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Friction Stir Welding Of Dissimilar Alloys And Materials: A Comprehensive Review

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ABSTRACT

Primarily, in 1964, the Friction Stir Welding (FSW) concept is patented in the Soviet Union. FSW, which deploys a non-consumable tool for joining '2' facing workpieces without melting the workpiece materials, is a solid-state joining process. (a) Intermetallic alloys, (b) silicides, (c) Laves phase alloys (2-phase Nb-Ti-Cr alloys), (d) platinum alloys, (e) iridium alloys, and (f) ceramics are the classifications of materials. Till the probe pierces into the workpiece as well as its shoulder touches the workpiece's surface, the tool in the FSW is fed into a butt joint betwixt '2' clamped workpieces. The FSW helps in joining dissimilar metals and ions. Especially, the attention is focused on deleterious Intermetallic Compounds' (IMCs) control and dispersion while considering the joining of dissimilar metals and alloys. For joining dissimilar alloys and materials, FSW has emerged as a promising technique, which results in advantages like enhanced mechanical properties, reduced distortion, and enhanced weld quality compared to the traditional Fusion Welding (FW) method. Thus, this paper provides an overview of the advancements in FSW of dissimilar alloys and materials. Also, the significant aspects like mechanical properties, microstructural analysis, and challenges that are associated with the FSW of dissimilar alloys as well as materials are explored in this paper.

Keywords: *Friction stir welding, Dissimilar alloys, Mechanical properties, Dissimilar materials, Tool geometries and Microstructural analysis*

1. INTRODUCTION

FSW has become an advanced solid-state thermo mechanical joining technique throughout the last 20 years in the field of mechanical engineering. The solid-state joining technique, which offers an innovative method of combining materials without having to melt, is termed the FSW [1]. There are still several significant rewards over standard welding techniques, including the lack of consumable material availability, reduced power usage, and improved weld strength despite the fact that FSW involves welding materials in a solid state [2]. FSW focused on the sections with a thickness of more than 1 mm in a few of the previous investigations [3]. This is because it allows for better control over the process variables together with heat generation. To achieve a successful weld, thicker materials typically require more heat input and better mechanical force. But, owing to higher surface area-to-volume ratio, variations in material properties, enhanced heat loss from workpieces, and welding of thin sheets will be complex [4]. In industrial applications like shipbuilding and offshore, automotive, aerospace, rolling stock for railways, robotics, general fabrication, as well as computers, FSW is used [5]. FSW offers advantages over traditional welding methods like reduced distortion, higher mechanical properties, and improved fatigue performance. To combine dissimilar materials, which are puzzling to weld employing prevailing FW methodologies, FSW is particularly advantageous [6]. FSW's solid-state nature reduces intermetallic formation risk and allows for the joining of materials with significant differences in properties.

Moreover, in FSW, analyzing the Tool Wear (TW) characterization is crucial for several reasons, including tool condition monitoring. Brian, *et al.* [7] appraised the potential intended for TW's remote in-process monitoring in stainless steel's FSW. In-situ as well as ex-situ laser profilometry are the principal approaches for monitoring tool geometry degradation. To detect volumetric defects, both destructive together with non-destructive

methods were employed. The performance was an effective demo of TW as well as weld quality in-process monitoring in high melting temperature as well as higher hardness material FSW with implications aimed at remote monitoring experiences. It also found that FSW's versatility extends to joining both similar and dissimilar materials [8]. This capability is advantageous in applications, where hybrid structures or assemblies of different materials are required to achieve optimal performance characteristics [9]. It is essential to consider some of the significant factors like metal properties, compatibility of metals, joint design, and selection of filler metal at the time of welding dissimilar metals using arc welding or FSW [10]. A filler metal is often required to facilitate the bonding between the two base metals in dissimilar metal welding [11]. FSW allows for the welding of dissimilar alloys that may have different compositions, microstructures, and mechanical properties [12]. Specific parameters like (A) welding current, (B) voltage, (C) travel speed, (D) heat input, as well as (E) shielding gas (if applicable) are encompassed in every welding process utilized in dissimilar metals. While minimizing the risks of defects, such as cracking, porosity, or excessive distortion, those parameters are requisite to be optimized to confirm dissimilar metals' proper fusion [13]. FSW offers precise control over the welding parameters, thus allowing for consistent and high-quality welds between dissimilar alloys [14]. Thus, in industries requiring complex and reliable joining solutions, FSW's ability to effectively weld dissimilar alloys and metals while preserving their properties makes it a preferred choice.
Currently, the complete area of FSW is explained in the paper. In the area of FSW, the significance of dissimilar metals and alloys is explored by this investigation. Analyzing information regarding the FSW and proposing potential solutions is the goal, thus, aiming at (i) process parameters, (ii) joint integrity, as well as (iii) mechanical properties.

2. Friction Stir Welding technique

A solid-state joining process wielded in manufacturing for joining materials, which are tedious to weld employing traditional FW methodologies, is termed the FSW. For engendering a bond between two pieces of metal without melting the materials, frictional heat joined with an exactly controlled forging pressure is wielded by FSW [15]. For joining aluminium and its alloys along with other non-ferrous metals, FSW is particularly effective. It can also be used with some thermoplastics and composites [16, 17].

For engendering very higher-strength joints, which are virtually defect-free with minimum Heat Affected Zone (HAZ), lower mechanical distortion, along with outstanding surface finish, frictional heat joined with accurately controlled forging pressure is deployed by the FSW. It's a solid-state welding process, which means the metal pieces didn't melt during welding. The diagrammatic format of the FSW process is elucidated in Figure 1 [18].

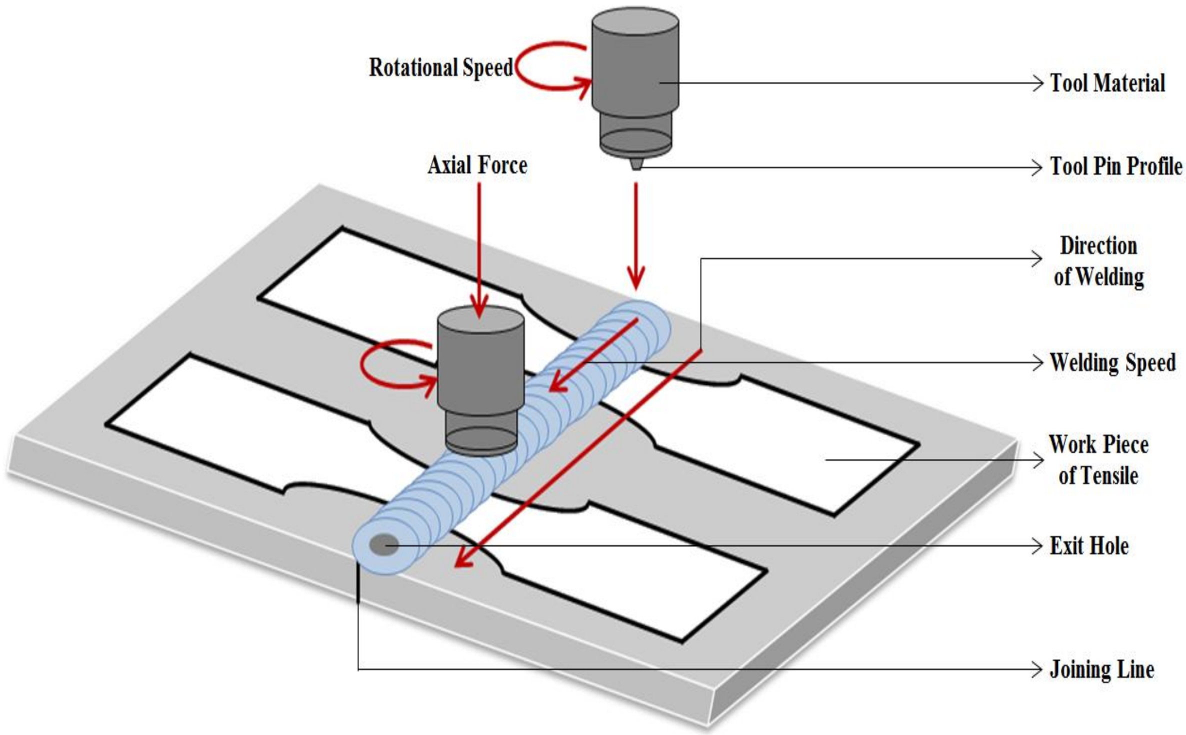

Figure 1: Diagrammatic format of the FSW process

Engendering heat via frictional forces is encompassed in the key principle of FSW. Flow, process forces, as well as strains during FSW, were analyzed as a comprehensive first principle approach in the study of Dhruv, *et al* [19]. Precise fundamental assessments of (a) forces, (b) material flow, as well as (c) strain were lacking even though a number of empirical and simulation models had been applied. The outcomes was expressed as precise mathematical terms regarding material qualities as well as process parameters. It was shown to undergo both direct and shear strains in stirring since the material moves as of the evolving to the receding side in the tool's front as well as after rotation bonds after the tool. Other than principle, it is essential to explain the industrial applications of FSW. Grimm, *et al* [20] defined the FSW of light metals for industrial applications. by employing a 3D-capable technology that was strong to withstand the higher process stresses, complex geometries could be directly machined and friction stir-welded in one setup. Enormous and intricate three-dimensional structures could be constructed using this parallel-kinematic method up to seven meters in length. Also, it is essential to explain the FSW tools in a deeper way to analyze the importance of FSW.

2.1. FSW tools

In the process's success, the FSW tool is obviously a perilous component. Usually, the tool is made up of a threaded cylindrical pin as well as a revolving round shoulder that works together to heat the workpiece primarily through friction; also, move the softened alloy around for producing the joint [21, 22]. Shoulder, pin, and tool material are some important parts of FSW welding tools [23].

The following are some of the significant explanations regarding the components of FSW welding tools,

✓ **Shoulder**: The larger diameter section that connects the surface of the workpieces. It generates most of the heat through friction.

✓ **Pin (or Probe)**: The smaller diameter section that penetrates the materials to be joined. It aids to mix as well as forge the materials together.

✓ **Tool Material**: It is made of hard and wear-resistant materials like tool steels, tungsten carbide, or ceramics to withstand high forces and temperatures.

Hence, for successful FSW, the right tool material, geometry, and design are essential, thus enabling strong and defect-free welds in various industrial applications. the specifications of FSW are explained in Figure 2.

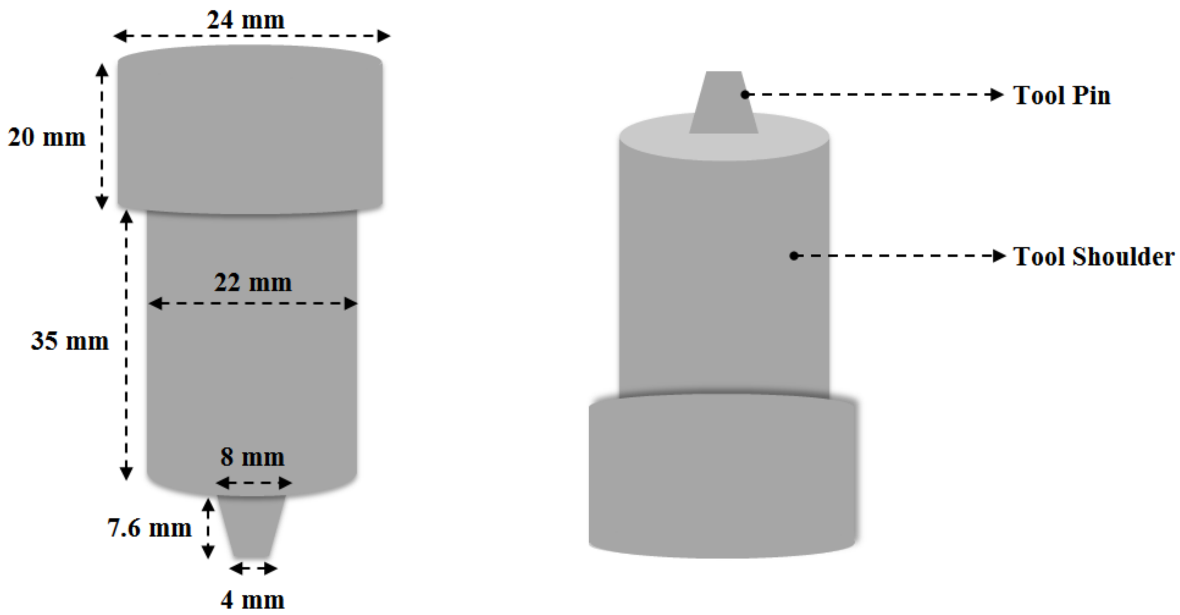

Figure 2: Specifications of FSW

The FSW tool is made from a hard and wear-resistant material capable of withstanding high temperatures and mechanical stresses. Due to frictional heat and mechanical abrasion, FSW tools undergo wear during operation. To ensure consistent weld quality, regular inspection and maintenance are essential [24]. Tools may need periodic reconditioning or replacement depending on the application and material being welded. To ensure dimensional accuracy and performance, FSW tools are manufactured with precision machining techniques. Quality control measures include inspection of tool geometry, surface finish, and material integrity to meet welding specifications [25]. Shihui, *et al* [26] elucidated quality control parameter variations' impact on aluminium FSW joints' fatigue performance with its tool. The fatigue test outcomes were given together with associate metallurgical as well as nonlinear fracture mechanics analysis. This research leads to the conclusion that kissing bond flaws with a size range of 0.3–1.0 mm can significantly shorten fatigue life and cause the failure mode to shift to the weld root. Also, explaining the FSW tools with diverse Pin Profiles (PPs) (every dimension is in mm) is necessary. The FSW tools with diverse PPs are elucidated in Figure 3.

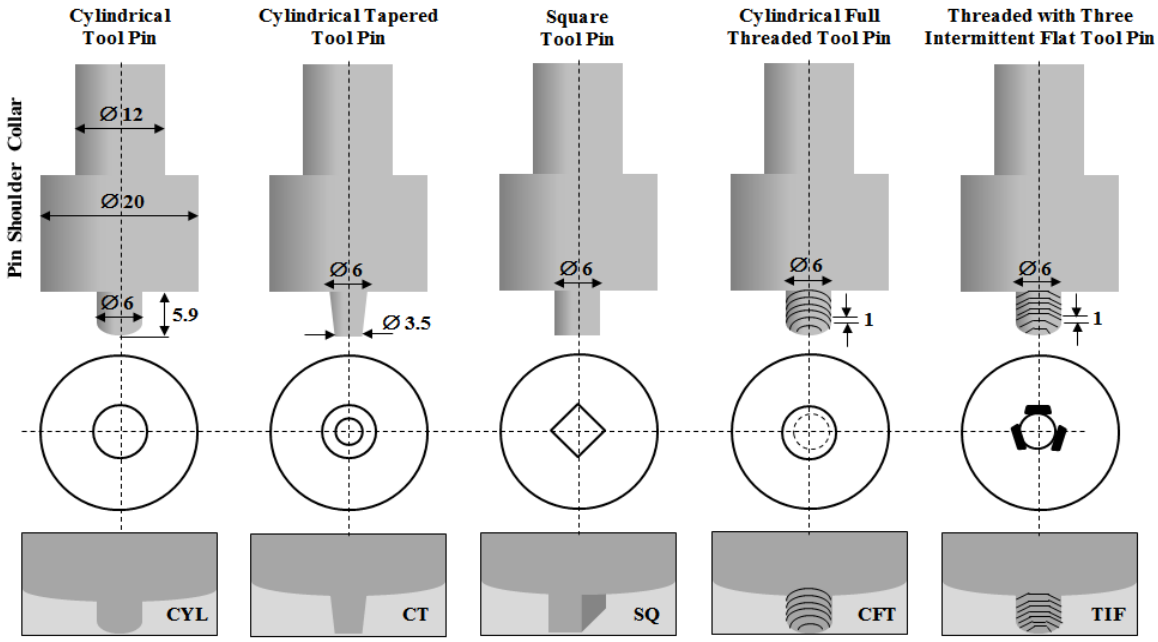

Figure 3: FSW tools with different pin profiles

In the FSW tools, there are different kinds of PPs present. For optimizing the welding process for different materials, joint configurations, and desired weld properties, FSW tools can be designed with various PPs. Some of the PPs presented in the FSW tools are (A) Cylindrical tool pin, (B) cylindrical tapered tool pin, (C) Square tool pin, (D) Cylindrical full threaded tool pin, and (E) Threaded with 3 intermittent flat faces tool pin [27,28]. Some of the explanations regarding the diverse sorts of PPs are given further:

→ **Cylindrical Tool Pin**: For alignment or fastening purposes in mechanical assemblies, a straight cylindrical pin is used typically. It can vary in diameter and length depending on its intended function. For the eccentric cylindrical pin in FSW, an analytical model of heat generation was analyzed Ahmed, *et al* [29]. The FSW was done at numerous welding 100, 300, as well as 500 mm/min speeds in addition to 600 rpm constant tool rotation speed. As per experimental findings, eccentric cylindrical pins produce less heat than cylindrical pins devoid of eccentricity underneath the specified FSW process parameters.

→ **Cylindrical Tapered Tool Pin**: Similar to the cylindrical pin but with a tapered shape, which means it gradually narrows towards one end. Tapered pins are often used for alignment purposes, where a snug fit is required [30]. For fabricating the joints at 3 diverse Rotational Speeds (RSs) (that is., 900, 1400, 1800 rpm), 5 diverse tool PPs like (i) Taper cylindrical, (ii) cylindrical, (iii) triangular, (iv) square, as well as (v) cone was wielded beneath 16 mm/min constant traverse speed was analyzed by the prof chandresh, *et al* [31]. For this alloy, a taper-threaded cylindrical PP with 800 rpm maximum speed engendered the best Tensile Strength (TS), HAZ 172,168, and weld outcomes in Weld Zone (WZ) 165,163.

→ **Square Tool Pin**: A pin with a square cross-section instead of cylindrical. Square pins are used in applications, where rotational movement needs to be prevented or controlled, such as in fixtures [32]. By employing a square PP tool, techniques for FSW forces were analysed by Caroline, *et al* [33]. Welding, radial, transverse, ads well as tangential forces were modelled as rotational function, welding speeds as well as rotation's instantaneous angle. As per the outcome, a good agreement was shown; also, the data with a correlation coefficient was greater than 0.97. The torque declined linearly, as well as the axial force was almost constant with cumulative RS.

→ **Cylindrical Full Threaded Tool Pin**: A cylindrical pin that is threaded along its entire length. Full-threaded pins are used when a strong and threaded connection is needed, often in situations requiring disassembly and reassembly [34]. Hao, *et al* [35] analysed the cylindrical full-threaded tool pin with 3 flats in aluminum alloy's FSW. A technique was used centered on the numerical model to optimize the tool PP's design with 3 flats. Determining the various torque components on the flat area together with taking the TW propensity as well as material flow behavior into account was involved in this technique. Moreover, the optimization outcome's precision was also reviewed; in addition, by employing the applicable approach, the tool PP was optimized for process parameters' variety. For the tool PP in FSW's computer-assisted optimization design along with reliability evaluation, the method offered a clear solution.

These explanations cover the basic functions and typical applications of each type of tool pin. One type may be more suitable than another in terms of strength, alignment precision, or ease of assembly/disassembly depending on the specific needs.

2.2. TOOL MATERIALS AND PROCESS PARAMETERS USED FOR WELDING OF DISSIMILAR MATERIALS IN FSW

Materials that are distinct or different from each other in terms of their composition, properties, or structure are termed dissimilar materials [36]. In various fields of engineering, manufacturing, and science, dealing with dissimilar materials can present challenges owing to variances in thermal expansion coefficients, mechanical properties, compatibility, and bonding characteristics. Examples include combinations like metal and plastic, ceramics and metals, or composites with different matrices and reinforcements [37]. Frictional heating of the '2' dissimilar materials in which residual stresses formed plays a key role due to the welded workpiece's linear coefficient thermal expansion, which intensely affects the welding's fatigue behavior is encompassed in the FSW [38]. The FSW tool design showing geometric parameters is elucidated in Figure 4.

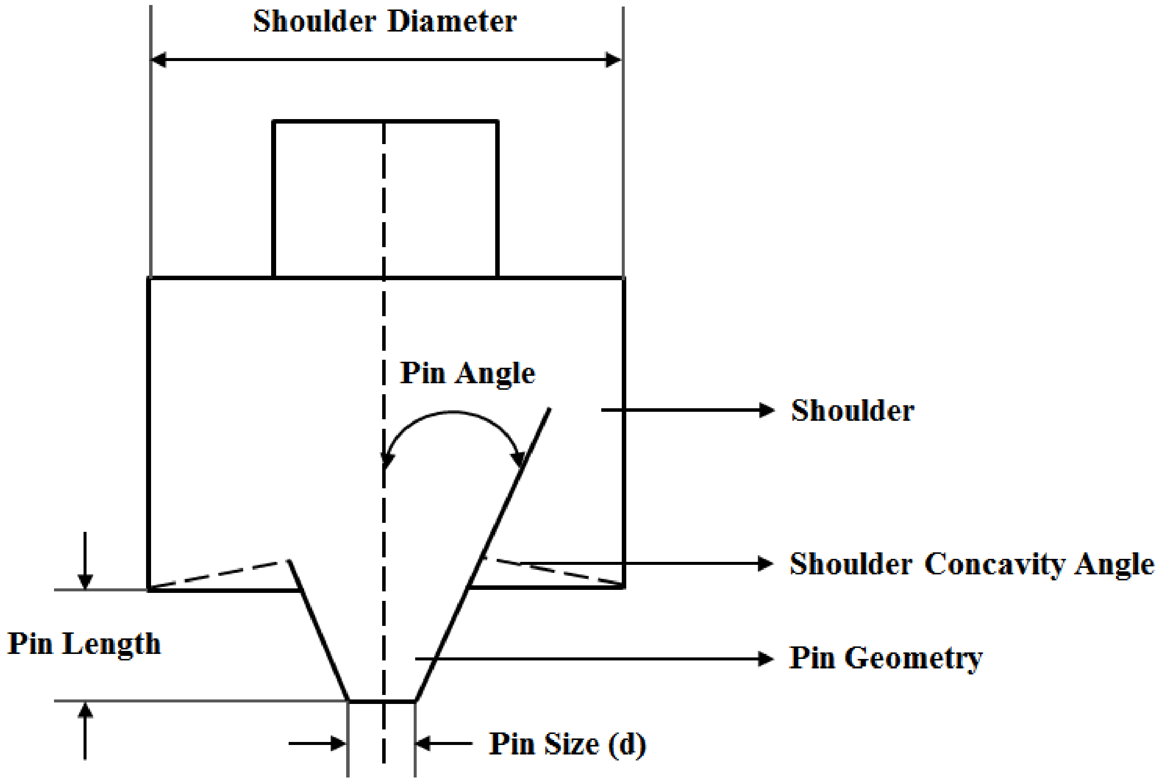

Figure 4: FSW tool design showing geometric parameters

Some of the significant Geometric parameters are Shoulder diameter, Pin angle, Pin length, Pin size, and Pin geometry. The diameter of the cylindrical part of the tool that connects the materials being welded is termed the shoulder diameter [39]. It exerts downward pressure along with generates frictional heat at the joint interface. The pin angle relative to the tool's vertical axis is termed the pin angle [40]. It affects the penetration depth together with the material flow in the welding. The protruding cylindrical pin's length from the shoulder is termed the pin length [41]. It defines the depth to which the tool penetrates the materials welded. The shape and features (e.g., threads and grooves) on the pin surface are encompassed in the pin geometry. It affects the material flow, heat generation, as well as joint formation characteristics [42]. The research studies of recommended as well as wielded dissimilar tool materials, tool geometries, as well as process parameters for FSW are elucidated in Table 1.

Table 1: Research studies of recommended/used dissimilar tool materials, tool geometries, and process parameters for FSW

Dissimilar material	***Thickness***	***Tool geometry***	***Operation parameters***	***Observations***	***References***
2024-T3 Al as well as AZ31 Mg alloy	3 mm	Threaded pin tool	Tool RS as well as welding speed: 1200 along with 20 mm/min	As per the outcome, a progressive rise in hardness as of ZE41A BM's 69 HV0.1 mean value to Al 2024-T3 BM's 117 HV0.1 mean value is shown.	[43]
Al 6061	4 mm	Triangular tool pin	Rotating as well as welding speed: 1750 and 60 mm/min	In the joints made up of other tool PPs (T1 as well as T3), brittle fracture modes were observed.	[44]

Al 6082 with Mild Steel	6 mm	Pin-less mild steel tool	Tool RSs range as of 800 to 1600 rpm; also, the feed rate was 55 mm/min	With the pin-less tool, the FSW joints' maximal strength was 82.41% of the base metal at 1200 as well as 55 mm/min of feed.	[45]
AA2024 T3 and AA7075 T6	5 mm in AA2024 T3 and 6.5 mm in AA7075 T6	Cylindrical tool	RS: 710, 1000, and 1400 r/min	By using the FS welding process, tailor-welded blanks of AA2024 along with AA7075, with a thickness ratio of 1.3, were buttwelded successfully.	[46]
SS400 Steel and A5083 Al alloy	2	Threaded pin tool	Tool rotation speeds: 450, 560, as well as 710 rpm	Maximum joint efficiency of 62.83% of the Base Material (BM) AA 7475 was achieved at 560 rpm RS with 6.89% elongation.	[47]
Al 6063-T4	6.5 mm	Square tool pin	Tool RS: 450 rpm	The lowest thermal diffusivity was available in the asbestos backing plate; also, it could offer the largest process window within defect-free welds.	[48]
AA2024	3 mm	Threaded pin tool	Constant tool RS: 600 rpm	For both orientations, TS values were very similar; however, there was an increase in the yield strength.	[49]
SPD Aluminium by constant groove pressing (CGP)	3 mm	Not mentioned clearly	Rotation speeds: 600, 800, 900, 1000, 1200, 1400 r/min. Traverse speeds: 50, 63, 80, 100, and 125 mm/min	Grain growth as well as a drop in hardness value were brought by the welding heat input at the stir zone's Al side.	[50]

There are other significant dissimilar materials named AA 2219 as well as AA 7039 Alloys. In the T9 temper, 6262-T9 aluminum was 6262 aluminum. The metal was solution heat-treated, artificially aged, and strain-hardened for attaining this temper. When analogized to other variants of 6262 aluminum, it had the 2^{nd} lowest ductility. The processing as well as optimization of dissimilar FSW of AA 2219 together with AA 7039 Alloys were analysed in the study of Venkateswarlu, *et al* [51]. It was found that the weld quality was highly impacted by the tool's shoulder flat surface together with the tool's RS degree. For engendering a mathematical model that predicted how tool geometry, as well as process variables, would affect dissimilar AA 2219 together with AA 7039 alloy welding, response surface regression analysis was also used. Friction stir spot welding's parametric study of aluminium alloy 5754 was analysed in another study of Klobčar, *et al* [52]. To design the experimental plan with tool rotation speed ranging from 988 to 3511 rpm, plunge rate from 24,4 to 150 mm/min, together with dwell period from 1 to 3,5 s, the Response Surface Methodology (RSM) was wielded. The depth of the plunge was maintained at 0.4 mm. The microstructure was examined, and the welds were subjected to stress and shear tests. By developing mathematical models that illustrate the link betwixt welding parameters as well as spot strength, axial force, together with the rotational moment, the ideal FSSW parameters were discovered.

2.3. Analysis of mechanical properties of FSW

When analogized to traditional FW techniques, FSW is known for achieving superior mechanical properties. Due to its solid-state nature, joints with high strength and integrity are engendered by FSW [53]. Unlike FW, where melting and solidification can introduce defects like porosity and solidification cracks, FSW joins materials by plasticizing them without reaching the melting point [54]. The weld joint's mechanical properties are influenced by the FSW tool's design and material. Tools with appropriate shoulder and pin geometries could control heat input, plastic flow, together with material mixing during welding [55].

Ni, *et al* [56] analysed the tool design role on higher-speed micro friction stir welded 7075-T6 aluminum alloy's thermal cycling as well as mechanical properties. In comparison to traditional FSW, experiments were done at 6000 rpm greater rotating and 1200 mm/min welding speeds. The junction made with the pin-less tool exhibited larger tensile capabilities as well as less softening as weighed against the joints made with pin tools. The Effect of Tool Design on Bobbin Friction Stir Welded 6061-T6 Aluminum Alloy's Mechanical Properties together with tool shape effect along with process parameters on AW-3004 aluminium alloy FSW Joints' mechanical properties were analysed likewise in another study of Samir, *et al* [57] and Anna, *et al* [58]. Tensile, together with bending tests were conducted for selecting the best bobbin tool design that would yield the best mechanical qualities for the welded zone [57]. The cylindrical tool's use produced advanced values of approximately 37% for mechanical attributes when weighed against the greatest result for the tapered threaded junction [58].

Yield strength, elongation, flow stress, and temperature profile that were analyzed in the studies of [59], [60] are FSW's other most important mechanical properties. In ugender, *et al* [59], as per the outcome, when analogized to a straight cylindrical tool profile, better mechanical properties were resulted by the joints

fabricated at a taper cylindrical profile with a three mm radius of curvature. During FSW, tool parameters' effect on (A) mechanical properties, (B) temperature, together with (C) force generation was analysed in the study of Mostafa, *et al* [60]. Peak temperature rises as shoulder, pin diameter, along with pin height increase. It was discovered that the location, which was welded by a tool with 3 D/d ratio, was flawless. Raising the pin height resulted in deeper penetration and higher ultimate TS [60].
In the studies of [61] [62], the mechanical properties of tool RS impact was analyzed. The RS on friction stir welded AZ31B magnesium alloy's mechanical properties was analysed in the study of Ugender, *et al* [61]. By the FSW, AZ31B magnesium alloy is welded; also, underneath the following range of process parameters, no macro-level defects were initiated. Tool RS's effect on aluminium alloy 5083 weldments' mechanical properties in FSW was analysed in another study of Aruna, *et al* [62]. A better weld of good TS was depicted by the mechanical testing methods on sample weldments.
Moreover, here, the TS of FSW AA6061-T4 Joints was analysed [63]. With '2' welding parameters (tool RS as well as feed rate), FSW worked in 6061-T4 aluminum alloy's 4 mm thick plate was investigated. In Figure 5, the feed rate effect on welds' TS for diverse tool RSs was analysed.

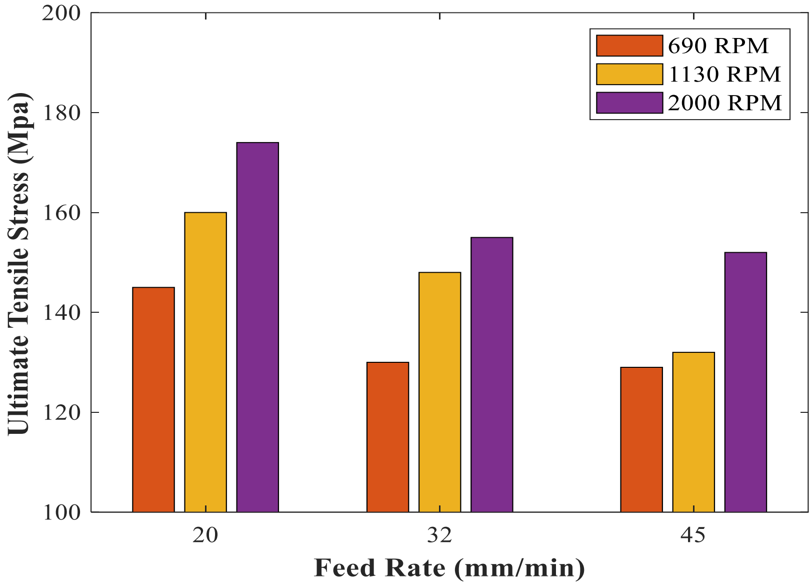

Figure 5: Effect of feed rate on TS of welds for different tool RSs

The TS increased while the tool RS was augmented as of 690 to 2000 rpm at 20 mm/min same feed rate, which is depicted in Figure 5. This was because of augmented friction betwixt the tool and base metal plate because of the high heat input as well as proper bonding between the two edges that needed to be welded. Likewise, in Figure 6, the analysis for the welded microhardness profile at 20 mm/min travel speed along with different RSs was analyzed.

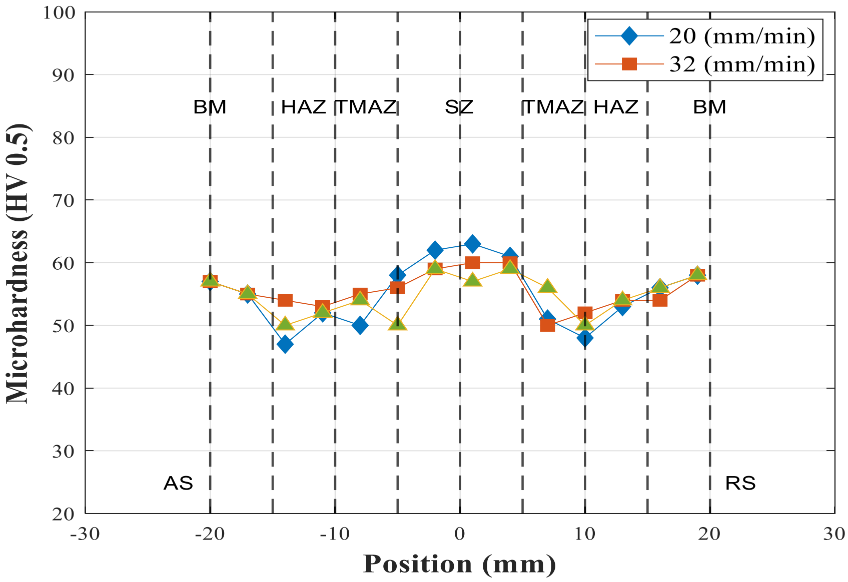

Figure 6: Analysis of microhardness profile of the welded at travel speed 20 mm/min and different RS

The optical microscope microstructural of the sample welds at 690 rpm, as well as 20 mm/min for SZ, TMAZ, HAZ, and BM, are depicted in Figure 6. As a result of the production process, both HAZ and BM's microstructural features were elongated grains.

2.4.Analysis of microstructure properties of FSW with dissimilar materials

Both materials' grain structure near the WZ is refined by FSW, thus promoting finer grains weighed against the BMs [64]. This refinement often enhances mechanical properties, namely hardness and fatigue resistance. The orientation of grains can vary within the WZ, thereby affecting anisotropic properties, such as strength and ductility in different directions [65]. The microstructural analysis of these joints involves understanding the formation of IMCs, the distribution of alloying elements, and the evolution of grain structure.

The material's final performance depends on processing, microstructure, and properties. Microstructure reveals grain arrangement, size, shape, phases, grain boundaries, and dislocations. The microstructure studies for the FSW joint of dissimilar materials betwixt AZ31B magnesium together with 6061 aluminum alloys were analysed in the study of [66, 67]. The failure mode was controlled by the presence in the WZ [66]. It was discovered that the Ultimate TS (UTS) together with Yield Strength (YS) was greater than while AA1050 was placed on the advancing side when AA6082 was placed on the proceeding side during FSW along with FSP [67].

Also, in the study of [68], the dissimilar friction stir welded Al alloy was analysed. By employing EBSD, the microstructural evolution was studied in the optimum sample in more detail. In the optimum sample, by employing EBSD, the microstructural evolution was studied. Grain refinement took place by employing different dynamic recrystallization (DRX) during FSW. During dissimilar FSW of duplex stainless steel to lower carbon-manganese structural steel, microstructure as well as crystallographic texture evolution was analysed Rahimi, *et al* [69]. Temperatures betwixt Ac1 and Ac3 were attained by the temperature in the stirred zone's center. This caused a small phase transition of ferrite to austenite in the S275 steel; but, there were no variations in ferrite together with austenite proportions in the DSS.
Likewise, Sirvan, *et al* [70], elucidated the microstructure analysis of dissimilar FSW of 430 stainless steel as well as 6061 aluminum alloy. The optimum appearance quality was detected at 900 r/min RS, 120 mm/min traversal speed, together with zero tool offset according to the results. Tool offset was the considerable factor influencing the weld quality. Dissimilar friction stir welded aluminium alloys' Microstructural as well as corrosion behaviors were analysed [71]. An 'onion ring' pattern was presented by the optimal weldments' microstructure, which depicts suitable alloy mixing during FSW.

2.5. Challenges of FSW of dissimilar alloys and materials

Knowing the FSW challenges of dissimilar alloys as well as materials is required. For successful FSW of dissimilar alloys and materials, the challenges are crucial. For dissimilar materials, FSW parameters like (A) RS, (B) traverse speed, (C) tool geometry, and (D) tilt angle must be optimized differently when weighed against similar materials [72, 73]. The challenges of FSW of dissimilar alloys and materials are elucidated in Table 2.

Table 2: Challenges of FSW of dissimilar alloys and materials

Challenges	*Explanation*	*References*
Material affinity	Mostly, Dissimilar materials have different thermal properties like (i) melting points, (ii) thermal conductivities, along with (iii) coefficients of thermal expansion. These differences result in thermal gradients and residual stresses during welding, thus affecting the integrity of the weld joint.	[74]
TW and selection	The weld's quality as well as consistency could be influenced by TW, which causes changes in microstructure as well as mechanical properties. Hard tool materials with good wear resistance were typically required for welding dissimilar alloys.	[75]
Process improvement	Improving the parameters was challenging because of the variations in the material properties and required to balance heat input, material flow, and TW across dissimilar materials.	[76]
Quality assurance	Assessing the quality of FSW joints in dissimilar materials could be challenging due to the heterogeneous nature of the WZ and potential internal defects.	[77]
Non-destructive testing	For detecting defects like voids, cracks, and incomplete bonding without compromising the integrity of the welded joint, Non-destructive testing techniques like ultrasonic testing, radiography, and eddy current testing were often used.	[78]

Thermal management and applications are the other 2 most significant challenges. The challenges of thermal management associated with dissimilar materials were analysed in the study of [79]. Different thermal conductivities can be encompassed in dissimilar materials, which causes uneven heating during welding. This can affect the weld's microstructure along with mechanical properties. In [80], the other challenge application was detailed. There may be specific requirements, such as corrosion resistance, fatigue strength, or temperature resistance depending on the application. Knowledge of the challenges in welding dissimilar materials helps in selecting appropriate welding techniques and materials to meet these requirements.

Thus, for ensuring successful welding processes, significant challenges of FSW of dissimilar alloys and materials are essential, thus attaining high-quality welds and meeting the performance criteria required for various engineering applications.

3. CONCLUSION

In the welding technology field, a significant advancement is represented by FSW of dissimilar alloys and materials, which offers distinct advantages over conventional FW methods. FSW has demonstrated its capability to engender higher-quality joints with enhanced mechanical properties despite the essential challenges, such as managing IMC formation, controlling microstructural gradients, and optimizing welding parameters. The evolution of microstructure within dissimilar material joints, influenced by the mechanical mixing and thermal effects during FSW, highlights the complexity and criticality of process control. For achieving desired weld properties and ensuring joint integrity, effective tool design, precise parameter selection, and advanced characterization techniques are essential. IMC formation at the weld interface is the limitation identified from the different studies. These IMCs could be brittle and detrimental to the joint's mechanical properties, thereby potentially reducing its strength, toughness, and fatigue resistance. Thus, this limitation should be considered by future researchers, and should find another method to ignore the formation of IMC. Thus, for joining dissimilar alloys and materials, numerous benefits are delivered by FSW, but, the development of IMCs remains an important limitation that requires ongoing research and development efforts to moderate and overcome broader industrial applications.

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