Review Paper

Friction stir process: a green fabrication technique for surface composites—a review paper

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Abstract
In many applications, surface properties of materials or components are more important than the entire volume material properties. The hardness, wear and corrosion resistance of material mainly depends on the surface properties. Improved surface properties also increased the life span of components. The friction stir process is a novel solid-state processing technique that is widely used for welding difficult-to-weld materials. In this paper, the applications of the friction stir process in surface modifications and fabrication of aluminum matrix surface composites were discussed. The effects of friction stir process parameters, tool design, reinforcement and reinforcement techniques on the surface properties were also reported.

Keywords Friction stir process · Grain refinement · Reinforcement · Surface composites · Hardness · Wear

1 Introduction

The principle of the friction stir process (FSP) is based on the friction stir welding technique. The friction stir welding (FSW) mostly used for welding difficult-to-weld materials in the automobile and aerospace industries. In this process, a friction is generated between the friction stir process tool and work-piece material which is required to be weld. The frictional force generates heat that used to weld the material by plasticizing it in the stir zone. The FSP is a green Fabrication process because it required less heat input and does not generate any kinds of dangerous fumes, gases, and rays during welding and processing. Nowadays, the friction stir process is used in the modification of surfaces and fabrication of surface composites. In the current scenario, industry required stronger, lighter and low-cost materials for various applications. The monolithic material systems do not have broad-spectrum mechanical properties [1]. The metal matrix surface composites have a potential advantage over monolithic alloys. The surface properties of material decide the life of products in many applications. The combined properties of high surface wear resistance and high toughness of the core material are required to prolong the life duration of the components. These kinds of properties are not achievable in monolithic materials. Therefore, the modification of the surface layer is necessary by impregnating the hard ceramic particles retaining the toughness and ductility of the matrix material know as surface composites. The surface composites have improved surface properties while core material properties remain unchanged. These unique properties of surface composite make high toughness and wear resistance material. The surface composites one of the advanced engineering materials having potential applications in various areas of aircraft, automobile, electronics, nuclear, general engineering and other advanced structural components. In surface composites substrate matrix materials such as titanium, aluminum, silver, magnesium, beryllium, copper, cobalt, and nickel, etc. are used. Amongst these materials, the aluminum and aluminum

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alloys are mostly used as a substrate material in the fabrication of aluminum matrix surface composites. The summary of substrate materials used for the fabrication of surface metal matrix composites depicted in Fig. 1.

The Fig. 1 shows that the contribution of aluminum is 63% as compared to other materials [2]. Aluminum matrix surface composites are known as lightweight, high-performance metal matrix composite materials. The aluminum matrix surface composites widely used in aerospace, sports, marine, defense and automotive industries due to its high strength to weight ratio, improved stiffness, controlled thermal expansion coefficient, improved abrasion and wear resistance as compared to the conventional alloys [3]. Carbides, borides, nitrides, and oxides of ceramics particulates are used as conventional reinforcement materials for the fabrication of composites. The availability and high-cost ceramic reinforcing materials have a major constraint for the development of metal matrix composites particularly in developing countries [4]. Other challenges of metal matrix composites are its poor ductility and fracture toughness [5]. The various researchers addressed and resolved these problems by selecting the proper reinforcing materials. The literature review reveals that reinforcing materials has a major role in determining the performance of composite materials. Mainly three strategies were used by the researchers for the fabrication of composites to improve the performance of composites materials as well as to curtail the cost. The first strategy involves finding alternative and cheaper reinforcements. The aim is to provide a solution to the problems of high-cost conventional reinforcements. The Agro and industrial wastes ashes such as Rice husk ash, Coconut shell, and Sugar cane bagasse, Bamboo leaf, Pine needle ash, and Fly ash are some of the alternatives reinforcing materials that have been reported to resolve issues of high cost and limited availability of conventional reinforcements [6–10]. The use of these alternative reinforcements showed

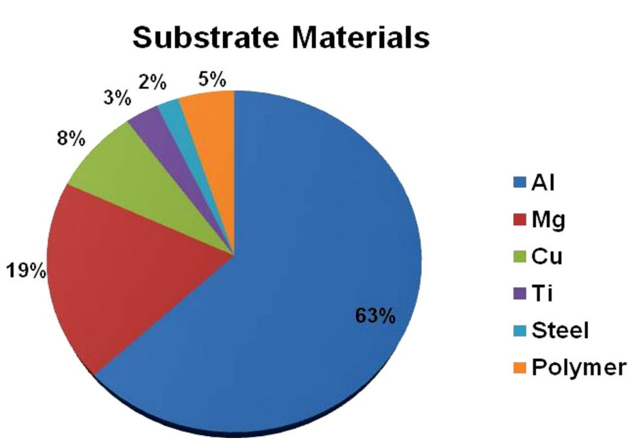

Fig. 1 Substrate materials for surface composites [2]

noteworthy enhancement in the properties of the composites as compared to the matrix material. The second strategy is to optimize the properties of composites by using nanoscale particle size of reinforcement materials instead of micron-scale particles [11–18]. The third strategy involves using two or more reinforcing materials to developed hybrid composites. This approach aims to reduce the cost of composite coupled with property optimization [1, 19].

The Friction stir process is a novel fabrication process to modify the surface of the material without changing bulk material properties. In this paper critical review of friction stir process (FSP), FSP processes variable, tool design, reinforcement materials and their effects on the surface properties were discussed. The research gaps in this field were also discussed.

2 Friction stir process

The surface properties of the material can be modified by various surface modification techniques such as laser melts injection, high energy laser beam, spraying, electron beam irradiation, and cast sinter. These techniques are based on the liquid state processing methods which carried out at elevated temperature. In liquid state processing, the formation interfacial reaction between matrix and reinforcement materials, and certain deleterious state are difficult to avoid. Furthermore, controlling the process parameters is also a difficult task. To overcome the above-mentioned problem, a solid-state processing method i.e. Friction Stir Process is recommended for the fabrication of surface composites. The friction stir processing is a solid-state material processing technique based on the principles of friction stirs welding [20]. It is an environmentally friendly green processes technique which is used to modify the structure of the surface of the material and fabricated surface composites by introducing hard particulates of reinforcement material on the surface of substrate (matrix) materials. In this process, the surface composite is fabricated by severe plastic deformation of the material and stirring action imposed by the FSP tool [21]. The thickness of the surface composite layer in the range of 0.1–6 mm can be achieved in the different material systems using FSP [22]. The FSP is also used for microstructural modification and homogenization of components fabricated by castings and powder metallurgy [23–26]. In FSP, a non-consumable rotating tool having a shoulder with a pin is placed on the work-piece and traversed over the surface. When the tool shoulder touches the work-piece friction force generates heat as a result plastic deformation of material takes place. The combination of tool rotation and translation caused by localized heating softens the material around the pin and leads to the movement of material from the front to the back of the pin. Generally, reinforcing techniques such as a groove or holes filling is used for the incorporation of the reinforcement into the matrix materials. In this technique, reinforcement material filled in a groove or holes on the surface of the metal matrix plate and then passes the stirring tool to mix and distribute reinforcement effectively within the matrix as shown in Fig. 2a [27, 28]. In FSP, surface properties of materials changed due to thermo-mechanical stirring effect. The FSP zones such as friction stir zone (FSZ)/ Nugget zone, thermo-mechanically affected zone (TMAZ), heat affected zone (HAZ) and parent metal (PM) forms during the processing of materials as shown in Fig. 2b. The FSZ is a tool probe zone, the material has fine, equiaxed recrystallized grains and sub-grain boundaries. TMAZ region is an area just next and adhering to FSZ where processing tools plastically deformed material and microstructure influenced by heat dissipation during the process. The HAZ region lies closer to the TMAZ in which the material experienced a thermal cycle. The microstructure and mechanical properties of this zone changed without undergoing any plastic deformation. The HAZ zone is characterized by a larger grain than the base material. The FSP can be characterized by attributes like low-temperature processing, fine grain microstructure, healing of casting defects, and mixing of surface layers.

2.1 Process variables

The mechanical properties such as strength, hardness, and ductility of substrate material are important in surface composite fabrication because these properties control the plastic deformation of the substrate in FSP. The high heat input required for high melting point materials. However, low heat input for low melting point and ductile material such as aluminum alloys. The heat input also depends on the thermal conductivity of the processed material. More heat input is required for high thermal conductivity materials. The maximum temperature in the stirred zone during FSP of aluminum alloys is found to be 0.6 to 0.9 times to the melting temperature. The various FSP process variables are shown in Fig. 3. The properties and uniform distribution of reinforcement in surface composite depend on the FSP processing conditions like tool rotational speed and feed rate, tool geometry, number of FSP passes, and groove design.

2.2 Tool geometry

The material flow, heat generation, microstructure and properties of FSZ in FSP primarily depend on the tool geometry like probe shape and dimensions, shoulder configuration and diameter. Generally, Flat, Concave and Convex shoulder end were used. Other profiles such as scroll, spiral, concentric circles, ridges, etc. were also used to reduce the flash formation and increase the amount of plastic material that enhanced material blending [29, 30]. Mostly, the ratio of shoulder diameter (D)/d (pin diameter) is used as 3:1 to achieve desired properties [31, 32]. The tool probe geometry greatly impacts on particle blending during FSP. The different tool probe configurations reported in the literature are straight, cylindrical, taper cylindrical, square, threaded, flute, etc. [33–36]. The different probe shapes are depicted in Fig. 4. In FSP, tool wear is the most serious issue in FSP. Sert [37], reported that tool wear of taper pin profile is less. The selection of tools mainly depends upon the properties of reinforcement and substrate materials. The tool material H13 steel was preferred for aluminum and its alloys. The poly cubic boron nitride (PCBN), tungsten carbide (WC), cobalt (Co) alloys and cermets were used for harder materials.

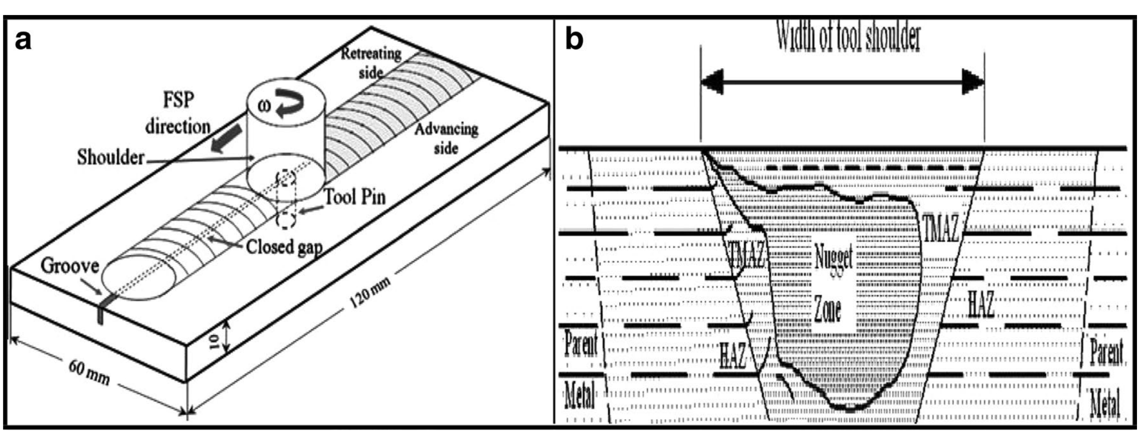

Fig. 2 **a** Friction stir process [27], **b** Friction stir processing zones [28]

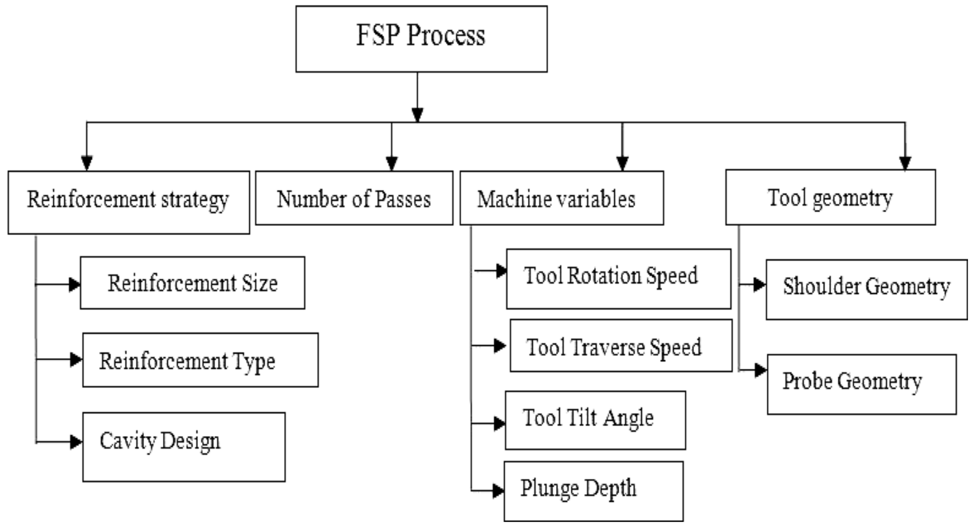

Fig. 3 Friction stir process variables

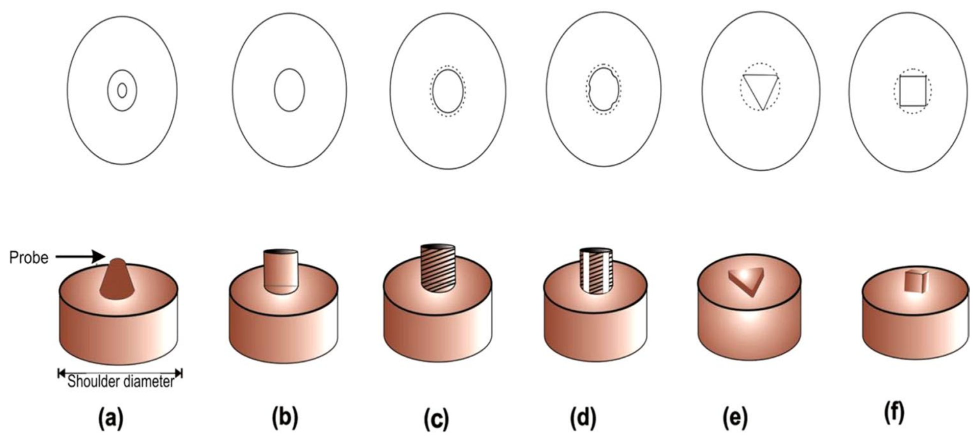

Fig. 4 Profile of FSP tool probes **a** conical, **b** cylindrical, **c** threaded cylindrical, **d** threaded cylindrical flutes, **e** triangular, **f** square [33]

2.2.1 Effects of Tool Geometry on Composite Properties

The FSP tool geometry has vital in determining the quality of surface composites. It was found that the threaded cylindrical pin profile tool exhibited better mechanical properties than other pin profiles such as square, plain cylindrical, triangle, tri-flute and hexagonal [38]. Gupta and Rakesh [12] reported surface composite fabricated with a taper pin tool showed better properties as compared to the cylindrical threaded pin tool. Suresha et al. [36] reported that properties of stir zone material fabricated with the taper pin tool were superior as compared to the plane cylindrical tool. However, Elangovan and Balasubramanian [39] reported that the square tool pin profile produces better mechanical properties. Eftekharinia et al. [40] investigated the effects of pin geometry microstructure, wear rate and microhardness of 6061-T6/SiC surface composite fabricated via friction stir processing (FSP). It was reported that the square pin

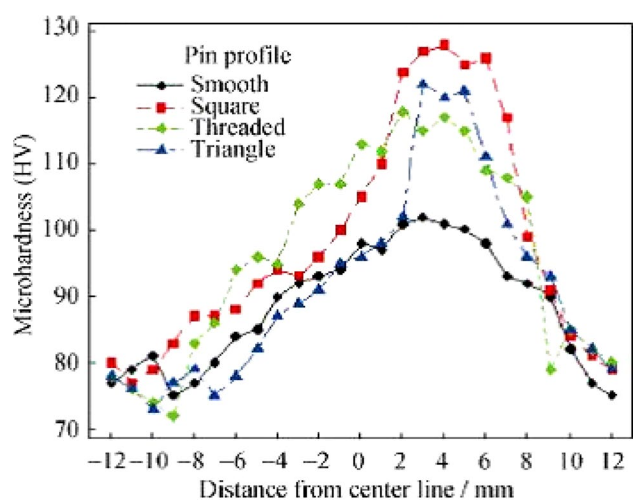

Fig. 5 Effects of tool pin profile on microhardness [40]

and straight cylindrical pin fabricated composite exhibited the highest hardness as shown in Fig. 5.

Mahesh and Arora [41] studied the effect of tool shoulder diameter on Al/Mo fabricated composite and found that hardness of composites increased with a decrease of tool shoulder diameter.

2.3 Machine variables

The Rotation speed, traverse speeds, tilt angle, plunge depth, and axial force are the machine variables in FSP. However, the FSP tool rotational and transverse speed is major influencing variables because these parameters affect the amount of heat generated FSP and rate of material deformation during processing.

2.3.1 Effects of Tool Rotation and Transverse Speed

The literature reviews revealed that the mechanical properties of surface composites depend on FSP process parameters. It was reported that higher tool rotational and traverse speed increased heat input and material flow rates which improved the blending of the reinforcing particles and softened matrix material [42, 43]. The higher rotational speed is required for uniform distribution and to avoid reinforcing particulate clustering. On the other hand, high rotational speed adversely affects grain refinement because of high heat input. A few studies have reported the best particulate distribution was achieved at lower rotation speeds [44]. It was reported that the tool feed rate is more influence parameters to improve the tensile strength of fabricated composite [45]. The higher hardness and wear resistance of fabricated the composite were observed at less tool rotational speed and higher feed rate [46, 47]. In a nutshell, the rotational and traverse speed of tool should be optimized to get finer grain and defect-free friction stir zone. The various tool rotational and transverse speeds used for the fabrication of different surface composites are depicted in Table 1.

Table 1 revealed that the tool rotational speed in the range of 600–2000 rpm was used for the processing of deferment aluminum matrix surface composites. The feed rate mostly in the range of 30–80 mm/min was preferred for the fabrication of various surface composites. In carbon nanotubes/Mg alloy surface composite fabricated through FSP at constant tool rpm and varying feed rates, It was found that composite processed at 25 mm/min showed the improved distribution of the Multiwall carbon nanotubes reinforcement in the matrix material [18]. In SiC reinforced aluminum surface composite, it

Table 1 Rotational and transverse speed used in surface composites fabrication

Composites	Rotational speed (rpm)	Transverse speed (mm/min)	References
Al/SiC	1400	40	[59]
Al/Gr/MoS_2	1400	56	[8]
Al/CNT	1250–2000	12–31	[18]
Al/Pine Needle Ash	1400	40, 56, 80	[13]
Al-Al11Ce3-Al_2O_3	500	30–120	[31]
Al/TiN	1200	40	[34]
Al/SiC/Al_2O_3	1500	100	[43]
Al-7Si-3Cu	600	12	[63]
Al5083/(CeO_2 + SiC)	600, 800	45	[55]
Al-TiC	710, 900, 1120, 1400	16	[49]
Al/SiC	1250	100	[70]
Al/RHA	1400	26	[81]
Al/Ni	1200	60	[44]
Al/B_4C	1000	25	[68]
Al–B4C–TiC	1000	40	[78]
Al/Ni	1200	18	[83]
Al-Tin-Graphite	1800	80	[90]
Al/SiC	700	20, 40, 56	[86]
Al/Cu/Gr	1040	52	[92]
Al/SiO_2	1600	60	[85]
Al/TiC	1200	60	[47]
Al/SiC, Al_2O_3, TiC, B_4C,WC	1600	60	[50]
SiC/$ZnAl_2O_4$/Al	600	20	[92]

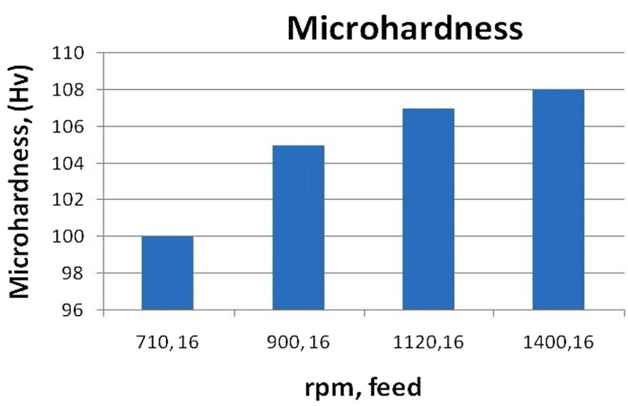

Fig. 6 Effects of tool rotational speed [49]

was reported that uniform distribution of SiC particles was directly proportional to rotational and traverse speed. It was also observed that very high traverse speed adversely affects bonding between SiC and Al alloy [48]. The rotational speed also affects the surface composite fabricated by FSP. It was reported that hardness of developed composite was directly proportional to the rotational speed of the tool as shown in Fig. 6 [49]. Dinaharan [50] fabricated aluminum surface composite reinforced with SiC, Al_2O_3, TiC, B_4C and WC reinforcement particle and reported that TiC reinforced composite exhibited superior hardness and wear resistance compared to others. Shahraki et al. [51] reported that AA5083/ZrO_2 nanocomposite fabricated at 800 rotational speeds and feed speed 40 mm/min exhibited the highest tensile strength as compared to other combination of rotation and feed speed.

The rotational and transverse speed of the FSP tool plays an important role in grain refinement. The grain size increased with an increase of rotational speed whereas the increase in traverse speed reduces grain size, which leads to improving the mechanical properties of the surface composites [52]. The improved grain structure enhanced the superplastic forming properties of materials [53]. The refined grain structure also makes a material biodegradable. It was reported that nano-hydroxyapatite reinforced magnesium alloy biodegradable composite by FSP, grain refinement, and nano-hydroxyapatite particles enhance the controlling of degradation of magnesium. The rapid biomineralization in the composite is due to the nucleation of nano-hydroxyapatite particles. The traverse speed is a major influencing factor for improving the formability due to grain refinement of material [54, 55]. It was reported that the distribution of reinforcement particles and their grain refinement in substrate material was significantly affected by tool pin stirring action which leads to improving surface properties of the material [56]. Chen et al. [31] reported that specimen produced at higher tool traversing speed shows a lower strength than those produced by lower tool traversing speeds due to larger size and a lower amount of reinforcing at higher tool traversing speed. Mathur et al. [57] reported that hardness of Al/TiO_2 surface composites increased up to 1000 rpm and a further increase in the rotational speed of 1300 rpm causes a decrease in the hardness due to scattering of particulates from the FSP region.

2.3.2 Effects of Tool tilt angle and Plunge depth

The tool tilt angle helps to cut matrix material by tool front face, tool pin performs mixing and stirring and tool shoulder squeezing the material in the groove effectively [58]. Generally, tool tilt angles in the range of 2°–3° were used in FSP as shown in Table 2. Tool tilt angle and plunge depth are interconnected and responsible for the tool/workpiece contact area. Increasing the tilt angle with constant plunge depth instigates lower heat generation owing to a reduction in the interface area. At the same time, increasing the plunge depth counterbalances the reduced interface area and heat generation thereby. Axial load counts for holding the tool and stirred material intact against the workpiece movement. Thus, the combined efforts of stated parameters govern the heat input in FSP. It was reported that low plunge depth results in less material flow and cavity formation at the center of SZ owing to less heat generation at the low contact area between tool shoulder and base metal [59]. Sert [37] carried out with a tool tilt angle 2.5 and without angle. They reported that processing with the tilt angle, the substrate surface produced without lack of

Table 2 Tool tilt angle

Composite	Tilt angle (°)	References
AA6061/SiC	2.5	[59]
Al/Gr/MoS_2	2	[8]
Al/Pine Needle Ash	2	[13]
Al/CNT	3	[18]
Al-Al11Ce3-Al_2O_3	3	[31]
Al/TiN	2.5	[34]
Al/SiC/Al_2O_3	3	[43]
Al5083/(CeO_2 + SiC)	3	[55]
Al-TiC	3	[49]
Al/SiC	3	[70]
Al-Tin-Graphite	3	[90]
Al/SiC	2.5	[86]
Ti/TiN	3	[88]
Cu/Gr	1.5	[91]
Al/Cu/Gr	2	[92]
Al/TiC	2	[47]
SiC/$ZnAl_2O_4$/Al	1	[92]

fill and flash formation in the surface composite as shown in Fig. 7.

2.3.3 Effects of Number of FSP Passes

The refined grain of surface composites enhanced corrosion resistance, hardness and wear resistance properties. It was reported that ultrafine structure formed surrounding the rotating tool pin due to the deformation field generated for this reason [60–62]. The FSP pass affects the grain structure of the surface composite. The heat gathered in multiple FSP passes increased dissolution of precipitates, grain size and breaking reinforcement particles. It was reported that as an increase in the number of FSP passes, the grain size of composites becomes smaller and gets refined [40, 63–65] as shown in Fig. 8. It was also reported that the clustering of reinforcement in the stirred zone was enhanced as the number of FSP pass increased [66, 67]. Generally, 1–2 FSP pass was used for the processing of surface composites as shown in Table 3.

Yuvaraj N, Aravindan [68] reported that hardness of surface composites increased with an increasing number of passes as shown in Fig. 9a. However, Abdulmalik and Ahmad [69] found that hardness of 4- FSP passes composites were less than the 1- pass and 2- FSP passes due to due annealing effect as shown in Fig. 9b.

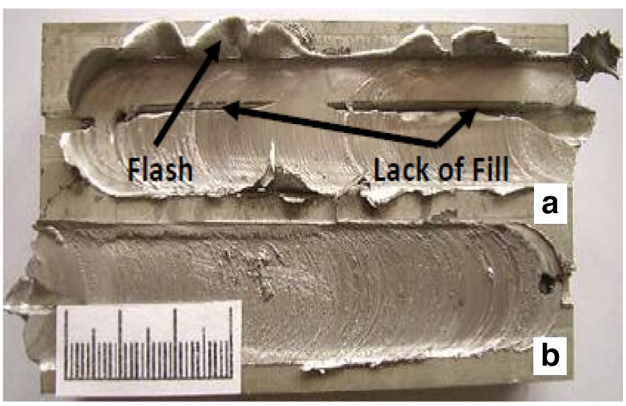

Fig. 7 Composites fabricated **a** without a tilt angle, **b** with a tilt angle of 2.5° [37]

2.4 Reinforcement strategy

A reinforcement strategy means introducing reinforcing particles over the surface of matrix material before processing. A reinforcement strategy is necessary for the fabrication of flawless surface composites. The different reinforcing methods used in FSP are:-

- Directly pasting on the surface
- Packing particles in the groove cavity
- Packing the particles in a net of blind holes/dimples.

These above methods are selected based on different criteria such as groove design, types of particle and its dimensions. The various reinforcing methods used in FSP such as direct methods, sandwich method, groove and holes filled, and surface coating as shown in Fig. 10 [22]. It was reported that the volume percentage of doping reinforcement in surface composites fabricated through FSP mainly affected by reinforcing methods and size of groove. It was found that composite fabricated by three gradient grooves reinforcing techniques, experiences better in hardness compared to other techniques [70, 71].

The impact strength of surface composite fabricated with reinforcing B_4C on aluminum alloy 6063 substrates using serial holes reinforcing technique with a square pin profile tool exhibited maximum impact strength

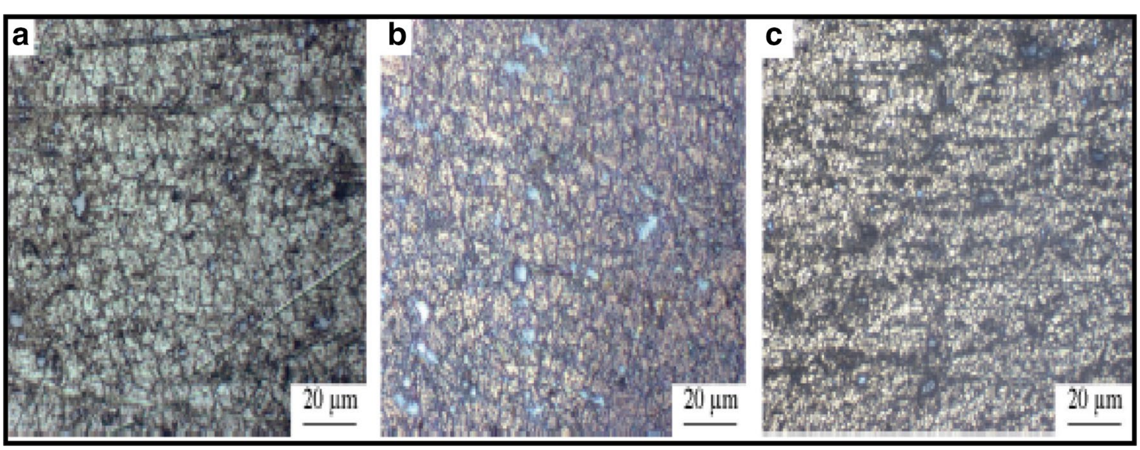

Fig. 8 Images of SiC reinforced composites fabricated using: **a** 1-pass, **b** 2-passes and **c** 4-passes [40]

Table 3 FSP Passes used in composites fabrication

Composites	Number of passes	References
AA6061/SiC	2	[59]
Al/Gr/MoS_2	2	[8]
Al/Pine Needle Ash	2	[13]
Cu/TiB_2	2	[17]
Al/CNT	1, 2, 4	[18]
Cu/Al_2O_3	1	[19]
Mg–Al-Zn	2	[20]
Al-Al11Ce3-Al_2O_3	4	[31]
Al/TiN	4	[34]
Al/SiC/Al_2O_3	3, 4	[43]
Al-7Si-3Cu	2,3	[63]
Ti/Al_2O_3	4	[67]
Al5083/(CeO_2 + SiC)	3	[55]
Al-TiC	2	[49]
Al/SiC	1	[70]
Al/RHA	1, 2, 4	[69]
Al/B_4C	1,3	[68]
Al/Ni	1	[83]
Cu/Gr	1, 2, 3, 4	[91]
Al/SiO_2	1	[85]
Al/SiC, Al_2O_3, TiC, B4C,WC	2	[50]

as shown in Fig. 11 [69]. The groove or holes fill was proposed as the most excellent method to the dope maximum amount of reinforcement on the surface of the substrate material.

3 Reinforcements and composite properties

The properties of reinforcements have a critical role in determining the properties of the composite [72]. The selection of the reinforcement mostly depends on the targeted application and compatibility of particles with the substrate matrix. Boron carbide (B_4C) offers outstanding neutron absorptivity along with thermal and wear resistance. The B_4C reinforced composites have excellent neutron absorbing capability and used as main neutron shield material in reactors. The mechanical property of Mg-CNT composites has outstanding whereas Mg–Al_2O_3 composite possesses greater wear resistance [73]. In carbon nanotubes/Mg alloy surface composite fabricated through FSP, the hardness of the fabricated composite was increased up to 92% of the base metal [18]. The surface composite fabricated by reinforcing Al_2O_3 particle aluminum substrate exhibited enhanced hardness as compared to substrate material [16]. In SiC reinforced aluminum surface composite, it was reported that hardness and flexural strength of surface composite improved considerably because of the incorporation of silicon carbide particles [74]. The hardness of the Al7075/B_4C surface composite was reported that 62% higher that of matrix [75]. It was found that hardness of Al7075/Al_2O_3 surface composite approximately double whereas impact toughness increases up to 29% [16]. In one study, the nanocomposite layer was made by introducing aluminum oxide nanoparticles among the tool and drilled holes in Al 1200 aluminum plate by using friction stirring. It was found that the nanocomposite layer improved the fatigue, compressive strength, and hardness of the hole [76]. Al/Fe surface composites showed

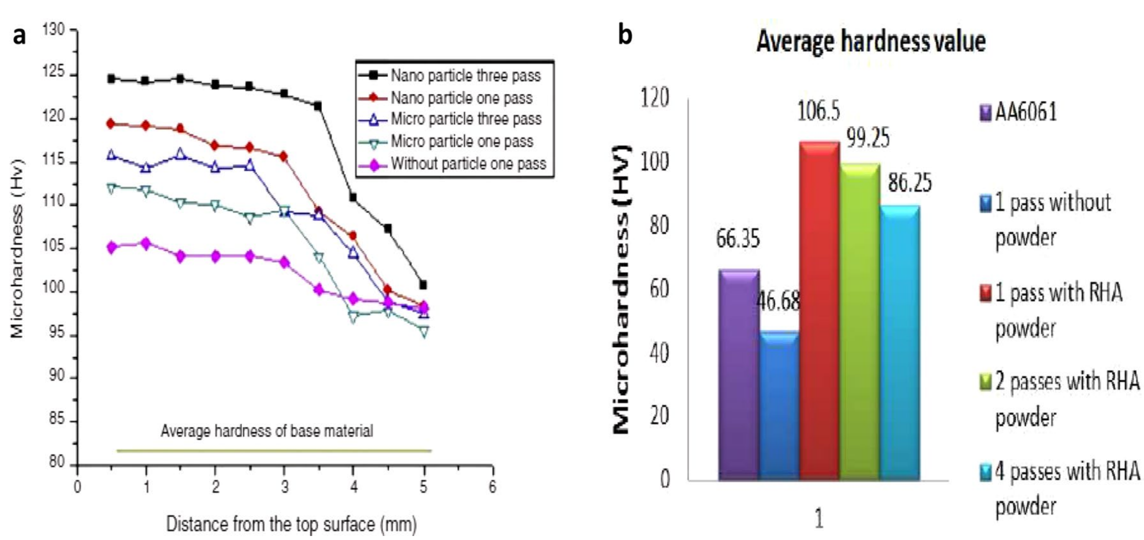

Fig. 9 Effects of FSP passes on hardness [68, 69]

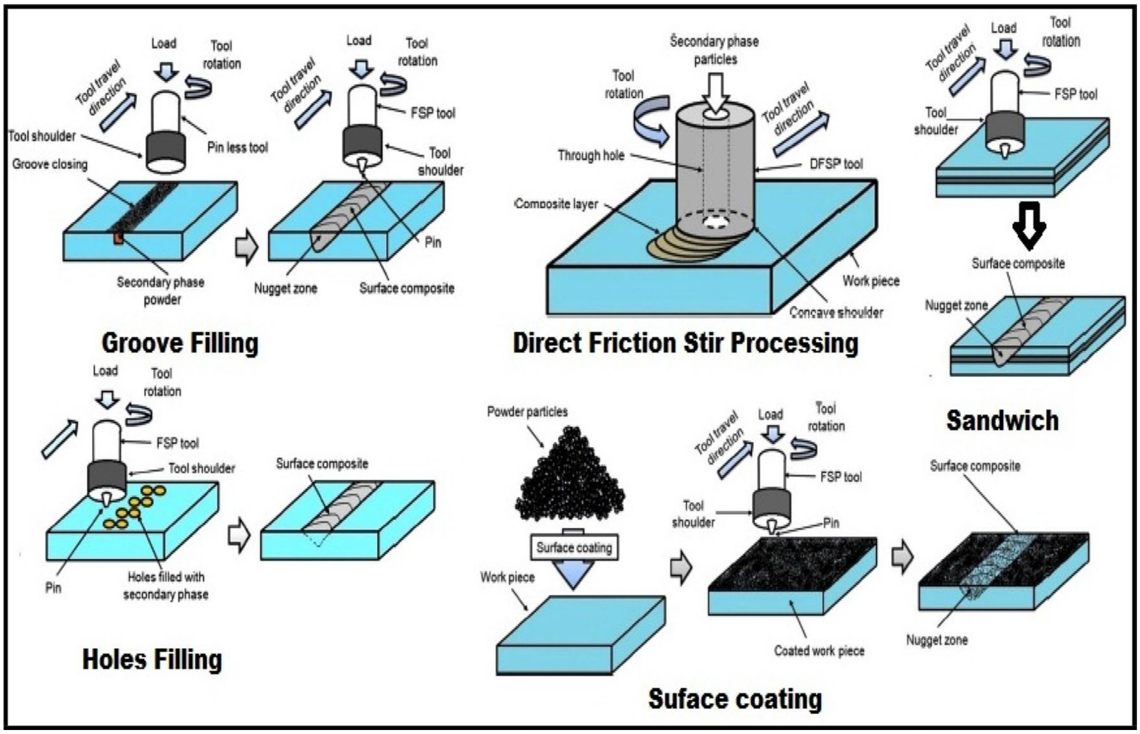

Fig. 10 Reinforcing methods [22]

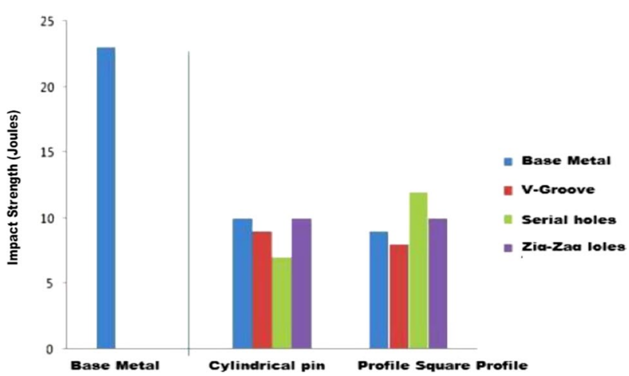

Fig. 11 Effects reinforcement and Methods on Surface composites properties [69]

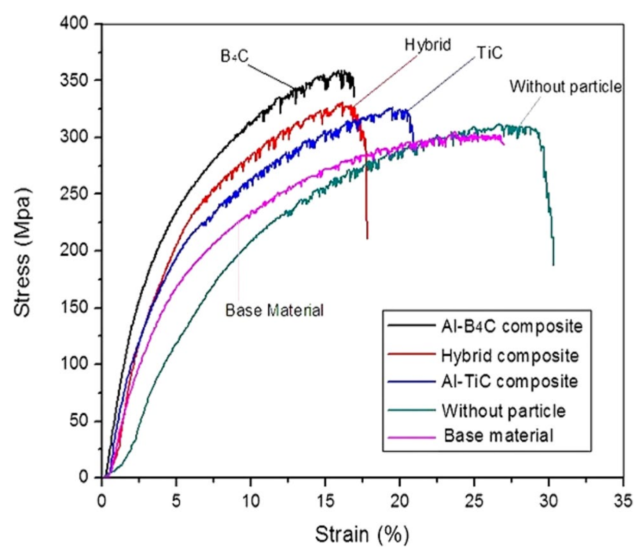

Fig. 12 Stress-Strain curves of composites [78]

improved creep behavior due to iron aluminides formed on the surface of the composite [77]. The hybrid composites consist of more than one reinforcement particles. The Al/B_4C/TiC hybrid composites [78] exhibited higher tensile strength as compared to TiC fabricated composite as shown in Fig. 12.

The reinforcement particle shape and size are an important factor and required to be considered in surface composite fabrication because it affects the properties of the surface composite. Normally, two scales viz. micrometer and nanometer of particles are incorporated in the composites. The coarse particles form larger grains during recrystallization whereas fine particle size reduces grain size. The nano size and harder particles reinforced composites showed better properties. The dimensions and volume fraction of the particles extensively affect the properties and microstructure of surface composites. It was found that nano-sized reinforced surface composite showed

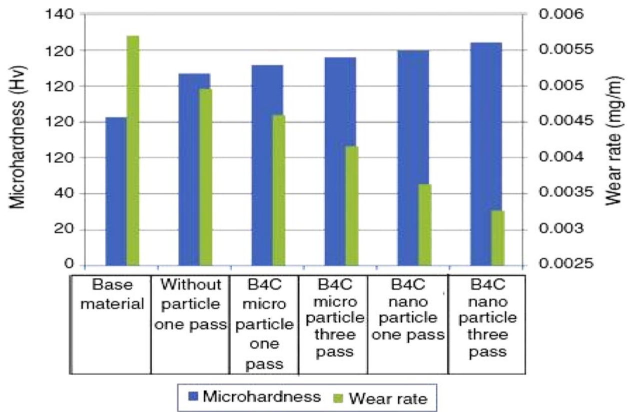

Fig. 13 Effects of particulate size on surface composites [68]

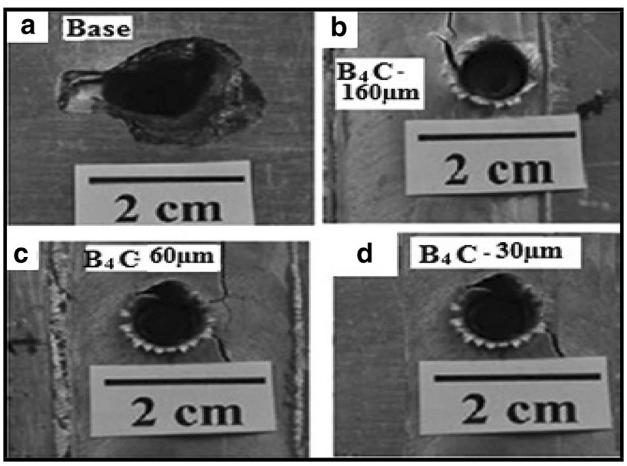

Fig. 14 Front view of targets after the ballistic test [79]

superior properties than micro as shown in Fig. 13. Sudhakar et al. [79] reported that ballistic efficiency of Al 7075/B_4C fabricated composite increased due to the frictional attribute of armor surface which favors the damage to the surface of the projectile tip due to abrasive action of B_4C particles on the target as shown in Fig. 14. Pol et et al. [80] fabricated different surface composites made of 25B4C-75TiB_2, 50B_4C-50TiB_2 and 75B_4C-25TiB_2 reinforced AA7005 surface using friction stir processing and reported that The ballistic efficiency of 75B_4C-25TiB_2 surface composite was found 1.6 times higher than of the base alloy.

The agro and industrial waste such as Rice hush ash, Pine needle ash, Fly ash, Sugarcane Bagasse ash, Coconut shell ash, Corn cob ash, and Groundnut shell ash [5–7, 9–12] have been used as reinforcements to fabricate cost-effective composites. It was reported that the microhardness of Al/Rice Husk Ash surface composite 40% higher that of aluminum (Matrix material) [81]. Gupta and Rakesh [12] also reported that Al/Pine leaf ash exhibited superior mechanical properties than unreinforced matrix materials.

The harder surfaces and lubricating behavior of material surface exhibited improved wear resistance properties [82]. The literature review explained that hard and stiff reinforcement materials were reinforced on the substrate material to improve the tribological properties of surfaces as shown in Fig. 15a. It was reported that wear resistance properties of composite increased with the increase of percentage volume of reinforcement in matrix materials as shown in Fig. 15b. Kishan et al. [83] observed that composite having 4 vol % TiB_2 exhibited wear resistance properties as compared with 2 and 8 vol % of TiB2 reinforced composites.

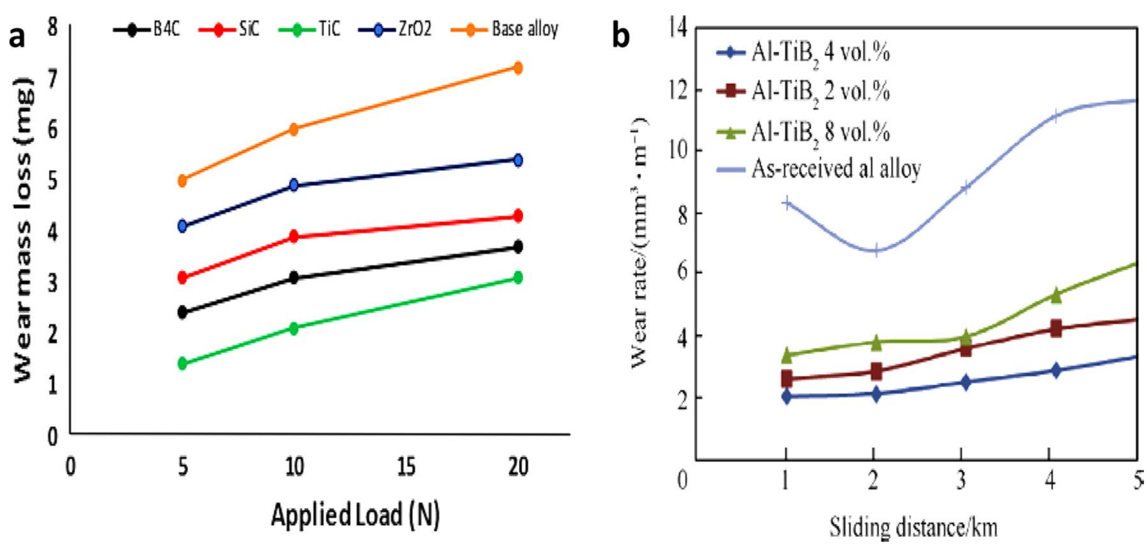

Fig. 15 Effects of reinforcement and volume % on Wear [82, 83]

In the hybrid nanosurface composite of Al/Al_2O_3-Al_3Ni, it was accounted for that NiO particles react with Al and formed Al_3Ni and Al_2O_3 favorable properties improvement compounds during FSP and tribological properties of fabricated composites were significantly improved [84]. In the surface composite of Al6063/SiO_2, it was reported that the hardness of surface composites was directly proportional to the volume percentage of SiO_2. However, wear properties reduced with an increase in the volume percentage of SiO_2 in surface composites [85]. The composite fabricated with TiC particle reinforced exhibited less wear and high in hardness as compared to alumina, silicon carbide, titanium, boron carbide, and tungsten reinforced composites [40]. It was reported that composite fabricated with straight and square pin tool exhibited less wear resistance [50]. It was found wear properties of Al7075-T651/SiC surface composites improved due to the existence of SiC in the composite. It was also suggested that the tool wear rate of the taper profile tool is less as compared to other profiles [86]. The FSP can be carried out in N_2 atmosphere to form an ultra-fine nitride layer on the matrix surface to improve hardness and wear resistance properties [87, 88]. In-situ Al1050/Fe_3O_4 nanocomposites surface composite exhibited 65% higher wear resistance properties than Al 1050 [40].

The solid lubricates materials such as graphite and molybdenum reinforcement materials are used to enhance wear resistance properties of composites as shown in Fig. 16.

The wear resistance of surface composites reinforced with MoS_2 improved due to solid lubricant particulate MoS_2 present in the surface composite [89]. The surface composite of Al-TiN-Gr fabricated through FSP, it was found that TiN/Gr reinforced surface composite exhibited improved the wear resistance rather than individual Gr or TiN of the composite [90]. The effects of tool profiles on wear performance of Cu/Gr surface composite were examined and reported that the triangular pin tool performed better dispersion of Gr which decrease coefficients of friction of composites decreased [91]. It also was reported that hybrid surface composite of Al/Cu/Gr exhibited better wear resistance properties than Gr and Cu reinforced [92]. The ashes of Pine needle (PNA), Bamboo leaf, Rice husk, etc. as reinforcement in matrix material also improved wear resistance fabricated surface composites as depicted in Fig. 17.

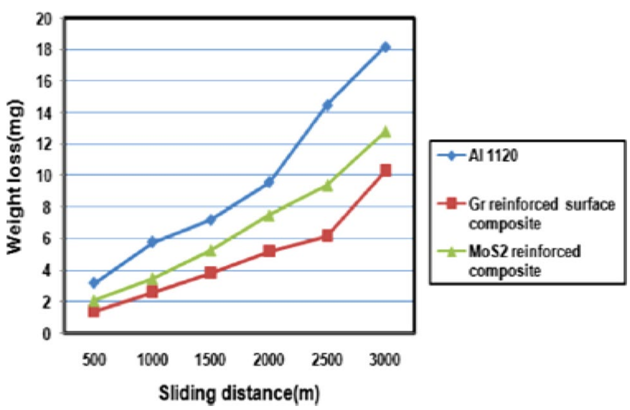

Fig. 16 Effects of Graphite and Molybdenum Disulphide on Wear [8]

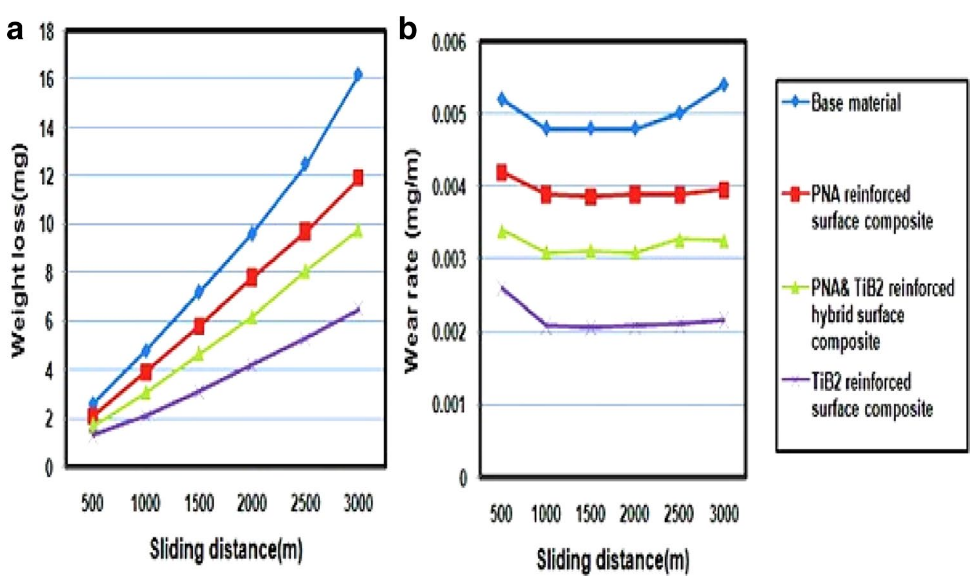

Fig. 17 Effects of Pine needle ash on Wear Properties [17]

4 Conclusions

The FSP has been proven a novel technique to enhance the grain structure of the material surface and the fabrication of surface composites. The H-13 tool was preferred for the fabrication of aluminum metal matrix surface composite. The threaded pin tool has better reinforcement mixing and distributing properties in comparison to other profiles. The properties of fabricated surface composites depend on the FSP process parameters and reinforcement properties. The tool rotational speed 600–2000 rpm, transverse speed of 30–80 mm/min, tool tilt angle of 2°–3° and FSP passes 1–2 have been reported as a range of FSP process parameters for fabrication of various categories of aluminum matrix surface composites. The surface composite fabricated with nano size and harder reinforcement materials exhibited better mechanical and tribological properties as compared to maco size reinforced composites. Solid lubricant reinforcements such as Graphite and Molybdenum Disulphide are reinforced in a matrix material to enhanced wear resistance properties of fabricated composites. The reinforcement techniques such as groove filling, holes filling, zig-zag holes, serial holes, sandwich, and direct methods have been used. However, mostly the groove fill method was used for the fabrication of surface composite. Very few literatures are available on the effects of number of FSP passes and plunge depth on the properties of surface composites. The study on these FSP processes parameters may be explored.

Compliance with ethical standards

Conflict of interest The author declare that they have no competing interests.

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