3	16
F (kN)	F1	4	6	8	F2

After proposing values for F1 and F2, only the final two (shaded) rows ought to be taken into account for the design of experiments. Another intriguing aspect of employing N is that there are three figures to obtain the best value of components that produce the best reaction. The process of identifying the factor values that provide the best reaction will be difficult, but it is getting closer. As a result, there is an approximate; however, when N is used, the relationship between N, F, and tensile strength is unique, and there is only one unique optimum position for maximum strength.

6.0 ASSOCIATED CHALLENGES OF FSW AND THEIR IMPLICATIONS

The following points highlight the most important challenges in the development of FSW and its industrial application:

- The rotational and welding speeds, applied force, and tool shape must all be precisely controlled when using FSW. Finding the optimal process settings can be difficult, particularly for different materials and joint types. The process's complexity requires knowledgeable operators and advanced machinery, which can increase costs and limit its widespread use in certain industries.
- FSW causes tool wear and deterioration over time due to high contact pressures and frictional heat. Continuous contact with the workpiece material can result in tool deformation, reducing weld quality and increasing the time needed for tool maintenance or replacement. Ensuring reliable tool performance and managing tool wear are significant concerns in industrial FSW applications.
- FSW has primarily been applied to aluminium alloys; other materials, including steel and titanium alloys, pose additional challenges. Different materials require different process parameters and tool designs due to varying thermal properties, flow characteristics, and defect susceptibility. Expanding FSW's industrial applications necessitates adapting the process to various materials and addressing their unique challenges.
- FSW works best with flat or slightly curved surfaces. Joining complex geometries, such as tubular or three-dimensional objects, is challenging due to limited joint accessibility. Ensuring good tool-to-workpiece contact and consistent heat generation in such arrangements can be difficult, potentially leading to joint flaws or uneven weld quality.
- While FSW has proven effective in laboratory and small-scale applications, scaling the process for large and complex structures presents difficulties. Consistent welding quality, heat dissipation control, and joint integrity on a larger scale require sophisticated machinery, process control, and automation. The challenges of integrating FSW and optimising productivity in industrial-scale manufacturing lines are ongoing.

7.0 CONCLUSIONS

The purpose of this review was to examine the fundamental aspects of Friction Stir Welding (FSW) and present the latest advancements in its applications. Specifically, the goal was to investigate the impact of design parameters, rotational and welding speeds on weld quality and joint efficiency.

The final outcomes of this study can be summarised as follows:

- Managing heat generation during FSW is crucial for maintaining weld joint excellence and integrity. Tool shape, rotational and welding speeds play a pivotal role in this process.
- Friction stir welding allows for selecting the optimal rotating speed corresponding to a given welding speed to achieve maximum tensile stress in materials or alloys.
- Pure materials exhibit higher joint efficiency than alloys, with alloys possessing high melting points demonstrating superior joint efficiency compared to those with lower melting points.
- Design parameters such as pin profile and shoulder geometry significantly influence heat generation, material flow, and defect development during FSW.
- Optimising tool design factors and selecting suitable tool materials with desirable qualities contribute to improved welding quality, tool longevity, and reliability, facilitating the production of dependable and high-quality FSW welds.
- FSW faces various challenges, including process complexity, tool wear and maintenance, joint accessibility and configuration, material compatibility and variability, scale-up, and automation. These challenges impact FSW industrial applications, limiting process scalability, increasing equipment and maintenance costs, prolonging development times, and requiring skilled operators. Addressing these issues through research, process improvement, and technological advancements is essential to fully harness the potential of FSW across diverse industries.

Overall, FSW has significantly enhanced the metal joining process by enabling the joining of challenging materials, offering good joint efficiency, environmental sustainability, and diverse applications. These advancements have positioned FSW as a promising welding method widely used in contemporary production sectors.

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Appendix A

Table A.1. The welding factors and joint efficacy of various materials

Work pieces materials and [references]	Tool geometry	Tool material	Welding parameters				Joint or processing efficiency	N revolution/mm
			Feed (mm/min)	Rotational speed (rpm)	Force (kN)	Tilt angle (degree)		
AA2219-T6 [56]	Conical threaded pin with concave rotational sub-size and outer moving shoulder	/	100	800-900	/	2.5	69%	8.5
AA2219-T87 [88]	Square tool profile	High carbon steel	45.6	1600	12	/	61%	35.1
AA2024 [89]	Square pin profile	Tool Steel H13	60	900	9.9	2	87%	15
FSP of AA3003-H18 [90]	Cylindrical pin	Tool Steel H13	100	1200	/	2.5	54%	12
AA5083-H321 [91]	Flute threaded pin		85	266	/	2.5	85%	3.1
AA6082-T6 [61]	Cavity shoulder (concave) and cylindrical pin	56NiCrMoV7-KU	460	1810	/	2	77%	3.9
AA6351 [92]	Cylindrical tapered	High speed steel (WC-Co)	115	1350	/	2	68.8%	11.7
AA6005C-T5 [93]	Cylindrically	/	350	1200	/	0	82.1%	3.4
AA7075-T651 [94]	Tapered (conical) threaded the helix to the right once and to the right once more	/	100	1600	/	/	63%	16.0
AA7075-T6 [95]	Concave shoulder with cylindrical pin tool	Tool Steel H13	40	1300	/	3	75.8%	32.5
AA7039 [87]	/	High carbon steel	40	460	6.5	/	83.3%	11.5
AA2024-0 and AA5754-H22 [96]	Cylindrically screw thread pin	/	5	2000	/	/	66.93%	400.0
AA5083 and Pure Copper [57]	Cylindrical pin	Tool Steel H13	32	825	/	3.5k	74%	25.8
Pure Copper and AA1350 [97]	Concave shoulder with conical threaded pin	/	80	1000	/	2.5	74%	12.5
Magnesium AlloyAZ31B-H24 [98]	Scrolled shoulder with left hand threaded prope	Tool Steel H13	1200	1000	/	0.5	62% tensile shear	0.8
Magnesium AlloyAZ31B-H24 [99]	Scrolled shoulder with right hand threaded prope	Tool Steel H13	1800	2000	/	/	78%	1.1
Al-Mg-Si Alloy [100]	Screwed pin and hybrid shoulder	/	800	1800	8	/	82.8%	2.25
Dissimilar AA6063 and Metal Matrix Composites Al-B4C [78]	Conical unthreaded	WC-Co Alloy	100	2000	9.8E-6 on MMC Al-B4C and 9.8E-5 on AA6063 side	3	100%	20.0
AA 6061-T6 and 430Stainlesssteel [101]	Incomplete cone-shaped pin	Tungsten carbide–cobalt	80	560	/	3	62.8%	7

Table A.1. (cont.)

Work pieces materials and [references]	Tool geometry	Tool material	Welding parameters				Joint or processing efficiency	N revolution/mm
			Feed (mm/min)	Rotational speed (rpm)	Force (kN)	Tilt angle (degree)		
Titanium alloy Ti-Al6V4 and AA2024 [102]	Concave shoulder with threaded tapered pin	Standard tool steel coated with a voidex excessive wear	80	800	/	/	73%	10.0
Oxide Desperit Strengthen MA956 [103]	Tapered cylindrical	Hybrid Carbide WC-Co face and W-Ni-Fe shank	51	1000	/	3	125%	19.6
Acrylonitrile Butadiene Styrene ABS [68]	Threaded cylindrical pin tool with shoe shoulder geometry assistant to provide heat	CK45 Steel and using a shoe made from common Structural Steel	20	1600	/	0	88.8%	80.0
Martensitic Steels [104]	Cylinderical pin	WC-based material	150	400	/	3	92%	2.67
AISI 304 Stainless steel [105]	Equilateral triangle pin and shank with mill cutter	Cemented carbide specifications: K10, 94% WC and 6% Co	60	950	9	1.5	85.14%	15.8
Copper DHP [106]	Scrolled shoulder with threaded cylindrical pin	/	160-250	1000	7	0	100%	4.9
Pure copper [107]	/	SKD61	200-800	<1300	9.81	3	100%	1.6
Pure Titanium [108]	Threaded cylinder	Shoulder made from tungsten (W) and a pin made from tungsten carbide (WC)	60	1500	/	1	100%	25.0
Electro-galvanized mild steel (EG) to magnesium alloy AZ31 [109]	Scrolled convex shoulder and cylindrical pin with curved tip at the end of the pin	Tool Steel H13	100	700	6.5	0	80%	7.0
HSLA-65 Steel [110]	Cylindrical with tapered end tip	W-25%Re pin with Mo-TZM shoulder	76.2	400	/		108%	5.2
Ni-Al Bronze Alloy [111]	Threaded conical pin with concave shoulder	Nickel- Alloy super alloy	50	1200	/	3	100%	24.0
Mg-10Gd-3Y-0.5Zr casting [27]	Threaded conical pin	/	50	800	/		100%	16.0
Cu-Ni alloy and Low-carbon steel (SS400) with Ni coating assistant [112]	Cylindrically	High speed steel SKH51	10	800-1400	/	1	Shear strength will be 2.9 times that without Ni coating	110.0