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A comprehensive literature review on friction stir welding: Process parameters, joint integrity, and mechanical properties

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ABSTRACT

Friction stir welding is not only a solid-state joining method used mostly for metals and alloys, but also, used for joining various polymer materials. This literature review includes information about the process parameters, joint integrity, and mechanical properties of FSW welded joints. Process parameters have a great influence on the quality of the weld joints. In particular, basic process variables such as tool design, rotational speed, welding speed, and axial force were reviewed in this study. By optimizing these process parameters, weld strength can be increased by minimizing welding defects. In addition, the effects of the FSW method on mechanical properties such as hardness, tensile, and fatigue behaviors were discussed. Finally, some suggestions were made for using the method. This literature review aims to be a resource for researchers and those interested in the FSW method to make decisions based on process optimization, design, and material selection.

Introduction

Friction stir welding (FSW) is a solid state joining technique developed for various types of materials such as metals and metal alloys [124]. Furthermore, the joining processes of polymer materials with this method is quite possible [68]. Unlike conventional fusion welding methods, the FSW takes place at lower process temperatures [55]. Thus, it minimizes the thermal degradation and solidification-related defects that occur in traditional methods. This new welding process is done by means of a rotating tool. Its schematic representation is given in Fig. 1. The tool contacts the material surface and generates frictional heat. At the same time, it causes the formation of weld joint by mechanically mixing the material thanks to the pin on the tool tip. The FSW has numerous advantages over traditional welding methods, including improved mechanical properties, improved joint integrity, and environmental impact [8,9,108,131]. In this process, the material pair, tool and process parameters selected for welding are very important and need to be analyzed in detail.

The purpose of this literature review is to analyze information about the FSW and propose potential solutions, focusing on process parameters, joint integrity, and mechanical properties. In order to achieve optimum weld quality, it is essential to understand the influence of process variables, especially rotational speed, welding speed, and axial force. Most of the researches are on understanding these parameters and determining their optimum process values. Researchers examine, in detail, the effects of the FSW process parameters, different parameters such as tool material, effects of coating on the tool, pin profiles. By determining the optimum values of these parameters, welding defects can be reduced and welding performance can be improved. In particular, the issue of tool design is a subject of study in itself (material, coating, pin design etc.). Because, factors such as the necessary friction heat generation, mixing the material, compressing the material, and ensuring the material flow properly should be examined in detail. Different pin profiles used in this welding method are shown schematically in Fig. 2.

In this study, the mechanical properties of the FSW welded joints were investigated. To understand the mechanical performance of the FSW welds, mechanical properties such as tensile strength, fatigue behavior, hardness were mentioned. In one part of the study, a wide variety of research articles, conference proceedings, master's and doctoral theses and related industrial reports in the literature were given in detail.

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The FSW process

The FSW process is a solid-state joining technique that offers numerous advantages over traditional fusion welding methods. The process involves the use of a rotating tool, typically made of some hard materials such as tungsten carbide or hot work tool steels, with a specially designed shoulder and in different forms pin. The shape of this pin also has an effect [46,119]. The tool creates frictional heat through its rotational motion and axial force applied to the material. Therefore, the tool used must meet certain qualifications for the welding process. It should be durable, maintaining its toughness when facing high temperatures in the welding area. The tool needs to exhibit resistance against both axial and lateral loads experienced during the plunging and advancing phases. It should not undergo plastic deformation due to temperature, preserving its mechanical properties against the stresses it will experience. Additionally, it should efficiently dissipate the heat generated by friction during the process [28]. The tool is produced in different geometries depending on the thickness of material. Special tools, such as coil sets, are manufactured to meet specific needs. The tool geometry should be designed based on the type and thickness of the material to be welded, considering the required heat generated by friction. To weld thick materials, double-shouldered tools are produced, aiming to generate more heat through shoulder friction and achieve a successful the FSW process [39].

Due to the friction heat produced during the FSW process, the material softens, and the resulting maximum temperature varies between 0.8 and 0.95 times the melting temperature [74]. Because of the pin at the end of the tool, the material is mixed. Plastic deformation arises from the tool and pin rotation, accompanied by alterations in the initial grain structure. The modifications in the microstructure within the welded region are suggested for thorough investigation [73,86]. Pin eccentricity is said to have a positive effect without promoting material flow and grain refinement in the mixing zone [47]. Changes in the microstructure change the mechanical properties [63,70].

The FSW process consists of several basic steps. First, the tool is brought into contact with the workpiece surface and exerts a downward force to generate sufficient frictional heat. In this process, it is necessary to wait for a certain period of time for the temperature to reach a sufficient level. The tool then moves along the joint line to mix the material. Process parameters such as tool dwell time, welding speed, rotational speed, and axial force are very important in determining the quality of the weld [31,75,124].

Due to the bonding ability of the FSW method, it has widespread applications in various industries including aluminum alloys, copper, steel, and other non-ferrous metals [88,98,110,139]. The ability to join materials traditionally considered difficult to weld with the FSW process is also being studied [26,82,103,123]. The FSW provides hybrid material structures by combining different materials with different melting points. It combines materials with significantly different thermal properties from aluminum to steel, providing design flexibility and helping to reduce weight in multi-material assemblies [13,15,51]. The microstructure and grain size of the base material also play a role in determining weldability [118]. Better weld quality can be achieved if soft material is placed in the tool rotation direction [100]. Since the FSW works at lower temperatures compared to conventional welding, minimizing the heat affected zone, it is seen that the weld obtained with the FSW is more durable compared to traditional welding methods [53]. Although there is grain growth in the heat-affected region, a reduction in grain size is observed in the weld region [87]. There are also studies on the effects of friction temperature [69]. The findings of this study highlight the significance of comprehensive force and temperature monitoring during the FSW process to unravel the intricate interplay between these factors. This approach facilitates an in-depth exploration of how process parameters, such as power and specific energy, are influenced. Within the examined processing range, the FSW of aluminum alloy exhibited noteworthy fluctuations in both temperature and main forces. These results quantified the impact of processing conditions on temperature and force dynamics throughout the FSW. Conditions characterized by higher tool rotation speed and lower welding speed displayed a pronounced rise in temperature along the welding line.

Selection of suitable materials to ensure successful joint formation and desired mechanical properties is an important and researched aspect of the FSW. Factors such as material compatibility, thermal conductivity, flow behavior, and metallurgical compatibility need to be considered. Metallurgical compatibility between materials to be joined is essential to obtain solid and reliable welds. Compatibility can be affected by factors such as chemical composition, phase transformations, and formation of intermetallic compounds [65,112]. Appropriate material selection and joint design can help reduce potential compatibility issues [129]. The suitability of the material for the FSW depends on its ability to undergo plastic deformation before

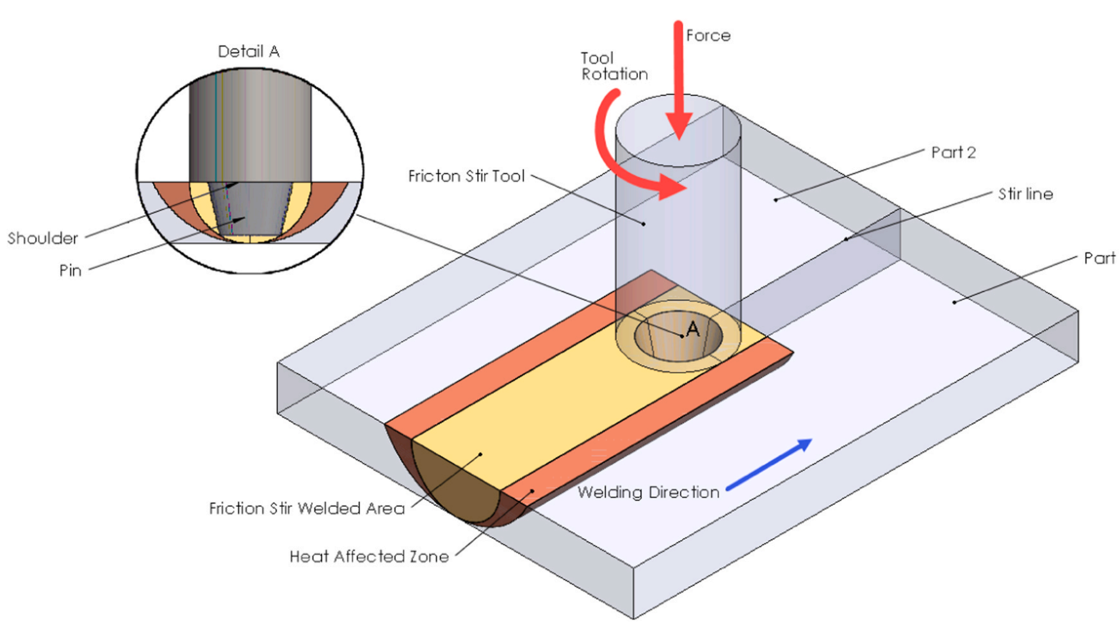

Fig. 1. Schematic representation of friction stir welding (FSW).

reaching its melting point.

One of the key advantages of the FSW is its ability to produce high quality welds with excellent mechanical properties. It can be easily accomplished on both conventional milling and CNC machines using a suitable tool, by determining the appropriate process parameters. The solid state nature of the process eliminates problems associated with fusion welding such as porosity, solidification cracking, and degradation [50]. The FSW joints exhibit high strength, fatigue resistance, and toughness, making them suitable for critical applications [21,32,42,136].

The FSW also offers advantages in terms of process efficiency and productivity. It is a relatively fast welding method that allows efficient production [6,38]. The absence of filler material contributes to reduced heat input, minimal material loss, and lower cost and improved dimensional accuracy [30,38,56].

Mechanical properties of the FSW joints

The FSW is known for producing weld joints with excellent mechanical properties. Often, the FSW joints exhibit high joint strength, approaching the strength of base materials. Combined with the thinned microstructure in the weld zone, it contributes to the increase in the strength of the joints due to the solid-state nature of the process. The absence of fusion-related defects such as porosity and solidification cracking further improves joint integrity [55]. The strength properties of the FSW joints can be affected by a variety of factors, including process parameters, tool design, and material properties. Welding speed, rotational speed, axial force, plunge depth, and tool tilt angle play an important role in the mechanical strength of the joint [2,19,31,116]. By optimizing these parameters, welds with desired strength properties can be obtained [33,67]. The tensile behavior of the FSW joints is also important for assessing the structural integrity of welded components. Finite element analysis and experimental test methods are widely used to investigate the load bearing capacity and stress distribution of the FSW joints under different loading conditions [64,83,84]. Understanding stress behavior aids in the design and optimization of the FSW welded joints for specific applications.

In a study, it was investigated the impact of cold rolling (CR) on the formability limits, resulting microstructure, and mechanical behavior of the FSW joints. The experimentation involves an AA5754 aluminum alloy. When the base material's yield strength was 165 MPa, the FSW specimen showed a yield strength of 100 MPa, while the FSW+CR specimen exhibited a yield strength of 170 MPa [18]. When the cold rolling process was applied to the FSW welded material, the base material strength was regained. Feed rate, rotation speed, applied load parameters were investigated in AA6061-T6 alloy [113]. It has been observed that welded materials provide approximately 75 % of the base material mechanical properties. A welding efficiency of 100 % was obtained in AZ61 magnesium alloy [140]. In an investigation of the FSW in AZ61 magnesium alloy, a welding efficiency of 67 % was attained. Khalid et al., [60]. An engineering grade glass fiber-reinforced (GFR) polymer resin and an aluminum-magnesium-silicon alloy AA6082-T6 were joined using the FSW method. Dynamic tensile tests demonstrated that the average tensile strengths corresponded to joint efficiencies ranging from 19.9 % to 47.4 % [24]. Increasing the tool rotation speed has an effect on increasing the yield and tensile strength [62]. A higher tool rotation speed might lead to a more efficient stirring and mixing of the material at the weld interface, resulting in a more uniform distribution of grains and microstructures. This improved microstructural homogeneity can contribute to enhanced mechanical properties. Additionally, the increased heat generated due to higher tool rotation speed can lead to better material plasticity and flow during the welding process, thereby reducing the likelihood of defects and promoting better bonding between the joined materials.

Fatigue performance of welded joints is a major problem, especially in applications subject to cyclic loading. Residual stresses occur as a result of temperature and plastic deformations [142]. The FSW joints show excellent fatigue resistance, which is attributed to their thinned microstructure and absence of fusion defects [52,71,114]. The absence of a fusion line sensitive to crack initiation contributes to the improvement of fatigue behavior. In the fatigue tests performed on AA3003 and AA6013 alloys, the samples were broken from the mixing zone [40]. The behavior exhibited by the AA2024 and AA7075 alloys in conjunction with the FSW process was examined. Niu et al. [92]. The positioning of the material (placement of the alloys) affects the fatigue resistance. Fractures occurred on the AA2024 side due to the precipitates that enlarged with crack propagation, characterized by crack initiation and typical fatigue lines. In studies on low carbon steels, base metal and the FSW joints were found to have the same fatigue strength [135]. The experiments performed on Ti-6Al-4 V alloy, it has been shown that the increase in the FSW welding speed decreases the fatigue strength and shoulder-shaped line marks have crack initiation points [78]. The observed reduction in fatigue strength with an increase in the FSW welding speed can be attributed to the complex interactions between microstructural changes and stress distribution within the weld zone. As the welding speed increases, there may be a compromise in the metallurgical integrity of the weld, leading to the formation of microstructural defects that could serve as stress concentration points. These defects could function as preferred sites for crack initiation, particularly in regions with altered microstructures due to the welding process. Therefore, it can be inferred that the interplay between welding speed, microstructure evolution, and the presence of stress concentration features influences the observed decrease in fatigue strength.

Hardness measurements are commonly used to evaluate the mechanical properties of the FSW joints. The hardness of the weld zone, the heat affected zone, and the base material gives an idea about the

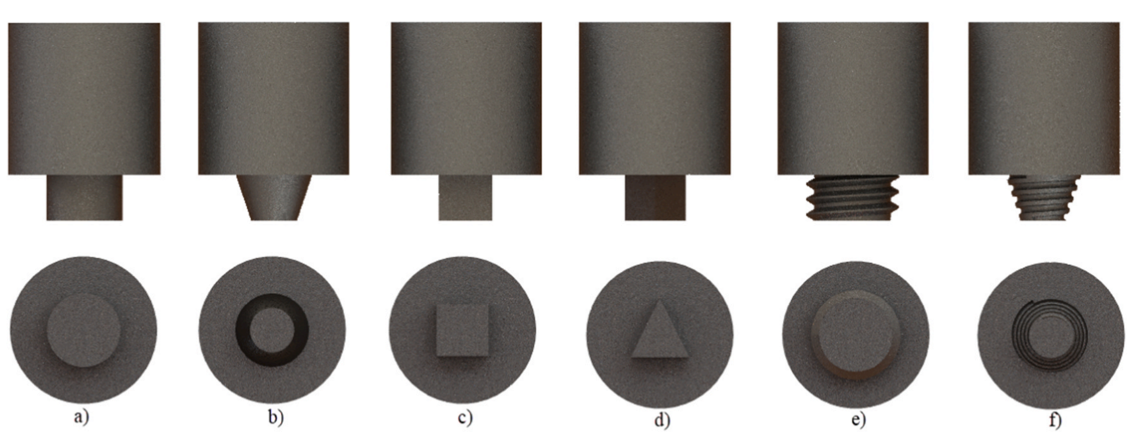

Fig. 2. Schematic representation of different pin profiles, a) cylindrical, b) conical, c) square, d) triangular, e) screw, f) conical screw.

microstructural changes and the resulting mechanical behavior. Microhardness testing allows a more detailed analysis of hardness changes within the weld, revealing the influence of process parameters on the material microstructure. In the FSW welding of AA2519-T62 alloy, an increase in microhardness was observed with increasing tool rotation speed [62]. The tool rotation speed directly affects the extent and efficiency of material mixing and stirring within the weld zone. As the tool rotation speed increases, it leads to more intense plastic deformation and heat generation due to the friction between the tool and the workpiece material. This intensified mechanical and thermal interaction promotes dynamic recrystallization and grain refinement, resulting in finer and more uniform microstructures. These refined microstructures often exhibit higher hardness values due to the reduced grain size and improved crystallographic alignment. In a study examining AA6082 and AA2014 alloys, higher hardness values were obtained in the FSW-joined sample than the base alloys [100].

The deformation behavior during the FSW process is another important consideration [37,48,107,138]. Material flow, plastic deformation, and recrystallization events affect the resulting microstructure and mechanical properties. Techniques such as electron backscatter diffraction (EBSD) and optical microscopy are used to analyze the deformation behavior and grain structure development in the weld zone.

In Table 1, the mechanical properties obtained from the FSW welding of various similar and dissimilar materials are presented.

Improvement of the FSW process

The FSW is a multi-parameter solid state welding technique that undergoes continuous improvement and modification to improve welding performance and expand its application range. Studies have been performed on the development of new techniques and modifications to improve the welding performance of the FSW [1133,134,143]. These advances include issues such as joint defects, material compatibility, process efficiency, and tool design. Tool design and tool material selection are the subjects studied [77,80,122,127]. Various tool geometries such as tapered, threaded, and profiles without teethes are explored to optimize heat generation, material flow and defect reduction during the welding process. In addition, the use of advanced tool materials, coatings and surface treatments is known to affect tool life, heat dissipation, and joint quality [3,4,76,95,109]. The utilization of advanced tool materials, coatings, and surface treatments can significantly influence several aspects of the FSW process. These enhancements contribute to extended tool life by providing better wear resistance and durability against the harsh conditions during welding. Moreover, incorporating specialized coatings and surface treatments can improve heat dissipation properties, allowing for more efficient cooling and preventing excessive tool wear due to elevated temperatures. As a result, these advancements not only prolong the tool's lifespan but also contribute to maintaining stable and controlled welding conditions, leading to enhanced joint quality.

Another research topic that contributes to the improvement of the FSW performance is the optimization of process parameters. Advanced sensing and control systems such as instantaneous temperature distribution monitoring, force feedback, and adaptive control algorithms are integrated into the FSW installations to achieve real-time process control and ensure consistent weld quality [35,85,144]. Also, hybrid approaches combining the FSW with other welding techniques or additional energy sources are being studied to improve welded joints properties and increase the welding capabilities of the FSW [54,81,90].

The areas where the FSW method is used are automotive, aerospace, shipbuilding, and other structural applications [7,59,97,101,106]. Research is being conducted on the FSW weld joints for materials used in the battery enclosures of hybrid vehicles. All welds tested under different parameters have demonstrated good quality, proven by the stability of tensile tests and consistency of microhardness measurements [89]. Moreover, the industrial applications of the FSW exemplify its far-reaching utility in different industries. Examples include the manufacture of lightweight structures such as aluminum and magnesium components in the automotive industry, the manufacture of airframe panels and propulsion system components in aerospace applications, and the construction of offshore structures in the marine industry [16,36,41,43,57,137]. These applications demonstrate the advantages of the FSW such as the ability to combine different materials, the potential for automation and cost effectiveness in large-scale production.

Ongoing research efforts to improve the FSW have contributed to the development of new techniques, modifications, and approaches to improve weld performance. Higher welding performance values are achieved by the integration of advanced tool designs, process parameter optimization, and hybridization with other welding techniques.

Table 1
Change of mechanical properties in joints made with the FSW.

Material	Thickness	Tool Pin Type	Base Material Strength (MPa)	UTS (MPa) (max.)	Elongation (%) (max)	References
AA2024-AA7075	3–3 mm	Pyramidal- Conical- Cylindrical	405.7 527.49	305.27 354.81 388.21	2.84 7.4 4.96	Beygi et al. [14]
AA2519-T62	5 mm	Threaded	469	405,6	8.3	Kosturek et al. [61]
AA8011	4 mm	Cylinder	-	140	18	Sundar et al. [120])
AA6061-T6	5 mm	Different Tapered Angle Tool	330	168 (min.) 276 (max.)	10 (min.) 14 (max.)	Hassanifard et al. [46]
AZ80A Mg alloy	6 mm	Cylindrical	290	234.8	-	Gunasekaran et al. [45]
Polypropylene	6 mm	Angle of 45^0	33	22.41	-	Kusharjanta et al. [66]
AA8090	6 mm	Square Trapezoidal- Hexagonal- threaded	440	191 342 224	5.98 7.12 5.96	Di Lorenzo [29]
AA7075-T651	10 mm	-	470	412	9	Parasuraman et al. [94]
AA2195-AA2219	5 mm	Threaded pin	570 489	350	-	Agilan et al. [5]
AA3003-clad AA6013	0.15–1.5 mm	Threaded pin	152.9	187	25.6	Gao et al. [40]
AA6063-T6	6 mm	Cylindrical	-	286.15	-	Rajkumar et al. [102]
Ti6Al4V titanium- T2 pure copper	3 mm	Cone	-	127	1.2	Li et al. [72]
AA6061-Galvanized Steel (DX54D)	2–1 mm	Flat cylindrical	-	Fracture load 4.42 (kN)	30.14	Kaushik and Dwivedi [58]

Limitations and challenges of the FSW method

Like other welding methods, the FSW has its challenges. The process involves complex thermo-mechanical interactions and material flow dynamics, which can pose various challenges during welding operations. One of the common problems is the presence of defects such as voids, lack of joint and tunnel formation, which can affect the integrity, and mechanical properties of the weld joint [79,121,125,145]. Such defects can emerge due to inappropriate process parameters, inadequately designed tools, or factors related to the materials being used [44]. According to the experimental results, increasing the rotational speed creates tunnel defects [146]. An increase in welding speed causes larger wormhole defects to occur [25]. Addressing these issues requires a comprehensive understanding of the underlying mechanisms and careful optimization of the welding conditions.

Another difficulty concerns geometric constraints. The FSW typically requires access to only one side of the join. This may limit its applicability in some cases. In addition, complex joint configurations such as T-joints and corner joints can create difficulties in obtaining smooth material flow and faultless welds. To overcome these limitations, innovative tool designs, fixture arrangements, or alternative welding approaches are often explored [22,23,99,105,117].

Joint inspection post-welding poses a challenge. The inadequacy of non-destructive testing methods is a cost-increasing factor in this method and needs to be resolved [50].

In terms of future research directions, the combination of the FSW and alternative heat sources such as laser/electromagnetic induction could play a role in further improving the coupling properties. Researching new materials and their compatibility with the FSW, as well as investigating the effect of microstructure and grain boundaries on weld integrity are the main research areas.

While the FSW offers numerous advantages, it also has limitations and challenges. By addressing challenges such as defect formation and accessibility, the application of the FSW can be further enhanced by focusing on potential solutions and future research directions. Tool design, process optimization, and alternative heating approaches will also lead to ongoing research and innovation to contribute to the advancement and wider use of the FSW in various industries.

Dissimilar materials joining

The process of joining different materials is a highly intriguing field in the FSW method. Joining materials with distinct mechanical, thermal, and chemical properties poses complex challenges. The aim is to produce lighter, stronger, and cost-effective components through the fusion of diverse materials [104]. For instance, in aerospace, automotive, and shipbuilding industries, combinations of different materials such as aluminum-titanium, aluminum-steel, and copper-aluminum are employed to achieve lightweight and resilient structures. The FSW method was utilized in the assembly of the engine cradle of the Honda Accord 2013 model, combining steel and aluminum materials [111]. Moreover, detailed application examples in the automotive sector can be found through references (W. M. [132]). The FSW technique is also effectively employed in the production of hydrogen tanks in launch vehicles for space applications [115].

Among the most significant challenges, differences in thermal expansion, various chemical interactions, high-temperature resistance, plastic deformation capacity, viscosity, and mechanical incompatibilities stand out [10,27,141]. Achieving a more homogeneous microstructure holds importance, requiring the optimization of parameters. Elrefaey et al. [34], examined the effect of the FSW on aluminum/copper materials, resulting in various microstructures with distinct morphologies and properties in the stirred region of aluminum and the Al/Cu interface region. Through the utilization of a Zn interlayer between Al and Cu, harmful intermetallic compounds were dispersed over larger areas, substantially enhancing the performance of the joints.

Chen and Nakata [20] examined the friction stir lap joining of a 1.6 mm thick AZ31 Mg alloy and a 0.8 mm thick steel. They used two different lengths of probe (1.5 and 1.8) and demonstrated the effect of probe length on tensile strength. Due to the difference in material thickness, the 1.5 mm probe length exhibited higher tensile strength.

Aonuma and Nakata [11] employed the FSW to weld Mg-Zn-Zr alloy (ZK60) with titanium material. The average tensile strength of the joint experienced fractures at approximately 69 % of that of ZK60. The fractures occurred within the stirring zone of ZK60 and partially at the joint interface.

Anaç [10] investigated the joining of two different polymer materials using the FSW method. In the research, two different pin profiles were used along with varying rotational and traverse speeds. The highest weld strength in PLA Plus/PLA Plus and PLA Plus/HDPE combinations was achieved using by a triangular pin profile. It was observed that welding defects occurred due to changes in welding speed and tool rotation speed.

Recent developments in the FSW

In this section, detailed information is given from some studies in the literature regarding recent research and development activities. It is thought that it provides an idea in choosing the appropriate parameter for those working on the same material.

Bevilacqua et al. [12] investigated the effects of different rotational and welding speeds on 2 mm thick AA5754 aluminum alloy. The tool made of tool steel with a shoulder diameter of 12 mm has a taper with a base diameter of 3.5 and a tip diameter of 1.8 mm. The effects of various rotational speeds (1200, 1500, 2000, and 2500 rpm) and feed rates (30, 60, and 100 mm/min) on the welding process were investigated. It has been determined that 1200 rpm rotation and 100 mm/min welding speeds are the most efficient parameter pair.

Mahany et al. [75] investigated the effects of tool rotation speed and axial load on stress corrosion cracking performance in different aluminum alloys. In their work, they used 2024-T4 and 7075-T6 aluminum alloys with 4 and 5 mm thickness. A tool with bevel gear pin and concave shoulder made of H13 steel is used. They used a specially manufactured machine for the FSW. This machine performs welding process at 50 mm/min speed in one pass by tilting the tool at 3^{o} angle. Rotation speeds were selected between 400 and 1600 rpm, while axial force was applied between 1000 and 1450 kg. After the tool was immersed in the weld material at a speed of 3 mm/min, sufficient heat generation was obtained by waiting for 15 s. Tool rotation speed and increase in axial load caused an increase in temperature in the weld zone. A maximum tensile strength of 378.7 MPa was obtained under a rotational speed of 1200 rpm and an axial load of approximately 1300 kg. As a result of increasing the values, it was observed that there were deteriorations in the weld area and the strength values decreased.

Vignesh et al. [130] investigated the heat transfer that occur during the FSW 6061-T6 aluminum alloy with 3 mm thickness by finite element method. It has been observed that the peak temperature increase in the welding zone is directly proportional to the tool rotation speed and shoulder diameter, while it is inversely proportional to the tool feed rate. It has been found that the pin diameter has no effect on the peak temperature. In experimental studies, it has been observed that the temperature distribution within the material is not symmetrical, meaning that different regions have varying temperatures. Additionally, the maximum temperature reached is found to be between 85 % and 90 % of the material's melting temperature.

Verma and Misra [128] investigated the heat dissipation in the weld zone in a 6.35 mm thick 6082 aluminum alloy. Eight thermocouples were used to measure the obtained temperature. The effect of giving tilt angle ($1–3^{o}$) to the tools and the effect of dwell times (10, 20, 30 s) in the part were investigated. When the tool was rotated clockwise, elevated temperatures were observed on the opposite side to the tool's advancing side. The highest temperature was measured at 2^{o} tilt angle and 30 s waiting time.

Panzer et al. [93] investigated the effect of the FSW on 2 mm thick AA6016 and AA6111 alloys tempered as T4 and T6. During the welding operation conducted on the ESAB Legio 3 ST FSW machine, a tool with a shoulder diameter of 15 mm, a probe diameter of 5 mm, and a probe length of 1.7 mm was utilized. The study reveals that the rotational speed of the tool significantly affects the welding process. Simultaneously, it is evident that the forces exerted during welding exhibit variations aligned with the mechanical properties of the welded part. This observation underscores the intricate interplay between material characteristics and the dynamic forces encountered in the FSW process. In summary, in the FSW, changes in input parameters such as tool rotation speed can significantly change the output forces, and variations in output forces, such as process forces, can also affect the input parameters, indicating a bidirectional relationship between them, revealing a complex interaction between the two.

Cabibbo et al. [17] successfully applied double-sided FSW on AA6082 material. They also investigated the effects of some deflection in the rotating pin. Experiments were carried out in CNC machining center using tools with HRC 52 hardness with a shoulder diameter of 15 and a pin diameter of 3.9 with a 30° conical pin according to the shoulder height. They used two different tools with 2.0 and 2.3 mm pin heights to apply different plunge depths. Welding parameters were applied as 1200 rpm rotation speed and 100 mm/min feed speed. A clear improvement in the mechanical properties of both age-hardened and non-age-hardened aluminum alloys was observed in both approaches.

Nie et al. [91] welded two sheets of 2219-T8 aluminum alloy with a thickness of 10 mm by the FSW and developed a thermal model. Thermocouples were used to measure heat. They showed that the increase in axial force and tool rotation speed increased the temperature, while the increase in tool feed rate decreased the temperature. It has been observed that axial force and welding speed have a major role in residual stresses, and it has been verified by experiments that the increase in these two parameters leads to greater residual stresses.

Patel et al. [96] in the application of the FSW of different aluminum alloys; Ancillary parameters such as part positioning, tool rotation speed, welding speed, and tool geometry have been investigated. They stated that the tool rotation speed has a great effect on the plastic deformation and has an effect on the residual stresses. Therefore, they emphasized that these values should be determined as optimum for welding quality and strength. They stated that high rotation speed and slow feed cause an increase in grain size, while low rotation speed and fast feed cause defects.

Huang et al. [49] successfully combined an ultra-thin 0.5 mm thick 6061-T4 aluminum alloy. Two different sets were used for welding. While the optimum immersion depth was seen as 0.05 mm, it was observed that the tensile property increased with increasing welding speed, but decreased at a welding speed higher than 500 mm/min.

Ugender [126] investigated the effects of tool pin profiles, rotational speed, and welding speed on the mechanical properties of the FSW parameters in AZ31 magnesium alloy. The plates to be welded were prepared in 240 × 60 x 5 mm dimensions. Experiments were carried out at rotational speeds of 900, 1120, and 1400 rpm. It was determined that tool rotation speed had the highest statistical effect on tensile strength and hardness. It was stated that the mechanical properties predicted by regression analyzes were compatible with experimental studies.

Conclusion

Through this literature review, information about the process parameters, joint integrity, and mechanical properties in the FSW method was discussed. In addition, it has tried to give information about the improvement studies, application areas, and difficulties related to this method.

The FSW offers several advantages over conventional melt welding methods. The absence of filling material is the best part of the process, and it eliminates the need for consumables. It is a method that can be applied on conventional benches as well as on special production benches. This method aims to eliminate the disadvantages of traditional methods such as porosity, cracking, and deterioration. If the appropriate parameters are not selected, defects such as pores may occur in this method. It is necessary to determine the optimum values of these parameters for each material pair. In particular, the determination of parameters such as welding speed, rotational speed, axial force, and tool geometry is very important to achieve error-free welded joints and desired material properties.

This study reveals that review of the FSW demonstrates its significant advantages such as solid state joining, improved mechanical properties and applicability to a variety of materials. It is necessary to address the identified challenges and provide a clear direction for future research and development on the above-mentioned issues. In newly developed welding methods like the FSW, there exist unexplored realms with numerous undiscovered areas. Particularly, studies should focus on predicting microstructures and controlling crystal orientations. Moreover, research needs to be conducted on topics such as the welding of multi-layered materials, welding under different temperature and pressure conditions, biomedical applications, and novel research areas in the aerospace and space industries.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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