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REVIEW ARTICLE

A Review on Influence of Process Parameters, Preheating and Cooling on Friction Stir Welded Joint Performance

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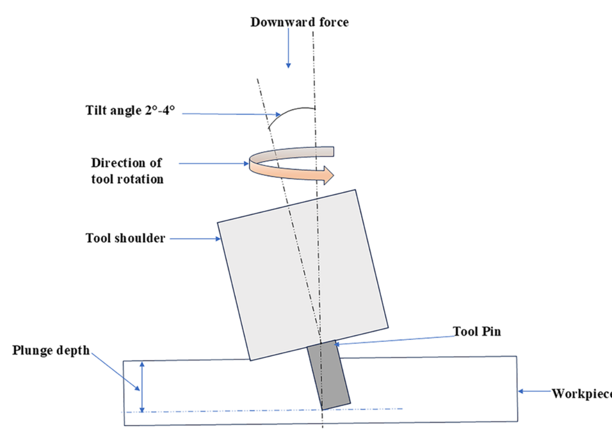
Abstract The investigation of dissimilar materials joining using Friction Stir Welding process has become a prominent research trend due to its growing use in aerospace, automotive, and shipbuilding industries. Over the past two decades, it has emerged as one of the most significant advancements in metal joining technology. This review brings together the key insights of research developments in the field, with an emphasis on the fundamental concepts behind Friction Stir Welding, tool design and materials, and the essential process parameters influencing joint quality. Also, the paper focuses on friction stir welding of dissimilar materials, examining the impact of preheating and water cooling on various characteristics like hardness, tensile strength, and fatigue behavior. This literature review critically examines recent advancements in dissimilar welding of aluminum–magnesium alloys, offering essential design recommendations for future studies. It presents a comprehensive overview of existing knowledge and points out important areas that need more investigation.

Graphical Abstract



Keywords Friction stir welding · Dissimilar metals · Effect of preheating

1 Introduction

The welding of materials has been a significant concern of various industries. Traditionally, welding practices were largely confined to similar materials. However, the rapid advancement of industrial technologies and the growing need for complex, high-performance components have driven increased interest in welding dissimilar materials [1]. A diverse range of industrial applications now demand joining of dissimilar materials, utilizing both solid-state and fusion welding techniques to meet performance and design needs [2]. Welding is a process used to join metallic parts whether similar or dissimilar by applying heat, pressure, or combination of both. Main types of welding include resistance welding, fusion welding, soldering and brazing, and

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solid-state welding. As human needs continue to rise with increasing demand of fuel, growth of population, and growing desire for comfort the use of automobiles and air travel has increased significantly. This has spurred research toward lightweight materials like magnesium and aluminum, focusing to improve efficiency of fuel through weight reduction [3]. Dealing with aluminum and magnesium alloys poses significant challenges particularly when using conventional fusion welding techniques like MIG, TIG, electron beam welding (EBW), and laser welding. These methods often lead to various issues which make it difficult to produce high-quality joints [4].

Fusion welding methods including arc welding, resistance welding, and laser welding are generally unsuitable for joining dissimilar materials as they often lead to defects like cracks, porosity, voids, particularly at higher temperatures. These defects adversely affect quality of weld and reduce mechanical properties of the joint [5]. Moreover, many components are anticipated to illustrate multiple functional properties, necessitating the integration of different materials into a single part. From this perspective, FSW has demonstrated considerable potential for effectively joining both similar and dissimilar materials [6]. Friction Stir Welding (FSW) offers several advantages over conventional fusion welding techniques, particularly as it does not involve melting the base materials. This eliminates common weld defects associated with molten state processes, such as porosity and solidification cracking. FSW is increasingly recognized as an energy-efficient and environmentally friendly “green” technology, as it requires no shielding gases and produces no harmful emissions. This literature review aims to assess current research on FSW, with emphasis on optimizing process parameters, ensuring joint integrity, and improving mechanical properties. Understanding the influence of key process variables is critical for achieving optimal weld quality. One of the major strengths of FSW lies in its ability to deliver high-quality welds with superior mechanical performance. Additionally, FSW can be effectively carried out using conventional or CNC milling machines equipped with appropriate tools and carefully selected process settings [7]

Friction Stir Welding (FSW) operates at relatively low temperatures and avoids melting, which helps eliminate many of the safety and environmental concerns associated with conventional welding techniques. Since it’s a solid-state process, FSW produces joints that are typically free of common welding defects and shows better mechanical performance than those formed by traditional fusion-based welding methods [8]. In the early stages, aluminum alloys—widely used in structural applications due to their low weight, high strength, and excellent corrosion resistance—were readily joined using FSW process. As the technique matured, it was successfully extended to other materials such as magnesium alloys, copper alloys, steel, and various metallic composites. Among these, magnesium alloys gained attention for their distinctive properties, including lightweight, good ductility, low density, high strength-to-weight ratio, and, importantly, their abundance and cost-effectiveness [9]. There are significant applications in FSW, including welding of aluminum–magnesium alloys in automobile industry, the aerospace industry, the railway industry, the shipbuilding industry [3]. The high strength-to-weight ratio makes the magnesium alloys ideal for applications where reducing weight and minimizing inertial forces are crucial. Owing to this advantage, magnesium-based alloys are used progressively to replace heavier materials including not only steels, cast iron, and copper-based alloys, but even aluminum alloys in various automotive and structural applications [10] To reduce structural weight and enhance environmental sustainability, lightweight materials like aluminum (Al) and magnesium (Mg) are used progressively as substitutes for traditional steel structures across various industries [11]

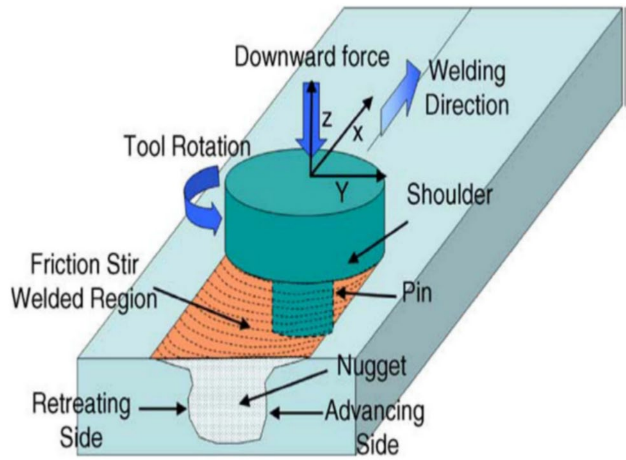


Fig. 1 Visual representation of friction stir welding [12]

2 Friction Stir Welding Working Principle

Friction Stir Welding is a solid-state joining process that provides several advantages over conventional fusion welding techniques. In this method, a cylindrical, shouldered tool with a specially shaped probe rotates and is gradually inserted into the joint line between two adjoining sheets or plates, as demonstrated in Fig. 1 (Reproduced from Ref. [12] with permission from Elsevier). These components must be securely clamped to the worktable to prevent separation at the joint during welding. The tool commonly made from durable materials such as tungsten carbide or hardened tool steels features a uniquely designed shoulder and pin. As it rotates and applies axial pressure, frictional heat is generated, softening the material without melting it. This

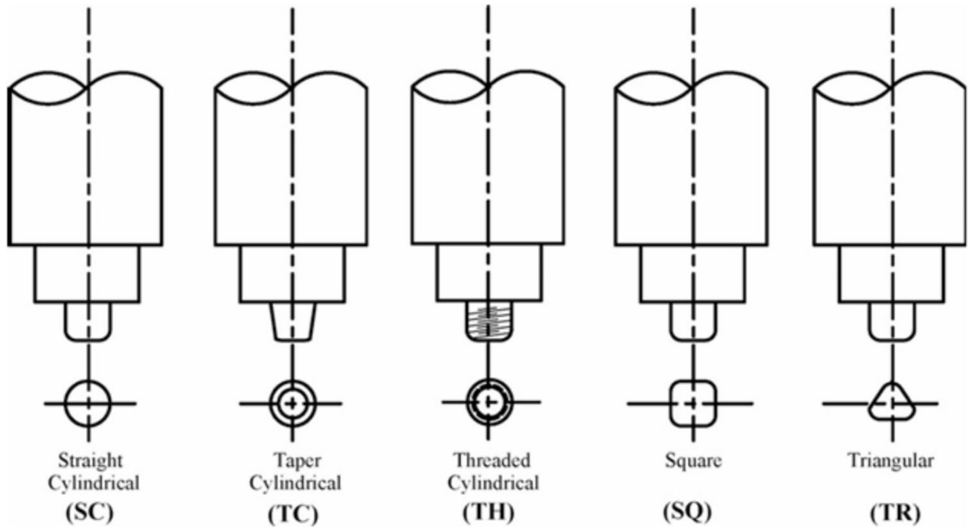


Fig. 2 Different geometrical profiles of the tool pin [14]

softening allows for plastic flow and mixing the material around the rotating pin. The combined effects of heating due to friction and plastic deformation modify the original grain structure, enabling a high-strength, defect-free weld [7].

2.1 Process Parameters

A thorough understanding of key FSW parameters including welding speed, tool design, plunge depth, tilt angle, and rotational speed, is essential for optimizing joint quality. These primary variables play an important role in defining the mechanical behavior and metallurgical structure of weld. Therefore, comprehensive investigation and control of these parameters is crucial to ensure production of high-quality, defect-free joints by employing the process of FSW.

2.1.1 Tool Geometry

Tool geometry has significant impact on the FSW process effectiveness. The tool composed of two primary parts: the pin and the shoulder, which may either be a single integrated piece or separate components made from different materials. Both the pin and shoulder are essential in tool design and selection. Tools with varying geometries serve multiple functions during welding, including generating heat through friction, facilitating material mixing, cutting along the joint line, disrupting surface oxides, applying forging pressure, and aiding in material flow to form a sound joint [13]. Elangovan and Balasubramanian studied the influence of distinct pin profiles of tool namely triangular, toothed cylindrical, straight cylindrical, square, and conical cylindrical (as shown in Fig. 2, Reproduced from Ref. [14] with permission from Elsevier) on the microstructure, tensile strength, and microhardness of AA2219 alloy butt welds. Among the five pin designs, the square-profiled pin consistently produced a defect-free friction stir processed (FSP) region across all welding speeds, indicating its superior performance in achieving high-quality welds [14].

Padmanaban et al. [15] this study focused on selecting appropriate tool pin profiles, shoulder diameters for friction stir welding (FSW) of AZ31B alloy of magnesium. Five different tool pin geometries: straight cylindrical, triangular, threaded cylindrical, square, and tapered cylindrical were evaluated in combination with shoulder diameters of 15 mm, 18 mm, and 21 mm. AZ31B magnesium alloy plates, 6 mm thick and measuring 220 × 75 mm, were prepared with a square butt joint configuration for welding. Mechanical testing, including tensile strength using a universal testing machine and Vickers microhardness testing, was performed. The effect of different geometrical profiles of the tool pin on joint properties is given in Table 1., (Reproduced from Ref. [15] with permission from Elsevier) below. It was observed that the threaded cylindrical pin profile delivered the best performance, achieving maximum tensile strength and a hardness of 76 HV in the nugget zone. Through optical microscopy, it was observed that this joint was defect-free and featured refined grains averaging 6.3 µm. The combined use of a threaded pin profile and 18 mm shoulder diameter produced the most favorable tensile properties among the configurations tested.

2.1.2 Tool Rotation and Traverse Speeds

Friction stir welding mainly has two key tool movement parameters that are critical: tool rotation speed and its traverse speed along the joint line. Along with plunge force and tilt angle, these constitute the primary welding parameters. During welding, the rotating tool stirs and transports the softened material from pin's front side to the rear side, promoting bonding. Accomplishing

Table 1 Effect of different geometrical profiles of the tool pin on joint properties [15]

Tool pin profile	UTS (MPa)	YS (MPa)	Hardness (Hv)	Joint efficiency (%)
Straight Cylindrical (SC)	128	102	72	59.3
Tapered Cylindrical (TC)	105	84	71	48.8
Threaded Cylindrical (TH)	208	166	76	96.7
Square (SQ)	149	119	73	69.1
Triangular (TRI)	173	138	74	80.5

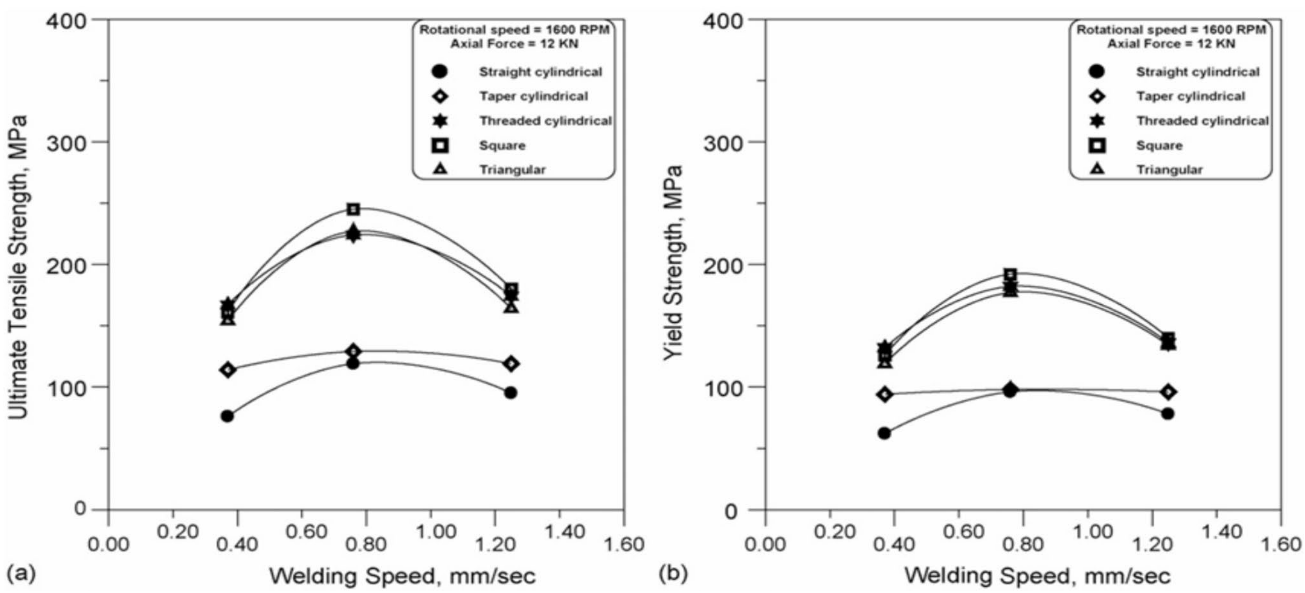


Fig. 3 Effect of welding speed on **a** UTS **b** Yield strength [14]

high-quality weld depends on selection of suitable rotation and traverse speeds, as well as ensuring firm contact of the shoulder with the workpiece to generate sufficient frictional heat. Heat input, a key factor that directly affects the quality and characteristics of the weld, is significantly governed by these welding parameters—particularly the rotation and welding speeds.

Elangovan and Balasubramanian [14] explored impact of different tool pin profiles and welding speed on the FSW joint of AA2219 aluminum alloy. Five different pin geometries: straight cylindrical, triangular, threaded cylindrical, square, and tapered cylindrical, were tested across three welding speeds. FSW joints were fabricated using 6 mm thick AA2219 alloy plates in a square butt configuration. Microstructural analysis using optical microscopy revealed that the pin profile square shape produced defect-free and mechanically sound welds compared to other profiles. The influence of welding speed on different properties is shown in Fig. 3 (Reproduced from Ref. [14] with permission from Elsevier). Tensile testing results indicated that the joint made with the square pin profile demonstrated the highest tensile strength, achieving a joint efficiency of 61%. The joint fabricated with 0.76 mm/s welding speed showed superior tensile properties compared to others as 0.37 mm/s and 1.25 mm/s, respectively.

Mohammadi et al. [16] focused on lap joint FSW of dissimilar AZ31B magnesium and aluminum alloy Al 6061 sheets, examining how welding parameters specifically tool pin geometry, rotational speed, and travel speed affect the weld's microstructure and mechanical properties. Two types of tool geometries were used: a tapered threaded pin and a tapered pin. The rotational speeds ranged from 560 to 1400 rpm, while travel speeds varied from 16 to 40 mm/min. It was observed that FSW lap joints between magnesium and aluminum displayed enhanced tensile strength and ductility, particularly when tool rotation speeds were higher. Enhanced intermixing in the upper portion of the stir zone was noticed with increasing rotational speed. Formation of intermetallic compounds, specifically $Al_{12}Mg_{17}$ and Al_3Mg_2, was confirmed in the stir zone, contributing to increased microhardness values. Furthermore, higher rotational and travel speeds led to finer microstructures and better material mixing. Among the two tool geometries, the tapered threaded pin produced superior mechanical properties and intermixing compared to the tapered pin, making it more effective for FSW of dissimilar Al–Mg lap joints.

2.1.3 Tool Tilt and Plunge Depth

The tool tilt angle plays a critical role in FSW by enhancing the generation of heat at the weld zone and ensuring effective downward pressure from the tool's shoulder onto the materials being joined. This tilt not only improves the contact between the tool and the workpiece, promoting better heat input, but also facilitates the forward flow of the plasticized material, contributing to a more stable and defect-free weld [17]. However, changes in the tool tilt angle lead to variations in the mechanical characteristics of welded joint. A rise in tilt angle generally enhances the stiffness of the weld, as it promotes better flow of the material and consolidation. Additionally, a higher tilt angle results in a rise in temperature within the stirring zone, which further aids in improving weld quality by softening the material more effectively and reducing defects [4]. The plunge depth refers to how deeply the lowest part of the tool shoulder penetrates below the surface of the workpiece. It is a crucial parameter for achieving high-quality welds in Friction Stir Welding (FSW). Setting the correct plunge depth is essential to apply adequate downward force and to guarantee that the tool fully engages the joint, ensuring proper material flow, sufficient heat generation, and defect-free bonding throughout the weld zone [7].

The study by Zhikang Shen et al. [11] presents the successful fabrication of Al/Mg dissimilar welds employing Friction Stir Spot Welding with a specially designed grooved sleeve tool. Materials utilized were 0.9 mm thick Al 7075-T6 and 1.5 mm thick magnesium alloy ZEK100-O. A systematic investigation was conducted to assess the effects of tool rotational speed (1000, 1500, and 1800 rpm) and sleeve penetration depths (0.6, 0.9, and 1.2 mm) on weld formation and mechanical performance. The tool is made up of H13 tool steel. It was found from results that the lap shear strength of the welds decreased as the rotational speed increased. A maximum joint strength of 3.6 kN was attained under optimal conditions. Successful welds were only obtained when the tool sleeve penetration depth was approximately 90% sheet thickness of the aluminum. Penetration depths above or below this value resulted either weak bonding or nugget pull-out, highlighting the critical role of precise penetration control in achieving sound Al/Mg dissimilar welds through FSW.

3 Methods and Materials

3.1 Preheating and its Effect on Properties

3.1.1 Purpose and Methods of Preheating

In Friction Stir Welding (FSW), preheating plays an important role in improving the quality of the weld, specifically when dealing with hard or dissimilar materials. By decreasing the thermal gradient between tool and workpiece, preheating helps soften the material in advance, making it more malleable and easier to deform plastically during the welding process.

Common methods include:

- Electrical resistance heating
- Induction heating
- Infrared or laser-based heating
- Flame heating

Choosing an appropriate preheating technique in FSW is affected by factors like properties of the material, the precision of temperature control needed, and how well the method integrates with current equipment. Preheating adds extra heat to material prior to welding, which raises the temperature at the beginning of the welding process in the weld area and alters the thermal profile. Several studies have indicated that controlled preheating can improve weld quality by enabling better material flow and producing stronger, more ductile, and defect-free joints.

Xun Liu et al. [18] developed an electrically assisted FSW technique to join dissimilar materials Al 6061 aluminum alloy and TRIP 780, an advanced high-strength steel. This case study concentrated on evaluating the electro-plastic effect, a case where high-density electrical current produces material softening during plastic deformation, thereby improving the welding process. It is found that electro-plastic effect can help to reduce axial welding force as compared to conventional FSW. Resistance heating causes a modest temperature rise when combined with greater tool rotational speeds and offset. However, offset of the tool alone has minimal influence on temperature rise. In contrast, higher rotational speeds respond more noticeably to electrical current, resulting in a greater temperature increase. EAFSW significantly raises temperature after plunge stage more than variations in rotational speed. The electro-plastic effect is more pronounced under conditions of lower rotational speed and reduced tool offset.

Table 2 Data properties of three flat sides pin profile at different preheat temperatures [19]

FSW Process	Tensile Strength (Mpa)	Hardness value (Hv)
Without preheating	196.31	66.91
With preheating		
150 °C	208.90	64.42
200 °C	210.13	65.54
250 °C	211.22	67.52
300 °C	210.76	60.45

Investigation by Nurul Muhayat et al. [19] addressed the effect of various pin profiles and preheating temperatures on structure of grain and mechanical characteristics of FSW welds in AA5052-H32 aluminum alloy. Three pin geometries cylindrical, two-flat-sided, and three-flat-sided—were evaluated under two preheating temperature ranges (150–300 °C). Among tested designs, the three-flat-sided pin profile showed superior mechanical performance, including higher hardness, tensile strength, and bending strength, relative to others. This geometry promoted better flow of material and stirring, resulting in improved weld quality. Notably, it achieved a tensile strength of 196 MPa, reflecting a 12.2% increase in tensile strength and an 11.2% improvement in hardness. Preheating up to 250 °C enhanced joint quality by enhancing surface finish and minimizing weld defects. However, temperatures above 250 °C led to degraded performance due to grain coarsening from slower cooling. Table 2 presents the property data for the three-flat-sided pin profile at different preheating temperatures, confirming that 250 °C offers the optimal welding condition.

Yaduwanshi et al. [20] reported the effects of plasma arc preheating—referred to as hybrid FSW or P-FSW—on the thermal and mechanical characteristics, and grain structure of aluminum alloy AA1100 welds, in comparison with conventional FSW. The experimental setup included a vertical milling machine equipped with a micro-plasma arc welding unit. Butt welding was carried out on commercial-grade aluminum alloy specimens measuring 200 mm × 100 mm × 6 mm. A flat cylindrical tool was employed, featuring a shoulder diameter of 20 mm, pin diameter of 6 mm, and pin height of 5.75 mm. The study compared both conventional FSW and P-FSW processes under varying conditions: tool rotational speeds of 600–815 rpm, welding speeds of 63–98 mm/min, and preheat currents between 25 and 35A. Preheating in FSW leads to increased heat input, with the advancing side consistently exhibiting a higher temperature than the retreating side. Preheating via plasma arc increases the total heat input, as indicated by the larger area under the temperature–time curve. This additional heat raises the surrounding material temperature, reduces mechanical strength locally, and facilitates easier material flow during welding. In plasma-assisted FSW (P-FSW), the peak weld temperature reaches approximately 425 K, which is higher than that observed in conventional FSW. The results indicate that P-FSW achieves greater tensile strength—134 MPa compared to 122 MPa in standard FSW. The joint efficiency for P-FSW reaches 95.9%, showing improved results over the conventional process. The additional heat generated by preheating contributes to a notable reduction in plunging force, ranging from 22 to 28% within the tested process parameters.

HanSur Bang et al. [21] assessed the potential of employing a gas tungsten arc welding (GTAW)-assisted hybrid Friction Stir Welding (HFSW) technique to join stainless steel (STS304) with aluminum alloy (Al6061) to enhance weld strength. A GTAW torch was positioned ahead of the tool, which featured a shoulder diameter of 18 mm, a probe diameter of 6 mm, and a pin length of 2.7 mm for the welding operation. Mechanical characteristics of joints were assessed using Vickers hardness testing with tensile testing. The HFSW process achieved a transverse tensile strength approximately 93% of the base metal strength of Al6061 aluminum alloy (290 MPa), representing a 15% improvement over conventional FSW, which reached only 78% (244 MPa) compared to the base metal strength. This improvement can be attributed to enhanced material plastic flow and the partial annealing effect in the dissimilar materials caused by preheating the stainless steel surface with GTAW, which leads to a notable increase in weld elongation. There is increased hardness in stainless steel zones due to work hardening. GTAW-assisted HFSW is more effective than traditional FSW for joining aluminum to stainless steel. It enhances material flow, reduces tool wear, and significantly improves mechanical performance.

Wenming Liu et al. [22] Presented Friction Stir Welding of ME20M magnesium alloy, which was performed both with and without preheating at various temperatures. ME20M Mg alloy specimens with the dimensions of 5 mm × 160 mm × 65 mm were welded. ME20M magnesium alloys were Friction Stir Welded under five different conditions: without preheating, and with preheating at 50 °C, 100 °C, 150 °C, and 200 °C, respectively. Tensile strength increases with preheating up to 150 °C, reaching a peak of 169.6 MPa, compared to 145.1 MPa with no preheating. Beyond 150 °C, at 200 °C, tensile strength decreases to 151.3 MPa, indicating excessive preheating reduces joint performance. As per the hardness profiles seen across the weld area, preheating improves the overall hardness, specifically in the stir zone (center). Higher preheating temperatures significantly elevate baseline and peak weld zone temperatures, which may enhance plastic flow and reduce plunging force. The thermal history of welds under various preheating temperatures shows that advancing side (AS) temperatures are consistently higher than retreating side (RS). However, this temperature gap narrows with increasing distance from the weld center, primarily due to the fast heat-dissipating nature of magnesium alloys. Dynamic recrystallization occurred in the weld nugget zone (WNZ), producing finer grains than in the base metal (BM). At higher preheating (≥ 150 °C), coarser grains and increased flash defects were observed.

Shen et al. [23] examined how various lap joint configurations and the application of preheating affect the grain structure and mechanical performance of friction stir spot welds, involving materials of both similar and different composition, specifically 6061-T6 aluminum alloy and AZ31B magnesium alloy. AZ31B magnesium alloy and 6061-T6 aluminum alloy plates, each 2 mm thick and machined to dimensions of 1006 × 23 mm, were welded using four different lap joint configurations: Mg/Mg, Al/Al, Mg/Al (with magnesium as the upper sheet), and Al/Mg (with aluminum as the upper sheet). The welding samples were heated to 473 K by resistance heating rods before welding. The tool machined from a stainless steel had a flat shoulder and a smooth cylindrical pin. The similar material joints, Mg/Mg and Al/Al, resulted in defect-free welds and demonstrated the highest tensile-shear strengths among all configurations. The dissimilar joints (Mg/Al and Al/Mg) consistently formed intermetallic compound (IMC) layers, predominantly $Mg_{17}Al_{12}$, with the thickest IMC layer observed in the Al/Mg configuration. Mg/Al configuration (with magnesium on top) produced a nugget containing a partially mixed region contributed to a tensile strength higher compared to the Al/Mg configuration. The similar Mg/Mg joints exhibited tensile strength higher than Al/Al joints, and the preheating further improved the strength in both configurations. While preheating enhanced tensile strength of both similar joints and the Mg/Al dissimilar joint, it had an adverse effect on the Al/Mg configuration due to excessive formation of brittle intermetallic compounds. Among all the dissimilar welds, the Mg/Al configuration with preheating provided the best balance of mechanical strength and microstructural integrity, making it the most favorable option for dissimilar friction stir spot welding.

3.2 Cooling and its Effect on Properties

Cooling techniques are employed to regulate the post-weld cooling rate, which significantly influences residual stresses and weld grain structure. Rate of cooling following Friction Stir Welding has a significant impact in determining the characteristics of both the weld zone and the zone affected by heat (HAZ). Rapid cooling methods, such as water quenching or cryogenic cooling during or after welding, tend to refine grain structures, increase hardness, and frequently result in stronger weld joints. Common methods include:

- Natural air cooling
- Forced air cooling
- Water-assisted cooling (e.g., water spray or submerged FSW)
- Cryogenic cooling (e.g., using liquid nitrogen)

Kush P. Mehta et al. [24] investigated the joining of dissimilar materials by performing both conventional and cooling-assisted FSW on 6 mm thickness AA6061 aluminum alloy and AZ31B magnesium alloy. For joining, a butt joint configuration was considered. In both welding processes, an H13 tool was used, featuring a shoulder diameter of 20 mm, a pin diameter of 7 mm, and a left-threaded cylindrical pin profile with a 1 mm pitch. The FSW process was performed with 2 mm tool pin offset toward the magnesium side, placing the aluminum alloy on the advancing side and the magnesium alloy on the retreating side (RS). The welding parameters included a rotational speed of 1070 RPM, a travel speed of 70 mm/min, and a tilt angle of 3°. C-FSW was conducted with additional water cooling facility. The impact of microstructure modification of local mechanical properties was investigated by Vickers microhardness tests. The tensile test was carried out as per the ASTM E8 standards on mini specimens of 6 mm thickness. The tensile strength of 182 MPa is reported for C-FSW joint while 128 MPa is reported for FSW joint. The C-FSW presents a higher joint efficiency of approximately 73%, than the conventional FSW.

In the study by Harshadkumar H. Jadav et al. [25], friction Stir Welding was performed on 6061-T6 aluminum alloy and AZ31B magnesium alloy using a rotational speed of tool 545 rpm, a feed rate of 31.5 mm/min, 2° tilt angle and 2 mm offset toward the magnesium alloy on the advancing side. The experiments were conducted under varying tool pin diameters and cooling conditions. Heat-treated H13 steel tools were used for welding, featuring an 18 mm shoulder diameter and a cylindrical pin length of 2.8 mm, with pin diameters of 5 mm, 6 mm, and 7 mm. To regulate heat input during welding, compressed air and CO_2 were employed as cooling methods. The highest weld quality was achieved using a 5 mm pin diameter, while larger pin sizes led to defects such as grooves and incomplete fusion. CO_2-cooled samples displayed smoother and cleaner surfaces, attributed to more effective heat dissipation. In terms of tensile strength, the CO_2-cooled joints reached 108.94 MPa, followed by air-cooled at 102.78 MPa, and 98.61 MPa for joints without cooling. The peak microhardness near advancing side (AS) of stir zone was 111.3 HV for the air-cooled sample and 103.1 HV for the CO_2-cooled sample. Microhardness slightly decreased with cooling, indicating reduced intermetallic compound (IMC) formation.

A study by Shubham Verma et al. [26] investigated the heat treatment effects and cooling on Friction Stir welded material AA6082 joints. Joints were formed under varying conditions, including heat treatment (FSW-P) and water cooling (FSW-C). For heat treatment, the electro-thermal-filament-based system of heating with temperature controller was developed. A vertical milling machine was adapted for the experiments by designing a custom fixture, enabling the fabrication of joints under controlled conditions. All welded joints were produced using a uniform tool rotational speed 2000 rpm, 60 mm/min feed rate, 2° tilt angle and varying thermal conditions including heat treatment and water cooling. Experiments included three main setups: welding in atmospheric air (FSW-A), preheated plate welding (FSW-P), and water-cooled welding (FSW-C). Preheating was applied at three different plate temperatures—100 °C (FSW-P1), 125 °C (FSW-P2), and 150 °C (FSW-P3)—while water cooling was implemented using water at 2 °C (FSW-C1), 22 °C (FSW-C2), and 65 °C (FSW-C3). Joints produced with preheating at 100 °C and 125 °C exhibited tensile strengths 295 MPa and 276 MPa, respectively—representing increases of 13.5% and 6% compared to the strength of joint achieved under atmospheric conditions. According to thermal analysis heat treatment results in a higher initial temperature compared to other welding conditions. In contrast, during water-cooled welding, the temperature drops sharply after the processing phase. Finer grains were observed under heat treatment and cooling with water due to dynamic recrystallization.

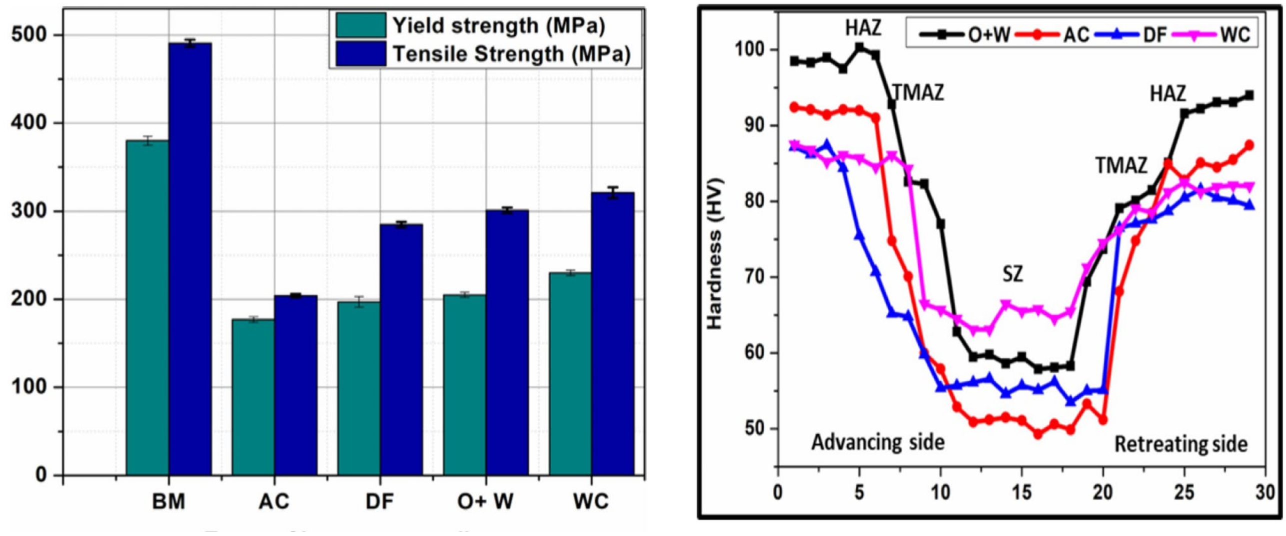
A study by Wang et al. [27] aims to examine how tool rotational speed and water cooling influence the mechanical and microstructural properties of FSW joints made from work-hardened 5083Al-H19 aluminum alloy. Defect-free FSW joints of 5083Al-H19 aluminum alloy were successfully produced at both 800 rpm and 200 rpm tool rotation speeds, with and without the application of additional water cooling. The microstructural analysis revealed that all FSW joints, including those with water cooling, developed uniformly shaped grains in the nugget zone (NZ) through dynamic recrystallization. As input of heat decreased either by lowering rotation speed of tool or applying water cooling size of grain in the NZ progressively reduced. At 800 rpm, water cooling slightly refined the grain structure (from 3.6 to 2.7 µm), this confirms that reduced heat input enhances grain refinement during FSW. The BM exhibited elevated UTS of 425 MPa, and joint efficiency was only 74% for the normal FSW joint (A-800).

The study by Liu et al. [28] demonstrated the evolution of microstructure during Friction Stir Welding (FSW) aluminum alloy of 1050 using a rapid cooling system based on liquid CO_2, especially emphasis on distinguishing the individual impacts of deformation and cooling phases. Cold-rolled Al 1050-H24 sheets with dimensions of 200L × 60W × 3 T mm were butt-welded by C-FSW (Conventional) and RCFSW (rapid cooling). A tool made up of tungsten carbide featuring a shoulder with a concave shape and a smooth cylindrical probe measuring 2.8 mm in length was employed. The shoulder and probe had diameters of 12 mm and 4 mm, respectively. Welding was conducted with 3° tool tilt, a travel speed of 200 mm/min, and 800 rpm speed of rotation. The tensile strength achieved through rapidly cooled Friction Stir Welding (RCFSW) was approximately 110 MPa, which is close to the strength of the base metal, whereas conventional FSW (C-FSW) resulted in around 94 MPa tensile strength. The use of liquid CO_2 for rapid cooling improved microstructural control by limiting grain growth and suppressing texture development. As a result, RCFSW exhibited higher toughness, attributed to its finer grain structure and lower texture intensity.

Ghulam Hussain et al. [29] proposed different methods of cooling FSW AA 2219-T-6 alloy joints and their influence on mechanical and microstructural characteristics. The cooling methods used were air cooling (AC), dry fan cooling (DF), oil + water cooling (OW) and only water cooling (WC). AA 2219-T-6 plates of 120 * 60 mm with 5 mm thickness were used for experimentation. The 14 mm shoulder diameter tool with square pin shape was used with travels speed 25 mm per minute and rotation of 1750 rpm. Tensile and Vickers hardness tests were carried out to find out the microhardness and tensile strength of joints. Figure 4a shows the results of Ultimate tensile strength (UTS) and yield strength with different cooling methods. Results of Ultimate tensile strength (UTS) revealed that all FSW joints have lower values than Base metal (BM) strengths. However, the water-cooled joint achieved the highest Ultimate tensile strength (UTS) and yield strength as shown in Table 3 below. Also, the water-cooled joint shows the highest efficiency, i.e., 65.4%, due to fine-grain microstructure and uniform precipitate distribution. Microhardness measurement showed W-shaped hardness profile with the stir zone (SZ) and the thermos mechanically (TMAZ) affected zone displayed reduced hardness values due to plastic deformation. Water-cooled joint showed the highest hardness 66.07 HV due to rapid cooling as illustrated in Fig. 4b. Also, the hardness value was also higher on advancing side (AS) than on retreating side (RS).

4 Conclusion

Friction Stir Welding is a solid-state joining technique with significant potential for welding a different materials range in various configurations. Extensive research has been conducted on FSW for both similar and dissimilar metals. Due to advantages in producing high-quality, defect-free welds, the FSW technique has been implemented successfully in industries such as aerospace, automotive, and others. Friction Stir Welding has been applied across a broad spectrum of materials, including aluminum, magnesium,



(a) (b)

Fig. 4 **a** Influence of cooling on Tensile and Yield strength **b** Hardness profiles of FSW-cooled samples [Hussain, Shehbaz, and Alkahtani [29] under license: CC BY-NC-ND 4.0]

Table 3 Effect of cooling methods on joint properties. [Hussain, Shehbaz, and Alkahtani [29] under license: CC BY-NC-ND 4.0]

Joint variants (Cooling methods)	UTS (MPa)	YS (MPa)	Avg. hardness (Hv)	Joint efficiency (%)
Base metal (BM)	490.6	380	–	–
Air cooled (AC)	204	177.1	52.5	41.6
Dry fan cooled (DF)	284.8	197.6	55.7	58.1
Oil + Water cooled (OW)	301	205	61.3	61.4
Water cooled (WC)	321	230.3	66.07	65.4

titanium, and steel, also for dissimilar combinations such as aluminum–magnesium, magnesium–copper, and copper–aluminum. To enhance the quality and sustainability of dissimilar joints, particularly for aluminum and magnesium alloys, numerous studies over recent decades have explored utilization of various assisting techniques. Significant advancement has been the introduction of auxiliary energy assistance (external heating), aimed at reducing excessive tool load requirements during the welding process for harder materials. The employment of additional softening either during or prior to FSW enhances tool performance and longevity, leading to improved joint quality in aluminum and magnesium alloys. Preheating and post-weld air or water cooling have shown to significantly boost the mechanical properties of dissimilar Al–Mg joints, particularly tensile strength, and hardness. Key input parameters influencing FSW include plunge depth, pin profile, rotational speed, welding speed, while typical output parameters are tensile strength, yield strength, and hardness. Recent development in artificial intelligence technology has further enabled more precise selection and forecast of these parameters, contributing to better control and optimization of the process of FSW.

5 Research Gap/Future Scope

- While Friction Stir Welding (FSW) offers distinct advantages over traditional welding techniques, existing research still falls short in comprehensively addressing key challenges such as compatibility of dissimilar material combinations, thermal management, precise process control, and the long-term durability and performance of welded joints.
- Most experimental investigations have predominantly concentrated on specific combinations of similar alloys, leaving limited exploration into the welding of dissimilar metals such as aluminum–magnesium (Al–Mg) alloys using the FSW technique.

- Although preheating has shown potential in improving joint quality in FSW, its influence on fatigue behavior and corrosion resistance of dissimilar joints remains insufficiently studied. Moreover, there are insufficient investigations on the combined effects of preheating and cooling strategies in aluminum–magnesium alloy joints. Comparative studies involving different cooling media such as water, air, mist, and cryogenic cooling under identical FSW conditions are also notably scarce.
- Most of the existing literature has concentrated on tensile and hardness testing, while critical aspects such as fatigue behavior, fracture toughness, corrosion resistance, and thermal cycling performance remain largely underexplored.
- Several AI and computational techniques hold great prospective for advancing the investigation of FSW; however, many existing studies remain predominantly experimental and fail to incorporate optimization techniques like Response Surface Methodology (RSM), Taguchi methods or Artificial Neural Networks (ANN) for systematically identifying optimal preheating conditions and predicting mechanical properties. Additionally, thermal simulations such as infrared imaging or thermal modeling are underutilized for quantifying temperature gradients and level of the heat-affected zone (HAZ). There is also a notable absence of finite element analysis (FEA) and data-driven models capable of accurately predicting weld performance based on input parameters.

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Declarations

Conflict of interest The authors report there are no competing interests to declare.

References

1. Sun Y, Gong W, Feng J, Guipeng L, Zhu R, and Li Y, *Metals* **12** (2022) 675.
2. Hua W, Maa Z, Ji S, Songa Q, Chenb M, and Jiang W, *J Mater Sci Technol* **53** (2020) 41.
3. Khalafe W H, Sheng E L, Bin Isa M R, Omran A B, and Bin Shamsudin S, *Metals* **12** (2022) 2099.
4. Kah P, Rajan R, Martikainen J, and Suoranta R, *Int J Mech Mater Eng* **10** (2015) 26.
5. Singh B R, *A Hand Book on Friction Stir Welding*, LAP Lambert Academic Publishing (2012).
6. Isa M S M, Moghadasi K, Ariffin M A, Raja S, bin Muhamad M R, Yusof F, Jamaludin M F, bin Yusoff N, and Binabkarim M S, *J Mater Res Technol* **15** (2021) 2735.
7. Kilic S, and Ozturk F, *J Eng Res* **13** (2025) 122.
8. Pratap Kumar J, Anil Raj K, Arul V, and Mohanavel A, *Mater Today Proc* **47** (2021) 286.
9. Kumar M, Das A, and Ballav R, *Mater Today Proc* **1** (2020) 2123.
10. Gite R A, Loharkar P K, and Shimpi R, *Mater Today Proc* **19** (2019) 361.
11. Shen Z, Liu X, Li D, Ding Y, Hou W, Chen H, li W, and Gerlich W, *Crystals* **11** (2021) 429.
12. Mishra R S, and Ma Z Y, *Mater Sci Eng R* **50** (2005) 1.
13. Kaygusuz E, Karaömerlioğlu F, and Akıncı S, *J Eng* **7** (2023) 286.
14. Elangovana K, and Balasubramanian V, *J Mater Process Technol* **200** (2008) 163.
15. Padmanaban G, and Balasubramanian V, *Mater Des* **30** (2009) 2647.
16. Mohammadi J, Behnamian Y, Mostafaei A, and Gerlich A P, *Mater Des* **75** (2015) 95.
17. Yan J, Zhiwu X, Li Z, Li L, and Yang S, *Scripta Mater* **53** (2005) 585.
18. Liu X, Lan S, and Ni J, *J Mater Process Technol* **219** (2015) 112.
19. Muhayat N, Harjono M S, Depari Y P, Prabowo A R, Triyono T, Putri E D, and Tuswani T, *Metals* **12** (2022) 4.
20. Yaduwanshi D K, Bag S, and Pal S, *J Mater Eng Perform* **23** (2014) 3794.
21. Bang H, Bang H, Jeon G, Oh I, and Ro C, *Tungsten Arc Weld* **37** (2012) 48.
22. Liu W, Yan Y, Ni R, Sun Tao, Wu S, and Shen Y, *Sci Technol Weld Join* **26** (2021) 136.
23. Shen J, Li Y, Zhang T, Peng D, Wang D, and Xu N, *Sci Technol Weld Join* **20** (2015) 15.
24. Mehta K P, Carlone P, Astarita A, Scherillo F, Rubino F, and Vora P, *Mater Sci Eng A* **759** (2019) 252.
25. Jadav H H, Badheka V, Sharma D K, and Upadhyay G, *Mater Today Proc* **42** (2021) 362–9.
26. Verma S, Gupta M, and Misra J P, *J Mater Eng Perform* **28** (2019) 4209.
27. Wang B B, Chen F F, Liu F, Wang W G, Xue P, and Ma Z Y, *Mater. Sci Techn.* **33** (2017) 9.
28. Liu X C, Sun Y F, and Fujii H, *Mater De.* **129** (2017) 151.
29. Hussain G, Shehbaz T, and Alkahtani M, *Sci Rep* **14** (2024) 29251.