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Review

A comprehensive review of recent progress in fabrication of magnesium base composites by friction stir processing technique—A review

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Abstract: Metal matrix composites (MMCs) are the next generation materials, globally popular for having numerous potential applications in aircraft, automobile and biomedical industry. Magnesium being continuously replacing other conventional materials however it is a hard to process material. Recently, friction stir processing (FSP) is drawing attention among researchers to fabricate MMCs. Using FSP, superior properties of magnesium based MMCs being successfully achieved. The primary aim of this paper is to review and provide a thorough summary of FSP synthesized magnesium based composites. Additionally the effect of secondary phase particles on the tribological behavior of produced composite materials is also summed up. Mechanical along with microstructural properties produced from stirred process and contribution of strengthening mechanism is addressed, as well.

Keywords: friction stir processing; metal matrix composites; magnesium; strengthening mechanism

1. Introduction

Metal matrix composite (MMC), widely known as the cluster of smartly developed engineered materials, synthesized by adding secondary phase reinforced micro, macro or nano particulates with parent materials of different chemical composition [1]. Continuous phase of metal is called matrix, and depending upon the chemical composition of matrix, composites are classified as metal matrix

composites (MMCs), ceramic matrix composite (CMC) and polymer matrix composite (PMC) [2]. MMC's recently are drawing interests of the researchers for not only they demonstrate firm bond with reinforced particles also develops no chemical alteration in terms of composition but also exhibits superior properties. MMC's clearly proven themselves as a promising candidate with their wide application in various fields [3,4]. Copper, magnesium, aluminum and titanium are commonly used matrix materials and TiC, MWCNTs, SiO_2, B_4C and Al_2O_3 few types of reinforced particles. Various manufacturing techniques like diffusion bonding [5], powder metallurgy [6–8], in situ fabrication [9], spray deposition [10], stir and squeeze casting [11–14] and vapor deposition been adopted by researchers to fabricate bulk MMCs [15,16]. All these manufacturing process of developing composites transform material from solid to liquid phase. On the flip side, techniques which do not have phase change process like solid state processing comparatively shows many merits over conventional phase change techniques. Friction stir processing (FSP) is a newly developed technique based on the principle of friction stir welding (FSW) [17]. And the principles along with recent progresses on friction stir welding and processing reported in [18]. Stirring action of FSP been successfully used to disperse secondary phase particles in the parent metal and producing next generation materials as MMCs [19]. Till now FSP is widely used to fabricate aluminum based composites [20–28]. Presently the world is more concerned about ecofriendly low-emission transportation vehicles with light-weight and maximum-performance. Magnesium been adopted by researchers and scientists over aluminum not for having density two-thirds that of aluminum also for its high strength-to-weight ratio [29]. Magnesium itself or its alloy doesn't meet the today need. For full filling this purpose few percentage of particulates need to be added in magnesium or its alloys. Addition of these particulates not only increases the microstructure of the composite but also enhanced it mechanical properties. Recently, Sunil et al. [30] summarized all work related to magnesium based composites. This paper present extended study of literature survey and review all recent development in the area of magnesium based composites fabrication by FSP. The demanding situations and future bearing of FSP are summed up.

2. Synthesis of composites with the aid of FSP

FSP in its least difficult structure comprises of a rotating tool that is non-consumable, which is dove into the work piece and afterward moved toward intrigue. The schematic outline of FSP is appeared in Figure 1.

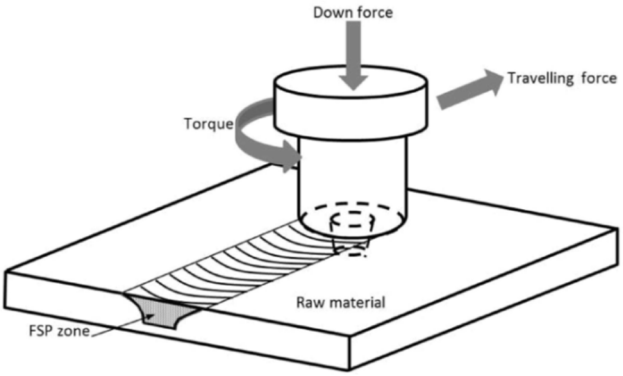

Figure 1. Schematic diagram of FSP technique.

FSP serves two essential capacities: (a) development of thermal energy thus deforming work piece material (b) mixing of secondary phase particles and form substrate. Intense rubbing of tool with material develop high frictional energy which results in producing enormous thermal energy. This thermal energy converts the metal into semi solid phase and makes it softer, while the turning of pin mixes and makes it flow around the pin. It then settle the soft metal depression at the back of the rotating tool. The material that flows around the tool is exposed to serious plastic deformation and heating, which prompts significant dynamic recrystallization thus refinement of microstructure in the stir zone (SZ) initiated [31].

2.1. FSP process variables

FSP machine process variables are classified into five categories. All these are the significant components that direct the successful achievement of the composite manufacture by FSP [32–40]. Variables are further divided into other various parameters. Figure 2 illustrates a schematic diagram of classification of the variables involved in the manufacture of the composite as well detalied by Rathee et al. [41].

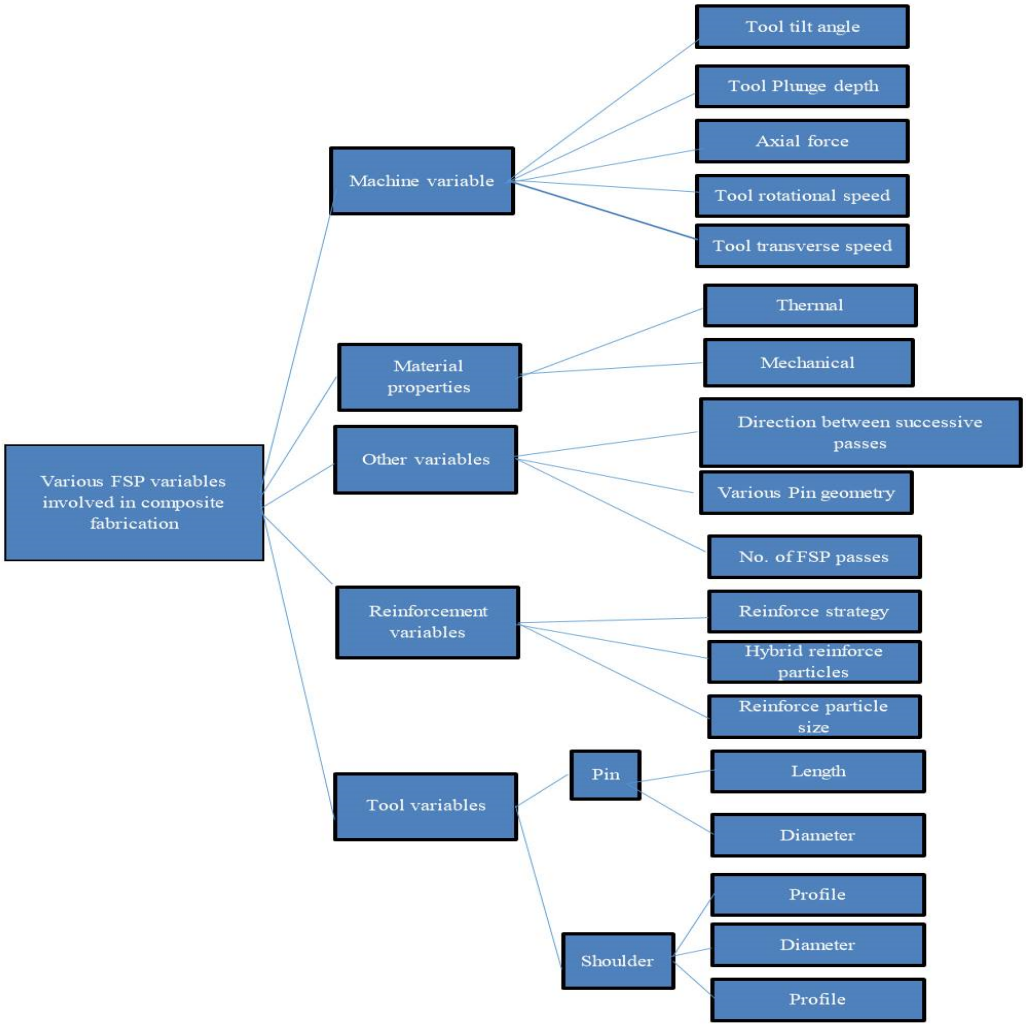

Figure 2. Various variables involved in FSP [41].

2.2. Doping method for reinforced particles

Prior investigations reveal that formation of composite materials was mainly via ceramic slurry layer for FSP process. Now a day's most common approaches for doping secondary phase particles into parent metal for composite manufacturing through FSP are shown schematically in Figure 3. Varity of secondary phase particles may considered, as reported by literature, i.e., TiC, SiC, MWCNT, Al_2O_3, B_4C and SiO_2, etc.

- Hole drilling approach: Holes filling is a common strategy where required blind holes usually in straight/zig-zag pattern bored on top of the work piece and loaded up with reinforce particles. However, before final experimentation a pin less FSP tool is employed after loading of reinforced particles to avoid scattering of these particles.
- Groove filling approach: Groove filling is another common strategy in which a section is created on work piece and loaded up with reinforced particles. However, before final experimentation a pin less FSP tool is employed after loading of reinforced particles to avoid scattering of these particles.
- Sandwich approach: In this approach a layer of reinforced particles is prepared between parent material plates like a sandwich. High Thermal energy generated by tool breaks the particles and help in fabricating composite. However, uniform distribution may require increased number of passes.

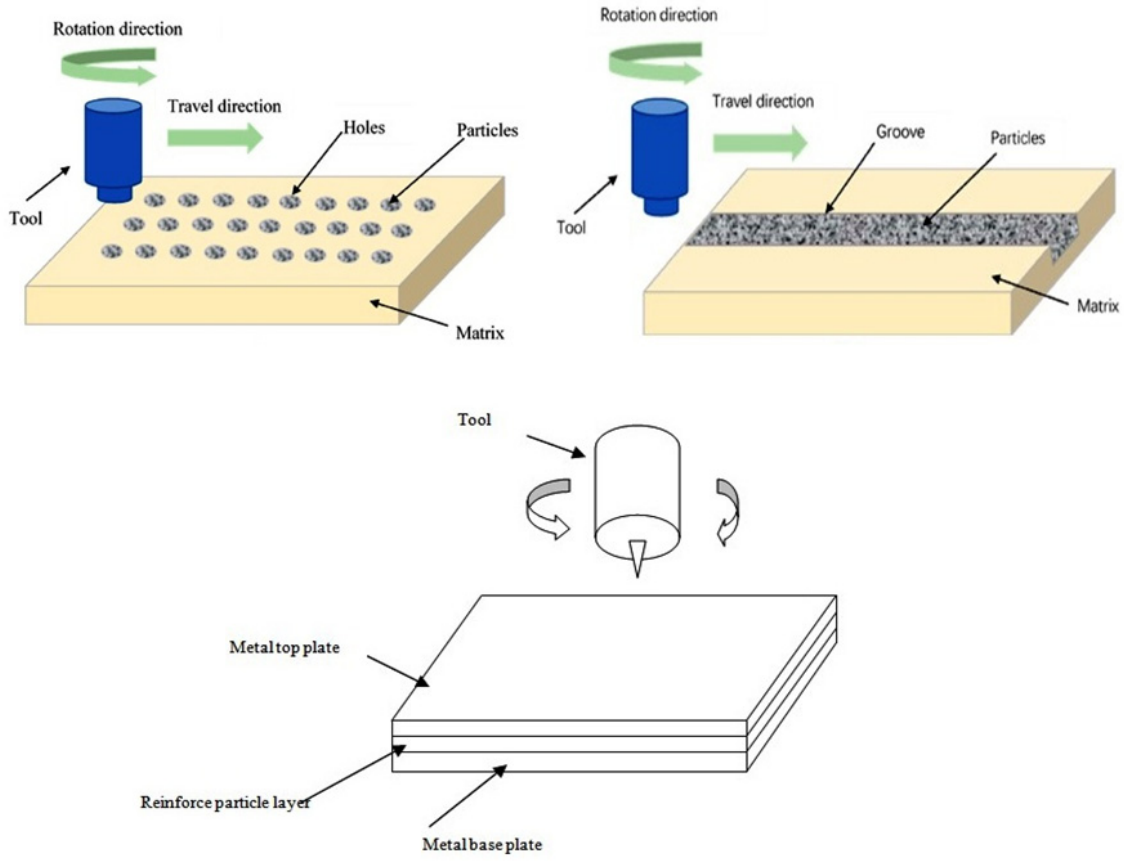

Figure 3. Schematic diagram of doping approaches [42].

2.3. Tool geometry

Tool geometry is a vital processing parameter which generates heat and guide material flow. The shoulder diameter affect heat generation at SZ and it is usually taken as, D/d = 3 (where D is shoulder diameter, d is pin diameter) [43]. Common types of tools used in FSP of magnesium based alloys are presented in Figure 4.

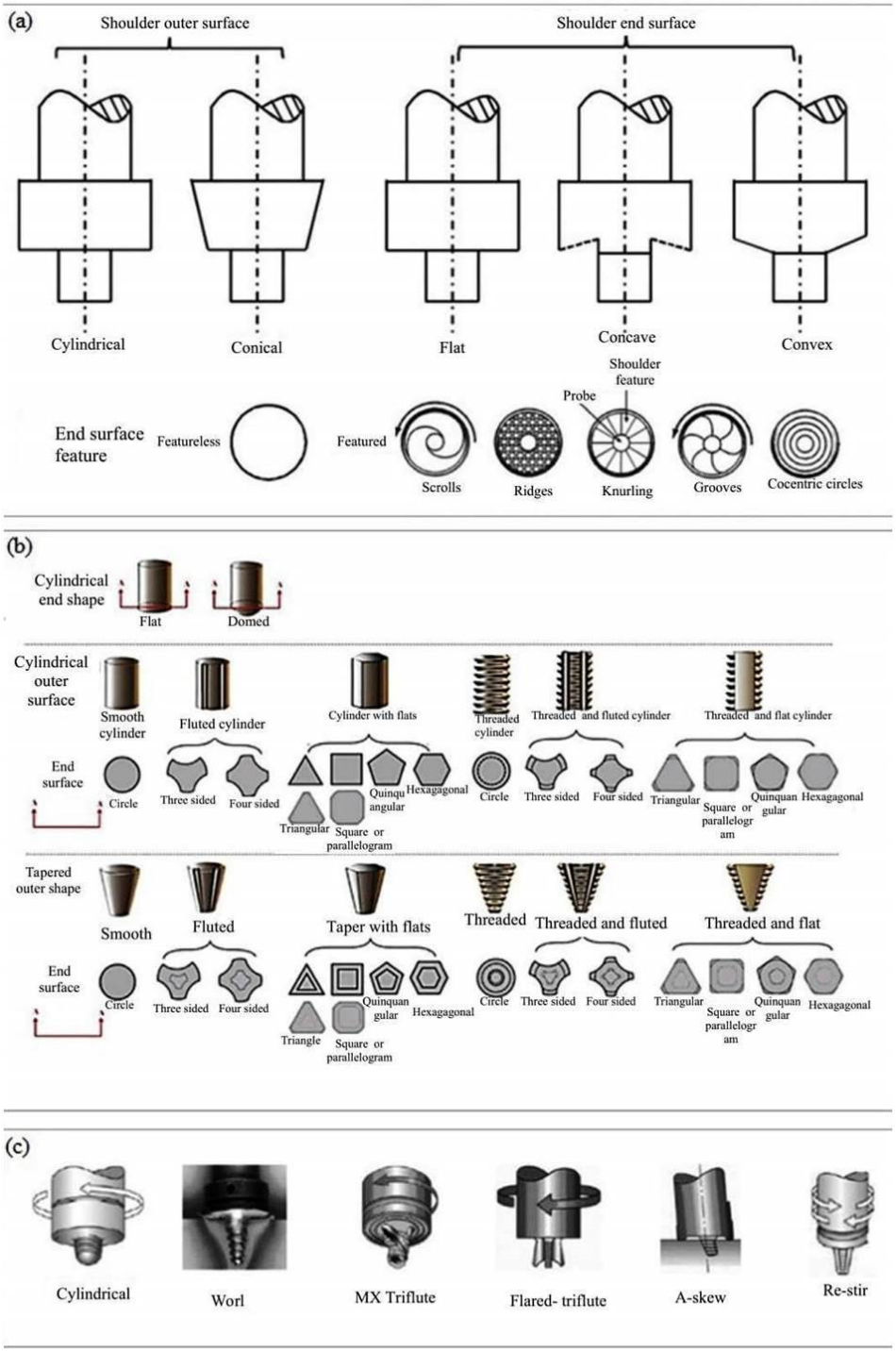

Figure 4. Common types of tools used for FSP processes [44].

3. Synthesis of Magnesium base composites with the aid of FSP

Most common magnesium alloys comprised of aluminum, zinc, thorium and uncommon earth. Using the ASTM alphanumeric designation system encourages grouping magnesium alloys by principal alloy composition like Mg–Al–Mn (AM), Mg–Al–Zn–Mn (AZ), Mg–Zr (K), Mg–Zn–Zr (ZK) with rare earth (ZE), Mg–Y–rare earth metal–Zr (WE). Initial two letters demonstrate the chief code for major alloying components followed by their concentration respectively. Last alphabet suggests alloy modification [45]. Studies considering major magnesium alloy for composite fabrication via FSP, as reported by the literature, are presented here.

3.1. AZ91Mg alloy

Asadi et al. [46] fabricate AZ91/SiC magnesium base composite considering square tool pin profile with three tool penetration depth (PD) 0.1, 0.2 and 0.3 mm and a tool tilt angle of 3°. They observed complete cracked processing zone for PD 0.1 mm, hole and tunneling cavity for PD 0.2 mm and sound surface quality for PD 0.3. They also studied the effect of tool rotational and tool transverse speed on grain size and micro hardness by considering groove filling approach for fabricating magnesium base AZ91 alloy with 5 μm SiC particles. They consider two 900 and 1400 rpm tool rotational speed and five 12.5, 25, 40, 50 and 63 mm/min tool transverse speeds. Finding of their research work suggests that best result for grain size and micro hardness were achieved at tool rotational speed of 900 rpm with transverse speed of 63 mm/min, i.e., 7.16 μm and 94 Hv. Asadi et al. [47] further extended their research for AZ91/SiC composite and suggests grain size increases with increase in rotational speed and lowers the micro hardness. Also it was noted that increasing transverse speed reduced the grain size, while the micro hardness increases. It was also added that changing the tool rotation speed resulting in fine grains and uniform distribution of particles. Faraji et al. [48] synthesized AZ91/Al_2O_3 composite by using friction stir processing, Their work included three different size nano particles ranging from nanometer to micrometer scale, i.e., 3000, 300 and 30 nm and two different tool geometries along with varying number of passes and also studies their effect on performance measures like grain size, cluster size, micro structure and mechanical properties. Findings of their work suggests that grain size in triangular tool is less than square tool but follows opposite trend in case of hardness. Finally the conclusion drawn from their work suggests that decrease in size of nanoparticle increases hardness of the composite. Khayyamin et al. [49] studied the effect of process parameters on micro structural characteristics of AZ91/SiO_2 composite fabricated by FSP. They fix tool rotation speed to 1250 rpm, tilt angle to 3° and number of passes to 4 passes with varying transverse speed to 20, 40 and 63 mm/min. They also examine metallurgical and mechanical properties by Optical Microscopy (OM), Scanning Electron Microscopy (SEM) and Vickers hardness tester. All optical microscopy and scanning electron microscopy tests were conducted on composites having all different passes and different transverse speed. Outline of the work concluded that grain size decreases and strength and hardness increase with increase in transverse speed. Increase number of pass increase hardness and reduce grain size. Faraji et al. [50] consider tool geometry of two types square and circular to examine the influence of process parameters on AZ91 with and without Al_2O_3 nano particles. It can be understood from the work that at tool rotation speed 900 rpm and transverse speed of 80 mm/min for square tool provides the best result with grain size 6 μm and microhardness 103 Hv as compared to 7.27 μm and 98.52 Hv

without particles. Ahmadkhaniha et al. [51] analyzed wear resistance on AZ91/Al_2O_3 as produced by FSP adopting groove filling approach with circular tool. They further consider different tool rotation speed, transverse speed and a fixed tool tilt angle of 3° to investigate mechanical and metallurgical properties. Finally outcome of the study suggests that tool rotation speed of 800 rpm and transverse speed 40 mm/min gives optimum results for grain refinement and wear behavior. Dadashpour et al. [52] introduced 10–15 nm SiO_2 particulates to study the fracture behavior AZ91C composite fabricated by FSP. H13 tool material was considered along with square pin geometry with a fixed tool rotational speed of 1250 rpm and feed rate 40 mm/min. Extreme refined grain from starting size of 140 to 4 μm was observed along with the hardness of 130 Hv and ultimate tensile stress of 239.6 MP for three FSP passes. Chen [53] mixes SiC particles and prepared a layer of surface composite on thixoformed AZ91 using FSP. Wear behavior of thixoformed AZ91/SiC was compared with thixoformed AZ91 alloy without composite surface. The authors concluded that found that increasing number of passes can minimize the agglomeration and maximize the SiC particles distribution. Further they reported reduced coefficient of friction and enhanced wear resistance of surface composite layer when compared with parent alloy. Very recently, Singh [54] developed AZ91/B_4C nano composite using drill hole approach with cylindrical tool rotating with 900 rpm and having feed of 45 mm/min. Three different sizes nano particles were considered for examine microhardness and wear behavior. Finally study concluded that average hardness, wear resistance increases and wear rate decreases as the reinforce particle size increases.

3.2. AZ31 Mg alloy

Morisada et al. [55] fabricate AZ31 magnesium alloy with SiC via using friction stir processing. They used SiC powder of mean diameter 1 μm into a groove of 1 × 2 mm of a 6 mm thick plate. A tool of columnar shape of material SKD61 with diameter 12 mm along with a probe of diameter 4 mm and length of 1.8 mm was used, also they fix the value of parameters like tool rotation 1500 rpm, tool tilt angle 3° and travel speed of range 25–200 mm/min for processing. OM, SEM and Transmission Electron Microscopy (TEM) tests were conducted to study the micro structural properties of the composite. Findings of the test reported a fine grain size, i.e., 6 μm in the developed AZ31/SiC as compared to the mean grain size, i.e., 79.1, 12.9 of as-received AZ31 and FSPed AZ31 respectively for the travel speed of 50 mm/min. Further they reported that as travel speed increase grain size of the composite decreases. Micro-vickers hardness tester with a load of 200 g was used to measure micro hardness and it shows a maximum value of 69.3 Hv for FSPed AZ31 with SiC particles and 48.1 Hv and 60.0 Hv for as-received AZ31 and FSPed AZ31 respectively. Morisada et al. [56] studied the influence of addition of multi walled carbon nano tubes on grain size and hardness of AZ31 magnesium composite prepared through friction stir processing. AZ31 rolled plate of 6 mm thickness with a groove of 1 × 2 mm, filled with multi walled carbon nanotubes of outer diameter 20–50 nm and of 250 nm length was used. A tool of columnar shape of material SKD61 with diameter 12 mm along with a probe of diameter 4 mm and length of 1.8 mm was used for fabrication. Good dispersion of nanoparticles was observed at 25 mm/min transverse speed and 1500 rpm tool rotation speed respectively. Hardness of 78 Hv was observed for AZ31/MWCNT as compared with hardness of 41 Hv of as received AZ31. Azizieh et al. [57] examine the effect of process parameters like tool profile, rotational speed and number of passes on micro structural and mechanical properties of FSPed fabricated AZ31/Al_2O_3.They used three kinds of Al_2O_3 particles

with mean diameters of 35, 350 and 1000 nm respectively. Rectangular shape of 60 × 100 × 10 mm as cast AZ31 was used along with a groove of 1.2 mm width and 5 mm depth with a grain size of 70 μm. Varying geometry of tools, i.e., tool with a columnar probe without threads, a tool with a columnar probe with threads and a tool with columnar probe with threads and three flutes heat treated till 53HRC hardness along a fixed tool transverse speed of 45 mm/min, tool rotational speed of 800, 1000, 1200 rpm and tool tilt angle of 2° and FSP 2–4 times passes was adopted. OM, SEM and micro hardness tests was conducted to examine the etched sample. Finally cavity formation was noticed when non-threaded tool was used also they reported that use of threaded pin leads to good grain size along with uniform distribution of nano particles. In case of threaded pin with flute they observed low homogeneity along with tunneling effect. Azizieh et al. [58] synthesized AZ31/Al_2O_3 composite by using friction stir processing. They considered parameters like rotational speed and number of passes to find out their effect on particle distribution, grain refinement, hardness and temperature changes in the magnesium metal composite. A constant travel speed of 45 mm/min, tool rotational speed of 800, 1000, 1200 rpm, tool tilt angle of 2° and FSP 2–4 times passes was adopted. Temperature in the stir zone was measured by the K-type thermocouple immersed in the stir region. Findings suggest that with increase in tool rotational speed average grain size, peak temperature and particle distribution increases. Also if number of passes increases nanoparticle agglomeration decreases and hardness increases which is good. Finally work concludes that at 800 rpm hardness is higher as compared to 1000 and 1200 rpm. Srinivasan et al. [59] developed AZ31B/Al_2O_3 magnesium metal matrix nanocomposites through rotational friction welding. Authors, further examine the influence on mechanical and microstructure for the various controllable parameters like upsetting and friction time, upsetting and friction pressure. Cumulative effect of machine parameters and thermo mechanical stresses results in typical grain refinement in the SZ. Authors reported increase in friction time decrease joint efficiency. Microhardness variation is attributed due to distribution of heat produces by friction pressure and time. Chang et al. [60] synthesized metal matrix magnesium based composite AZ31/nano-ZrO_2 and nano-SiO_2 via FSP and examined both the microstructure and mechanical properties of. A tool with cylindrical probe with shoulder diameter 18 mm and pin length and diameter of 6 mm with 2° tilt angle along with pin rotation of 800 rpm and advancing speed of 45 min/min was used. Two grooves each 6 mm in depth and 1.25 mm in width were cut, in which 10–20 vol% of nano-sized ZrO_2 and 5–10 vol% nano-sized SiO_2 particles was filled. Mechanical properties like vickers hardness was checked using a 200 gf load for 10 s along with optical microscopy, scanning and energy dispersive spectrometer was conducted to examine mechanical and metallurgical properties. Average grain size of composite produced 4P FSP resulted to be refined upto to 2–4 μm. Balakrishnan et al. [61] used magnesium alloy AZ31 with particulates like TiC to fabricate a magnesium matrix composite. They operate or execute or demonstrate the FSP by taking fixed tool rotational speed, transverse speed, and axial force on a 6 mm AZ31 plate by single pass. They engraved four different width (0, 0.4, 0.8, 1.2) and of equal depth 4.5 mm in the plate to introduced varying different fraction of the given (0, 6, 12, 18). Macrostructure and microstructure was studied by digital optical scanner and scanning electron microscope and it suggested TiC were properly distributed. Jiang et al. [62] dispersed nano SiO_2 reinforced by FSP into AZ31 Mg alloy. The main result reflects uniform grain refinement up to less than 1 μm and increase in hardness up to 1.83 times higher than that of the as-received AZ31 can be achieved. Sharma et al. [63] fabricated a novel hybrid nanocomposite AZ31/MWCNT–Graphene using multi-pass FSP with constant other parameters. Uniform, refined and more localized grains of average size

of 4.0 μm with lesser tensile twin fraction were reported for hybrid nano composites as shown in Figure 5.

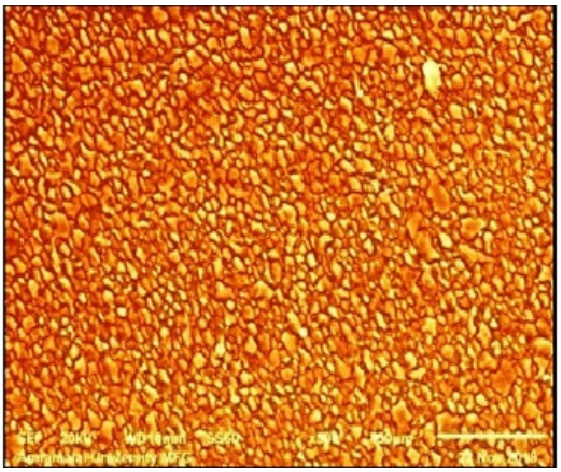

Figure 5. Microstructure of AZ31Mg–MWCNT–Graphene hybrid nanocomposite [63].

Also uniform dispersion of hybridized reinforce particles leads to significant enhancement of elastic modulus, tensile failure strains along with the improved mechanical properties like microhardness, i.e., 90.6 Hv and superior ultimate tensile strength as 49.23% as shown in Figure 6 with yield strength as 32.31%.

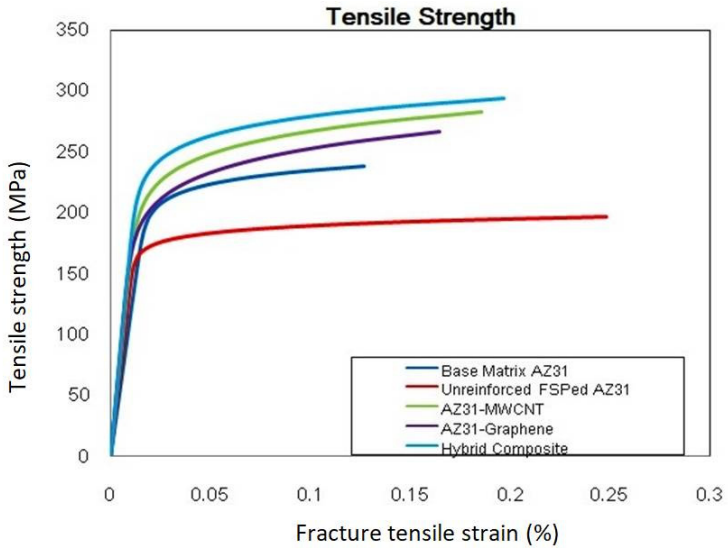

Figure 6. Tensile strengths of different specimens [63].

Huang et al. [64] executes the process of synthesized AZ31/SiC composite with a special FSP tool unlike other FSP tool. In this novel tool reinforce particles introduced via a hole prepared within this new direct friction stir process tool (DFSP). More than four times lesser grain was formed as compared to as cast magnesium alloy grain size of 16.57 μm. Authors further suggested groove or

hole filling step can completely be eliminated with new tool also better hardness can be achieved as compared to conventional FSP. Soltani et al. [65] synthesized AZ31B/CNT surface composite using FSP. For this research work author provides a suitable combination of transverse speed of 24 mm/min and rotational speed of 870 rpm for significant increase in hardness of 60 vickers and reduced grain size of less than 5 µm. Navazani and Dehghani [66] introduced 5 µm TiC particles for the fabrication of AZ31 magnesium base composite. Microstructural and hardness of the produced composite was examined. Authors suggested that three vital factors are responsible for dislocation of grain in composite i.e. dissimilar deformation behavior between particle and matrix, grain boundaries and thermal expansion. Finally, work suggests that defect free zone can be achieved at 1250 rpm and 50 mm/min with declined grain size. Sunil et al. [67] loaded nanohydroxypatite reinforced particles into the groove of base AZ31 magnesium alloy in order to produce composite material. Authors mainly investigate the composite for biomedical applications and degradation of material. Wettabilty, cytotoxicity and vitro bioactivity in super saturated simulated field is been checked. Grain refinement upto 2 µm been the main reason of enhanced surface energy. Further authors concluded that dissolution of iron at FSP zone was within tolerance limit and hence its effect on corrosion is negligible. Newly, Sharma et al. [68] examined the influence of tool rotation speeds on mechanical and microstructure properties of fabricated a novel hybrid nanocomposite AZ31/MWCNT–Graphene using FSP. Optimum ratio of 1.6 and 0.3 vol% of MWCNT and grapheme was used. Author obtained various values of microhardness at different tool rotation speeds and presented them into a graph form as shown in Figure 7.

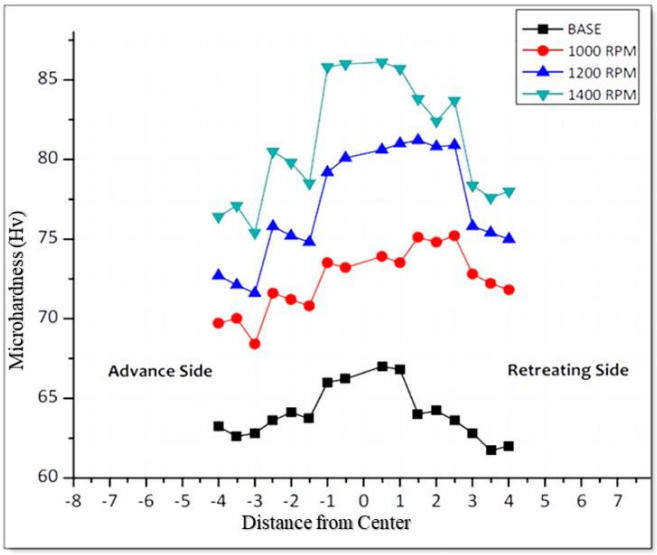

Figure 7. Range of microhardness at various tool rotation speeds [68].

3.3. WE43 and RZ5 Mg alloy

Das et al. [69] prepared a metal matrix composite WE43/B4C/6 vol% via friction stir processing. For the experimentation work they used 30 × 5 × 1.6 cm^3 of WE43 plate, B4C of 6 µm along with stepped tool. They drilled a set of holes into the plate for the friction processing and observe the microstructural and mechanical properties through scanning electron microscopy and tensile,

hardness tests. Finally they analyze reduction in grain size and increase in micro hardness for four passes as compare to single pass. Further they concluded that post treatment of composite at 210 ºC for 48 h not only increase yield strength from 189–281 but also increase the ultimate tensile strength and elastic modulus with reduction in ductility and elongation to failure. Recently, Vedabouriswaran and Aravindan [70] introduced boron carbide (B_4C), MWCNT and a mixture of ZrO_2 + Al_2O_3 secondary phase particulates for production of magnesium rare earth alloy—RZ 5 based composite of by single pass FSP. Pinning effect cause by the reinforce particles produces refined grains of range 0.8 to 1.87 μm. Microhardness from 125 to 403 Hv was reached with increased ultimate tensile strength with range of 250–320 MPa.

3.4. AZ61 Mg alloy

Valle et al. [71] like Chang et al. [60] used backing plates as of cooper to speed up heat transfer rate between tool and work piece. They studied the effect of FSP on AZ61 via examining mechanical and micro structural properties. Grain refinement was achieved with maximum size 45 to 1.8 μm. Further authors reported that the surface created during FSP favors basal slip during the tensile test, leading to increase of ductility, a decrease in yield stress and a decrease in strain rate sensitivity in comparison with rolled AZ61 alloy. Lee et al. [72] created AZ61 based nanocomposite by mixing 5–10 vol% nanosized SiO_2 via FSP. Fix parameters with tool rotation 800 rpm and tool transverse 45 mm/min was employed. A back plate for cooling purpose for the whole procedure was deployed beneath. Succeeded FSP, authors declared that as number of passes increases nano-SiO_2 particles turns into a cluster of size going from 0.1 to 3 μm and the degree of grouping decreases. TEM contemplates that nano-SiO_2 particles stayed as shapeless and opposes change to crystalline stage during whole procedure. Du and Wu [73] processed magnesium base AZ61 alloy with rapid heat sink via FSP and achieved fine-microstructure at the processed zone with enhanced mechanical properties. Authors, observed average grain size less than 300 nm with mean micro hardness of 120−130 Hv, two times higher than that of AZ61 substrate. They further declares that one pass FSP under a high cooling rate may produces ultra-fine structure in AZ61 alloy with superior mechanical properties.

Literature survey concludes that various magnesium based composites were developed in past decade. All these composite materials shows improved microstrurtural and mechanical properties. Tribological performance, however, is by far the most commonly encountered industrial problem where the material is mainly influenced by speed, environmental conditions, and workload. Wear is a gradual and progressive material loss that is continuously subjected to rubbing action. Wear resistance of the composite metal matrix depends primarily on different microstructural features, such as particle size, volume fraction, reinforcement material distribution, and shape.

4. Tribological performance of some magnesium based composites

Tribological performance of magnesium based composites is an other parameter which have been succesfully studied and improved by the various researchers. Table 1 provides the brief summary of the work carried out so far pretaning to tribological performance of magnesuim based composites.

Table 1. Brief summary of the tribological performance of developed magnesium based compoites as reported in literature.

Composite	Tool geometry	Grain size improvement	Machine parameters	Wear test specifications	Significant outcome	References
ZM21/SiC/B_4C	Straight cylindrical	40 μm refined up to 20 μm	1200 rpm, 50 mm/min	Pin on disc, load 0.5 kg, sliding speed 640 rpm for 6 km	Wear rate of composite decreases seventy six times to the base metal	Reddy et al. [74]
AZ91/Al_2O_3/SiC	Straight cylindrical	More refined grains as number of passes increases	730–1800 rpm, 14–80 mm/min with 1–4 passes	Tri pin on disc, load 50 N, sliding speed 1 mm/s for 500 m	Wear rate decreases as number of pass increases AZ91/ AZ91/Al_2O_3 & AZ91/SiC gives almost same wear rate	Abbasi et al. [75]
AZ91/TiC	Straight cylindrical	More refined grains	900 rpm, 40 mm/min with PD = 0.3 mm	Pin on disc, load 5–10 N, sliding speed 1 m/s for 2000 m	Wear rate of composite decreases half to the base metal	Singh et al. [76]
AZ31/TiC	Straight cylindrical	More refined grains	800 rpm, 40 mm/min	Pin on disc, load 5–20 N, sliding speed 1 m/s for 1.5 km	At 20 N higher wear resistance was noticed	H. S. Arora et al. [77]
AE42 as cast and FSPed AE42	Straight cylindrical	40% reduction in grain size and reached upto 1.5 μm	700 rpm, 60 mm/min	Pin on disc, load 5–20 N, sliding speed 0.3–3 m/s for 2500 m	Higher co-efficient of friction attended at low sliding velocities	Arora et al. [78]
As cast Mg/SiC	Threaded cyllindrical	Grain size reduced from 170 to 3 μm	1300 rpm, 50 mm/min	Pin on disc, load 1–5 Kg, sliding speed 1 m/s for 600 m	20% and 47% wear loss was noticed at 1 and 5 Kg	Ram et al. [79]
AZ31/Al_2O_3	Threaded cyllindrical	With development of refined grains hardness increases from 50 to 90 Hv	800, 1000, 1200 and 1400 rpm, 45 mm/min and 2° tilt angle	Pin on disc, load 10, 50 and 90 N, sliding velocity 0.12m/s for 600 m	Wear rate at 1000 and 1200 rpm is higher as compared to 800 rpm	Azizieh et al. [80]
AZ31/Fly ash	Straight cylindrical	Upto 4 μm grain size achevied	1200 rpm and 40mm/min	Pin on disc, load 20 N, sliding velocity 1.0 m/s for 3000 m	FSP exhibhits 33% lower wear rate as compared to stir cast	Dinaharan et al. [81]
AZ91/Al2O3	Circular and square tool	Average grain size 5–10 μm was obtained	900–1200 rpm, 40–80 mm/min with 3° tilt angle	Pin on disc, load 50 N, sliding velocity 1.0 mm/min for 500 m	Wear rate decreases more than three times to the base metal	Faraji and Asadi [82]
AZ31/MWCNT/ Al_2O_3	Cone shape	Much small size grains with microhardness 1.4 times higher than those of AZ31	1050 rpm, 33.4 mm/min	Pin on disc, disc rotation 200 rpm, load 0.65, 1.30, 1.95, 2.60 and 3.25 MPa	For load more to 1.95 MPa, the wear and friction coefficient of hybrid AZ31 composite is low and it only follows in case of 0.1% $A1_2O_3$ and 0.2% CNTs composites	Lu et al. [83]

5. Strengthening mechanism and valuable equations

Considering the development of magnesium based metal matrix composites via FSP as reported in literature only selective strengthening mechanism hold good. Grain boundary and secondary phase

mechanism are the two strengthening mechanism and both of them are Hall–Petch relationship, and Orowan strengthening.

5.1. Hall–Petch strengthening

Hall–Petch strengthening mechanism have a vital role in the upgradation of major properties like strength of a composites, and it's contribution is directly depend on refined grains existing in metal matrix zone. And the pinning action exerted by the secondary phase particles give rise to the concept of grain boundary and grain size which is further expresses by Zener equation as shown in Eq 1 where the grain size of the matrix d_m that can be achieved [70].

$$d_m = 4\alpha d_p/3v_p \tag{1}$$

Here d_p shows particle size, volume fraction of particles is vp and α is a constant of proportionality. It may be concluded that newly developed grain size is highly influenced by the size of the reinforcement particles and its volume fraction. Hall–Petch relationship states that hardness is inversely proportional to grain size in other words any reduction in the grain size attributes to increase the yield strength. According to Hall–Petch Eqs 2 and 3 [84–87].

$$\Delta\sigma_{\text{Hall–Petch}} = K_y(d^{-1/2}_{\text{composites}} - d^{-1/2}_{\text{matrix}}) \tag{2}$$

where $d_{composites}$ and d_{matrix} are the average grain size of the composite and matrix and K_y is the strengthening coefficient.

$$\sigma_y = \sigma_o + K_y/\sqrt{d} \tag{3}$$

where σ_y is the yield stress, σ_o is a materials constant for the starting stress for dislocation movement (or yield strength before FSP), k_y is the strengthening coefficient (a constant specific to each material), and d is the average grain diameter. Based on similar theory [46–47] reported that increases the tool transverse speed, grain size reduces in SZ which further increases hardness at SZ. The influence of grain size on yield strength of magnesium alloys has also been reported in number of studies [59,60,64,69]. Azizieh et al. [81] and Huang et al. [64] based on average grain size uses further simplified Hall–Petch relationship and uses Eqs 4 and 5 for calculating microhardness of the samples.

$$Hv = 43 + 78d^{-1/2} \tag{4}$$

$$Hv = 40 + 72d^{-1/2} \tag{5}$$

where d is the average grain size. Rather Hung [88] established a generalized equation (Eq 6) for AZ series magnesium alloys. As reported in literature Figure 8 shows the ultra-refinement in grain size of magnesium composites as compared to base metal and Figure 9 shows the corresponding values of microhardness for magnesium composites when compared to base metal.

$$Hv = 56 + 348d^{-1/2} \tag{6}$$

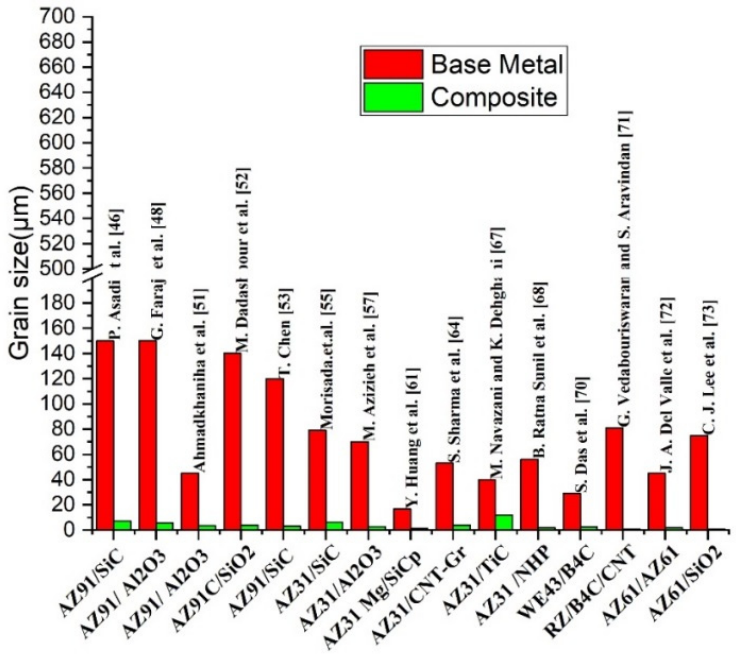

Figure 8. Comparisons of grain size values for fabricated magnesium base composites.

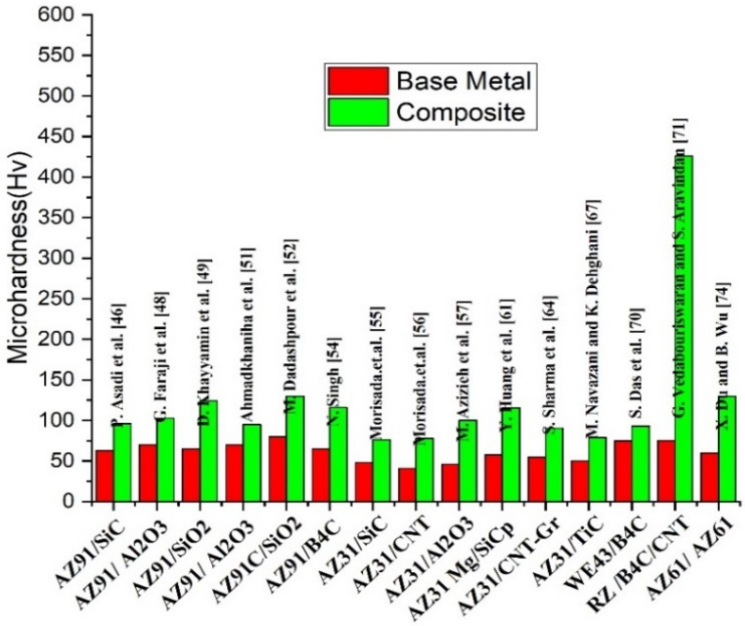

Figure 9. Enhancement in microhardness for various magnesium based composites as fabricated via FSP.

5.2. Orowan strengthening

Zhang and Chen [89] well explained the contribution of Orowan strengthening mechanism in reinforced metal matrix composites. Furthermore, Sanaty-Zadeh [90] studies different strengthening

mechanisms and it is worth maintaining that Hall–Petch strengthening mechanism is the most important factor, which should not be neglected even in micro-scale grain. Dadashpour et al. [52] concluded that in fabricating AZ/SiC magnesium based composite Orowan strengthening mechanism influence dislocation of grains, Vedabouriswaran and Aravindan [70] studies the effect of Orowan strengthening mechanism for fabricating magnesium based composite and concluded insignificant contribution of Orowan strengthening mechanism for their work. Sharma et al. [68] calculated as 58.65 MPa as the total contribution of Orowan strengthening by using Orowan equation as mention below in Eq 7.

$$\Delta\sigma\text{Orowan} = (0.8 \times \text{Gm} \times \text{M} \times \text{b})/\text{Lp} \tag{7}$$

where Gm is the shear modulus of alloy matrix, b is the magnitude of Burger's vector of the alloy matrix and M is Taylors factor. Lp is the inter-particle distance of the composites and can be calculated by equation mentioned below in Eq 8.

$$\text{Lp} = \sqrt{(\pi def2)/(2Vref)} \tag{8}$$

where, Vref is the volume fraction of the hybrid reinforcements and dref is the average grain sizes of nano composites used.

6. Demanding situations and future bearings

Above studies of literature clearly concludes that new materials especially composite manufacturing could be effectively achieved via FSP. Various reinforcements have been successfully incorporated in metallic matrix by FSP. The grain refinement accomplished by FSP along with high hardness, expanded wear and erosion opposition is the one of a kind point of interest of this procedure. MMCs manufactured by FSP are typically a kind of defect free composites with homogeneous distribution of particles. FSP has indicated promising outcomes in different investigations. Copper, titanium, aluminum, and magnesium materials are the most commonly accepted materials used to supply FSP surface MMCs. Magnesium based components are among them a category of tough to process materials. It has been unmistakably reported in literature and in reality there is a lot of improvement for as long as decade that distinctive magnesium based surface composites can be effectively delivered by FSP. Very recently Huang [91] suggested that singly dispersed CNTs formed compact bonding with the matrix, which contributed to the grain refinement and the mechanical properties enhancement of the Mg–6Zn matrix. In addition, they explanied about strengthening mechanism contributions to grain refinement, load transfer and Orowan looping mechanisms. Finally they acheived 144%, 156% and 87% higher values of yield strength, ultimate tensile strength and elongation of the FSPed CNTs/Mg–6Zn composites than those of the as-cast pristine Mg–6Zn alloy.

Apart from various applications of MMCs prepared by FSP yet production engineers are still wondering for the best outcome of the FSP process. Compound and articulate surfaces are hard to produce by FSP. More FSP passes could only have a homogeneous mixture of the reinforce particles into metal matrix, thereby increasing the cost of output. Tool wear is a significant issue in FSP particularly at high temperature. Basically this wear is due to prolonged contact between reinforce particles and tool pin. Literature also shows that various machine parameters affect the tool wear

such as tool rotaion speed, transverse speed and axial force [92]. In addition, it was observed that considering tool wear, shear phenomenon is more dominating than drag, as demostrated by Bist [92]. The development of wear-resistant tools is necessary for repetable solid-state joining. Hence tungsten base and high carbon high chromium based tools are highly recommended for FSP processes.

Also high thermal energy generation and its controlled is an major issue [93].These constraints confine the utilization of FSP to process hard surface composites. Flow of reinforce particles into the matrix is still wide area which need to be explore. Optimizing the FSP parameters and developing a model is still an area of future scope. Few recent developments such as fed friction stir technology reported in [94–95] may be considered for further improvement.

7. Conclusions

Literature study clearly summed up that even hard to processed material such as magnesium can be easily processed via FSP. Mainly two holes filling approach and groove filling approach been adapted for doping reinforce particles into the metal matrix. Every technique holds its advantages and limitations. Grain refinement, improved hardness, wear opposition, mechanical conduct, improved bioactivity and erosion obstruction are the normal perceptions in the entirety of the magnesium based composites produced by FSP. The relative contribution of Orowan strengthening effect increases with decreasing size of nanoparticles and Hall–Petch strengthening mechanisms increases with decreasing size of grains.

Also due to the stochastic nature of FSP machine parameters, an optimum combination of these parameters need to be established for producing defect free composite materials.

Dominant part of the work has been done utilizing AZ arrangement magnesium compounds. It is foreseen that composites of other magnesium combinations likewise will be created by FSP in future for a wide scope of uses.

Conflict of interests

All authors declare no conflicts of interest in this paper.

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