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REVIEW ARTICLE

Comprehensive review of microstructural and mechanical properties of aluminum composites fabricated by friction stir processing

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Abstract

Metal matrix composites (MMCs) have become integral to modern technological advancements due to their superior mechanical properties, such as enhanced tensile strength, hardness, and reduced weight. Among these, aluminum metal matrix composites (AMCs) have gained significant attention in research and industry because of their versatility and wide range of applications across aerospace, automotive, and structural sectors. Despite their advantages, challenges arise during the joining and fabrication processes.

This paper provides a comprehensive review of factors influencing the mechanical and microstructural properties of AMCs when joined using the friction stir welding (FSW) process. FSW, a solid-state joining technique, has shown great potential in overcoming issues associated with traditional welding methods, such as defects and poor joint quality. Key parameters, including tool geometry, welding speed, rotational speed, and the influence of reinforcements, are explored to understand their roles in optimizing the properties of AMCs.

1. Introduction

There is a huge potential for aerospace industries, and enhanced mechanical properties can be achieved with AMCs. A new generation of high-strength materials and lightweight materials is possible with the AMCs processed by FSW. With the conventional welding processes, the implementation of AMCs is not possible in the aviation industry. The fusion welding method confirms the formation of brittle secondary phases in the weld pool or decomposition of reinforcement in the molten metal due to the reaction between reinforcements and aluminum matrices. The various properties like solidification cracking, distortion, porosity, and reinforcement dissolution have been reduced with the FSW process, and efficient joints have been made [1]. AMCs have wide applications in the field of marine, defense, aerospace, sports, and automotive industries because of their inherent characteristics, i.e., improved stiffness, controlled thermal coefficient, high strength-to-weight ratio, improved abrasion, and wear resistance as compared to conventional alloys. The various conventional reinforcements like boron, nitrides, carbides, and oxides of ceramic particulates were used for the fabrication of such composites.

The significant constraints of metal matrix composites were the availability and high cost of ceramic reinforcing material in developing countries. Moreover, poor ductility and fracture toughness are the other challenges for metal matrix composites. From the literature review, the various problems were addressed and resolved by selecting the appropriate reinforcing material. Researchers considered the three strategies to improve the performance characteristics at an optimized cost; the initial strategy attributed to finding an

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alternative as well as cheaper reinforcing material when compared to conventional reinforcements. The following strategy is to enhance the properties of various composites by employing nanoparticles. The use of two or more reinforcing elements developed a hybrid composite, which was used as a third strategy by the researchers. These strategies result in the optimization of mechanical properties and cost as well [2].

1.1 Brief review of FSW

The Friction Stir Welding (FSW) process for joining aluminum was first developed in 1991 by The Welding Institute (TWI) in the United Kingdom. As a solid-state hot working process, FSW achieves peak welding temperatures up to 80% of the parent metal's melting point. This makes it particularly suitable for high-strength aluminum alloys, such as the AA2XXX, AA6XXX, and AA7XXX series, which are typically considered unweldable using conventional methods due to liquefaction cracking in the heat-affected zone (HAZ) and solidification cracking in the weld zone [1]. FSW has gained recognition as an effective method for producing high-performance joints at a relatively low cost. The process utilizes a non-consumable rotating tool composed of a shoulder and pin. During the welding operation, the tool pin is inserted between the faying surfaces of the plates and traverses along the weld joint line. Frictional heat generated by the interaction between the rotating tool and the workpiece softens the material near the tool pin. The softened material is plastically deformed and transported from the advancing side to the retreating side, resulting in the formation of a solid weld joint. The advancing and retreating sides of the weld are determined by the relative directions of tool rotation and traverse movement.

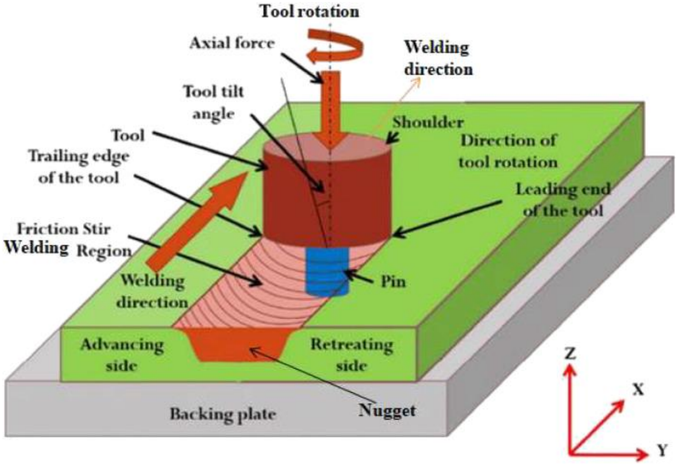

Figure 1: Schematic arrangements of tool and work material in friction stir processing [2]

The advancing side corresponds to the side where the tool rotation aligns with the direction of movement, while the retreating side is where the two directions oppose each other. This distinction plays a significant role in the weld's microstructural and mechanical properties. FSW is versatile and capable of welding various joint configurations, including butt, lap, and T-joints, with remarkable efficiency and integrity. Its ability to address challenges associated with welding aluminum alloys has made it a prominent technique in manufacturing and research applications [1]. FSW is regarded as an environmentally friendly and sustainable welding technique compared to conventional fusion welding methods. This is primarily due to its advantages of zero gas emissions, lower energy consumption, and the elimination of consumable materials such as filler metals, electrodes, and shielding gases. A survey conducted by the American Welding Society in 2002 revealed a significant expenditure of $34.4 billion in the United States on arc welding processes, which included costs associated with consumables, energy consumption, and repairs [1]. FSW's ability to minimize these costs while maintaining high-quality welds highlights its potential as a green alternative for industrial applications.

2. Results and Discussions

2.1 Microstructure evolution of AMSs fabricated by FSW process

The microstructure of Al5083/CeO2 /SiC mono and hybrid surface composites is processed by friction stir. The author reported a uniform distribution of reinforcements along the nugget zone and revealed the refinement of grains as well. The result obtained was that changing the processing directions and increasing the number of passes resulted in more refinement of grains as well as homogeneous distribution of reinforcements. After dynamic recrystallization, the peening effect occurs, which restricts the grain growth due to the addition of reinforcements [3]. Similarly, the microstructural and wear properties of the Hybrid surface composite of Al5083 processed by friction stir processing were analyzed. The effect of reinforcements such as SiO2, MoS2, and their mixture results in uniform distribution formation over the processed zone due to the dynamic recrystallization phenomenon. It can be seen from the figure that the Al alloy substrate and surface composite layer were well bonded to each other, resulting in no void defects [4]. The mechanical, microstructural, and corrosion resistance of Al6061 is reinforced with Boron reinforcement particles fabricated by friction stir processing. As the number of passes increases, the change in the direction of tool rotation between the passes results in the uniform dispersion of Boron reinforcement particles over the stir zone without defects. The fine equiaxed grain obtained due to the presence of boron reinforcements during the fabrication process leads to more refined and smaller size grains as compared with the FSPed base metal [5].

The characterization of fabricated surface composites of A359/(SiC+Si3N4) by stir casting techniques. The microstructure analysis showed the uniform distribution of SiC+Si3N4 reinforcement particles along the A359 metal matrix and showed better wettability [6]. From the XRD results, it was confirmed that there is no interfacial reaction between the reinforcement particles and A359. The effect of processing parameters on the microstructure and mechanical properties of AA1060 reinforced with SiC reinforcements processed by friction stir processing were investigated [7]. At the matchable values of traverse speeds, number of pins of tool, and rotational speed, the microstructure of the composite resulted in the uniform distribution of SiC particles and super refined as well. A higher degree of refinement of grains and uniform distribution of SiC reinforcement particles were obtained with the multi-pin tool than with a single-pin tool. The hybrid surface composites AA6061/(B4C+MoS2) were fabricated by friction stir processing. The smooth quality surface was obtained for the hybrid composite samples. The uniform dispersion of reinforcement particles without the formation of clusters and agglomeration is achieved with the multi-pass friction stir processing in accordance with the change in direction after each pass. The opposite direction of the multi-pass strategy can be applied for the production of surface composite. A healthy bond exists between AA6061 and the hybrid surface composite in the matrix without defects [8].

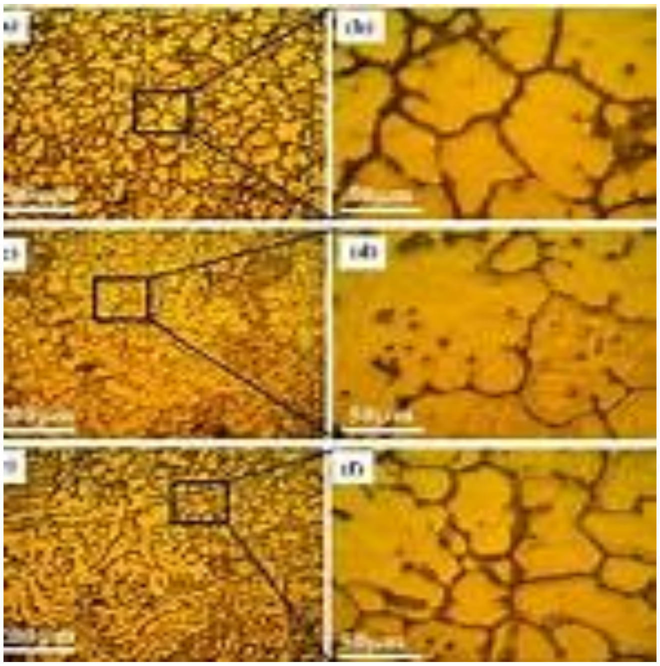

Figure 2: (a) SEM image showing microstructure of the base material, (b) TEM image from microstructure of FSPed sample, SEM micrographs showing (c) good bonding in hybrid composite–matrix interface, and(d) reinforcing particles distribution in the surface of hybrid composite [4].

The tribological properties of hybrid surface composite A413/SiC using MoS2 lubricant particles were investigated [9]. As compared with base metal, the FSPed region exhibited a much more homogeneous microstructure. In the stir zone, high frictional heating and intense plastic deformation occur during friction stir processing, leading to recrystallized fine-grained microstructure. The microstructural analyses of similar and dissimilar friction stir welding of aluminum metal matrix hybrid composite. The stir zone of AA7075 and AA5754 exhibits the equiaxed grain as the dynamic recrystallization occurs due to severe plastic deformation, viscous dissipation, and frictional heating. The microstructure revealed the uniform distribution of the nano-sized AL203 and micro-sized B4C reinforcements in both AA7075 and AA5754 [10]. The improved mechanical and tribological properties of CB and SiC reinforced Al 7075 hybrid composites fabricated by friction stir processing. Hybrid composite materials are processed by a bottom pouring stir casting machine with a vacuum facility [11]. The microstructure was analyzed using an optical microscope. With the addition of CB and SiC reinforcement particles in the matrix, the ultrafine-equiaxed grains were obtained after applying the FSP. As from the figure, it has been evident that proper distribution and de-agglomeration of SiC and CB reinforcement particles in the aluminum matrix results in better mechanical properties. Moreover, the addition of reinforcements leads to the increased density of castings.

The wear behavior of hybrid surface composites of AA6082 alloy fabricated by friction stir processing was investigated. The reinforcements used in the process were Yttrium oxide (Y2O3) and graphite (Gr). The volume % of graphite content was kept constant at 4vol. % and Yttrium oxide (Y2O3) was varied at 2,4 at 6 vol.%. The rotating tool causes vigorous stirring action, which leads to high plastic strains at the Stir Zone, resulting in the grain refinement of the FSPed hybrid surface composites. The grain refinement also occurs due to the effect of dynamic recrystallization, which was a result of the pinning effect [12]. The fabricated hybrid surface composite on Al-Zn-Mg-Cu alloy by friction stir processing. In this process, the reinforcement used were TiB2, Al2O3, Mg, and Zn in varied proportions such as 67.5, 22.5, 6.5, and 3.5 wt.%, respectively. The macro and microstructure showed a smooth surface texture with uniformly spaced ripples without any surface defects. With the increase in rpm of the tool, the heat input also increases, which results in the reduction of flow stress and enhances the movement of material. This leads to the better dispersion of reinforcement particles in the stir zone [13]. The mechanical properties of friction stir processed AA7075-T6 alloy surface hybrid composites. The SiC and Gr were used as reinforcement materials. There was no indication of interfacial reaction products between the composites Al-SiC and Al-Gr, as it exhibits a better interface for intimate bonding. Moreover, there is less oxygen content in the coating layer, which eliminates the oxidation reaction during FSP. There was a homogeneous distribution of reinforcement particles throughout the substrate, as shown in Fig (2). It is evident from the microstructure that the substrate and hybrid composite layer were well bonded to each other without any defects. The experiment on wear properties of aluminum alloy 6082/CaCO3 composite processed by friction stir processing was performed [15]. The CaCO3 particles broke into smaller particle sizes because of the stress developed by the tool rotation, which tends to stop the movement of grain boundaries and reduce the grain size during the FSP process. Moreover, there was a reduction in grain size because of dynamic recrystallization and the Zener pinning effect. The addition of CaCO3 in the AA matrix gives a better metallurgical bonding due to the flow stress of the plasticized material by the axial loading throughout the FSP process. The FSP-processed welding of AA6082/ CaCO3 is attributed to void-free joints. The effects of mono and hybrid composites of Al7075 fabricated by friction stir welding. The monohybrid composites were B4C and TiB2 reinforcement particles. The fine recrystallized grains were observed in the matrix of both mono and hybrid composites. In the processed composites, the ceramic particles were dispersed homogeneously throughout the processed zone. Initially, the grain size of ceramic particles was larger than that of recrystallized grains after the FSP fabrication. The decrease in particle size was achieved with 100% B4C mono composite, contrary to 100% TiB2 mono composite during the FSP process. The enhanced reinforcement particle size has been observed with 100% TiB2 and 50%B 4 C-50%TiB2 composites [16]. The effect of secondary phase particles of reinforcement on the tribological properties and microstructures of AA7075 hybrid surface composites fabricated by friction stir processing were analyzed. The AL203 and SiC were used as reinforcement particles. The as-cast AA7075 had agglomerations and a coarse-grained structure initially. The stirring action of the tool imparts force on the reinforcement particles along the groove into plasticized AA7075. Due to the dynamic recrystallization and Zener pinning effect, the reinforcement particles were uniformly dispersed throughout the stir zone of the aluminum metal matrix, resulting in finer grains [17].

2.2 *Mechanical and tribological properties of AMCs fabricated by FSW process*

To meet the requirement of ever-demanding various industrial sectors, there is a need to fabricate composites with tremendous mechanical and tribological properties. To overcome these requirements, in the past decade, researchers have shifted their focus to aluminum matrix composites (AMCs) fabricated by friction stir welding (FSW). The wear and mechanical properties of surface hybrid composites of Aluminum 6061-T6 alloy [(SiC+Gr)] and [(SiC+Al2O3)] prepared by friction stir processing were investigated. Both the reinforcements were analyzed at various rotational speeds (900 rpm, 1120 rpm, and 1200 rpm). As the rotational speed decreases, microhardness increases due to the availability and pinning effect of reinforcements. The microhardness of SiC with Al2O3 is higher than SiC-based Gr. The wear rate increases as the rotational speed increases due to the high heat generation, which leads to the softening of the matrix as over-aging occurs. The wear rate is higher in Al-SiC/Al2O3 when compared with Al-SiC/Gr. Moreover, tensile strength decreases with an increase in rotational speed [18]. The influence of process parameters on the wear properties of aluminum matrix composites was analyzed. The wear properties were tested at constant rotational speed and load. The investigation results showed an increase in wear resistance as the welding speed increases and a decrease as the rotational speed increases. Among different tool profiles (square, hexagonal, and octagonal), the square pin profile exhibited better wear resistance [19]. Tribological and microstructural performance of aluminum alloy-based hybrid composite fabricated by friction stir processing revealed higher hardness in hybrid composites when compared with the base material. Moreover, Al/SiCp/MoS2 particles show lesser hardness than Al/SiCp. The variation of wear rate with the sliding distance is higher for the base metal, and wear resistance for Al/SiCp/MoS2 was the highest among all others. The impact of reinforcements and rotational speed on the mechanical and wear properties of aluminum-based hybrid composites fabricated by friction stir processing. The optimum microhardness is achieved at a rotational speed of 900 rpm, with 8 vol.% of SiCp and 2 vol.% of Grp. Higher wear resistance is achieved at the optimum condition (1120 rpm, 6 vol.% of SiCp, and 3 vol.% of Grp) due to the presence of Gr [20]. The sliding wear behavior of AA6360/(TiC+B4C) hybrid surface composite layer fabricated by friction stir processing was examined. In this experiment, the AA6360/(TiC+B4C) hybrid surface composite is analyzed at different volume ratios of TiC and B4C. During FSP, both reinforcement particles acted as one particle. The lowest wear rate is exhibited by the 50%TiC+50%B4C hybrid surface composite layer [21].

The tribological properties of Al 5083 blades hybrid composite prepared by friction stir processing were also studied. AL/SiC and MoS2 were taken as reinforcements for sample preparation. The highest average hardness is achieved with the SiC sample (102 HV), followed by MoS2 composites. The lowest wear rate is achieved by the hybrid composites, followed by MoS2 composites, and the third place is shown by SiC composites [22]. Composite samples showed more wear resistance than the base metal. The experiment confirms that better wear resistance of Al 5083 is achieved by processing a hybrid composite on its surface. The wear behaviors of AA6063-B4C/TiB2 mono and hybrid composite layers fabricated by friction stir processing were analyzed. Different percentages of milled B4C and TiB2 were utilized in the process. Compared to AA6063 alloy, the incorporation of B4C and TiB2 reinforcements to the surface shows improvement in hardness. The 100% TiB2 surface composite layer indicates higher wear resistance and hardness [23]. The effect of process parameters on the mechanical and tribological properties of Al5052/SiC metal matrix composite prepared by friction stir processing was studied. Various parameters include transverse speed, tool rotational speed, number of FSP passes, particle size, and shift of rotational direction between passes. A decrease in SiC particle size, an increase in the number of particles, and a change in tool rotation between FSP passes improve hardness and wear characteristics [24]. The influences of pin geometry on the mechanical properties of A7075/SiC nanocomposite processed by friction stir welding were investigated. In the experiment, five types of different geometrically pin tools (threaded pin, square, four-flute square, and four-flute cylindrical) were used. The specimen fabricated with a triangular pin tool exhibited the highest ultimate tensile strength. Moreover, the specimen with the highest hardness was prepared with a threaded taper pin. On the contrary, the specimen prepared with a four-flute cylindrical pin showed the least hardness among all [25].

The mechanical properties of nickel particles embedded in aluminum matrix composites were also studied. Ductility and hardness improved through the process. The impact of friction stir processing on the mechanical properties of Al-TiC in situ composite was analyzed. Single and double pass FSP was applied to the composite. A single pass FSP resulted in the breakage of segregation near the grain boundaries and enhanced distribution. Homogeneous and complete dispersion of TiC due to two passes of FSP led to better mechanical properties. Without compromising ductility, strength and hardness were ameliorated by the process [27]. The characterization of titanium carbide-based AA6082 composite fabricated by friction stir processing attributed different volume percentages of TiC particles (0, 6, 12, 18, and 24 vol.%). The effect of the volume percentage of TiC results in a decrease in the area of the nugget zone as the volume percentage increases. The strength of AMC is enhanced by TiC particles. As the volume percentage of TiC particles increases, the microhardness and ultimate tensile strength also increase. The reduction in void formation occurs as well as stiffness in the matrix increases with the increased content of TiC particles. From the sliding wear behavior, the wear rate decreases as TiC particles in the composite increase. Moreover, the enhancement in TiC particles altered the wear mode from adhesive to abrasive [28].

The wear properties of Al 5083 surface hybrid nanocomposites fabricated by friction stir processing were analyzed. Titanium carbide (TiC) and boron carbide (B4C) were reinforced into the Al5083 matrix. Mono and hybrid surface composite layers were produced. The microhardness, tensile, and wear resistance tests were conducted to predict specimen behavior. The highest hardness and tensile strength were achieved with the Al-B4C nano-reinforced composite. High wear resistance was achieved by Al-B4C/TiC, followed by Al-B4C, Al-TiC, without particles, and the base metal [29]. The improvement of tribological and mechanical properties of SiC and CB-reinforced Al 7075 hybrid-based composites fabricated by friction stir processing was observed. The stir casting process was used for the fabrication of AL7075 with reinforcements. Variation of microhardness was observed through the heat-affected zone (HAZ), thermomechanically affected zone (TMAZ), and stir zone. There was an increment in the microhardness of FSP composites compared to cast AA7075, AA7075/SiC, and AA7075/SiC/CB. The aluminum matrix with CB and SiC showed greater wear resistance and 2.5 times increment in ultimate tensile strength (UTS) [30].

The influence of multi-pass friction stir processing on the mechanical and wear analysis of AA5083/ZrO2 nanocomposites was observed. The multi-pass technique using 2, 4, 6, and 8 passes by FSP consistently improved microhardness and tensile properties. Wear resistance was enhanced by multi-pass friction stir processing. The worn surface of the 8-pass FSP composite showed abrasive wear. Both the base metal and 8-pass FSP composite exhibited structures with dimples and voids, indicating ductile fracture. The addition of CNT reinforcement and cerium oxide nanoparticles to the Al5083 surface composites fabricated by friction stir processing led to enhanced tensile strength and hardness values at a 75-25 volume ratio of the mixture of CNTs and cerium oxide hybrid composite. Cerium oxide alone increased pitting resistance [32].

The fabricated Al/Al2Cu in situ nanocomposites by friction stir processing were also examined. The process parameters of FSP for microhardness investigation included travel speed, number of passes, pin profile, and rotational speed. The pin profile was the most dominant factor affecting microstructure. The Vickers microhardness number increased by 57% for in situ nanocomposites compared to the base metal due to the presence of intermetallic compounds and their distribution through the Al matrix [33]. Unreacted Cu nanoparticles and microvoids were observed even after the sixth pass of FSP. The mechanical properties of dissimilar welding of AA6083-T6 and AA5083-H11 reinforced with TiC via friction stir welding showed an 18% increase in microhardness compared to unreinforced ones.

The mechanical properties of hybrid nanocomposites via friction stir processing were analyzed. Mono composites (AA8026-TiB2 & AA8026-Al2O3) and hybrid composites (AA8026-TiB2-Al2O3) were studied. The best distribution of reinforcements in hybrid composites was observed at a rotational speed of 1600 rpm and a traverse speed of 40 mm/min after the fourth pass of FSP. High rotational speed, lower traverse speed, and higher number of FSP passes resulted in superior wear resistance and hardness. The yield and tensile strength improved due to uniform dispersion of ceramic inclusions and reduced grain size [35].

Mechanical properties of similar and dissimilar friction stir welding between commercial pure aluminum and powder metallurgy aluminum hybrid nanocomposite matrix were studied. Aluminum hybrid nanocomposites reinforced with Al2O3 and SiC with a volume percentage of 2 were processed by powder metallurgy routes. At a rotational speed of 1200 rpm and a speed of 50 mm/min, no cracks, voids, or unbounded areas were found on the retreating side. Enhancement in the hardness of the stir zone was attributed to grain refinement and dispersion of hard inclusions. Processing parameters and joint design affected the ductility and tensile strength of similar welds. Fracture occurred at the interface of the stir zone and base metal [36]. The influence of SiC nanopowder on the dissimilar friction stir welding of Al-Mg alloy to A316L stainless steel was investigated. Transverse welding speed played a vital role in enhancing the mechanical strength of dissimilar joints. Microhardness was enhanced by 250% in the stir zone [37].

The processing and tensile analysis of nanosized Al2O3 particle-reinforced aluminum matrix composites were carried out. The composite with nanoparticles was successfully prepared by solid-liquid mixed casting with ultrasonic treatment. Difficulty arose due to the poor wettability and distribution of nanoparticles in the matrix. During solidification, ultrasonic vibration of the composite slurry resulted in a fine grain microstructure and enhanced the distribution of Al2O3 nanoparticles in the matrix. The ultimate tensile strength of the composite under the influence of reinforcement particles improved by 37% [38].

The mechanical properties of dissimilar Al-Cu friction stir welding joints were examined. Al5042 and pure copper were welded. Low traverse speed and high rotational speed were employed. Presence of intermetallic compounds (IMCs) increased hardness at the Al/Cu interface. Nano-scale reaction layers and composite-like structures improved mechanical strength and metallurgical bonding. Joint efficiency and tensile properties also improved. Upon applying a bending test, no cracks were observed [39]. The influence of B4C particles on the mechanical properties of Al6061 alloy fabricated by FSW showed good bonding of reinforcement with the matrix at the fourth FSP pass with homogeneous distribution of B4C reinforcements. The nugget zone also exhibited higher average hardness. Wear resistance considerably improved due to enhanced hardness and distribution of hard reinforcement particles in the surface of the composite layer [40]. The impact of cylindrical pin diameters in dissimilar friction stir butt-welded aluminum alloy (AA7075-T6 and A384-T6) of 6.5 mm thickness was analyzed. Various parameters such as tool pin diameter, welding speed, and tool rotation speed were varied to analyze joint characteristics. Onion ring formation was observed due to the impact of tool thrust on the FSW joint surface. Fracture occurred on the welding neck of A384-T6 during UTS operation, indicating lower yield strength and elongation. The maximum ultimate tensile strength value was achieved at 800 rpm, 40 mm/min, and a 6 mm tool pin diameter.

The hybrid surface composites of AA5083, reinforced with titanium oxide and silicon carbide, were fabricated. Process parameters employed included welding speed, number of passes, and rotational speed. Ultimate tensile strength was computed, and a modeling equation was developed using response surface methodology, confirmed by ANOVA. Results showed the number of passes dominated by 18% over the tool's revolving speed, with a 12% enhancement. Ultimate tensile strength increased by 50%. The hybrid Gr/SiC reinforced AMCs (Al-5086) by friction stir processing were analyzed. A Taguchi-based L27 orthogonal array was used. Process parameters like rotational speed, traverse speed, and tool geometry were examined for their effects on mechanical properties. Developed AMCs confirmed improved hardness and tensile strength under optimum conditions, showing plasticized surface precipitates of matrix and reinforcements [43].

Processed AL5083 with CNTs and Al2O3 nanoparticles reinforcements by friction stir processing were investigated for mechanical and tribological properties. Mechanical properties such as hardness and strength increased due to the load barrier characteristics of hybrid reinforcement nanoparticles. Wear properties also enhanced as CNTs and Al2O3 nanoparticles reduced direct contact between the hardened steel disk and matrix. Hybrid aluminum bagasse ash graphite composite fabricated by friction stir welding was analyzed. Process parameters like tool rotation speed (1000 rpm, 1250 rpm, and 1500 rpm), welding speed (3, 6, and 9 mm/min), and reinforcement weight percentage were investigated using a parametric Taguchi approach. With an increase in reinforcement weight percentage, tensile strength improved. Welding speed showed minimal contribution to the output. ANOVA confirmed the response. Optimal parameters for better welding conditions were 1500 rpm tool rotation speed, 12 wt.% reinforcement volume, and 6 mm/min welding speed. RCS AA5754 and AA7075 stir cast with nanosized Al2O3 and microsized B4C were analyzed under varying pin and shoulder profiles, tool materials, rotational speed, tilt angle, and traverse speed. Better microstructures were observed with triangular and square pin profiles compared to cylindrical pins. Greater weld strength was attributed to tapered shoulders. Stainless steel tools exhibited lower wear rates than high-carbon, high-chromium steel tools [46]. Hybrid aluminum composite for optimized process parameters to achieve better hardness in the weld nugget joint welded by friction stir welding was investigated. Process parameters included tool rotation speed, welding speed, and varying bagasse ash percentages (4%, 8%, and 12%) with constant wt.% of molybdenum disulfide. Taguchi analysis was used for experimentation, and ANOVA confirmed the output response [47]. Reinforcement inclusion enhanced material hardness, with tool rotation speed being the most significant controlling parameter. Welding speed had minimal significance for FSP. AA7075/SiC-BN by friction stir processing was studied to investigate wear and microhardness behaviors. The microstructure showed good dispersion of nanoparticles without voids. Results indicated an inverse relationship between nano-particle mass fraction and wear rate, with wear resistance improving by 53.61%. Hardness increased by 45% on average due to SiC and BN reinforcement nanoparticles [48]. Comparative analysis of Al6061-SiC hybrid composites with graphene and CNT reinforcements processed by friction stir processing revealed better homogeneous dispersion of GNP reinforcement particles than CNT particles. Defect-free weld nugget zones were achieved with reinforcements. Nano-hardness improved by 207% with Al6061-SiC-GNPs and by 27% with Al6061-SiC-CNTs compared to as-received Al6061-SiC samples [49]. Microhardness improved by 36% and 17% for Al6061-SiC-GNPs and Al6061-SiC-CNTs, respectively, compared to as-received samples. Tribological properties also enhanced with reinforcements. Microstructural and mechanical properties of A356/Al2O3+SiO2 processed by friction stir processing indicated uniform dispersion of reinforcements in the weld zone. Hybrid composites increased hardness by 40% compared to FSPed A356, with hybrid composites showing higher nano hardness [50].

3. Conclusions

The following conclusions can be drawn from the results & discussion above.

- Microstructure refinement for enhanced properties has been achieved by adding reinforcement into the matrix.
- Uniform dispersion of the reinforcement in the stir zone can be evidently seen from the SEM and optical analysis.
- Microhardness results show significant improvement in the stir zone of the work piece. The hardness of the aluminum composites increases by an average of 45% when compared by the matrix.
- The wear test conducted on the tribomoter show tremendous improvement in the tribological properties of the composites.

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