Review of recent trends in friction stir welding process of aluminum alloys and aluminum metal matrix composites

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Abstract: Welding is a vital component of several industries such as automotive, aerospace, robotics, and construction. Without welding, these industries utilize aluminum alloys for the manufacturing of many components or systems. However, fusion welding of aluminum alloys is challenging due to several factors, including the presence of non-heat-treatable alloys, porosity, solidification, and liquation of cracks. Many manufacturers adopt conventional in-air friction stir welding (FSW) to weld metallic alloys and dissimilar materials. Many researchers reported the drawbacks of this traditional in-air FSW technique in welding metallic and polymeric materials in general and aluminum alloys and aluminum matrix composites in specific. A number of FSW techniques were developed recently, such as underwater friction stir welding (UFSW), vibrational friction-stir welding (VFSW), and others, for welding of aluminum alloy joints to overcome the issues of welding using conventional FSW. Therefore, the main objective of this review is to summarize the recent trends in FSW process of aluminum alloys and aluminum metal matrix composites (Al MMCs). Also, it discusses the effect of welding parameters of the traditional and state-of-the-art developed FSW techniques on the welding quality and strength of aluminum alloys and Al MMCs. Comparison among the techniques and advantages and limitations of each are considered. The review suggests that VFSW is a viable option for welding aluminum joints due to its energy efficiency, economic cost, and versatile modifications that can be employed based on the application. This review also illustrated that significantly less attention has been paid to FSW of Al-MMCs and considerable attention is demanded to produce qualified joint.

Key words: aluminum alloys; aluminum matrix composites; traditional FSW techniques; state-of-the-art FSW techniques; microstructure; mechanical properties

1 Introduction

There is an increasing demand for reducing the weight of components in the automobile and aerospace industries to enhance fuel efficiency. Therefore, there is a need for alternatives of lightweight metals and composites such as aluminum and magnesium alloys. Recently, the need for research in Al metal matrix composites (MMCs) has increased significantly owing to their high specific strength, low cost, and high wear

resistance. In 2012, global revenue for the MMC market was USD$ 228.7 million and expanded to USD$ 357.3 million in 2019. GUPTA and SATYANARAYANA [1] reported the utilization of more than 5.5×10^6 kg of MMCs in 2006 and predicted steep growth in the annual development rate of approximately 8%. Collectively, Al MMCs and Ni MMCs form the highest share in the global MMC market. This is due to the superior properties of the materials, involving thermal expansion, thermal diffusivity, and compressive strength, as well as tribological behavior.

Though Al MMCs have received significant attention in the industry due to their lightweight and high strength, they exhibit drawbacks with respect to welding [2]. Several researchers understood that the friction stir welding (FSW) process can significantly reduce the width of the heat-affected zone (HAZ) and the degree of thermal softening experienced in the weld region [3,4]. Several industries in automotive sector including rail transit, use FSW for joining its structures. Joining techniques commonly used to construct rail vehicles are metal inert gas welding (MIG), resistance spot welding, bolting and riveting [5]. Several rolling stock manufacturers adopted FSW as an alternative technique for rail carriage structures. The process is energy-efficient and environmentally friendly because it requires no filler wire or shielding gas and creates no fumes or ultraviolet rays [4]. A further benefit is that the heat input during the FSW process is relatively low compared to MIG welding, therefore reducing the overall level of component distortion [6].

The challenges of joining aluminum alloys include forming undesirable intermediate phases, voids, and porosity in the weld zone. Additionally, due to the differences in the coefficients of heat expansion of fillers and metal matrix, thermal and residual stresses are developed. While several researchers have focused on using brazing as a method for welding Al MMCs, it has not been using due to high filler costs and low welding accuracy [7]. FSW is considered as an enhanced alternative method for producing aluminum joints in a quick and reliable manner [8]. In the last decade, several researchers have reported various aspects of FSW and its impact on material strength [2,9−12].

Traditional welding methods result in matrix− reinforcement interactions at high temperatures,

leading to a secondary brittle material phase [2]. However, FSW and friction stir spot welding (FSSW) enhance the mechanical strength of MMC joints due to a reduction in weld zone defects such as porosity, distortion effect, cracking, and reinforcement resolution [13−15]. Some works were done to improve the quality of friction stir welded joints. Many researchers have investigated the feasibility of using submerged friction-stir welding (SFSW) for welding aluminum alloys. Welding while submerging the base material in water induces a significant cooling effect by accelerating the heat dissipation rate. This mechanism controls the residual stresses and intermetallic phases generated.

Although SFSW has led to improvements in the strength and quality of the weld, some studies have reported void formation due to material flow. A few investigators have focused on recycled Al MMCs [16−18]. In this work, recent developments in FSW joining techniques for Al alloys and Al MMCs are presented. The feasibility of different types of FSW such as traditional in-air FAW, submerged friction-stir welding (SFSW), underwater friction-stir welding (UFSW), and vibrational friction-stir welding (VFSW), is discussed. The effect of these techniques on the thermal distribution and microstructure of welded aluminum alloys is discussed. In addition, the gaps in the literature are identified and a number of recommendations for future work are made. In this review, more focus will be paid to Al MMCs.

2 Conventional friction-stir welding

The FSW was first developed in 1991 by the Welding Institute to bond aluminum alloys [9]. FSW uses a rotatory tooltip that moves in a traverse direction along the bonding path of two solids. As the tooltip rotates and moves on the metallic surface, heat is generated by friction due to the release of visco-plastic strains [19]. FSW operates below the melting point of the base material due to the action of the stir tool plunging into the workpiece. This leads to a hot-shear joint along the weld line. The frictional heat forms a plasticized zone and refines grains that enhance the mechanical strength. HAGHSHENAS et al [20] examined the impact of the solid-state welding process on the micro-structure and mechanical properties of a welded

section. FSW was used to weld Monel 400 and Inconel 600 lap joints and resulted in enhanced mechanical properties due to dynamic grain recrystallization in the stress zone. FSW is the preferred bonding mechanism for Al MMCs. It prevents the formation of theta phases and produces joints with higher strength as compared to other methodologies such as fusion welding [13]. However, the welding quality of the FSW is dependent on several factors [21]. Figure 1 illustrates an aluminum alloy joint welded using conventional friction stir welding.

FSW method for industrial-scale was firstly used in building ships of aluminum−magnesium alloys of 5xxx series in 1995 [3,23]. This method was then used in prefabrication of flat sections. This method also started to be used in other industry sectors, such as railways, car manufacturers, and aerospace. The mechanical analysis of the weld showed that the strength and plastic properties of FSW specimens are significantly higher than those of MIG and TIG welded ones [24]. Also, the UTS_{FSW}/UTS_{Native} ratio is equal to 0.94 and is higher than that for MIG (0.83) and TIG (0.81) welding methods [3]. It is shown that the FSW has near-native material properties. The research concluded that the FSW method is perfect to use in shipbuilding and railway industry to prefabricate flat sections made from aluminum alloys, e.g. decks, shell plating, bulkheads, and shell of railway carriages [25].

Honda was the first manufacturer to use FSW in the mass production of automobiles, utilizing the weld for its Accord 2013 model to join steel and aluminum [26]. In the automobile industry, the joining of dissimilar metals could result in lighter weight and higher strength, which would lead to enhanced fuel economy [27]. This joining of dissimilar metals has many benefits, including lighter weight and higher strength, which have resulted in enhanced fuel economy in the Accord model. Honda noted that the high frictional temperatures at the aluminum/steel joint resulted in the formation of an intermetallic compound (Fe_4Al_{13}). Further nondestructive inspection of the weld revealed the presence of vacancies and interstitial defects due to the intermetallic phase, adversely affecting the strength and corrosion properties of the weld. To address this issue, Honda now adds an anti-correction coat and surface treatments to eliminate the defects in bonds. Since the first introduction, many practical difficulties have been overcome in FSW, especially in welding aluminum [28−30]. Since Honda introduced FSW, researchers have sought to understand the relationship between FSW and strength better. In FSW, frictional heat forms a plasticized zone where the tool is plunged, and the microstructure analysis shows grain refinement, which enhances the mechanical strength. However, intermetallic phases are observed in the weld zone due to dynamic recrystallization, leading to detrimental effects on strength. One extant study examined the impact of the solid-state welding process on the micro-structure and mechanical properties of a welded section. JEON et al [31] used FSW to developed a graphite/aluminum MMC in the weld zone. Graphite colloidal was added on the surface of the
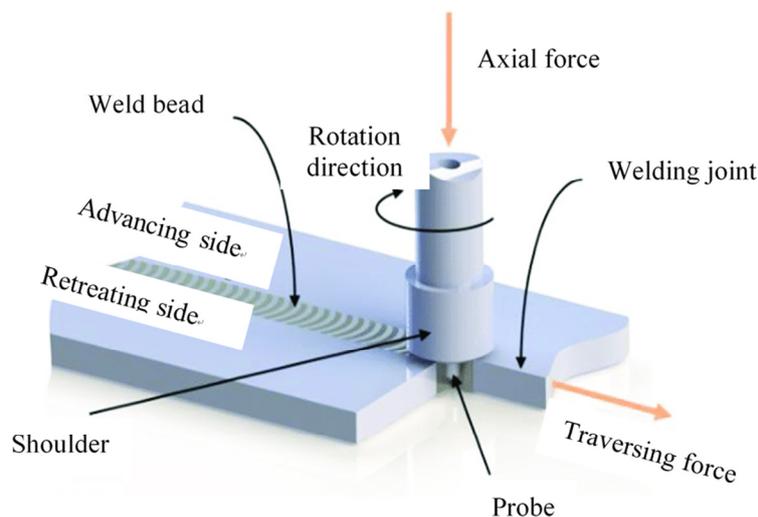

Fig. 1 Schematic of FSW process [22]

aluminum alloy matrix, and the tool action stirred the graphite into the aluminum matrix. The tests performed on the section showed an increase in the toughness of the weld zone, thereby increasing its mechanical strength. However, in this study, the tensile strength of the welded portion was not examined, and the ultimate peak stress of the weld was not determined. Several previous studies have reported the effects of the FSW pin shoulder and profile and the feasibility of the process. The studies showed that, when using tapered screw pin tools, the resultant tensile strength was as high as 75% that of the base material [28,32].

ZHANG et al [33] examined the development of stresses in SiC_p/2009Al-T4 MMC welded zone due to FSW, revealing the development of micro-scopic residual stresses (RSes) during FSW of MMCs. These stresses are generated due to differences in mechanical deformation owing to various thermal profiles [34]. Plunging the tool pin generates compressive stress in the weld zone, and shearing action combined with high temperatures and pressures induces a significant amount of stress around the weld zone. Additionally, various microstructural studies have revealed that the heat-affected zone (HAZ) is prone to form brittle intermetallic phases. These brittle phases degrade the mechanical strength of MMCs. They investigated the FSW of Al-MMC and reported that significant residual stresses are generated due to the micro- and macro-structure of the composite. The induced residual stresses adversely affect the welding quality of the composite [34]. In addition to the residual stresses, the ductility of the welding zone is affected by the grain flow patterns induced by the FSW tool traverse and rotational speed.

Furthermore, the tool pin profile, geometry and composition have a significant role in achieving a uniformly distributed microstructure across the welding joints [35]. The tool composition should be optimized to withstand high temperatures in the range of 70%−90% of the melting point of the base material [11]. The rapid changes in the microstructure of the weld zone were due to the frictional heat developed by the plunging tool in the workpiece. These changes, along with prolonged heat exposure, create intermetallic phases that decrease the strength of the weld. Thus, an effective cooling system is needed in FSW to improve weld strength.

Tool wear such as a reduction in the probe's length, inhibits material flow and increases the probability of forming defections [36]. ZHANG et al [37] indicated that the tool material is depended on the workpiece and melting point of the base material. In general, the rate of tool wear increases while welding base materials with high melting points such as steel, titanium and metal matrix composites (MMCs) [38]. Excessive tool wear will consequently alter the tool profile which affects the welding quality. Scanning electron microscope images in Fig. 2 illustrate that tool wear at low rotation rates is primarily due to adhesion (also known as seizing, galling, or scoring, galling); while high tool rotation wear can be attributed to abrasion. Excessive tool wear changes a tool's shape, consequently increasing the probability that a defect will occur and potentially degrading weld quality. The exact wear mechanism, therefore, depends on several factors, including interactions between workpieces and tool materials, the selected tool's geometry, and the parameters associated with a specific weld [39]. However, to prolong the
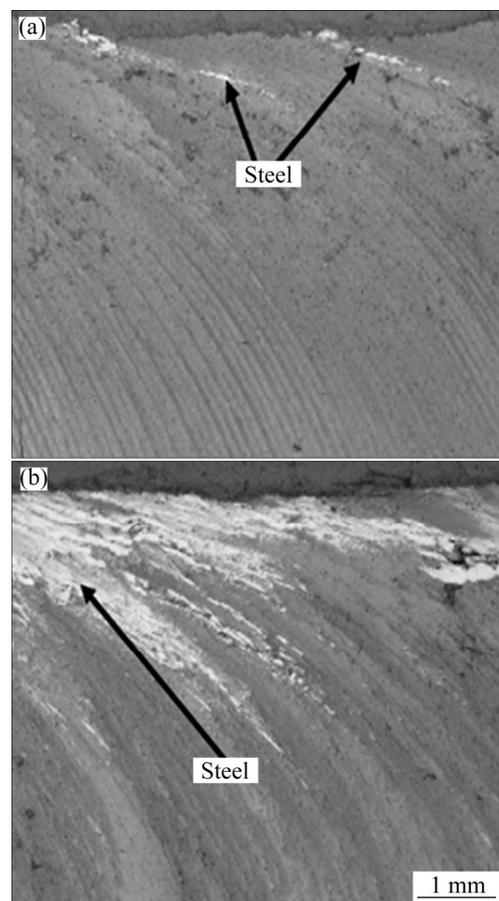

Fig. 2 Optical microscopic analysis of welded surface contaminated by tool wear [39]

lifetime of the FSW tools, surface treatment is applied by adding a coating to the base material. The coating improves surface hardness and wear resistance by reducing the coefficient of friction [20,21,36,40,41].

2.1 Traverse feed and rotational speed

Several investigations have been conducted to optimize tools' traverse and rotational speeds to prevent grain growth and generate the required heat for ensuring a proper weld. CARLONE et al [42] examined the effect of tools' rotation rates on FSW joints by comparing joint strength as obtained via a Hudson steel (H13) tool and a cubic boron nitride (CBN) tool by using tensile specimens. In general, an increase in rotational speed increases the welding temperature, which coarsens the material grains. Figure 3 shows the effect of tool rotation on the microstructure of 6082-T6 aluminum alloy [43].

The variation in the grain patterns leads to a variation in the ductile properties of the weld. PALANIVEL et al [8] illustrated that mixed-flow was absent in joints created by welding speeds at the lower and upper bounds. It is worth noting that an excessive increase in rotational speed can lead to

non-uniform grain refinement and strain localization or bulgings [44]. Figure 4 shows an increased strain-bulgings at 1600 r/min for FSW of 7075-T6 [44]. Furthermore, an increase in temperature above the optimal temperature would contribute to grain production and softening of the material and reduce the strength or toughness of the joint [7]. MEHTA and BADHEKA [45] observed that the increase of the rotational speed (above 1600 r/min) may result in an excessive increase in temperatures in Cu−Al alloys (AA6061-T651). Zones with excessive heat require a longer cooling time, which results in micro-voids that may decrease the joint strength [44].

Also, friction-stir welding feed rate impacts the generation of micro- and macroscopic residual stresses [33]. Figure 5 shows the microstructure analysis of AA5754 joints under various feed rates in FSW [46]. Therefore, it is essential to optimize the parameters of FSW for welding Al MMCs to form a defect-free stir zone in the weld regions.

KARTHIKEYAN et al [35] investigated the effect of traverse feed rate and rotational speed on the strength, ductility, and temperature of cast Al MMCs joint with a composition of $Al_{5.2}Si_{2.51}Cu$
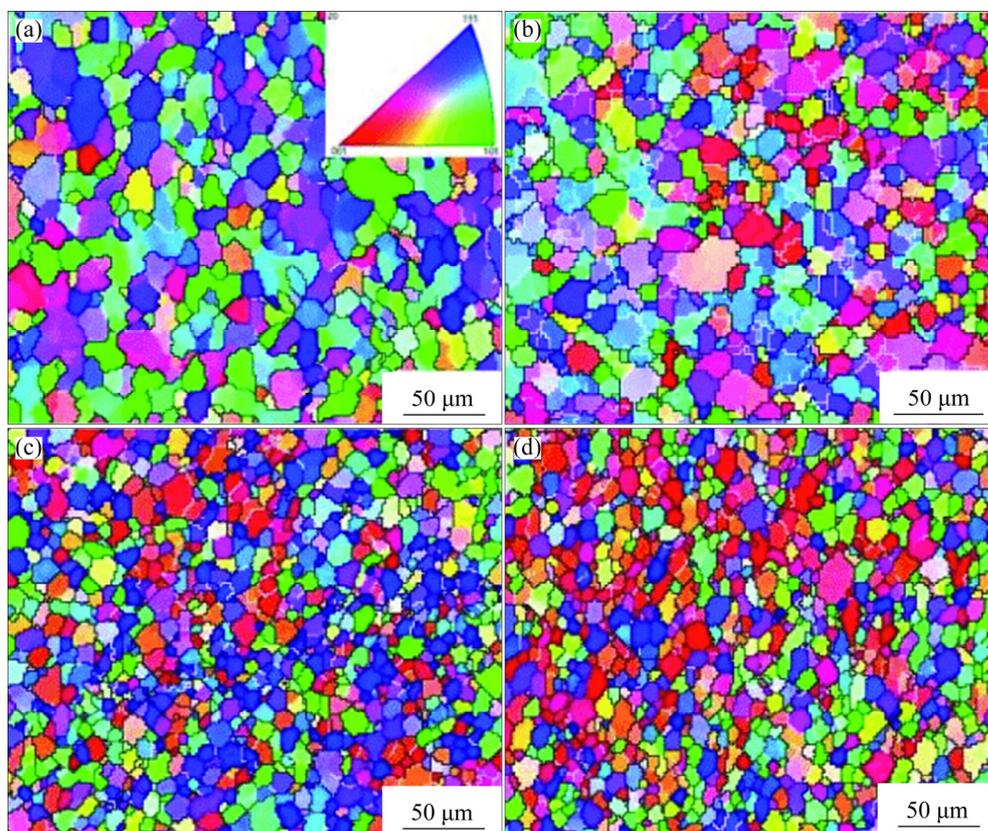

Fig. 3 Electron backscattered diffraction (EBSD) micrographs of stirring zone (SZ) at various rotational speeds: (a) 600 r/min; (b) 800 r/min; (c) 1000 r/min; (d) 1200 r/min [43]
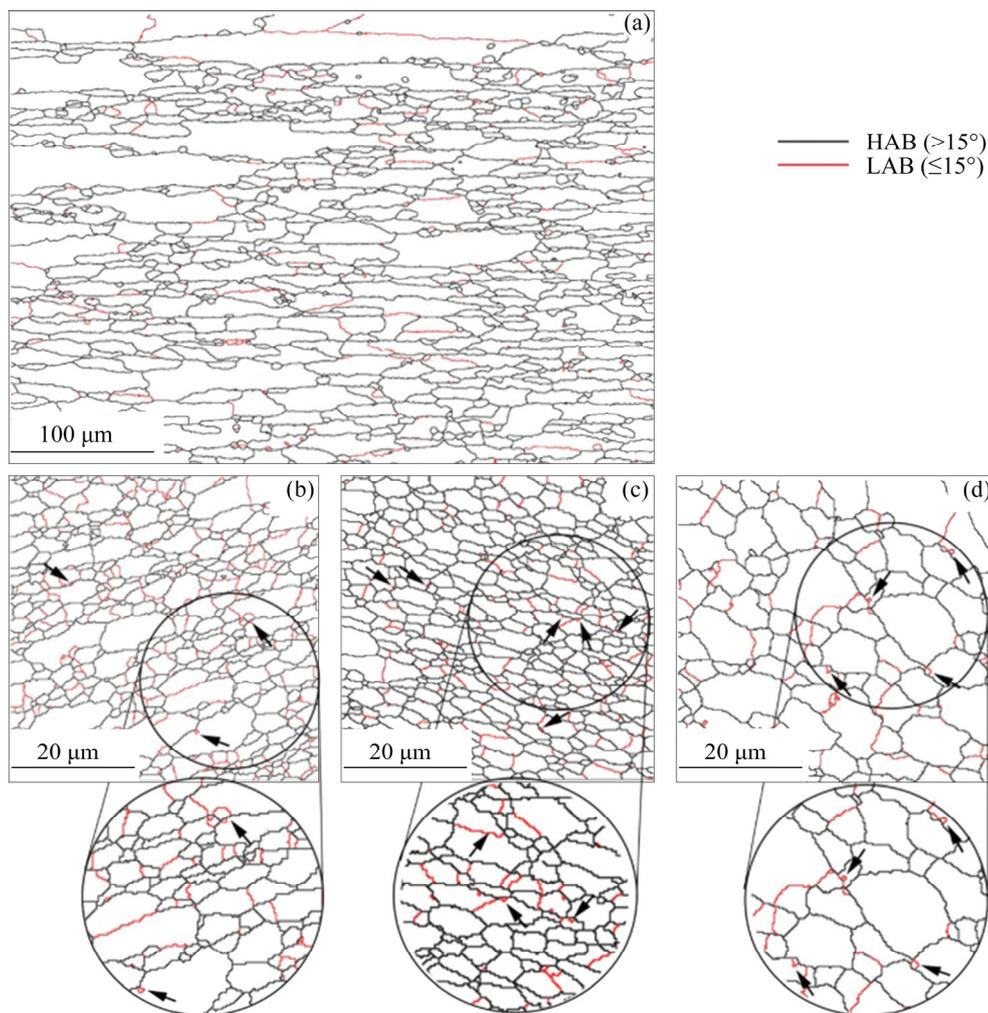
Fig. 4 EBSD grain boundary map of SZs (a) at rotational speeds of 600 r/min (b), 1000 r/min (c), and 1600 r/min (d) (Black-colored marked arrows in the microstructure indicate strain-bulgings) [44]

(A319). They reported that the increase of the traverse feed rate would cause a decrease in the generated heat. At the same time, an increase in the tool's rotational speed would cause an increase in the temperature of the joint, which refines the microstructure grains and improves the weld quality. However, it was observed that ductility and strength continue to increase until reaching a rotational speed of 1200 r/min (optimal speed). The maximum ductility and strength of 221 MPa were achieved with a feed rate of 22.2 mm/min. Experimental results indicated that the feed rate does not significantly affect the welding quality [40,41].

HAGHSHENAS et al [20] analyzed the effect of traverse rate with a constant rotational speed of 1800 r/min on the strength of welded joints of Al−Mg alloy (AA5754) with two types of high-strength steel. A dual-phase steal (DP600) with a

zinc coating and ultra-high-strength (22MnB5) grade steel with Al−12Si coating were used. The diffusion bonds were induced by applying high temperature and pressure, which aided in welding aluminum sheets using the overlapped method [47]. As shown in Fig. 6, it was observed that specimens with DP600 steel and specimens welded at low travel speeds had a higher fracture shear stress.

The decrease in strength with the increase in traverse and rotation speeds can be attributed to the creation of intermetallic phases due to dynamic recrystallization. The intermetallic phases, such as Al_5Fe_2 and FeAl, adversely affect the joint strength. However, specimens with a prominent intermetallic phase of FeAl had a lower impact.

Table 1 summarizes the reported results for the optimal traverse/feed and rotational rates with the corresponding maximum tensile strength observed
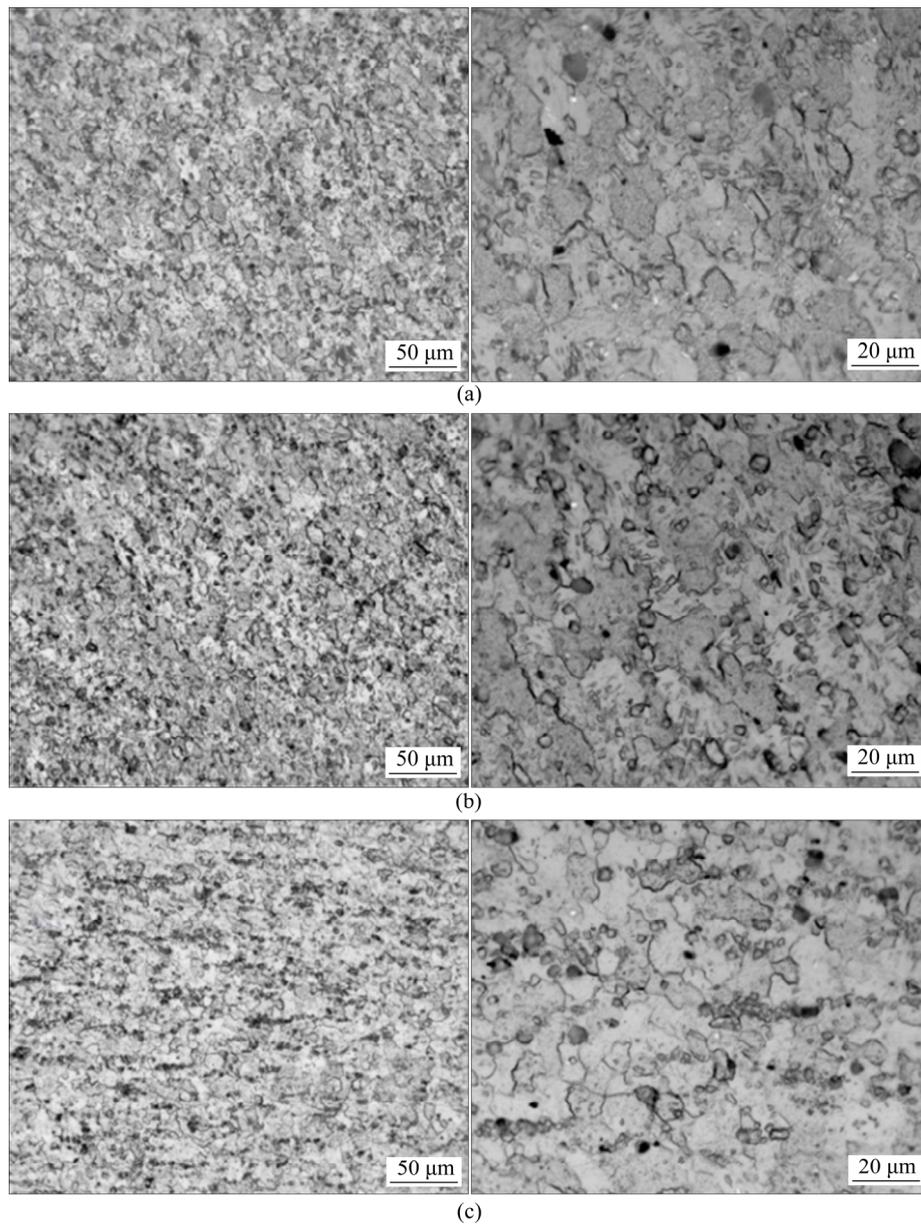
Fig. 5 Microstructures of stir zone (SZ) for friction stir welded samples at 1070 r/min and three feed rates: (a) 36 mm/min; (b) 70 mm/min; (c) 140 mm/min [46]
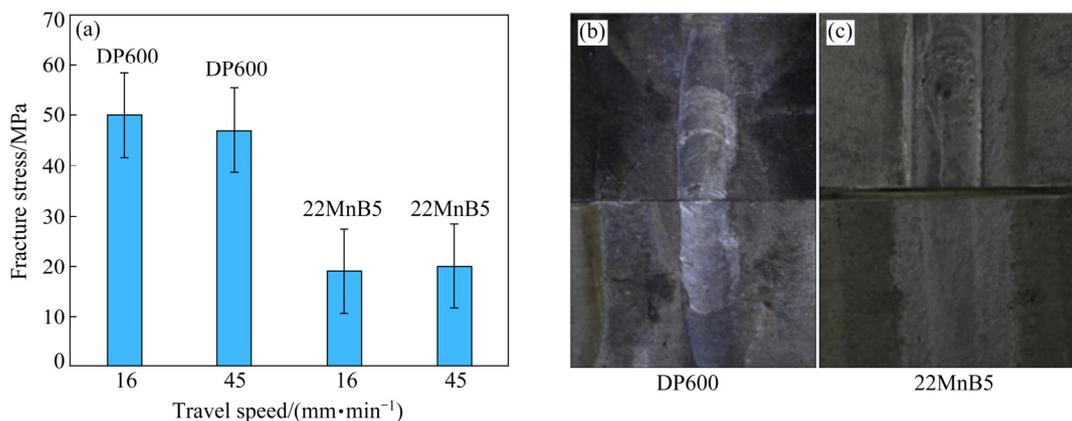

Fig. 6 Shear fracture stress values for travel speed of 16 and 45 mm/min (a) and surface morphologies of DP600 (b) and 22MnB5 (c) welded alloys [20]

Table 1 Reported ultimate tensile strength based on optimal feed and rotational rates for various base materials

Discussed Al MMC/AA	Optimal feed rate/(mm·min^{-1})	Optimal rotational rate/ (r·min^{-1})	Ultimate tensile strength/MPa	Reference
AA6061	100	1400	191	MANEIAH et al [48]
A319	40.2	1200	221	KARTHIKEYAN et al [35]
Al6351	29	1400	185	KARTHIKEYAN et al [9]
AA5083-H111, AA6351-T6	63	1200	275	PALANIVEL et al [8]
2009Al (SiC$_p$/2009Al-T4)	50	1000	135	ZHANG et al [33]
6061Al-T651	600	1400	243	MA et al [38]
7075Al-T651	400	800	532	
2024Al-T351	400	800	451	
2009Al (SiC$_p$/2009Al-T4)	50	1000	135	ZHANG et al [34]
AA2124-T4+25vol.%SiC$_p$	40	1120	366	
AA2009-T4+17vol.%SiC$_p$	800	1000	501	
AA2009+15vol.%SiC$_p$	100	800	441	
AA2009-T351+17vol.%SiC$_p$	50	1000	443	
AA6061+10vol.%SiC$_p$	45	1100	206	
AA2009+15vol.%SiC$_p$	100	800	441	
AC4A+30vol.%SiC$_p$	150	2000	140	ZUO et al [7]
AA2124-T1+25vol.%SiC$_p$	15	400	359	
AA2124-T4+25vol.% SiC$_p$	45	900	355	
AA6092-T6+17.5vol.%SiC$_p$	120	1500	347	
AA6092-T6+17vol.%SiC$_p$	800	1000	355	
AA6092-T6+17.5wt.%SiC$_p$	100	1500	314	
AA6092-T6+25vol.%SiC$_p$	100	900	256	
Al1050 (Al+AZ31BMg)	800	2000	210	SINGH et al [49]
AZ31B, 6061-T6	30	1000	115	MENG et al [50]
AZ91 Mg, A383 Al	40	900	97.5	LI et al [51]
AlSi10Mg, Mg−Al (AM50)	40	500	120	JEDRASIAK et al [52]
6022-T4 galvanized DP600	30	900	314	SHEN et al [53]
AA2024, AA5051	28	710	297	RAJKUMAR et al [54]
AA2024, AA6061	28	710	283	
AA2024-T3	70	1500	130	CARLONE et al [42]
AA5083	100	300	287	CASALINO [55]

for various base materials. The detailed literature study on AA and Al MMC shows efforts to optimize the parameters such as feed rate and tool rotation rates to improve the mechanical strengths. However, a comparative research is lacking to standardize the parameters for weldable AA and Al MMCs.

2.2 Tool geometry

The geometry of a tool is defined by several parameters, including the profile, link between tool and shoulder, shoulder type, and tool contours. In general, tools could be categorized into fixed, adjustable, and self-reacting depending on the type of link between the tool and the shoulder. Tool

profiles include square, hexagonal, conical, triangular and cylindrical. The shoulder which relates to the end surface can be cylindrical, conical, flat, concave, and convex. The contours of the tools could be plain, tapered or threaded. Figure 7 illustrates the various characteristics that define the geometry of an FSW tool according to BS EN ISO 25239-1: 2020 [56,57].

Tool geometry significantly impacts the mechanical properties and quality of a weld [7,14,15,19,34,58−61]. MOURAD and MAITI [62] illustrated that square tools generate more refined grains in the stress zones when compared to other profiles, leading to a higher tensile strength of the joint. ZUO et al [7] reported that the welding path affects joint strength. They examined using a diagonal path across the joint versus a straight path using a square tool to weld a SiC$_p$/Al composite. The results indicated that the diagonal path had higher strength than the straight path. Similarly, CASALINO [55] also reported that tool geometry played a critical role in the welding of dissimilar materials.

Several researchers reported that tools without any thread produce inferior and defective welds [12,36,53,63,64]. MEHTA and BADHEKA [45] examined the effect of tool profiles through altering the depth-to-diameter ratio and tool's composition in the welding of AA6061-T651. They investigated tool compositions including OHNS, HCHCr, and H13 steel. ABD ALKADIR et al [65] investigated the effect of FSW tools with threads on the weldability of 1050-H24 and 6061-T6 aluminum sheets. Their findings point to the benefits of threaded tools and, when joining thin aluminum

sheets, they advocate using an FSW tool with fillets and cavities. In support of this finding, ELAGNOVAN et al [66] investigated the effect of tool profile and contours including straight, tapered, and threaded cylindrical, square, and triangular pins with shoulders of 15, 18 and 21 mm on the welding quality of Al6061 alloys. Specimens welded using tapered and straight cylindrical tools had the highest amount of tunnel defects compared to specimens welded using threaded tools.

On the other hand, specimens welded with square pins had superior tensile properties and least number of defects (see Table 2). Table 2 presents a summary of the results related to various tool geometries with the corresponding maximum tensile strength observed for multiple base materials. Reviewing several literatures, it can be noted that tool pin profile and pin depth have a considerable effect on the strength of the joint.

2.3 Tool composition

PARIKH et al [12] state that aside from rotational tool rate, traverse speed, and profile, the tool composition can significantly affect the weld quality. The most common tool compositions are oil-hardened normalized steel (OHNS), Hudson tool steel (H13), HCHCr, high-speed hardened steel (HSS), high carbon steel, and tungsten carbide. Generally, tools manufactured using conventional material experience the slightest wear while welding aluminum alloys due to their hardness. However, while welding materials with hardness higher than that of aluminum, the tools exhibit excessive wear [40,41,70]. Researchers have determined that FSW tools fabricated from the
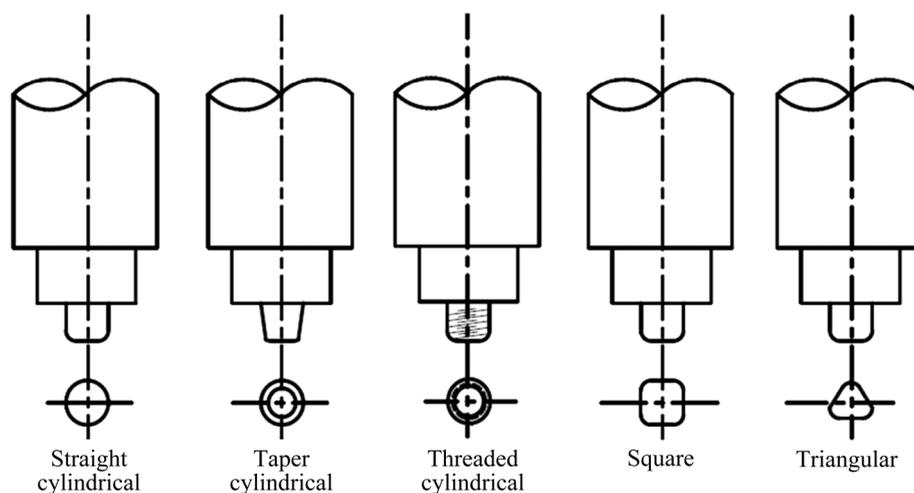

Fig. 7 Commonly used friction stir welding (FSW) tool pin profiles [56,57]

Table 2 Reported ultimate tensile strength based on tool geometry

Base material	Tool geometry	Tool pin diameter/ mm	Rotation speed/ (r·min⁻¹)	Feed rate/ (mm·min⁻¹)	Ultimate strength/ MPa	Ref.
AA6061	Cylindrical	6	1400	100	191	[48]
AA2024−AA5051	Cylindrical	6	1000	28	297	[54]
AA2024−AA6061	Cylindrical	6	1000	28	283	
AA6061	Taper square	3		30	276	[67]
AA6061−B₄C	Square	6	1000	78	203.1	[68]
Al6351	Square	5	1400	29	185.8	[9]
AA6061-T6	Threaded	3	1100	22	300	[69]
AA5086-T6	Threaded	3	1100	22	250	
AA6351−AA5083H111	Straight square	6	950	31.5	278	[8]
AA2009-T4+17vol.%SiCₚ	Threaded conical	4	1000	800	501	
AA2009+15vol.%SiCₚ	Cylindrical	5	800	100	441	
AA2009-T351+17vol.%SiCₚ	Cylindrical	6	1000	50	443	
AA6061+10vol.%SiCₚ	Threaded	6	1100	45	206	
AA2009+15vol.%SiCₚ	Cylindrical	6	800	100	441	
AC4A+30vol.%SiCₚ	Right-hand threaded	6	2000	150	140	[7]
AA2124-T1+25vol.%SiCₚ	Hand screw	6	400	15	359	
AA2124-T4+25vol.%SiCₚ	Cylindrical	6	900	45	355	
AA6092-T6+17.5vol.%SiCₚ	Tapered cylindrical	6	1500	120	347	
AA6092-T6+17vol.%SiCₚ	Tapered thread	6	1000	800	355	
AA6092-T6+17.5wt.%SiCₚ	Tapered cylindrical	6	1500	100	314	
AA6092-T6+25vol.% SiCₚ	Threaded	6	900	100	256	
AA6061-T651	Cylindrical	8	1500	50	89	[45]
AA6061	Conical	3	1400	8	252.69	[63]
Al2009	Cylindrical	6	1000	50	135	[34]
Al6061-T651	Cylindrical	3	1400	600	243	[38]
Al7075-T651	Tapered thread	3	800	400	532	
Al2024-T351	Tapered thread	3	800	400	451	
A319	Cylindrical	4	1200	40.2	221	[35]
AA2024-T3	Unthreaded conical	6	1500	70	130	[42]
AA5083	Tapered cylindrical	3	300	100	287	[55]

conventional materials last longer when used to join aluminum alloys because of the hardness of the materials in relation to one another; however, they exhibit wear when used to weld harder materials, including composites and steel [71]. MOURAD et al [62] observed that the tensile fracture occurred in the thermo-mechanically affected zone and dynamically recrystallized zone after using an H13 tool. Specimens welded with CBN had the fracture

occurring in the heat-affected zones. Figure 8 illustrates microscopic images for the various zones generated by FSW at 400, 600 and 1000 r/min.

Excessive tool wear changes a tool's shape, consequently increasing the probability that a defect will occur and potentially degrading weld quality. The exact wear mechanism, therefore, depends on many factors, including interactions between workpieces and tool materials, the selected tool's
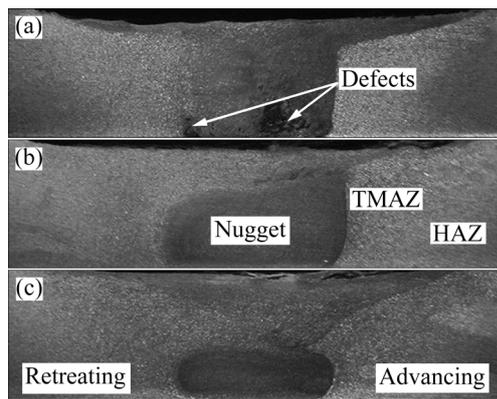
Fig. 8 Defects in weld zone generated by FSW at rotations speed of 400 r/min (a), 600 r/min (b), and 1000 r/min (c) [72]

geometry, and the parameters associated with a specific weld.

2.4 Tool wear and prediction models

Tool wear is influenced by multiple factors, including the degree of contact, applied axial force, tool's rotational and traverse rates, composition, and reinforcement percentage of the composite [73]. Tool wear is generally proportional to the rotational speed and traverse rate due to shear rather than drag [70]. DERAZKOLA and KHODABAKHSHI [74] investigated the tool wear while welding composites with compositions of Al6061 and Al6061 + Al_2O_3. The tool wear was insignificant while welding an Al6061 composite, using a heat-treated O1 tool-steel threaded pin with a Rockwell scale hardness of 62, at variable rotational rates between 500 and 2000 r/min and a traverse speed of 60 mm/min. However, significant tool wear was observed while welding specimens with Al6061 + Al_2O_3. Specifically, the wear rate was found to correlate positively with the increase of the linear welding distance [75,76].

Furthermore, the results indicated that the tool wear rate did not increase when the rotational rate is more than 1000 r/min [71,77]. Figures 9(a) and (b) illustrate the effect of welding distance and rotational rate on the tool wear, respectively. The improved microstructural flow at high rotational speeds is the primary factor in reducing tool wear. An increase in the applied axial force will increase the wear resistance of a tool up to an optimal limit, beyond which the wear resistance decreases [66].
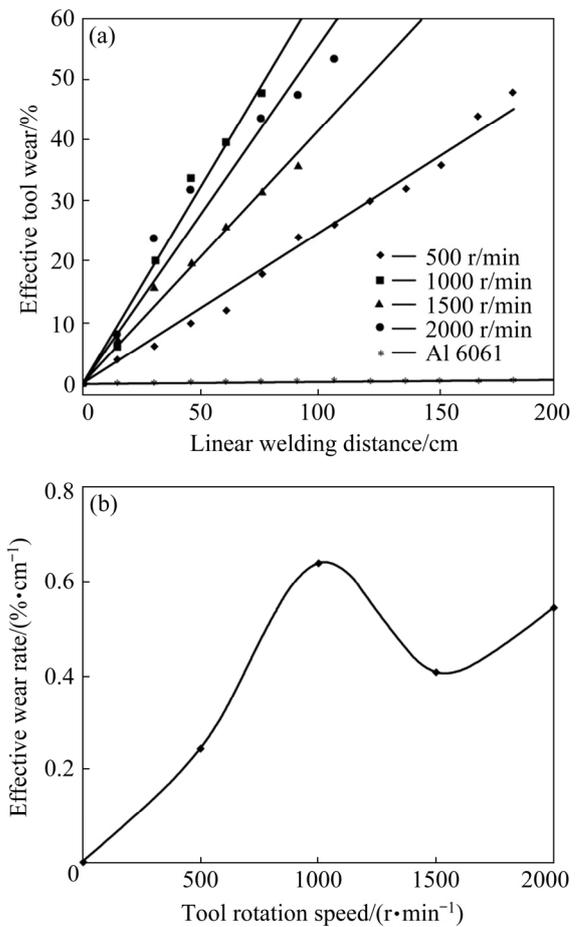
Tool wear can be quantified and predicted by

Fig. 9 Tool wear according to welding distance, rotation, and speed: (a) Effective tool wear versus welding distance; (b) Wear rate versus tool rotation speed [73]

using close-up images and measuring mass difference before and after welding, welding distance, welding quantity, and tool diameter. During welding, as the tool is in contact with hard reinforcing particles, the tool erodes and splatters. This phenomenon allows the quantification and detection of tool wear by analyzing the changes in the tool geometry, volume, and mass [34,73,78]. FERNANDEZ and MVRR [79] used an image-based approach to assess tool wear by capturing close-up images of tool probes before and after they traverse a given distance. Through this method, the images were assessed using an image analysis software that quantified wear by comparing pre- and post-weld images. ZUO et al [7] investigated tool wear after welding a SiC/Al composite using scanning electron microscopy (SEM) images with respect to the number of welds applied. Figure 10 illustrates optical images of tool wear after each welding cycle.
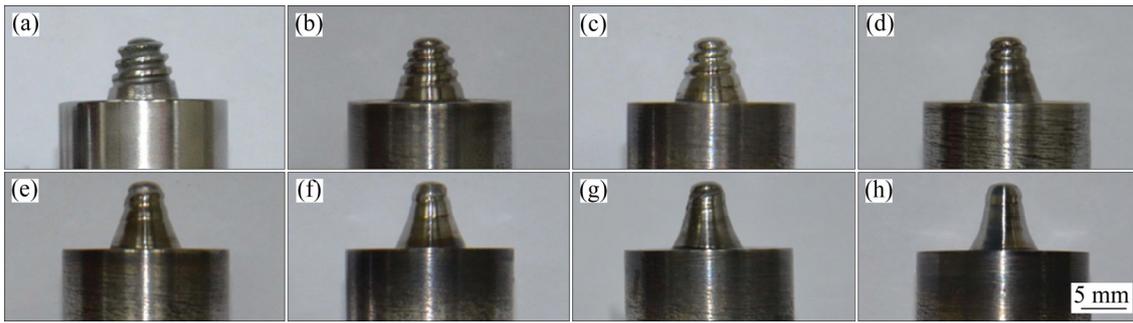
Fig. 10 Optical images of tool wear after each welding cycle: (a) Original; (b) 1st welding; (c) 2nd welding; (d) 3rd welding; (e) 4th welding; (f) 5th welding; (g) 6th welding; (h) 7th welding [72]

It was observed that severe wear occurred with consequent welding due to the formation of reinforcing SiC intermetallic phases during FSW. LIU et al [27] used the percentage of variation (r_w) in tool size as an evaluation index as given in Eq. (1):

$$r_w = \frac{d_0 - d_m}{d_0} \times 100\% \qquad (1)$$

where d_0 denotes the original diameter of the tool and d_m is the measured size after contact.

GIBSON et al [80] quantified tool wear by measuring and analyzing mass changes in FSW tools. In this approach, the tools were removed after each weld and the changes were quantified. After removal, the tools were immersed in a solution of NaOH and water until all the aluminum was eroded from the surface to determine accumulation on the tool's surface accurately. The tools were then reinstalled, and another weld was applied. The percentage of wear (R_w) was calculated using Eq. (2):

$$R_w = \frac{m_i - \Delta m}{m_i} \times 100\% \qquad (2)$$

where m_i is the initial mass of the tool and Δm denotes the mass after each weld.

KARTHIKEYAN et al [35] used an electronic digital balance with an accuracy of 0.1 mg to measure pre- and post-weld masses of FSW specimens. The tests were performed in a wear testing machine. After the specimens were placed for 3 h in the machine, they were removed and cleaned with alcohol to remove all worn particles still attached [20]. After cleaning, each specimen was weighed and the mass lost due to wear determined. The wear rates were then calculated by using the volume loss method as given in Eq. (3):

$$W = \frac{M}{\rho \cdot s} \qquad (3)$$

where W denotes the volume lost during the test period (cm^3/m), M is the mass lost during the wear test (g), ρ is the density of the composite, and s denotes the sliding distance (m).

3 Underwater friction stir-welding (UFSW)

Similar to the conventional FSW, submerged friction-stir welding (SFSW) is a solid-state joining method that occurs while the base material is submerged in a solvent/gas. Underwater friction-stir welding (UFSW) is a variant of SFSW where the welding is done on the base material while being submerged in water. In UFSW, the rotating tool applies force on the workpiece surface causing plastic deformations which leads to welding the joints. UFSW is commonly used in joint designs, including lap and butt joints.

Weld defects such as shrinkage, porosity, cracking, splattering, solidification could be reduced using UFSW. Due to the heat-treatment process provided by cooling the water surrounding the base material while being welded, the joints welded using UFSW have better mechanical properties than those welded using conventional FSW. In conventional FSW, the plunging/ compressive action with continuous friction while shearing during welding leads to the formation of micro- and macroscopic residual stresses. Due to the low heat dissipation rates, the residual stresses radiate through the weld zone and affect the joint's strength [81]. UPADHYAY and REYNOLDS [82] examined the effect of rapid and passive quenching

on welded aluminum alloys using conventional FSW. Due to quenching, the specimens exhibited increased tensile and yield strength by 8% and 10%, respectively.

Furthermore, the specimens illustrated an enhancement in transverse tensile elongation [83,84]. In UFSW, the water acts as a quencher and instantly dissipates the heat from the weld zone. As a result, the residual micro- and macro-stresses are reduced.

Applications of UFSW include, among others, the construction of massive ships, maintenance and repair of seagoing vessels, reconstruction of vehicles after accidents, construction of offshore pipelines, and recovery of containers from the sea-bed [82,85]. Also, fabrication using UFSW technique results in high-quality welds in a restricted cycle time, without filler metals and in the absence of shielding gas. Furthermore, UFSW generates fine-grained cast joints by eliminating weld inclusions while consuming less energy than the conventional FSW. Therefore, UFSW is an easy and inexpensive welding process. It produces refined grains due to interactions between two workpieces without reinforcement or intruder material [86,87].

FU et al [88] reported that the cooling rate enhanced the mechanical properties of the welded aluminum alloy (AA7075) due to its sensitivity to quenching. The aluminum alloy had an increase in tensile strength by 10% when welded by UFSW as compared to conventional FSW. Furthermore, the use of UFSW has led to the formation of fine-grained microstructure that reduces the residual stresses. DEBROY and BHADESHIA [89] elaborated that the use of UFSW to weld aluminum alloy (AA6061) pipe has reduced the heat generated and improved the mechanical properties such as hardness, tensile strength and plasticity.

3.1 Mechanical properties

LIU et al [87] concluded that using UFSW to weld aluminum alloys (AA2219-T6) enhances the mechanical properties at the lower, mid-, and upper layers of the welded joints when compared to conventional FSW. It was found that the use of water as a coolant improved the tensile strength by 5.2%. ZHAO et al [90] reported that aluminum alloys (AA7055) welded using UFSW had 33% enhanced tensile strength compared to specimens welded using conventional FSW. WANG et al [91]

indicated that aluminum alloys welded using UFSW exhibited an improvement of 1.96% and 30% in elongation and tensile strength, respectively, when compared to specimens welded using FSW.

SAKURADA et al [92] investigated the effect of the rotational speed of a cylindrical tool while welding using the UFSW. The results indicated that the use of UFSW has improved the strength by 86%. ZHANG and LIU [93] reported that aluminum alloys (AA2219-T6) welded using UFSW exhibited 6% enhancement in tensile strength compared to specimens welded using FSW. This was achieved by enhancing the distribution of heat and thereby improving the microstructure [93,94].

DERAZKOLA and KHODABAKHSHI [95] investigated in-air FSW and UFSW using hot water and water set to room temperature to weld an aluminum alloy (AZ31BOMg). Results indicated that the use of UFSW reduced in the welding rime and led to higher grain refinement. Specimens welded using UFSW exhibited an enhancement in the formability of the alloy and increased consistency. UPADHYAY and REYNOLDS [82] examined the impact of varying thermal preconditions and welding variables to join aluminum alloys (AA7050-T7) using in-air FSW, UFSW, and in sub-ambient temperature conditions (25 °C). It was concluded that welding using UFSW increased the cooling rate within the heat-affected zone, enhanced the hardness of weld lumps, and reduced probe temperatures. Furthermore, the UFSW with various parameters enhanced the elongation and durability of the joint.

ZHANG and LIU [96] analyzed the effect of multiple UFSW variables including rotation and travel speeds, on the welding of marine-grade aluminum alloys (AA5083). The results indicated that UFSW improved the weld quality due to numerous factors, including higher rotation speeds, larger thermal capability of water, and lower peak temperature. ABBAS et al [97] assessed the optimal UFSW parameters including tool profile, welding speed, and tool inclination angle to weld an aluminum alloy (AA6061) plate. They used the Taguchi optimization technique to maximize the durability of the joint. Furthermore, the results indicated that a cylindrical pin resulted in the highest tensile strength of the joint of 182 MPa [97]. LIU et al [27] examined the mechanical properties along the cross-section of Al MMC joints welded

using UFSW and FSW. The results indicate that specimens welded using UFSW have a higher strength and hardness at the bottom and middle layers when compared with specimens welded using FSW.

3.2 Thermal distribution and microstructural analysis

Boundary migration models can be used to obtain the thermal distribution in stirred materials and predict the grain sizes on the micro-level [47]. Additionally, transmission electron microscopy (TEM) can be used to characterize the micro-structure of material welded using conventional FSW and SFSW [98]. FRATINI et al [99] examined the effect of the in-process heat-treatment during welding aluminum alloy (AA7075-T6) butt joints using UFSW. The results were investigated through the analysis of the thermal and microstructural distributions. The UFSW technique has reduced the thermal flow and material softening in the weld nugget zone while enhancing the joint's strength. HOFFMANN and VECCHIO [100] compared welding using UFSW and FSW on an aluminum alloy (AA6061-T6). The results indicated that the finer grains produced by the UFSW along with the plastic deformations resulted in less thermal distribution. ZHAO et al [90] analyzed the hardness profile for specimens welded using conventional FSW and UFSW. Small hardness values in heat-affected zones in the joints welded by both methodologies were observed, as shown in Fig. 11(a). However, the hardness values for specimens welded using UFSW were higher than those of specimens welded using FSW, as illustrated in Fig. 11(a).

HOFMANN and VECCHIO [98] analyzed the fine-grained microstructure produced by a fast-cooling rate for a material welded by SFSW. ZHANG et al [37] performed a microstructural analysis of an aluminum alloy (AA2219-T6) welded using UFSW. UFSW reduced the precipitate-free zone and improved the hardness of the heat-affected zone. ZHAO et al [90] used an optical microscope and scanning electron micro-scope (SEM) to investigate the microstructure of a common 7055-T6 aluminum alloy welded using UFSW. The microstructural analysis indicated that the thermal cycles during the welding process developed a reinforcement mechanism at the joint.
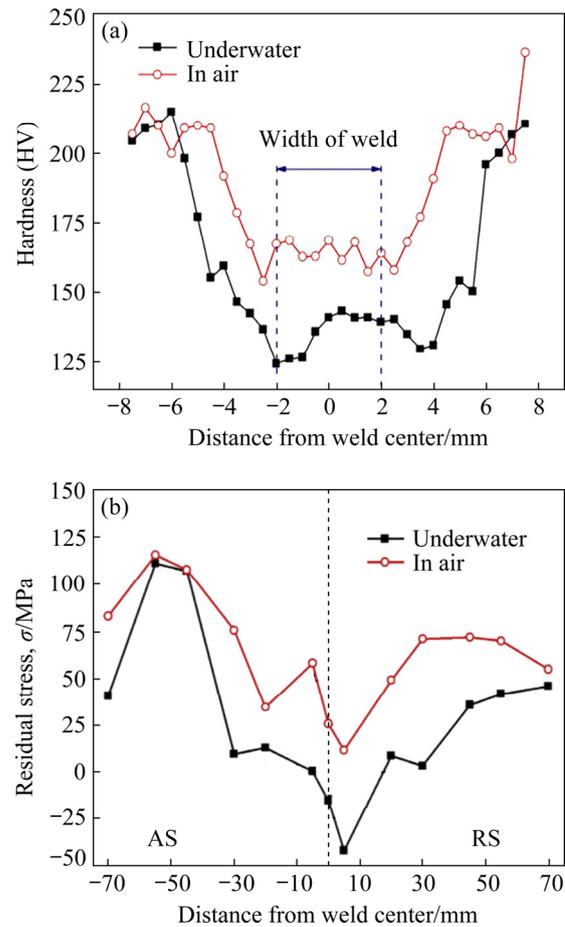

Fig. 11 Hardness values from weld centers (a) and distribution of residual stresses for plate welded in different media (b) [101]

HOSSEINI and DANESH MANESH [102] compared the microstructure of 1050 ultra-fine-grained strain-resistant aluminum alloy welded by UFSW with the microstructure of an alloy welded by FSW. TEM and X-ray diffraction were used to examine the rate of grain growth. The results indicated a reduced softening effect on fine grains and sub-grains in the defect-free stir zone for specimens welded using UFSW. These specimens displayed a small heat-affected zone with high tensile and yield strength. LIU et al [27] investigated the effect of welding speeds within the range of 50−200 mm/min and a rotational speed of 800 r/min on the quality of aluminum alloy (AA2219) joints welded using UFSW. ZHANG and LIU [93] examined the fabric flow patterns of an aluminum alloy (AA2219-T6) welded using UFSW. The results revealed quantities of extruding reflux in the stress zone with welding tools set at high rotation rates and low transverse speed. Figure 12
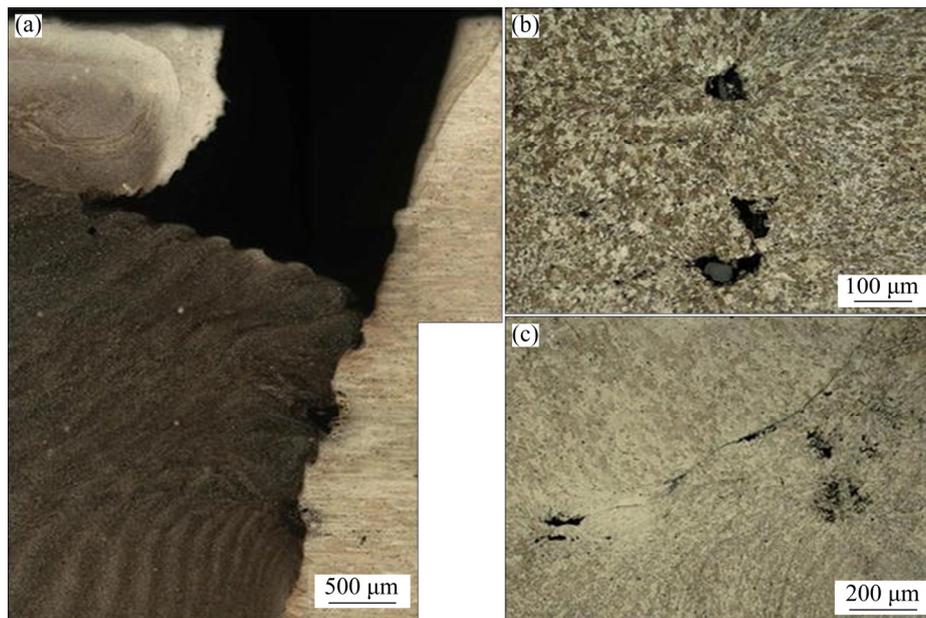
Fig. 12 Welding defects formed under different process parameters: (a) 800 r/min, 200 mm/min; (b) 1000 r/min, 300 mm/min; (c) 1400 r/min, 100 mm/min [96]

illustrates the welding defects formed in specimens subjected to various welding speeds and rotation rates.

ZHANG et al [103] used three-dimensional thermal and mathematical modeling verified with experimental data. They reported a reduction in thermal cycles while welding using UFSW. SABARI et al [104] examined the microstructure and mechanical properties of an aluminum alloy (A2519-T87) welded using FSW and UFSW. Using finite element analysis, the temperature distribution and microstructure in the thermo-mechanically affected zone were investigated. The results revealed that specimens welded using UFSW have a higher peak temperature reaching 547 °C, a higher cooling rate, and better thermal distributions as compared to specimens welded using FSW. The thermo-mechanical affected zone was reduced and an increase in the heat-affected zone was observed due to aging. As a result, the specimen welded using UFSW had an enhanced tensile strength of 60% as compared to specimens welded using FSW. It is worth noting that the fracture usually occurs in the heat-affected zone for specimens welded using UFSW [104−106].

KHALED [107] employed SEM and energy dispersive spectroscopy (EDS) to analyze the microstructure of different welds by evaluating the grain shape, size, and misorientation using electron backscattering diffraction (EBSD). Each specimen

was polished with a vibrator and then mechanically ground and machined with abrasive paper to dimensions of 20 mm × 3 mm. Specimens welded using air-cooled FSW display a clear boundary (known as S-line defect) between the weld-nugget zone and the heat-affected zone. Welding using UFSW led to the formation of refined grains that decreased the "S-line" defects [89]. Specimens welded using UFSW exhibited clear borderlines in the middle of the weld nugget zone and the thermo-mechanically affected zone. Furthermore, the heat-affected zone was reduced. Figures 13(a) and (b) illustrate the fracture surface of specimens welded using UFSW and FSW, respectively. Figure 13(a) exhibits the presence of white dots suggesting the presence of an intermetallic phase ($MgZn_2$) that prevents the movement of dislocations [107]. The intermetallic phase enhances the strength and ductility of the welded joints.

4 Vibration-assisted friction-stir welding (VFSW)

Specimens of aluminum alloys joined using fusion welding are susceptible to hot cracking, solidification, porosity, and heat-affected liquation cracking [108]. Joints of aluminum alloys welded with FSW remain in a quasi-steady-state condition. However, at terminating ends (weld crater) intense
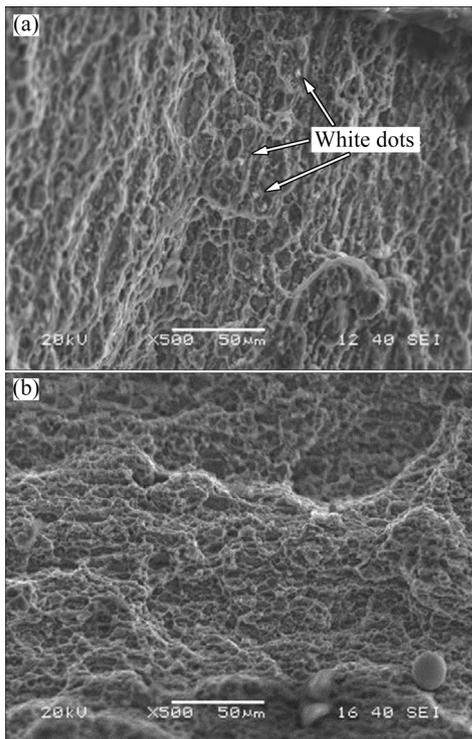
Fig. 13 Fracture surfaces of joints welded using underwater FSW (a) and FSW in air (b) [101]

variations occur in energy, temperature, mass, and momentum transfer [108,109]. Due to high heat conductivity of aluminum alloys and the termination of heat input, solidification of the weld pools occurs at faster rates resulting in cracks formation [110]. Also, high temperatures that occur during the FSW process significantly affect the microstructure of the metals and the mechanical properties of the alloys [111]. On the other hand, UFSW requires costly machines due to submerging the base material [110,112]. Therefore, several investigations have been conducted to improve the quality of joints produced by conventional FSW using secondary heat sources while being energy efficient.

Secondary heat sources such as warm FSW [113], tool preheat [114], plasma [114,115], and arc [116] have been investigated. Most of the above-referenced investigations use thermal energies that involve pre-heating the surface to soften the material during welding. However, these techniques cannot supply heat sufficiently and uniformly, which leads to a brittle structure formation that reduces the joint's quality and strength [29,30,117,118]. This drawback has led to the growth of solid-state welding methodologies

such as vibration-assisted friction-stir welding (VFSW). VFSW is a solid-state welding methodology in which two materials are welded under an inert environment without applying any filament material or using an external heat source. VFSW has numerous advantages including softening the weldment sufficiently without the use of significant heat [118], enhancement of the material plastic flow and mechanical interlocking [116,118,119], reducing the possibility of defect formation and improving joint strength [120]. Researchers have concluded that VFSW generates longitudinal residual stresses across the weld, while nominally affecting the transverse residual stresses [121]. Due to these advantages, VFSW has gained a significant interest in solving the challenging problems in joining aluminum alloys.

In general, VFSW can be subcategorized into three main classifications, namely, rotary, non-rotary, and friction processing. Rotary welding is the oldest commercial technique implemented to join materials using friction welding. In 1891, BEVINGTON revealed the rotary friction welding process for joining metallic wires, rods, and other solids [122]. In this technique, a cylindrical-shaped object is attached and rotated against a fixed element as predetermined stress is applied [123]. As the cylindrical object rotates, heat is generated due to friction [124]. This leads to the plasticization and softening of the fabric at the faying surface [122]. The compressive force displaces the plasticized material from the interface while expelling the surface oxide layer and other contaminants. This process leads to metallurgical and surface interlocking [125]. These deformations cause the workpiece to shorten in the direction of the compressive force. Once the required thickness/ shortening (known as burn-off distance) is achieved, the rotation is ceased, and the forging force is kept constant or increased for a period to consolidate the weld. Vibration-assisted rotary welding FSW is defined as welding using rotary friction welding while vibration and a compressive force is induced [126].

In non-rotary friction-stir welding, frictional heat is produced as one component is moved in a direct reciprocating mode relative to another under normal pressure [122]. The friction between the oscillating surfaces produces heat which results in a bond. In friction (hybrid) processing uses an

external heat source such as a laser beam to preheat the surface of the joint [116]. The preheating of the surface assists in overcoming the asymmetry in heat generation and enhances weldability [127].

The weld strength of specimens joined using VFSW is higher than that of the specimens welded using the conventional FSW. This is attributed to the oscillations generated due to the process of VFSW. The oscillations decrease the grain sizes and form grain boundaries that enhance ductility and inhibit crack growth [71]. ESTRIN et al [128] observed the enhancement in ductility of AZ31 magnesium alloy specimens due to the decrease in grain size. The fracture mechanism transformed from intergranular fracture for specimens welded using conventional FSW to a trans-granular fracture for specimens welded using VFSW [129]. MONTAZEROLGHAEM et al [130] observed an enhancement of 16% in the microhardness of the weld region for specimens welded using VFSW as compared to specimens welded using conventional FSW. In general, an increase in the vibrational frequency is associated with an enhancement in the hardness and strength of the weld region [70,130−133]. MERAN and CANYURT [129] illustrated that specimens welded using VFSW have 5% and 15% increase in ultimate tensile strength and elongation, respectively, compared with specimens welded using FSW. However, the results illustrated that increasing the vibrational frequency beyond an optimal limit would decrease the weld strength. BAGHERI et al [134] have worked on the design of VFSW, as shown in Fig. 14.

In general, specimens welded using VFSW exhibit good mechanical properties in tension and bending, high fatigue resistance [135,136], minimal porosity, and low shrinkage rates. Moreover, VFSW causes low distortions and small residual stresses, even in long welds, and has high energy efficiency compared to conventional FSW [82,85]. Therefore, the VFSW is reported as the best methodology for welding aluminum alloys for structurally challenging applications. The latest research conducted in the most common types of VFSW are (1) laser-assisted friction-stir welding (LSFW), (2) electrical current-aided friction stir welding (EFSW), and (3) ultrasonic-vibration-assisted friction-stir welding (UVFSW).

4.1 Laser-assisted friction-stir welding (LFSW)

Laser-assisted friction-stir welding uses a laser beam to introduce additional heat at localized points ahead of the weld zone [137]. This reduces the applied compressive force and enables higher welding speeds. CASALINO et al [138] investigated the use of laser-assisted friction-stir welding (LFSW) on welding AZ9lDMg alloy plates. They indicated that the use of LFSW resulted in a smaller applied force to achieve the weld as compared to conventional FSW [139]. The machine details are shown in Fig. 15.

In another study, CAMPANELLI et al [140] welded 3 mm-thick aluminum (5754H111) alloy plates in lap-joint configuration using conventional FSW and LFSW. The LFSW system used a ytterbium fiber laser with a maximum power of 4 kW. The results indicated that specimens welded using LFSW exhibited enhanced grain refinement
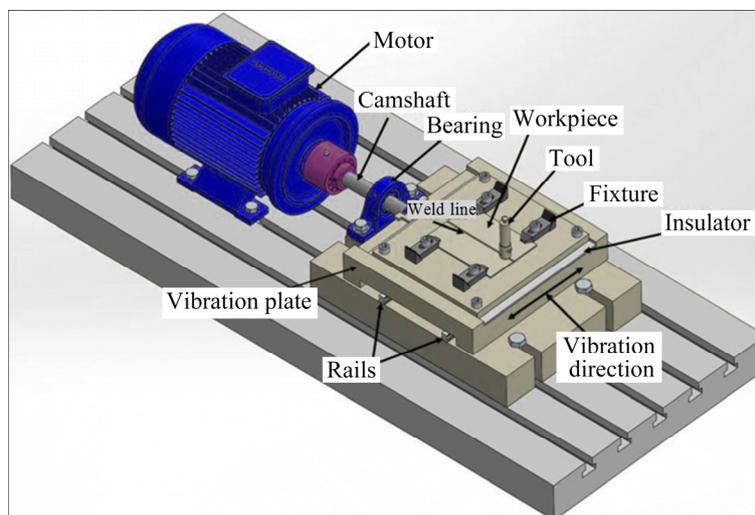

Fig. 14 Schematic design of fixture used for fastening specimens (VFSW) [134]
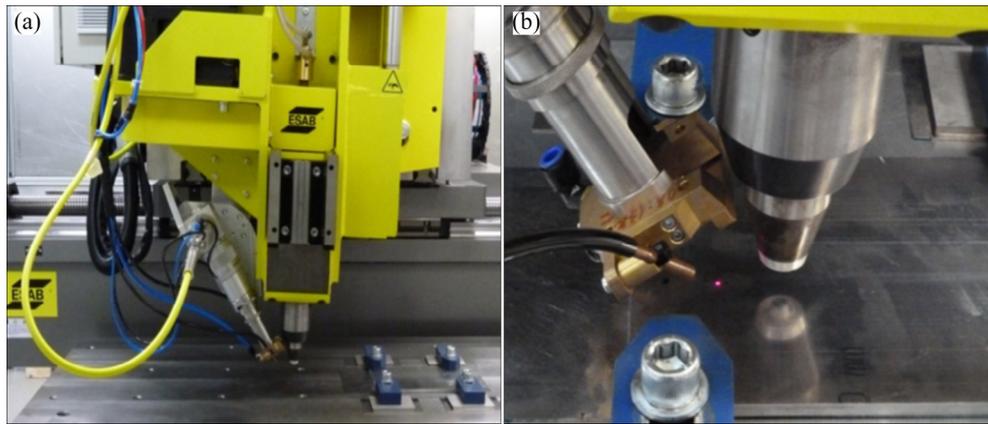
Fig. 15 LFSW machine setup [138]

at the joint and superior properties compared to specimens welded using conventional FSW. KOHN et al [127] investigated the use of LFSW to join aluminum alloy (AZ91DMG) and suggested the optimum values of the parameters to enhance the mechanical properties and strength of the joints. Due to the benefits and potentials of LFSW, the use of hybrid techniques in joining materials with high toughness and hardness, such as titanium alloys, has gained interest [140,141]. However, limited related research has been reported.

4.2 Electrical current-aided friction-stir welding (EFSW)

Electrical current-aided friction-stir welding (EFSW) is a hybrid FSW welding technology that uses electrical current applied through the joint interface. Consequently, the specimen is welded. EL-KASSAS and SABRY [142] investigated the effect of the current intensity of EFSW while welding aluminum alloys (AZ31B and Al7075). The results indicated that the EFSW significantly refined the grain size and enhanced the hardness in the weld nugget zone of the AZ31B alloy. Specimens with Al7075 revealed a direct correlation between the applied electric current intensity and the grain size in the regions of weld nugget and heat-affected zones.

HAGHSHENAS et al [20] modified the technique by adding two copper brushes to serve as electrodes (a cathode and an anode) instead of the welding tool. The brushes translated with the tool tip and were mounted on the spindle holder while being in contact with the surface of the specimen.

The modified approach enhanced the formation

of a thin intermetallic compound layer, while the applied axial welding force was reduced. The enhancement of the joint's weld quality can be attributed to the accelerated atom diffusion and the decrease in the activated energy of the chemical reactions due to the resistance heat. A few researchers investigated the use of high-current frequency induction before welding 1.6 mm-thick low-carbon steel plates [28−30]. The process assisted in pre-heating the specimens which resulted in enhancing the weld quality and strength. In general, specimens welded using EFSW technique have exhibited high joint strength and fractured through a plunge mode.

4.3 Ultrasonic vibration-assisted friction-stir welding (UVFSW)

Ultrasonic vibration-assisted friction-stir welding (UVFSW) is an FSW technology that is assisted by ultrasonic energy. The ultrasonic energy is transmitted directly to the localized joint area ahead of the welding tool by a sonotrode. LIU et al [143] investigated the microstructure, and mechanical properties of butt-welded aluminum alloy (2024Al-T4) joints welded using UVFSW. Figure 16 illustrates the equipment and procedure for welding using UVFSW. Upon investigation of the morphology and metallographic properties of the specimens through X-ray inspection, it was observed that the defect-free stir zone was broadened, while the grains in the heat-affected zone exhibited no significant growth. Furthermore, the tensile strength, ductility of the welded joint, and the micro-hardness of the defect-free stir zone were enhanced.
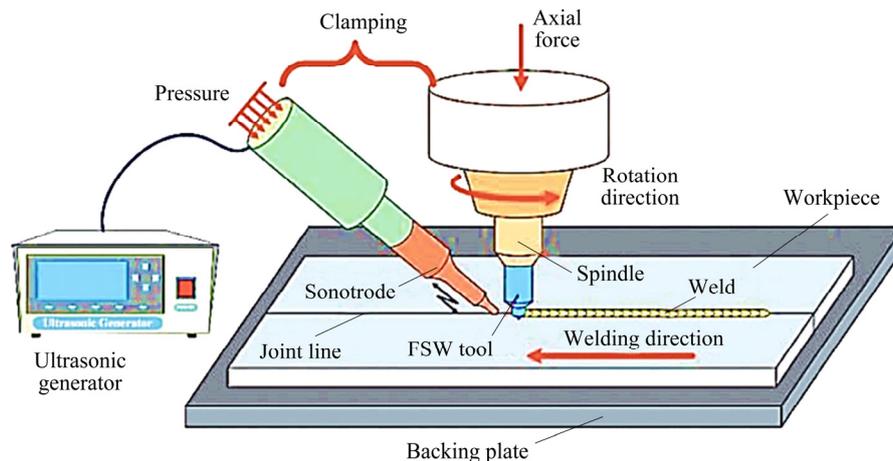
Fig. 16 Schematic diagram of ultrasonic vibration-assisted FSW [145]

AMINI and AMIRI [144] investigated the effect of ultrasonic vibrations on the tool's applied force, specimen's temperature, and tensile strength and hardness of the weld region. In their research, the aluminum alloy (AA6061-T6) specimens were vibrated using a motor-driven vibrating pad instead of a sonotrode. In general, the results revealed that using UVFSW decreased the tool's applied downward force and enhanced the strength and ductility of the weld region [130,145,146].

5 Dissimilar materials

Many researchers have worked on the joining of similar metals but a few works have been carried out on dissimilar metals [147]. A significant challenge offered for obtaining good joints between dissimilar materials are their differences in the chemistry of the materials, their melting points, thermal conductivity, coefficient of thermal expansion, etc [148]. These differences in chemical properties in turn, could lead to a possible formation of detrimental intermetallic compounds which would burden the selection of proper welding parameters [149−151]. ZHANG et al [152] have studied the mechanical properties of dissimilar Al−Cu joints by friction stir welding. Pure copper and 1060 aluminum alloy were welded successfully at a tool rotation rate of 1050 r/min and a welding speed of 30 mm/min. Several researchers mentioned that interface is a key to dissimilar joints, because it is often the position where the dissimilar joints fail [152,153].

PALANIVEL et al [154] investigated the effect of tool profiles on the mechanical and metallurgical properties of dissimilar aluminum alloys (AA6351 and AA5083-H111) welded using conventional FSW. Even though the traditional FSW is widely used for welding of dissimilar materials, it is tedious and time-consuming [7]. Therefore, many researchers have investigated the use of UFSW to weld dissimilar joints of Al MMC [2,38,59,74,155−158]. Figure 17 illustrates the procedure of SFSW to weld dissimilar materials. ZHANG and LIU [93] investigated the effect of dissipating heat using rapid quenching by water set at 0, 25, and 50 °C while welding aluminum dissimilar joints using submerged friction-stir welding (SFSW). The results indicated that water set at the room temperature is the optimal methodology of welding aluminum dissimilar joints using SFSW.

MOFID et al [159] compared the use of UFSW and FSW to weld dissimilar materials (Al5083 and AZ31COMg). Results indicated that FSW increased the fine-grains of the welds and reduced the occurrence of intermetallic phase. However, the hardness of the joints increased due to ideal peak temperatures in the stress zones. In another study, MOFID et al [160] investigated the feasibility of using UFSW and SFSW in cryogen to join dissimilar aluminum/magnesium alloys (AA5083-H4 and AZ31). They concluded that SFSW suppresses the formation of the interatomic compound at low peak temperatures.

SADEESH et al [151] used various pin profiles to perform friction stir welding of AA6061 and AA2024 alloys. The results showed that the tensile strength of the joints conducted with squared-pin profile tool, compared to the strength

obtained when tapered, as well as when cylindrical pin profile tools were used, was improved.

DINAHARAN et al [161] investigated the effect of material locations and tool rotational speed on the microstructure and tensile strength of the dissimilar friction stir welded, cast, and wrought aluminum alloy AA6061. The research concluded that the material placed in the advancing side (AS) occupied the major portion of the weld zone when rotational tool speed was increased, where the AS of the weld is hotter than the retreating side, as proven by COLE et al [162]. In addition, SUNDARAM and MURUGAN [163] studied the effect of the pin profile used in FSW on the mechanical properties of 2024-T6/5083-H321 dissimilar aluminum alloys where the alloy of higher strength (2024) was located at the retreating side (RS). The work showed that when the combinations of parameters create either very low or very high frictional heat, a plastic flow of material, lower tensile strength and elongation are observed.

KHODIR and SHIBAYANAGI [164] experimentally examined the FSW of dissimilar materials, namely AA2024 and AA7075, and recommended that the low-strength material should be placed on the AS to produce better welds. On the other hand, GOETZ et al [165] and XUE et al [166] confirmed that locating hard materials at the AS will improve the joint strength. Accordingly, the material flow and joint performance, irrespective of material placement, are dependent on the welding conditions and their effects on generated heat and stir zone (SZ) temperatures [162,167]. Additionally, heat dissipation depends on material thickness, the welding speed, and the ambient temperature [162,168]. The use of high heat input such as low welding speed and high rotation rate can result in improper tool/material contact conditions (slipping conditions), which can produce joints with defects [169].

MAHTO et al [64] assessed the feasibility of welding dissimilar materials (AA6061-T6 and AISI304) of 1 mm-thick sheets via UFSW and continuous fillet stir welding (CFSW). They investigated the effect of welding tool rotational speeds and plunging depth (PD) on the strength and weld quality of the joint, as shown in Figs. 18 and 19. Less heat inhibited the formation of thick intermetallic compounds. In addition, a faster
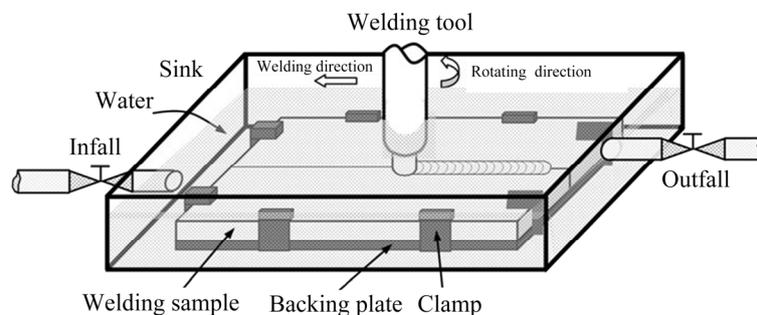

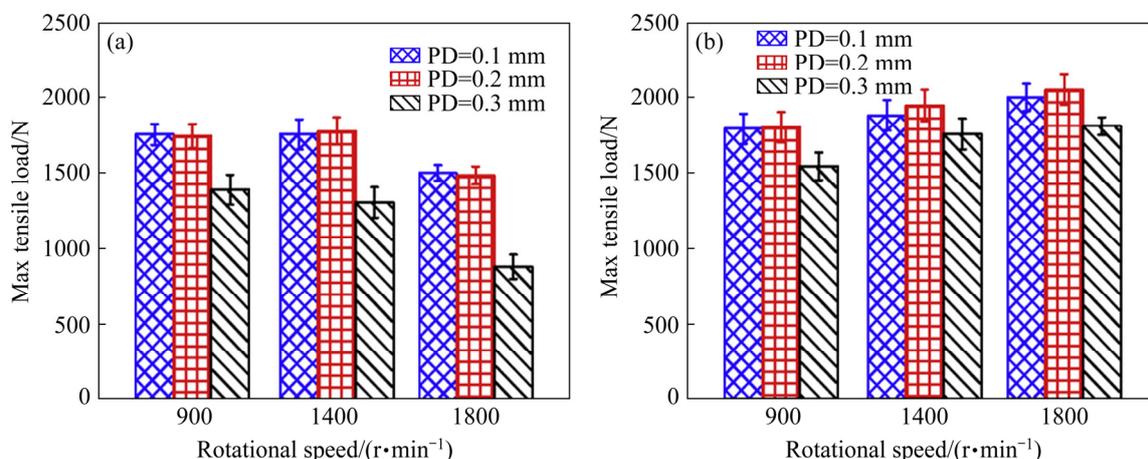**Fig. 17** Submerged friction stir welding (SFSW) [93]

Fig. 18 Comparative analysis between tensile strength and pin depth (PD) at rotational speed of 900, 1400, and 1800 r/min using conventional FSW (a) and UFSW (b) [64]
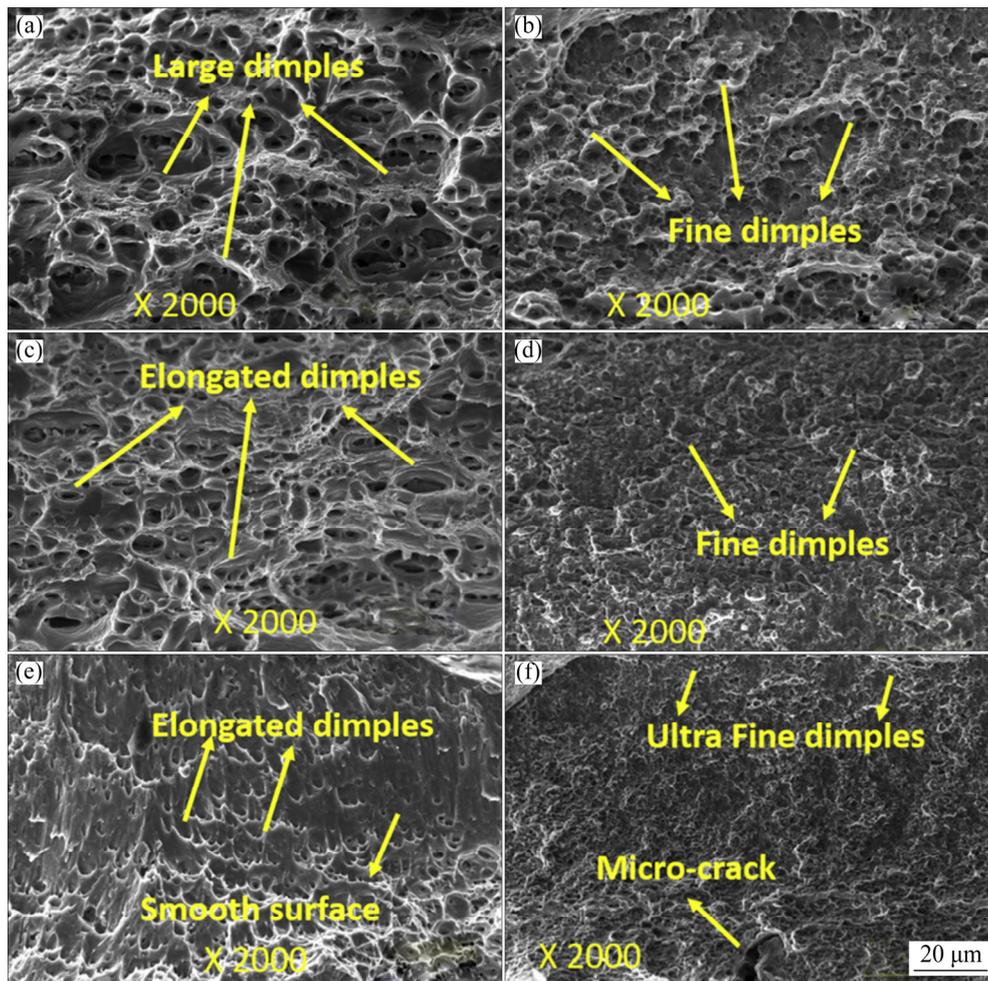
Fig. 19 Comparative SEM images of fractured surface using conventional FSW and UFSW: (a) CFSW, ω=900 r/min, PD=0.3 mm; (b) UFSW, ω=900 r/min, PD=0.3 mm; (c) CFSW, ω=1400 r/min, PD=0.3 mm; (d) UFSW, ω=1400 r/min, PD=0.3 mm; (e) CFSW, ω=1800 r/min, PD=0.3 mm; (f) UFSW, ω=1800 r/min, PD=0.3 mm [64]

cooling rate in UFSW produced fine microstructure in the weld zone. Figure 19 shows that UFSW reduced the weld porosity, thickness of intermetallic compound and yielded fine microstructure, which collectively improved the weld strength.

6 Summary and future directions

This review summarizes the most recent research in the conventional and state-of-the-art techniques of friction stir-welding (FSW) for aluminum alloys and aluminum metal matrix composites (Al MMC). The latest developments in conventional, underwater, and energy-assisted FSW processes such as vibration, electric, and ultrasonic-assisted FSW were discussed. These processes were employed in various industries. However, research on the most recent techniques

and their process parameters and impact on the weld quality is limited. Further work on Al MMCs is very lacking and no work is reported on recycled Al MMCs. This review illustrated the significant advantages and limitations of the available friction-stir welding techniques specially for aluminum alloys and Al MMCs. The review revealed many relevant issues and concerns. The following is a summary of the limitations in the current research and recommendations for future work in the area of FSW for aluminum alloys and Al MMCs:

(1) It is necessary to develop theoretical models to understand the physics of joint formation in FSW comprehensively. Furthermore, these models could be used to optimize the welding parameters based on the joint characteristics required.

(2) Many FSW techniques have been developed and partly investigated. However, it is a kind of individual work based on the available facilities in researcher's laboratories. It is essential to extensively investigate and compare the joint quality of a specific material produced by the available FSW techniques. This would assist in the development of standards to achieve consistent high-quality welds.

(3) State-of-the-art techniques such as vibration-assisted friction welding have a huge potential. Future work should be focused on the automation of auxiliary energy-assisted FSW processes to achieve a sustainable manufacturing process.

(4) It is worth noting that energy-assisted FSW reduces mechanical force applied on the welding tools and enhances the tool's life.

(5) The weld's exit hole adversely affects the joint quality. Although there have been many approaches to refill the pinhole left after welding, there isn't a process that fully accomplishes the needs of the commercial applications.

(6) The extensive review of the recent research revealed that there is no work, to the best of our knowledge, on FSW of recycled Al alloys or MMCs. In our latest works, production and testing of a novel recycled Al MMC is considered one of the main objectives, and the results obtained are promising.

Table 3 summarizes the challenges of welding aluminum alloys by the FSW techniques discussed in this review. In general, welding with improper parameters such as tool design, joint configuration,

Table 3 Summary of challenges faced and future directions

Technique	Challenges
Fusion FSW	(1) Solidification cracking, heat-affected liquation cracking, weld porosity, hydrogen embrittlement. (2) Due to uneven heating and cooling of weld joint distort resulting in additional stresses.
Conventional FSW	(1) Generation of weld defects such as shrinkage, porosity, cracking, splattering, and solidification. (2) Excess heat input induced by high rotation speed. This increases the fluidity of the metal and creates turbulent flow in the weld zone. (3) It is less flexible compared to other manual and arc welding processes. (4) Considerable downforce is required with heavy-duty clamping necessary to hold the plates together.
Underwater friction stir-welding (UFSW)	(1) Due to the presence of water, the heat generated by the rotating tool is not sufficient to plasticize the material, such as dissimilar alloys. Resulting in finer grains at the weld sections. This leads to a lower tensile strength of the welded joint.
Vibration-assisted friction-stir welding (VFSW)	(1) Vibrations and tool torque increase tool wear and reduce the tool's performance and life. (2) Vibration causes low distortions and small residual stresses. (3) The size of the equipment should be large enough to include vibration assistance. (4) VFSW welding speeds are low and fall within a narrow window leading to a reduction in productivity rate. (5) Joints exhibit good mechanical properties in tension and bending, high fatigue resistance, minimal porosity, and low shrinkage rates.
Laser-assisted friction-stir welding (LFSW)	(1) Lack of studies to optimize the welding parameters. (2) Available investigations are limited to aluminum composites that have a low melting point. (3) It is not recommended for welding thick joints.
Electrical current-aided friction-stir welding (EFSW)	(1) Fluctuation in electrical current due to joints resistance causes temperature variation, negatively affecting the welding process. (2) High electric current intensities result in extra grain refinement. This leads to the formation of a ductile and soft joint at the welding zone. (3) High energy requirements.
Ultrasonic vibration-assisted friction-stir welding (UVFSW)	(1) Lack of research in stabilizing and optimizing process parameters. (2) The duration of vibrations can adversely affect the intermetallic formations resulting in crack nucleation and propagation.

rotational and transitional rates can lead to the formation of defects like cavities, tunneling defects, and hook defects. These defects significantly deteriorate the mechanical performance of the joint. FSW reduces mechanical force applied on the welding tools and enhances the tool's life.

Acknowledgments

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铝合金及铝金属基复合材料搅拌摩擦焊接工艺的研究进展

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摘　要：焊接在汽车、航空航天、机器人、建筑等行业具有重要的作用。这些行业常用非焊接方法制造很多铝合金零部件或系统。然而，由于不可热处理合金的存在、孔隙、凝固和熔融裂纹等因素，铝合金的熔焊具有挑战性。许多制造商采用传统的空气搅拌摩擦焊(FSW)焊接合金和异质材料，也有许多研究报道关于该传统 FSW 技术在焊接金属和聚合物材料，尤其是铝合金和铝基复合材料方面的缺点。近年来，为了克服传统 FSW 技术焊接铝合金的缺点，开发出很多其他 FSW 技术，例如水下搅拌摩擦焊 (UFSW)和振动搅拌摩擦焊(VFSW)等。本文综述了近年来铝合金及铝基复合材料(Al MMCs)搅拌摩擦焊接工艺的研究进展，讨论了传统的 FSW 技术和最先进的 FSW 工艺参数对铝合金和铝基复合材料焊接质量和强度的影响，并比较了每种方法的优缺点。VFSW 在能源效率和经济成本方面具有优势，并可根据应用情况进行多种改进，是焊接铝接头的一种可行的选择。然而，目前对 Al MMCs 搅拌摩擦焊的研究明显较少，这应给予足够的关注。

关键词：铝合金；铝基复合材料；传统 FSW 技术；先进 FSW 技术；显微组织；力学性能

(Edited by Bing YANG)