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Review article

Friction Stir Welding: A Comprehensive Review of Non-Metallic Particle Reinforcement in Joints

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A B S T R A C T

Friction Stir Welding (FSW), a solid-state joining technique, has demonstrated superior efficiency in welding metal-matrix-reinforced composite joints. FSW has garnered significant attention in recent years as a viable technique for joining similar and dissimilar materials, particularly those reinforced with non-metallic particles. By utilizing diverse mixture of reinforcement particles and base matrices, FSW outperforms traditional fusion joining methods in terms of effectiveness and reliability. Despite significant progress, challenges persist in achieving a homogeneous distribution of Non-metallic particles in the weld zone, which directly impacts macrostructural and microstructural characteristics. Moreover, the mechanical properties of these welds are intricately linked to process parameters, influencing grain enhancement and reinforcement particle distribution. This review critically evaluates these aspects, providing insights into the current understanding and highlighting areas for future research.

1. INTRODUCTION

Friction Stir Welding (FSW) has revolutionized the field of materials joining by introducing a solid-state welding process that offers distinct advantages over conventional fusion welding techniques [1,2]. Unlike fusion welding, which involves the melting of base materials to form a joint, FSW achieves bonding through a combination of frictional heat and mechanical deformation without melting the workpieces [3]. This characteristic of FSW not only eliminates the risk of solidification defects and welds metal contamination but also provides several environmental and operational benefits, such as reduced energy consumption, elimination of toxic fumes, and enhanced safety [4,5].

One area where FSW has particularly excelled is in the welding of non-metallic particles reinforced composites. These materials, consisting of a matrix material reinforced with non-metallic particles such as ceramics, polymers, or carbon fibers, are widely used in various industries including aerospace, automotive, and transportation due to their unique combination of properties such as high strength, lightweight, and corrosion resistance

[6–8]. However, joining these materials using traditional fusion welding techniques poses several challenges, including the formation of solidification defects, degradation of reinforcement particles, and difficulties in achieving a uniform distribution of reinforcement within the weld zone [9,10].

In contrast, FSW offers a viable solution to these challenges by its solid-state nature. Throughout the FSW process, a specially designed rotating tool generates frictional heat and applies mechanical pressure to the workpieces, causing plasticized material to flow and form a joint. Since there is no melting of the base material, the integrity of reinforcement particles is preserved, and the risk of defects associated with fusion welding is minimized. Moreover, the absence of molten metal reduces the likelihood of intermetallic formation and ensures a cleaner, more homogeneous joint interface [11,12]. One area where FSW has particularly excelled is in the welding of non-metallic particles reinforced composites. These materials, consisting of a matrix material reinforced with non-metallic particles such as ceramics, polymers, or carbon fibers, are widely used in various industries including aerospace, automotive, and transportation due to their unique combination of properties such as high strength, lightweight, and corrosion resistance. For instance, carbon nanotubes (CNTs) are often incorporated into polymer matrices to enhance mechanical properties, electrical conductivity, and thermal stability [13–15]. However, joining these materials using traditional fusion welding techniques poses several challenges, including the structure of solidification defects, degradation of strengthening particles, and difficulties in achieving a uniform distribution of added particles within the weld zone.

In contrast, FSW offers a viable solution to these challenges by its solid-state nature. During the FSW process, a specially designed rotating tool generates frictional heat and applies mechanical pressure to the workpieces, causing plasticized material to flow and form a joint. Since there is no melting of the base material, the integrity of reinforcement particles is preserved, and the risk of defects associated with fusion welding is minimized. Moreover, the absence of molten metal reduces the likelihood of intermetallic formation and ensures a cleaner, more homogeneous joint interface. The success of FSW in welding non-metallic particle-reinforced composites lies in its ability to accommodate a variety of combinations of base matrices and reinforcement particles. This versatility allows for tailored joint properties, including enhanced mechanical strength, improved fatigue resistance, and optimized thermal conductivity, to meet the specific requirements of different applications. Furthermore, the solid-state nature of FSW enables precise control over the microstructure and distribution of reinforcement particles within the weld zone, leading to superior mechanical and metallurgical properties compared to fusion welding [16].

In this review, a comprehensive summary is provided of the state-of-the-art developments in FSW of non-metallic particle-reinforced joints. It discusses the influence of different types of reinforcement particles and base matrices on the welding process and resultant joint properties, as well as the challenges and opportunities associated with FSW in this domain. Additionally, recent advancements in process optimization techniques and modeling approaches aimed at enhancing the weld quality of non-metallic particle-reinforced joints are examined.

2. FRICTION STIR WELDING: OVERVIEW

FSW stands out as a solid-state welding method that has revolutionized the field of materials joining. Unlike conventional fusion welding methods that involve melting the base materials to form a joint, FSW achieves bonding through a combination of frictional heat and mechanical pressure, prior to the attainment the melting point of the workpieces. In this approach, the joining process is initiated through the localized application of heat produced by the stirring action of a non-consumable cylindrical tool, accompanied by a moderate clamping force (Fig. 1). This process offers several advantages, including the absence of solidification defects, minimal distortion, and reduced risk of metallurgical changes or contamination. FSW has gained popularity across various industries due to its ability to join materials that are traditionally difficult to weld, including non-metallic particle-reinforced composites [13,17].

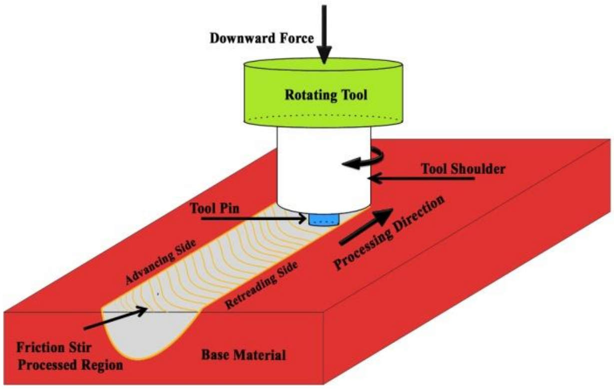

Fig. 1. Schematics of the FSW process.

FSW involves several input process parameters that influence the excellence and characteristics of the welded joint. These parameters include the rotational speed of the FSW tool, the traverse rate of the tool along the joint line, the axial force applied by the tool, and the tilt angle of the tool [18,19]. The tools rotational speed determines the amount of heat generated through friction, while the traverse speed controls the rate of material flow and consolidation [20]. The axial force applied by the tool affects the depth of material penetration and the overall strength of the joint [21]. Additionally, the tilt angle of the tool influences the material flow pattern and the formation of the weld nugget [22,23].

In addition to these primary parameters, other parameters such as material properties, tool geometry and welding environment also play a important task in the FSW process [24]. The FSW tool design, including the shape and profile of the pin and shoulder, affects heat generation, material flow, and joint formation [25]. The properties of the base materials, including their composition, microstructure, and mechanical properties, influence the weldability and joint performance. Furthermore, the welding environment, including feature such as temperature, pressure, and atmosphere, can influence the metallurgical reactions and the excellence of the welded joint.

FSW has found applications in various industries, including aerospace, automotive, shipbuilding, and railways, where it is used to join an extensive variety of materials, including aluminum alloys, steel, titanium, and composites [22,26]. The process offers several advantages over traditional fusion welding techniques, including higher welding speeds, lower energy consumption, and reduced distortion. Moreover, FSW enables the dissimilar materials joining and the fabrication of complex geometries [27].

3. REINFORCING PARTICLES AND METHODS

Various types of particles have been utilized for reinforcement in FSW, aimed at fabricating Metal Matrix Composite (MMC) joints. The quality of MMCs hinges significantly upon attaining an incoherent matrix/reinforcement interface alongside an optimal distribution of reinforcing particles, thereby providing additional benefits to the strengthening process [28–30]. Among the different types of reinforcement particles, non-metallic particles have gained significant attention for their ability to enhance the properties of MMCs [31]. Nano-ceramic reinforcement, in particular, has been extensively studied due to its higher capabilities in improving weld structures. Nano-ceramic reinforcements offer improved mechanical character and tribological properties, making them desirable for creating composites [28]. Ceramic nanoparticles, such as Silicon Carbide (SiC), are widely employed in FSW to enhance common characteristics. Among the various options, SiC nanoparticles stand out for their exceptional wear resistance, impressive chemical durability and elevated hardness, leading to stronger joints with reduced chances of cracking due to the excellent bonding between the nanoparticles and matrix.

Prior to the emergence of ceramic reinforcements, carbon-based materials, including graphene and Carbon Nanotubes (CNTs), have emerged as significant contributors to research in the realm of Metal Matrix Composites (MMCs)[32]. Renowned for their excellent mechanical, physical, thermal and electrical properties, graphene and CNTs stand out as ideal reinforcements for composite structures. Their extensive surface area enables effective interfacial bonding with the composite matrix, consequently leading to noteworthy enhancements in wear resistance and thermal conductivity throughout processing [33]. Nevertheless, the integration of nanoparticles into the FSW procedure and achieving uniform diffusion within the weld, along with the identification of suitable nanoparticles, present certain minor hurdles. For example, groove preparation may be needed to incorporate nanoparticles as reinforcement in the FSW process [34]. Groove preparation facilitates easier incorporation of nanoparticles (Fig. 2a), but squeezing the FSW tool may cause uneven distribution over the weld zone. To address this issue, researchers have explored methods such as creating nanoparticle paste using ethanol solution or using pinless tools to avoid nanoparticle expulsion during welding.

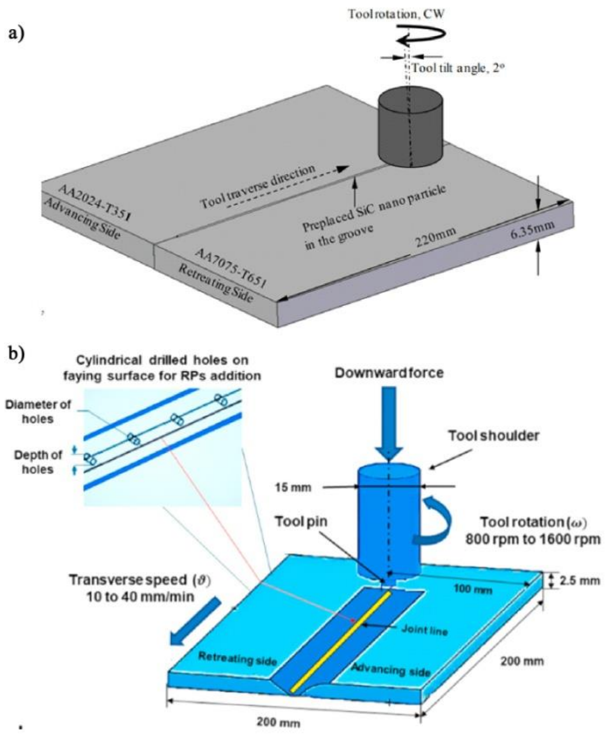

Fig. 2. FSW process illustrates the incorporation of nanoparticles into the base matrix a) drilled holes [34] and b) narrow open-top groove [35].

Further research is needed to explore techniques for consistently scattering nanoparticles all over the weld. One method for nanoparticle reinforcement involves the use of drilled holes in weld surfaces (Fig. 2b), another technique utilizes a Nano-particle Deposition System (NPDS) specially designed to deliver graphite powder through a nozzle for the fabrication of FSSWelded Aluminum alloy 6061-T4 sheets [36]. Carbon-based reinforcement can be deposited in the form of powder, slurry or interlayer, depending on the desired application and characteristics of the composite.

4. MACROSTRUCTURAL AND MICROSTRUCTURAL CHARACTERISTICS OF FSW-MMR JOINTS

During FSW of metal-matrix reinforced joints, assessing the weldment's excellence primarily involves examining the macrostructure and microstructure. However, the method becomes more intricate when excessive or insufficient heat contribution occurs in the welded zone, especially with the addition of Reinforcement Particles (RPs), as highlighted by Kumar et al [37]. This complexity can lead to the creation of weld flaws such as tunnels and pinholes within the weld zone of FSW-based Metal-Matrix Reinforced (MMR) joints. Abioye et al [38]. emphasized that these defects cause important alterations in the structural geometry of the weld area, thereby affecting the mechanical strength of the reinforced FSW joints. Consequently, Paidar et al. [39] advocated for careful selection of welding process parameters to mitigate such defects during FSW joints. Thus, a comprehensive examination of various metallurgical characteristics of FSW-reinforced joints is crucial for ensuring the weldment's integrity and performance, as discussed thoroughly in the subsequent sections. During the macrostructure examination of composite FSW joints, one of the key features identified is the profile and dimension of the nugget zone, which can vary considerably depending on various factors. The shape of the nugget zone is significantly influenced by various factors, including the profile of the tool, the temperature during the process, the thermal conductivity of the materials involved, and the incorporation of reinforcement particles.

When conducting FSW on AA7075-O with the addition of SiC, Hamdollahzadeh et al. [40] found a basin-shaped nugget area in the core of each weldment. They found that altering the rotational direction of the tool between passes had minimal impact on the nugget area shape. On the other hand, Bahrami et al. [41] discovered the shape of the nugget zone was not significantly changed by changing the tool geometry in between FSW runs. However, they noted that the inclusion of reinforcement particles played a crucial role in determining the overall appearance of the nugget zone.

The elliptical nugget zone (NZ) during dissimilar Friction Stir Welding (FSW) of AA5083-H116/AA7075-T6/Al2O3 welds was noted by Saeidi et al. [42]. They pointed out that several variables, including fabrication criteria, shapes, temperatures, and the heat conductivity of the materials, affect the NZ shape. Interestingly, they found that the addition of Reinforcement Particles (RPs) in the NZ does not affect its shape during FSW. Similar to this, Nikoo et al.'s [43] study of the FSW of AA6061-T6/Al_2O_3 welds found no influence on the form of the NZ during FSW from post-weld thermal treatment, changes in traveling speed, or the addition of RPs. A similar elliptical-shaped NZ was seen during FSW of an AZ31Mg alloy supplemented with SiC nanoparticles by Abdolahzadeh et al. [44]. They explained that the thermal input produced throughout the process is what caused the formation of an elliptical NZ shape.

A difficult process combining thermal-mechanical interactions between the reinforcement material, work material and tool is creating a joint in FSW reinforced by nanoparticles [45]. The dimension and volume addition of reinforcing particles are pivotal factors influencing grain refinement. According to the Zener pinning effect, the presence of reinforcing particles leads to grain boundary displacement and recrystallization. FSW was successfully employed to fabricate dissimilar joints between AA 7475-T7 and AA7075-T6 by incorporating varying volume fractions of ceramic particles such as Al_2O_3 and SiC, as demonstrated by Anand & Sridhar [46]. Their study revealed that the addition of these ceramic particles significantly improve the mechanical strength of the different aluminum joints due to the homogeneous circulation of reinforced particles within the SZ. Specifically, SiC particles reinforced joints exhibit superior joint strength compared to Al_2O_3 joints, attributed to the grain enhancement within the SZ. The effect of particle strengthening on SZ grain size after FSW is briefly summarized in Table 1, emphasizing the difference from unreinforced joints [47-51].

Table 1. Grain Size of the FSW-reinforced aluminum alloy with nanoparticles.

Base Material	Reinforcement particles	Avg. Grain Size		% of Reduction in Grain Size	Ref
		With particles	Without particles		
AA6082	SiC	5.5	4.2	23	[47]
AA 5083	TiO_2	18.5	8.5	54	[48]
AA 2021-T3	Al_2O_3	2.2	2.1	4.5	[49]
AA 5083 H111	SiC	6.6	5.3	19.6	[50]
AA 5083 H111	TiC	6.6	4.7	28.78	[50]
AA 7075	SiC	4.8	3.8	20	[41]

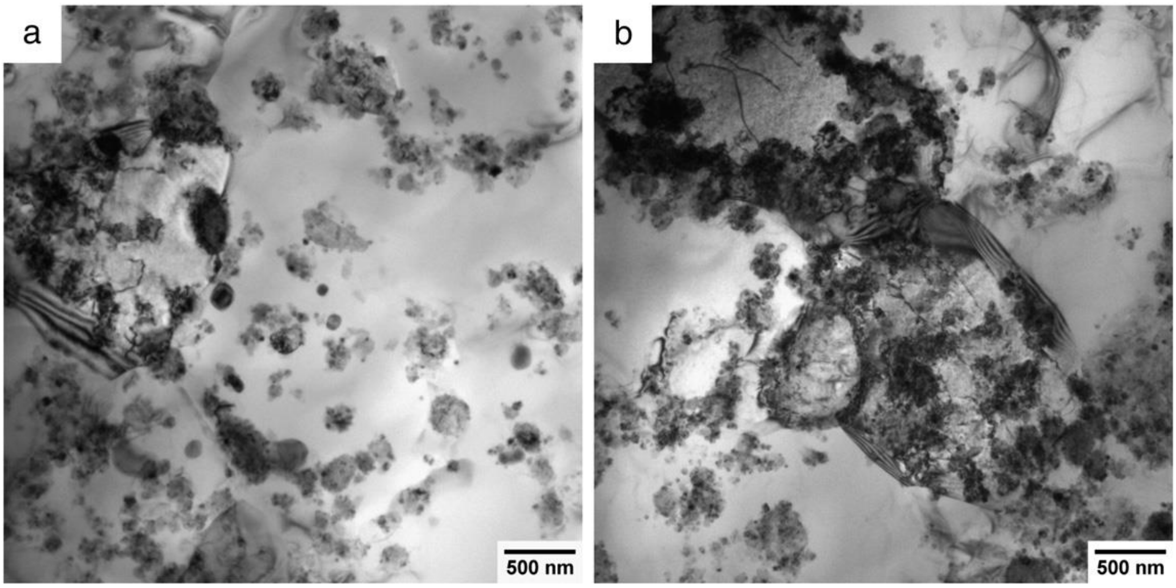

Fig. 3. TEM images of Al-SiO_2 Friction stir processed samples by the tool rotation speed of (a) 500 rpm and (b) 1400 rpm [52].

The distribution of SiO_2 nanoparticles in aluminum matrix composites development using Friction Stir Processing (FSP) at various tool rotational speeds is depicted in Fig. 3. In the weld produced at a lower speed, the majority of nanoparticles are equally detached throughout the weld region. Fig. 3 (b) illustrates the observed nanoparticle agglomeration in the specimen treated at an increased tool rotational speed.

The quantity of pass conducted during FSW/FSP is pivotal in influencing the diffusion of nanoparticles within the weld zone. By adding nanoparticles, Patel et al. [51] examined the effects of using one, two, four, and six passes for FSP on AA6063-T4. Their research unveiled that specimens subjected to six passes demonstrated enhanced fatigue strength in comparison to others, owing to the uniform dispersion of nanoparticles, as depicted in Fig. 4. Bahrami et al. [41] researched on FSW of AA7075-O/SiC and found reduction in the SZ was correlated with the decreasing grain size of the weld surface. Abioye et al. [38] investigated the FSW of AA6061-T6 with various particles such as SiC, B_4C, and Al_2O_3. They observed that the larger size of B_4C compared to Al_2O_3 and SiC nanoparticles resulted in more concentrated fragmentation within the NZ. Because fewer particles offered less resistance to the FSW tool's stirring action, larger particles broke into smaller ones, resulting in an intensive fragmentation that ultimately decreased the average size of B_4C nanoparticles in the NZ. Conversely, the initial size of Al_2O_3 and SiC nanoparticles resulted in less intense fragmentation, leading to only marginal differences in the dimension of the reinforced particles.

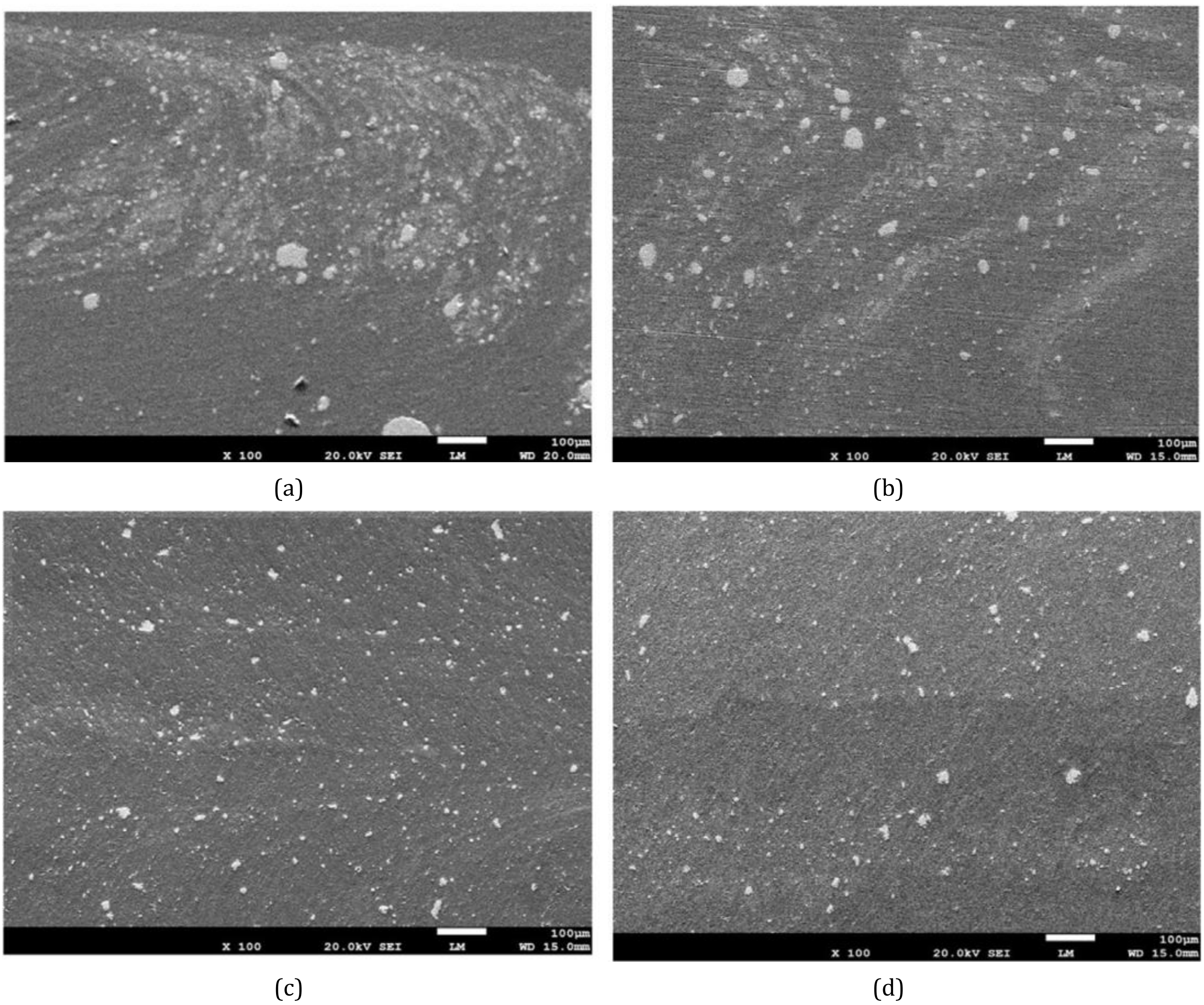

Fig. 4. SEM images illustrating the particles distribution in the AA6063-T4 with different passes (a) single (b) two (c) Four and (d) six [51].

Abioye et al. [53] attribute the stirring action caused by the rotating tool for the homogeneous dispersion of B4C augmentation in the weld zone as compared to Al_2O_3 and SiC augmentation through FSW of AA6061-T6/B4C/Al2O3/SiC. This stirring action guide to the fragmentation of large B_4C nanoparticles into smaller ones with minimal resistance during the FSW process, resulting in a uniform distribution of B_4C nanoparticles in the NZ, as depicted in Fig. 5. In addition, some studies have used a range of heat treatment method, including maximum aging, re-aging and retrogression to stop annealing-induced grain coarsening in the weld zone. This grain coarsening significantly affects the distribution of reinforcement particles in the NZ during FSW, as illustrated in Fig. 5. These heat treatment processes play a crucial role in optimizing the mechanical properties and microstructure of the FSW processed joints.

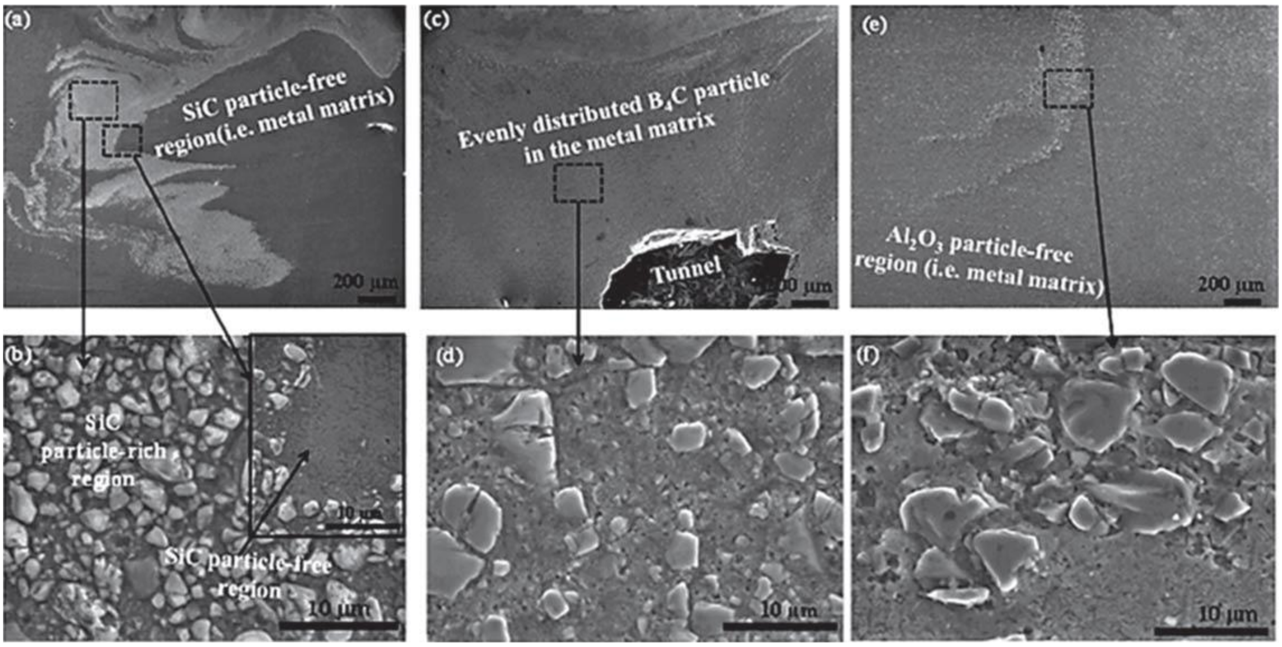

Fig. 5. SEM pictures depicting the microstructures of the friction stir welded joints added with (a), (b) SiC, (c), (d) B_4C, and (e), (f) Al_2O_3 [53].

5. MECHANICAL CHARACTERISTICS OF FSW-MMR JOINTS

Numerous factors contribute to the mechanical property of joints reinforced with nanoparticles during FSW, including metallurgical relationship among particles and the matrix under dissimilar input constraint and grain size. To improve mechanical quality such as tensile strength, hardness, toughness, and fatigue resistance, nanoparticles are incorporated during the FSW process. Mechanical characterization plays a pivotal role in determining the overall quality of the weld.

In a study by Moradi et al. [54], macro and micro SiC particles were integrated to produce dissimilar FSW joints between AA6061 and AA2024 alloys. The research revealed that the nugget grain size in joints reinforced with nano-size SiC decreased more significantly compared to those reinforced with micro SiC particles. Additionally, mechanical properties exhibited improvement in joints reinforced with nano SiC particles compared to those reinforced with micro SiC. Furthermore, it was observed that agglomerations of micro-scale particles were more noticeable within the nugget zone than in joints reinforced with nano SiC particles.

Similarly, Nosko et al. [55] investigated the effect of three different sizes of reinforcement particles on Al_2O_3-reinforced FSW of aluminum composite. Their findings echoed those of Moradi et al. [56], indicating a related development in nugget grain size reduction and mechanical property enhancement with the use of smaller reinforcement particles. These studies underscore the significance of particle size in influencing the microstructural evolution and mechanical properties of FSW joints reinforced with ceramic particles. The finer size of nanoscale particles facilitates more uniform dispersion within the matrix, leading to improved grain refinement and enhanced mechanical performance. These insights contribute to the ongoing efforts in optimizing the fabrication process of MMC joints through FSW, aiming to achieve superior weld quality.

Increases in tool rotational speed significantly influence the strength of particle-reinforced joints [57,58]. Fig. 6 illustrates the variations in strength of SiC-reinforced dissimilar aluminum joints at different tool rotation speeds. Additionally, higher rotational speeds generally correlate with improved interfacial bonding and more homogeneous dispersion of reinforcement particles within the joint, contributing to enhanced mechanical properties.

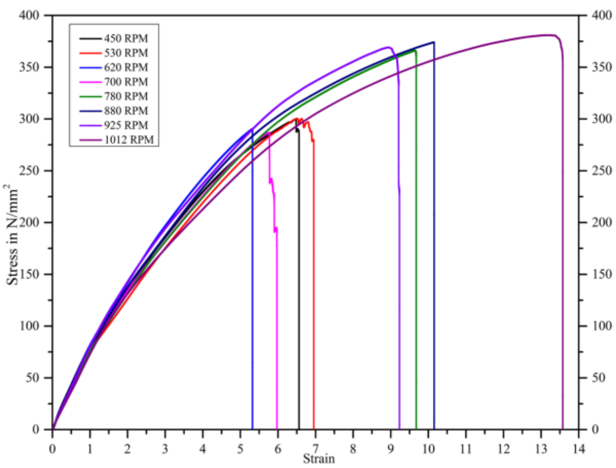

Fig. 6. Tensile behavior of SiC-reinforced FSW dissimilar joints at varying tool rotation speeds [34].

Variations in microstructural features such as grain size and grain orientation in the nugget zone (NZ) are key factors influencing the hardness of FSW joints. Conversely, Singh et al. [59] attribute anisotropy in the microstructure, affecting microhardness, to factors such as strain rate in the NZ, the adding of Reinforcement Particles, and heat input, particularly in particles reinforced FSW joints. Because of the variance in the Coefficient of Thermal between particles and matrix, Bahrami et al. [41] have observed that attaining a homogenous distribution of RPs in the NZ during FSW causes the pinning up of dislocations and rises in dislocation density. This phenomenon leads to the generation of residual stress during cooling, thereby increasing the microhardness of the NZ. This increase in microhardness is primarily attributed to grain size, according to the Hall-Petch relationship. The correlation between grain size and microhardness highlights that smaller grain sizes in the NZ correspond to higher microhardness. However, Aleem et al. [60] propose that the annealing effect brought on by heat input during the welding process is responsible for the decrease in microhardness of the NZ.

These findings collectively underscore the intricate interplay of various factors, including microstructural features, RP distribution, heat input, and grain size, in determining the microhardness of FSW welds, particularly in metal-matrix reinforced butt joints. Understanding and optimizing these factors are essential for achieving desired mechanical properties and overall weld quality in FSW applications.

In recent studies, the incorporation of macro and micro SiC particles in the fabrication of dissimilar FSW joints, particularly involving AA6061 and AA2024 alloys, has yielded valuable insights. Research conducted by Moradi et al. [56] found notable differences between nano-size SiC-reinforced joints and those reinforced with micro-sized SiC particles during the FSW process. In particular, it was noted that in nano SiC-reinforced joints, the particle size inside the weld nugget zone decreased considerably compared to micro SiC-reinforced joints. Additionally, nano SiC-reinforced joints exhibited improved mechanical properties, including enhanced, in comparison to micro SiC-reinforced joints. Moreover, observations revealed a higher prevalence of particle agglomerations within the nugget zone of welds reinforced with micro-scale particles as opposed to nano SiC.

Similar findings were reported by Nosko et al. [55] in their study of Al_2O_3-reinforced FSW of aluminum composites. By incorporating three different sizes of reinforcement particles, they confirmed the Zener pinning effect, which has significant implications for weld characteristics and microstructural development. This effect underscores the importance of careful control over the adding of nanoparticles within the joint zone, as it substantially influences the tensile strength and hardness of the resulting joints, as shown in Fig. 7. Notably, a raise in the volume addition of nanoparticles correlates with higher joint hardness.

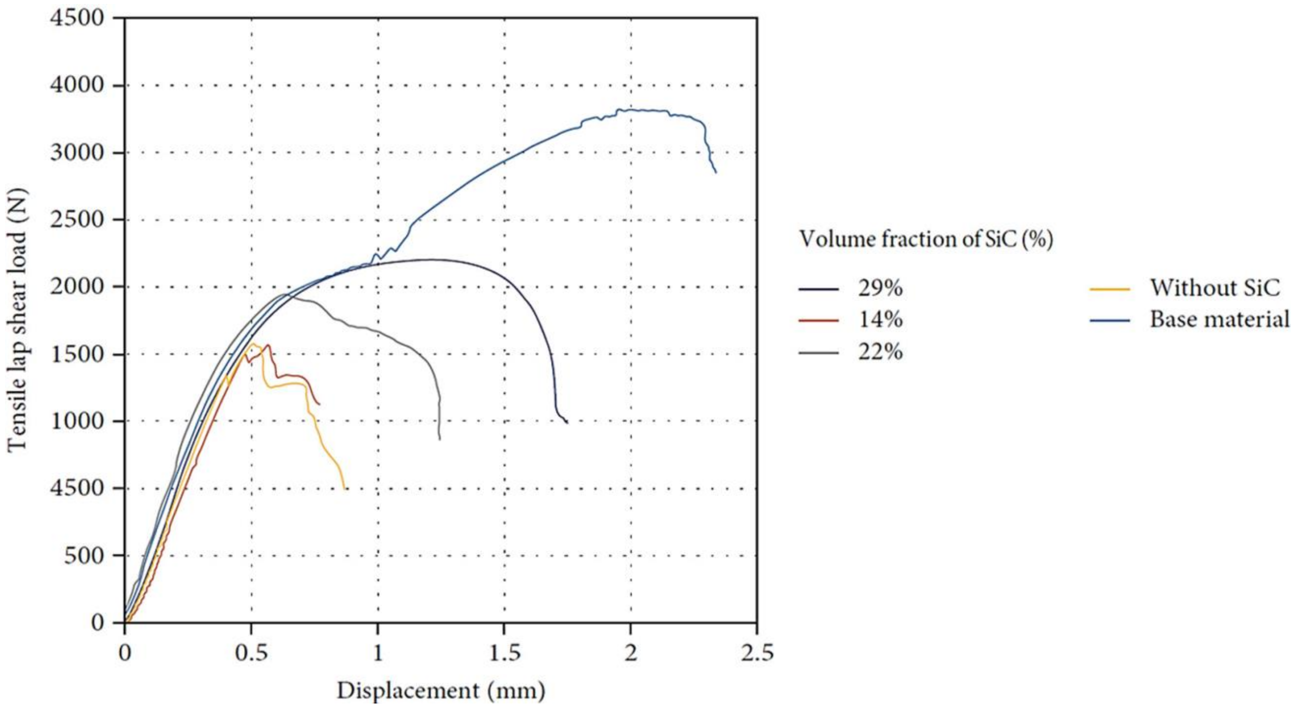

Fig. 7 Tensile shear force with different SiC adding levels [61].

Furthermore, because of the SZ's grain improvements, SiC-reinforced welded samples have shown a noticeably longer fatigue life than unreinforced welds. During fatigue testing, SiC nanoparticle-reinforced specimens exhibited fracture away from the SZ, whereas unreinforced specimens fractured within the stir zone. Additionally, SiC reinforcements have been shown to positively impact energy absorption, thereby enhancing toughness [62]. These findings collectively underscore the promising potential of incorporating reinforcing element in FSW processes. Not only do they contribute to enhanced mechanical strength and fatigue resistance, but they also enable the growth of microstructures conducive to enhanced joint performance. Further research in this area holds significant promise for advancing the understanding and application of MMC in FSW joints.

6. CONCLUSIONS

FSW has appeared as a highly efficient technique for welding particle-reinforced composite joints, offering advantages over conventional fusion welding methods. Particularly, FSW has demonstrated exceptional capabilities in joining materials reinforced with non-metallic particles, such as ceramics, polymers, and carbon fibers.

Through the incorporation of various configurations of base matrices and reinforcement particles, FSW enables the fabrication of joints with tailored properties, including enhanced mechanical strength, improved fatigue resistance, and optimized thermal conductivity.

Even with great advancements, it is still difficult to distribute reinforcing particles uniformly throughout the weld zone, which affects both macrostructural and microstructural properties.

In addition, the mechanical properties of these welds are intricately linked to process parameters, influencing grain refinement and reinforcement particle distribution. The combination of metal matrix materials and reinforcing particles affects the fracture and wear properties as well. Studies have shown that adding nanoparticles to FSW can improve the properties of the weld, facilitate the production of microstructures, and reduce the occurrence of joint flaws.

Moving forward, it is essential to address the challenges associated with reinforcement particle distribution and optimize process parameters to achieve superior weld quality and performance. Future research should focus on refining process optimization techniques and modeling approaches to enhance the quality and reliability of non-metallic particle-reinforced joints.

Overall, FSW holds immense promise for advancing the field of materials joining, particularly in the fabrication of metal-matrix reinforced composite joints. Through leveraging the solid-state nature of the process and optimizing reinforcement particle distribution, FSW has the possibility to transform various industries, including aerospace, automotive, and transportation, by enabling the production of high-performance and lightweight components.

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