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Review Article

Review and analysis of the effect of variables on aluminium based surface composite fabricated through friction stir processing method

Abdul Jabbar Ansari[1*] and Mohd. Anas[2]
Research Scholar, Department of Mechanical Engineering, Integral University, Lucknow-226026 U.P. India[1]
Associate Professor, Department of Mechanical Engineering, Integral University, Lucknow-226026 U.P. India[2]

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Abstract
Friction stir processing (FSP) is a remarkable technique to create metal matrix composites (MMCs). FSP can be used to produce MMCs of different materials like aluminium, copper, magnesium, steel etc. Due to the excellent mechanical properties like higher strength to weight ratio, higher corrosion resistance and lighter weight density brand aluminium as a material of choice for different structural application in different industries like defense, marine, automobile and aircraft. Many researchers have found that the microstructure as well as mechanical properties of aluminium can be altered through reinforcing particles like SiC, TiC, Al_2O_3, etc. Microstructure, mechanical and wear properties of aluminium base material can also be altered by modifying different variables involved in FSP. This paper is a state of art review of consequences of different variables of FSP on mechanical properties of aluminium metal matrix composites (AMMCs) fabricated through the FSP method. This review article will also provide the future research direction for aluminium as a base metal.

Keywords
Aluminium metal matrix composite, Friction stir processing, Surface composite, Parameters of friction stir processing.

1.Introduction
Composite is a combination of distinct materials of metals, ceramics and polymers which exhibits collective functioning properties of the base material. The broad application of metal matrix composites (MMCs) is due to their different physical and mechanical properties such as higher strength and stiffness, high resistance of corrosion and excellent wear resistance properties. Aluminium is one of the largest widely used metals in structural industry due to its excellent mechanical properties. Its superior corrosion resistance, good machinability, high specific strength, high thermal conductivity increases the application in different industries. Applications of aluminium alloys are limited in some areas due to its low surface hardness. To overcome this challenge reinforcing ceramic particles is a better option and increases the application areas like engine components [1]. For the fabrication of aluminium metal matrix composites (AMMCs), powder metallurgy, compo casting and stir casting are well known techniques [2–4].

High fabrication cost and constrained size are the major problems related with powder metallurgy method. Common defects arise in liquid metallurgy processing are non-uniform distribution, agglomeration, porosity and interfacial reaction. High operating temperature in thermal spraying technique and laser beam techniques make it very difficult to stop formation of obnoxious phases [5, 6]. Friction stir processing (FSP) is an ingenious method for the fabrication of surface composite among the several other conventional methods. Basically, FSP is a solid-state surface properties modification process in which fabrication and synthesis of materials undergoes and base properties of material are reserved. By applying FSP, better structure of grains of the base material is obtained due to refinement of grain size [7–10]. In several metals like aluminium and magnesium, super-plasticity can be achieved by operating FSP. Several other properties like surface hardness, wear resistance and coefficient of friction can be enhanced by FSP [11–13]. Many researchers have investigated about the enhancement in surface properties with introduction of second phase particle materials through FSP [14–18]. The ability to create MMCs on the desired surface which enhanced the

*Author for correspondence

properties and durability of the material is the most unique advantage of the FSP [19–21].

Origin of FSP is friction stir welding, developed by Mishra et al. [22]. FSP successfully extended to develop surface composites (SCs) of alloys like copper alloys [23, 24], magnesium alloys [25], Titanium alloys [26] and even steel [27, 28]. Several researchers successfully reinforced different particles in aluminium as a base metal and reported about the effect of different variables of FSP technique on the properties of AMMCs [9–11].

Different researchers obtained excellent results by reinforcing different reinforcement particles (RPs) at different tool rotational speed (RS), tool traverse speed (TS), tool pin profile and number of passes [7–12]. However, there is no organized review which summarizes the effect of different variables of processing parameters of FSP on the microstructure and mechanical properties of AMMCs. Main research questions arise regarding the combined effect of machine variables, tool variables and reinforcement variables of FSP on the microstructure and mechanical properties of AMMCs.

This paper presents the solution of problems and challenges faced by various researchers regarding effect of processing parameters of FSP for the fabrication of AMMCs. This article presents a critical review on the effect of variables involved in FSP for the fabrication of AMMCs. Papers are included in this article is on the basis of certain criteria that are given in *Table 1* and year wise distribution of these papers are shown in *Figure 1.* Important parameters and factors which directly affect the microstructure and mechanical properties of the AMMCs are systematically classified and followed with detailed discussion.

Extensive literature surveys for comparison of these parameters are presented in tabular format for easy and quick reference. In the end paper is summarized with concluding summary, future scope and major challenges.

Table 1 Inclusion and exclusion criteria of the papers

S. No.	Inclusion criteria	Exclusion criteria
1	Peer reviewed articles from 1990-2022.	Articles that do not published from 1990-2022.
2	Published in English language.	Articles which were not available in English language.
3	Content directly related to FSP of aluminium alloy.	Content related to other disciplines, not concerned with the field of FSP of aluminium alloy.
4	Articles that investigated about the effect of processing parameters of FSP on microstructure and mechanical properties of AMMCs.	Content which was not focuses on the processing parameters of FSP.

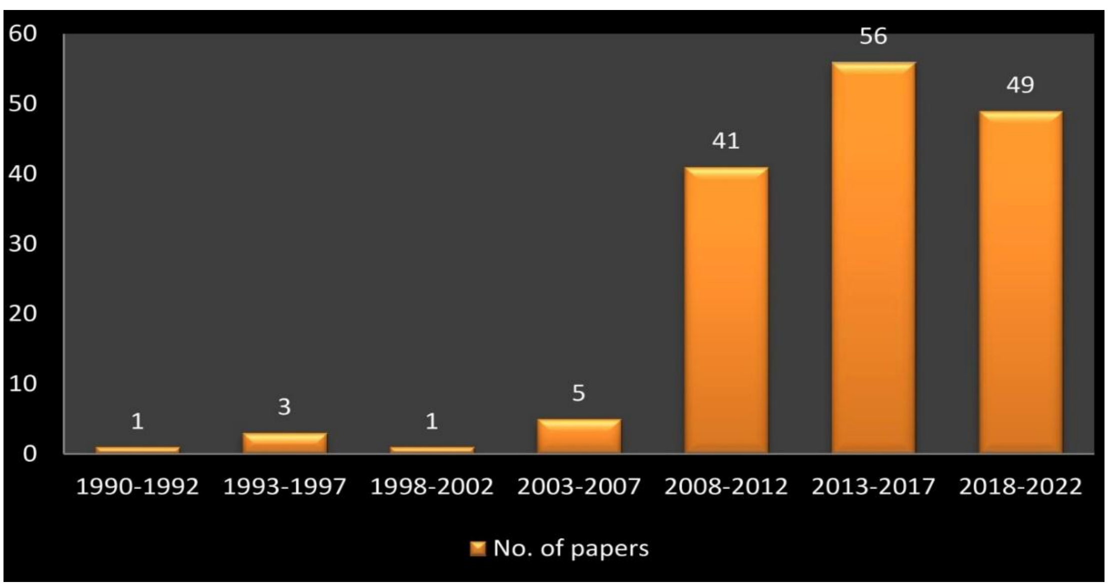

Figure 1 Year wise distribution of papers

2.Fabrication of AMMCs through FSP

Basically, in FSP the workpiece is fixed and a non-consumable tool rotating in clockwise direction is steeped into the workpiece (*Figure 2*). The rotating tool moves in forward direction with traverse speed. Due to the friction available between rotating tool and workpiece heat is developed. Rotating tool plasticized the base material and reinforced material in the stir zone. For the reinforcement of the particles like SiC, TiC, Al_2O_3 etc. generally two methods are used: (a) groove method [29–32] (b) series of holes method [33–36]. To avoid splashing of the reinforcing powder a tool of without pin is used to close the groove. In series of holes method, the reinforcing powder is compacted by means of pressure [35, 37]. According to required properties of the composites volume fraction of reinforcing powder, size and shape of the groove and hole can be changed [38]. FSP is most commonly used to fabricate AMMCs [39, 40]. Silicon carbide and aluminium oxide particle as a RPs to fabricate AMMCs well studied [41–48]. Many researchers investigated the effect of TiC particles, ZrB particles, SiO_2 particles, Mg-TiO_2 nano particles on aluminium base metal through FSP [49–59]. Specifically, the consequence of different variables and parameters of the FSP technique on the properties of AMMCs were explored [60, 61].

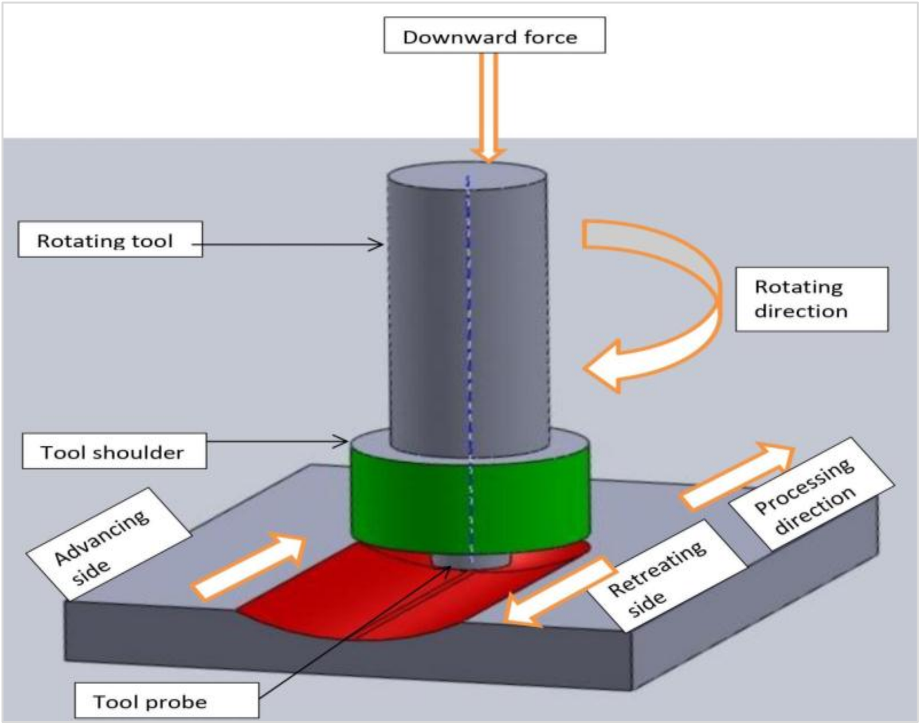

Figure 2 Processing technique of FSP

3.Variables in FSP technique

Microstructure and mechanical properties of the base material can be modified by FSP technique. Different RPs are augmented into the base metal. Distribution of RPs in SCs has huge outcomes on microstructural changes and different properties enhancement of the AMMCs [62]. Distribution of RPs depends on the different variables of FSP. These variables are classified into four groups namely machine variables, tool variables, reinforcement variables, miscellaneous variables. All variables of FSP are shown in *Figure 3*. Each variable of FSP has different effect on the properties of AMMCs and contribution in the enhancement in properties varies because some parameters/ variables have higher contribution and some have lower. However, enhancement in properties depends on different strategies and different combination of factors involved in FSP.

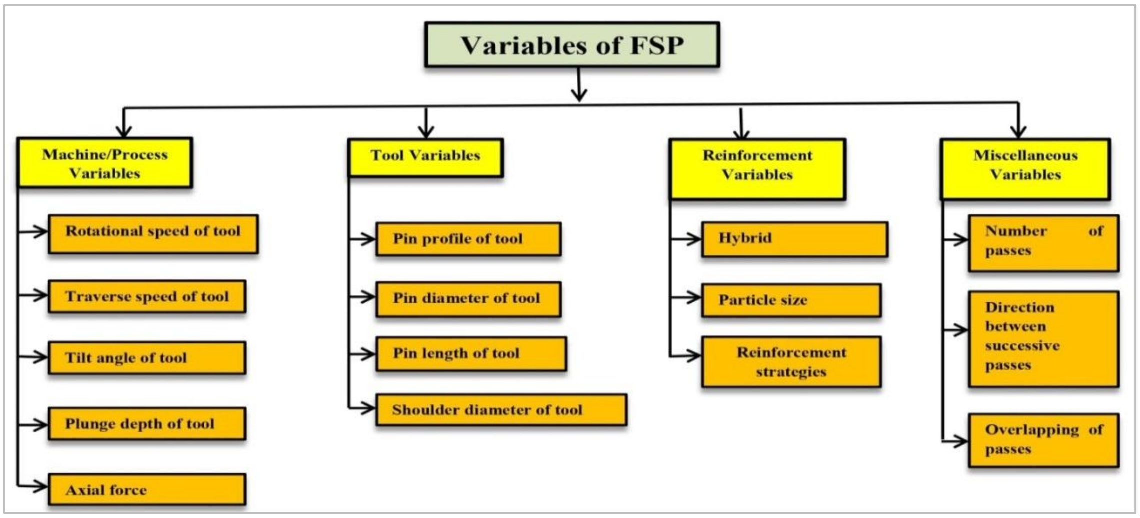

Figure 3 Variables in FSP technique

3.1Machine/process variables

Several researchers have found that machine variables need to be optimized during FSP for getting prominent result. They have significant effect on microstructure characteristics of the composite zone. *Table 2* shows the comparative results by variation of machine/process variables in aluminium based SCs. Salehi et al. [63] investigated about the effect of RS, TS and tool plunge depth (TPD) in the fabrication of AA6061/SiC nano composite through FSP. For finding optimum process parameters combination they applied Taguchi method. A total 16 samples were fabricated through different combination of process parameters. RS of tool changes from 800 r.p.m. to 1600 r.p.m, TS changes from 40 mm/min to 160 mm/min and TPD varies between 0.12 mm to 0.3 mm. Highest tensile strength were obtained at RS 1600 r.p.m., TS 40 mm/min and TPD 0.3 mm due to increased dislocation density by thermal mismatch between RPs and matrix [64] and grain refinement [49, 65, 66]. Rana et al. [67] reinforced 12-15 µm size of boron carbide (B_4C) particles into aluminium alloy 7075-T651 through FSP. Three specimens were investigated with constant RS 545 rpm, and variable TS 50, 78 and 120 mm/min. The result shows that by increasing the TS reduction in grain refinement is obtained to less stirring time. Hence microhardness is reduced. Maximum microhardness was obtained at lowest TS. Highest friction coefficient and wear resistance was obtained at lowest TS due to mechanism of grain strengthening. Devaraju et al. [68] reported that highest microhardness value of the friction stir processed (FSPed) Al6061-T6/SiC-Gr obtained at optimum RS (900 rpm). This is due to the fact that more uniform distribution of RPs is obtained because enough heat input is available at this optimum RS. They used three ratio levels of RPs of SiC and Gr with combination of RS 900 rpm, 1120 rpm and 1400 rpm respectively. At optimum RS (900 rpm) highest tensile strength is obtained due the softening of matrix. Frictional heat generated between the tool and base material (workpiece) is due to the rubbing action between tool and workpiece. By increasing the RS, rubbing action per unit time also increases. Heat generation increases by increasing RS but amount of heat decreases by increasing the traverse speed of tool because TS construe the frictional heat residing time [68, 69]. Jamali and Mirsalehi [69] observed that increasing the RS from 100 r.p.m. to 1200 r.p.m. proper distribution of nanoparticles and growth of crystallized grains enhanced due to high heat input between tool and workpiece in AA7075/ZrO_2 composite. Murthy et al. [70] investigated the tensile strength of the composite Al7075-T651/SiC at optimized process parameters of FSP with the help of taguchi technique. There was a decrease of 9.16% in tensile strength at RS 710 r.p.m., TS 10 mm/min and base hole diameter 2mm. Ande et al. [71] says that by increasing RS from 1200 rpm to 1400 rpm by keeping TS at constant 30 mm/min, more refined grain structure obtained due to excess generation of heat and dynamic recrystallization. Dwarakesh and Puviyarasan [72] found defect free microstructure composite AA7075/$SrCO_3$ at RS 1200 r.p.m., TS 20 mm/min and 0.25 mm penetration depth which results 50% increase in microhardness and 3.2% decline in the tensile strength of the AMMCs. Different variables/ processing parameters affect the properties of AMMCs produced through FSP. Better results were obtained by the proper combination of optimized process parameters and number of FSP passes.

Table 2 Effect of machine/process variables and their respective result

S. No.	Aluminium base material	Reinforced material	Optimum machine variables	Results	References
1	AA6061	SiC (50 nm)	RS = 1600 rpm TS = 40 mm/min TPD = 0.3 mm	1. Higher tensile strength was obtained at high RS, low TS and high TPD.	[63]
2	AA7075-T651	B_4C (12-15 μm)	RS = 545 rpm TS = 50 mm/min	**1.** Maximum microhardness was obtained at lowest TS. **2.** Highest wear resistance was found at lowest TS. **3.** Highest Coefficient of Friction is obtained at lowest TS.	[67]
3	Al6061-T6	SiC and Gr	RS = 900 r.p.m. TS = 40 mm/min Axial force = 5 KN	1. Maximum microhardness value is obtained at lowest RS. 2. Highest tensile strength is obtained at optimum RS.	[68]
4.	AA7075	ZrO_2	RS = 1200 rpm TS = 40 mm/min	1. More uniform distribution of reinforcement observed.	[69]
5	Al7075-T651	SiC	RS = 710 rpm TS = 10 mm/min	1. 9.16% decrease in tensile strength at optimized process parameters.	[70]
6	Al7075-T651	SiC	RS = 1400 rpm TS = 30 mm/min	1. Microhardness of the composite increased. 2. TS has less effect on microhardness as compared to RS.	[71]
7	AA7075	$SrCO_3$	RS = 1200 rpm TS = 20 mm/min TPD = 0.25 mm	1. 50% increase in microhardness of composite. 2. 3.2% decrease in tensile strength of the composite.	[72]

3.2Tool variables

In FSP major fraction of frictional heat is generated mainly due to the tool. This heat softens the material and uniformly distributed the reinforced particles in composite. Pin profile and tool shoulder diameter performs major role on material flow and heat generation [73]. When optimized design of tool shoulder is used at controlled plastic deformation sufficient amount of heat is generated [74]. For achieving best generation of heat in plunge stage, tool pin profile also plays an important role [75]. *Figure 4* shows different types of tool pin profile. Design of tool pin mainly consist tool pin length, tool pin diameter and tool pin shape. For forging of material and heat generation, tool shoulder diameter is also an important parameter. Heat generated is depend upon the friction available between the workpiece and tool, RS, force/applied pressure and cube of shoulder radius [76, 77] and is represented by following Equation 1.

$$q_0 = \frac{4}{3\pi^2 \mu p \omega R^3} \quad (1)$$

where q0 = resultant power, μ = coefficient of friction, available between tool and workpiece, p = pressure, ω = RS and R = tool shoulder radius. By increasing shoulder diameter while keeping other parameters constant heat generation increased but optimum value of tool shoulder diameter is necessary for getting better properties. Some researchers found that shoulder to pin diameter (D/d) ratio should be design to get better properties of composite. Vijayavel et al. [78] found that when they use tool ratio (D/d) as 3 they obtained better microstructural and mechanical properties of composite. Mahmoud et al. [79] reported that better results were obtained in terms of microstructure and mechanical properties by using square pin instead of circular and triangular pin profile. Similar results were also obtained by Elangovan and Balasubramanian [80, 81]. Pin having threaded profile fabricated more uniform distribution of reinforced particles as compared to tool of plane shape profile [82]. In threaded pin profile contact area between tool and deformation zone is larger than in case of other tool pin profile which results larger amount of heat generation. *Table 3* presents some tool profile use in fabrication of AMMCs through FSP and their effect. Commonly hot work steel (H-13) tool is used for nonferrous metal alloys and in case of ferrous metal tungsten carbide (WC) material is mostly used. Tool wear takes place generally in ferrous metal like steel which requires consideration [27, 83, 84] while in case of nonferrous metal tool wear is not subject of matter. High friction force, better flow of material and large amount of heat is stemming due to incomplete contact surface between tool and workpiece due to tilt angle of tool. By increasing tilt angle strain rate is also increases [85, 86]. Sharifitabar et al. [87] also reported that higher tilt angle required for obtaining better results in fabrication of 5052Al/Al2O3 nano composite through FSP. For the fabrication of AMMCs through FSP several researchers have taken tilt angle from 2.5o to 3o [67, 88, 89]. Contact area between tool and workpiece is mainly depends on tool tilt angle and TPD which are significantly manage the amount of heat generation. TPD significantly changes by varying the vertical pressure between tool and workpiece which provide better forging action and flow of material [44]. For improving particle distribution and reduction in cavity defects, high amount of heat generation is needed which can be generated by increasing TPD. But excessive amount of heat can create some defects hence TPD should be taken as an optimum value [44, 90].

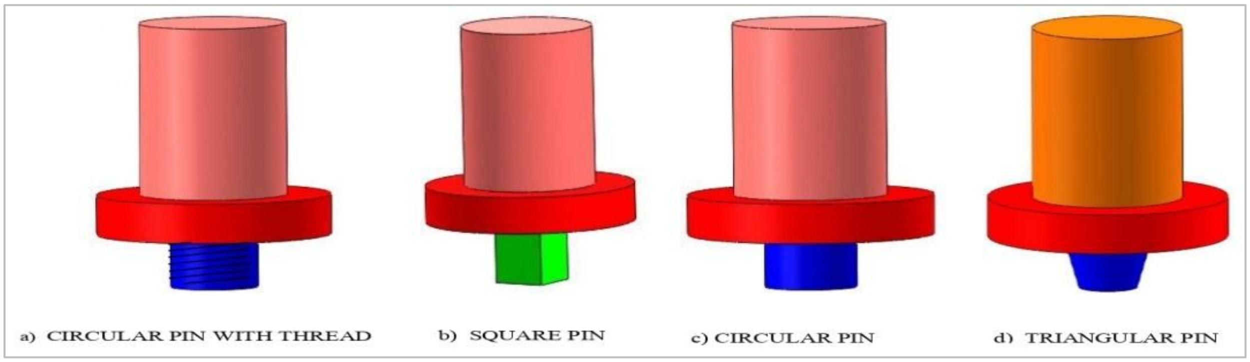

Figure 4 Different types of tool pin profile

Table 3 Some tool profile used in fabrication of AMMCs through FSP

S. No.	AMMCs	Diameter of pin	Pin length	Pin profile	Diameter of shoulder	Reference
1	AA7075-T6/ B_4C	6 mm	3 mm	Straight cylindrical	20 mm	[90]
2	AL1060-H14/W	6mm	4 mm	Unthreaded conical	20 mm	[91]
3	AA2014-T6/SiC	5 mm	3 mm	Round bottom conical	21 mm	[92]
4	Al5052/SiC	6 mm	3 mm	Square	18 mm	[93]
5	Al5083/B_4C	6 mm	5 mm	Threaded cylindrical	18 mm	[94]
6	Al6061/SiC+Gr	8 mm	3.5 mm	Screwed taper	24 mm	[95]
7	Al6061/Gr	3 mm	1.5 mm	Cylindrical	6 mm	[32]
8	AA1100	5 mm	5 mm	Square threaded and straight cylindrical	17 mm	[96]
9	Al6082/SiC	7 mm	5.2 mm, 3.2 mm and 1.7 mm	Threaded cylindrical	24 mm	[48]
10	LM Aluminium alloy/ SiC	6.2 mm	6.2 mm	Threaded cylindrical	-	[97]

3.3Reinforcement variables

In FSP, RPs is preplaced in the base metal through different methods. These methods can be classified mainly two groups as shown in *Figure 5.*

I. Reinforcement insertion into metal matrix [38, 87, 98–102]

II. Reinforcement deposition over metal matrix [63, 94, 103–106].

RPs deposition over the metal matrix is reported in literature are mainly two methods (i) direct pasting method and (ii) spray method. Mishra et al. [107] uses directing pasting method for the preplacement of

SiC RPs over the Al5083 alloy. Later on, researchers change method of preplacement of reinforcement from direct pasting to other techniques. Zahamatkesh et al. [100] fabricated Al2024/10% Al2O3 nano composite through FSP. They use air plasma spraying technique for producing 200 mm thick coating of Al2O3 on substrate prior to FSP. Anvari et al. [101] incorporated Al6061/Al-Cr-O hybrid nano composite through FSP. They used atmosphere plasma spray (APS) technique to produce coating of Cr2O3 powder on Al6061 base plate before FSP. Mazaheri et al. [102] used oxy fuel spraying technique with high velocity for producing coated layer A356-5vol% Al2O3 reinforcement on A356-T6 plate to produce AMMCs through FSP and fabricated flawless composite. Cold spraying technique was used by Hodder et al. [108] to create a layer of Al-Al2O3 powder on AA6061 substrate. After FSP, maximum microhardness achieved at 48% vol. Al2O3. At present time one of the most commonly used method for the preplacement of reinforcement is groove technique. A groove with suitable dimension is created in the base metal through suitable milling cutter and RPs is compacted into the groove. Khodabakhshi et al. [29] machined a shallow groove in the middle of aluminium base metal and filled it with TiO_2 nanoparticles. They observed uniform distribution of reinforcement after FSP. Kishan et al. [30] preplaced Ti_2B reinforcement particle through groove method. A square groove created at the center line of Al6061-T6 plate and filled with Ti_2B particle with different volume fraction (2%, 4% and 8%) by varying groove dimension. Narimani et al. [31] created a groove of width 1 mm, depth 4.5 mm and filled with B_4C and TiB_2 RPs with different volume fraction of reinforcement mixture. More uniform distribution of RPs is observed through scanning electron microscope (SEM) which results refined grain structure and increased microhardness and wear resistance properties. Second most popular technique for the preplacement of RPs is hole technique [33, 34, 102, 109, 110]. After filling the reinforcement particle in both methods certain care is necessary to avoid splashing of particles from hole and groove. A pinless tool is used to close the hole and groove [29, 30, 111]. Hole technique is more effective than groove method because in groove method material movement is higher as compare to hole method thus increasing the possibility of agglomeration [112].

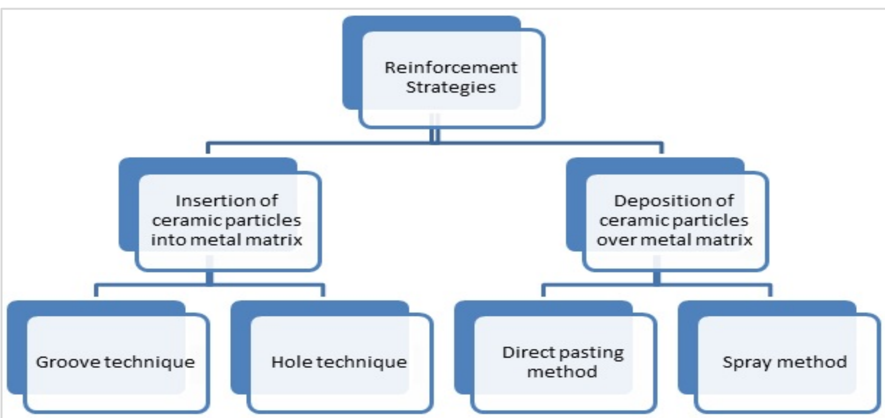

Figure 5 Different reinforcement strategies

3.4Miscellaneous variables

In FSP workpiece is processed in two side i.e., advancing side (ASD) and retreating side (RSD) which results in variation of microstructure and RPs distribution [110]. Velocity vector of tool rotation and velocity vector of tool traverse having same direction in ASD while in RSD velocity vector of tool rotation and velocity vector of too traverse having different direction. Initially in RSD the material is forged then deformed material extruded in ASD due the pin rotation and movement [111]. Sizes of grains are also differed due to temperature difference between ASD and RSD [112]. For removing this asymmetry researchers are using successive passes with direction change in tool rotation as in successive passes ASD becomes RSD and RSD becomes ASD [110, 113]. Huang et al. [91] dispersed tungsten particle of average particle size 1-5 µm size into 1060- pure aluminium alloy by multipass FSP to fabricate W/1060Al composite. They found that by increasing the number of passes additionally uniform distribution of reinforced particle is observed. As it observed that in first pass only little aluminium is immersed into W cluster because initially W particles are mechanically interlocked into the groove due to high pressure and second reason is that poor plastic deformation of aluminium is observed due to large residual stress and strain of as found rolled aluminium plate. They also found that composite's ultimate tensile strength increases with increase in number of passes because higher refined grains are obtained due to the restriction in grain boundaries movement and second aspect is that due to the effect of pinning (Orowan strengthening) W particles hindered the dislocation movement [114,115]. Patel et al. [116] observed about the outcome of FSP passes on the microhardness, microstructure and tensile strength of A7075/WC composite fabricated through FSP method. They found that the refined and homogenous grain structure is obtained at 6 numbers of passes as compared to 2 and 4 numbers of passes. By increasing number of passes high amount of heat is generated due to friction, hence WC particles mix uniformly by proper plastic deformation of matrix and particles [117, 118]. Microhardness value of the composite increases with number of passes increases as due to increasing the homogeneity of reinforced WC nano particles. Tensile results such as tensile strength and yield strength increases with increasing in number of passes because strength of molecules of aluminium matrix increased with grain refinement [119]. Yuvaraj and Aravindan [120] analysed the effect of number of passes on FSPed Al5083/B4C composite fabricated by reinforcing micro and nano size boron carbide particles. Reduced clustered and more homogeneous reinforced particles are shown with increment in pass number. In accord with Hall-Petch relationship by decreasing the size of grains, yield strength is increased which in turn increases the hardness of the composite. Many researchers reported about the grain refinement and uniformity in reinforced particle distribution which increases the hardness of the composite [65, 93,100, 121]. They also analyzed that the wear rate is reduced by increasing the number of passes. According to Archard's theory wear rate is inversely proportional to material's hardness. Due to high hardness of the reinforced composite the surface resists the cutting and penetration [122–124]. Mahmoud [125] found that by increment in pass number in FSP of Al390/Si composite their hardness and wear resistance property increased. Shafiei-Zarghani et al. [65] found that more uniform distribution of nano size alumina particles obtained in AMMCs due to higher number of passes. Patel et al. [126] reinforced Al2O3 particles of size 10 µm in aluminium alloy AA5053 through FSP and found more uniform and homogeneous distribution of RPs with increased FSP passes due to fine and grain's dynamic recrystallization which also results decreased wear rates and high microhardness. Maji et al. [127] analyzed the effect of pass number on MoS2 and CeO_2 reinforced hybrid Al7075 matrix composite fabricated through FSP. At first pass agglomeration is shown in ASD side and 2and pass more uniform particle distribution is observed. Microhardness and Ultimate tensile strength are also enhanced due homogeneous particle distribution, refinement of grain structure and less interparticle distance. Several researchers have established through their experimental results that optimized process parameters are necessary for obtaining uniform distribution of RPs in matrix [128]. Plastic deformation of the fabricated material can be enhanced by increasing number of FSP passes and adjusting the direction of FSP passes with tool rotation direction [129]. As a result, refined grains were obtained which enhanced the properties of material [56]. SCs produced through multipass FSP have more homogeneous strengthening phase distribution as compared to SCs produced through single pass FSP [130].

4. Discussion and analysis

Several researchers have published significant amount of research work on fabrication of SCs through FSP in literatures. Mostly researchers focused on aspects like effect of different RPs on AMMCs, optimization of processing parameters and use of different approaches in fabrication of SCs. Uniform distribution of RPs and improvement in mechanical properties of SCs are the two major points on which this review paper focused. Different strategies for obtaining uniform distribution of RPs with enhanced mechanical properties of SCs are discussed in detail. Common approach for achieving better results with their advantages, limitations and results summarized in *Table 4*. It is observed that for achieving uniform distribution of RPs multipass is an effective and efficient step. Hence obtaining uniform distribution of RPs in single pass is still a challenging task. Asymmetrical flow of material is the main reason behind the uneven distribution of RPs during single pass. By using tool offset technique can be used for obtaining symmetrical flow of material during single pass [131, 132]. This study has been limited to present critical review on the effect of important parameters and factors which directly affect the microstructure and mechanical properties of the AMMCs. Further investigation is required in suitable tool design system and process variants in

FSP to address these issues. This will also make FSP more effective and time saving technique. The combination of wear of tool and variation in types of RPs and process parameters in FSP has not been investigated till now. Flow of material in FSP aspect is also need detail investigation. This review article elaborated different aspect of current research work on the fabrication of AMMCs through FSP. It can be simply concluded that for the fabrication of MMCs, FSP now becomes a well-established technique. Due to its solid-state fabrication nature, it can be used for the fabrication of polymer matrix composites (PMCs) with advance tooling system [133–136]. More intentions are required to develop it as reliable technique for the fabrication of PMCs because it is still in growing phase. FSP can also be used for the development of metallic foams. Some researchers also investigated about the use of FSP for metallic foams [137–139]. However, for producing highly porous material using FSP technique, further efforts research needed. Several researchers investigated the effect of processing parameters of FSP on AMMCs for enhancing different properties. Authors envision that FSP have huge potential to enhance these properties and could produce multifunctional materials like magnetic ceramic composite, piezoelectric ceramic composite, polymer composite etc. These multifunctional materials can be used as humidity sensor, noise sensor, and heat exchanger. Problems and challenges faced by researchers for developing these materials can be removed by combining FSP with advanced and modern manufacturing processes like ultrasonic FSP and friction stir additive manufacturing.

Table 4 Most common approaches adopted by researchers

S. No.	Base material/ Reinforced material	Tool pin profile and dimension. Pin Profile (PP) Shoulder Diameter (SD) Pin Length (PL) Pin Diameter (PD) Tool Material I	Optimum Machine Variables, Reinforcement strategies	Advantages	Limitations	Results	Reference
1	AA6061-T651/ $B_4C+MoSO_2$	TM = WC	RS = 545 rpm TS = 50 mm/min Hole method	1. More uniform distribution of RPs was obtained due to multipass. 2. Percentage of reinforcement can easily control through hole method.	Appearance of surfaces becomes rough by increasing amount of $MoSO_2$.	1. Maximum hardness obtained in mono surface composite. 2. Maximum wear resistance found in hybrid surface composite.	[140]
2	Al6061-T6/B_4C	TM = WC	TS = 50 mm/min Groove method	Multipass in reverse direction increases the uniformity in distribution of RPs.		Wear is reduced with reversal in multipass.	[141]
3	Al1100/Al_2Cu	PP = Cylindrical threaded TM = H13 steel SD = 18 mm PL = 6 mm PD = 4, 5 and 6 mm	RS = 1120 and 1800 rpm TS = 56 and 112 mm/min Groove method	1) At 6 mm pin diameter, highest homogeneity was observed. 2) Pin diameter is more effective in formation of uniform particle distribution and microhardness as compared to rotation to travel ratio and no of FSP passes.	Unreacted Cu particles and microvoids were observed even after 6th pass.	1. Microhardness of the FSPed sample is increases by 57%.	[142]
4	Al5083/CeO_2+SiC	PP=Threaded cylindrical TM=H13 steel SD=18 mm PL=4.5 mm PD=6 mm	RS=600 and 800 rpm. TS=35 and 45 mm/min Groove method	FSP passes improve the reinforcement distribution and grain refinement.	Not applicable	1. Highest hardness was obtained in Al5083/SiC monocomposite. 2. Maximum wear resistance found in Al5083/CeO_2+SiC hybrid composite.	[143]
5	A359/Si_3N_4	PP=Square TM= HSS SD=20 mm PL=5 mm	RS=1000 rpm TS=25 mm/min Groove method	Homogeneous and refined grain structure was obtained on increasing number of FSP passes.	Wear loss of surface composite is increased by increasing FSP passes.	Mixing of RPs increases the hardness and tensile strength of surface composite.	[144]

S. No.	Base material/ Reinforced material	Tool pin profile and dimension. Pin Profile (PP) Shoulder Diameter (SD) Pin Length (PL) Pin Diameter (PD) Tool Material I	Optimum Machine Variables, Reinforcement strategies	Advantages	Limitations	Results	Reference
6	Al5083/CNTs+CeO_2	PP=Threaded cylindrical TM= H13 steel SD=18 mm PL=4.5 mm PD=6 mm	RS=800 and 600 rpm TS=35 and 45 mm/min Groove method	The average grain size of the material is reduced by increasing number of FSP passes.	Not applicable	The maximum hardness and tensile strength were achieved in hybrid composite.	[145]
7	AA1050/ MMO powder	PP=Threaded cylindrical TM= H13 steel SD=18 mm PL=3.5 mm PD=5 mm	RS=1600 rpm TS=100 mm/min Groove method	Uniform distribution of reinforced particle is obtained at these parameters.	Not applicable	Ultimate tensile strength of the composite is increased by 120%. 1. Microhardness of the FSPed sample is increased by 130%. 2. Wear rate is decreased by 40%.	[146]
8	A356/Fly ash + Red mud	PP=Threaded cylindrical TM= H13 steel SD=18 mm PL=4 mm PD=6 mm	RS=1000 rpm TS=40 mm/min Hole method	Refined grains were obtained by FSP.	Ductility of the material is decreased due to the RPs.	Incorporation of reinforcement increases the strength and wear resistance properties of material.	[11]
9	AA6082/ TiC	PP=Threaded cylindrical TM= HCHCr steel SD=18 mm PL=5.5 mm PD=6 mm	RS=1200 rpm TS=60 mm/min Groove method	Interface between aluminium matrix and TiC particles were obtained.	Not applicable	1. Microhardness and UTS of the material were increased by increasing volume fraction of RPs. 2. Wear resistance of the AMMCs was increased by reinforcing TiC particles.	[52]
10	Al7075/B_4C	PP=Taper cylindrical TM= WC-Co (12%)	RS=545 rpm TS=50, 78 and 120 mm/min Groove method	Not applicable	1. Lower powder distribution was found at higher tool TS. 2. Microhardness was decreased by increasing too TS.	Average hardness and wear resistance property is improved through incorporation of RPs.	[67]
11	AA2014/SiC	PP=Round bottom conical TM= Hot die steel SD=21 mm PL=3 mm PD=5 mm at top and 3 mm at bottom	RS=710 rpm TS=100 mm/min Groove method	Hardness of the FSPed base alloy was decreased due to the coarsening of precipitates.	Not applicable	Hardness of surface composite was increased due to the addition of RPs.	[92]
12	AA6061-T6/SiC	PP=Threaded cylindrical TM= H-13 tool steel SD=20 mm PL=2.8 mm PD=6 mm	RS=1400 rpm TS=40 mm/min TPD= 0.10, 0.15, 0.20, 0.25, 0.30 and 0.35 mm. Groove method	Uniform particle distribution is obtained at optimum TPD.	1. Cavity is created at low plunge depth. 2. At high penetration depth workpiece stick with tool shoulder and reinforcement material is flashed out from workpiece.	Uniform particle distribution is obtained at optimum TPD 0.25 mm.	[44]
13	AA7005/ TiB_2+B_4C	PP=Straight cylindrical TM= H-13 tool steel SD=18 mm PL=4 mm	RS=750 rpm TS=50 mm/min Hole method	Reinforced particle is uniformly distributed at these parameters.	Not applicable	Ballistic resistance of the material is improved due to the incorporation of RPs.	[147]

S. No.	Base material/ Reinforced material	Tool pin profile and dimension. Pin Profile (PP) Shoulder Diameter (SD) Pin Length (PL) Pin Diameter (PD) Tool Material I	Optimum Machine Variables, Reinforcement strategies	Advantages	Limitations	Results	Reference
		PD=6 mm					
14	Al5083/B_4C	PP=Threaded cylindrical TM= H-13 tool steel SD=18 mm PL=5 mm PD=6 mm	RS=1000 rpm TS=25 mm/min Groove method	Distribution of reinforced particles becomes more uniform by increasing number of passes.		Better mechanical properties of surface composite are obtained on reinforcement of nano size particles as compared to micro size particles.	[121]
15	Al7075/Ti+SiC+Al_2O_3+eggshell	PP=Triangular	RS=920, 1550 and 2250 rpm TS=25 mm/min Hole method	Best results are obtained at optimum TS=2250 rpm.	Not applicable	It is observed that the tool speed and reinforcement significantly affect the hardness of the material.	[148]
16	Al7075-T651/TiC	PP=Tapered TM=MP 159 alloy and H-13 tool steel SD=12 mm PL=2.8 mm PD=5 mm widest and 4 mm shortest.	RS=1000 rpm TS=300 mm/min Groove method	1. Defect free and homogeneous stir zone is formed at these processing parameters. 2. FSP passes in opposite direction exhibits more uniform distribution of RPs.	Hardness is decreases in stir zone due to plastic deformation.	Lower wear rate is obtained in stir zone due to the incorporation of RPs.	[149]
17	Al7075-T6/Al_2O_3+SiC	PP=Threaded cylindrical TM= EN31 tool steel SD=25 mm PL=3 mm PD=6 mm	RS=2000 rpm TS=56 mm/min TPD=0.1 mm Groove method	Coarse grain structure is converted into fine grains.	Mild particles chunk is seen in structure due to high amount of Al_2O_3.	Maximum microhardness is obtained at 50% Al_2O_3+50%SiC. Particle reinforcement.	[150]
18	AA6061-T6/Al_2O_3	PP=Taper threaded cylindrical TM= H13 tool steel SD=21 and 24 mm PL=3.5 mm PD=8 mm widest and 6 mm shortest	RS=900, 1150 and 1400 rpm TS=15, 20 30 and 40 mm/min Groove method	Defect free sample is prepared at 1150 rpm RS and 15 mm/min TS with 24 mm SD.	Defective sample is prepared at 21 mm SD.	Microhardness of the material is enhanced due to the incorporation of RPs.	[151]
19	Al6061-T6/SiC+Graphite	PP=Square probe TM= H-13 steel SD=25 mm PL=5 mm PD=5 mm	RS=1800, 2200 and 2500 rpm TS=25 mm/min TPD=0.2, 0.3 and 0.4 mm Groove method	At 2200 rpm RS and 25 mm/min TS uniform distribution of reinforced particle is found.	Not applicable	Better mechanical properties are obtained in hybrid composite as compared to mono composite.	[152]
20	AA7075-T651/Palm kernel shell ash (PKSA)	PP=Cylindrical tapered TM= AISI H13 hot working tool steel SD=18 mm PL=5 mm PD=5 mm	RS=1500 rpm TS=20 mm/min TPD=0.3 mm Groove method	Grain size is refined in FSPed composite.	Flaky type debris was found at higher load.	Corrosion protection rate is increased due to addition of reinforcement particle.	[153]
21	Al6061/SiC+Graphite powder	PP=Square pin TM=H13 tool steel SD=25 mm PL=5 mm PD=5 mm	RS=1800, 2200 and 2500 rpm TS=25 mm/min TPD=0.2, 0.3 and 0.4 mm Groove method	Best electromechanical properties are obtained at 2200 rpm RS.	Edge disorder in graphite crystal is observed.	Mechanical properties of the material are enhanced due to incorporation of RPs.	[154]
22	AA67050/TiB_2	PP=Square pin scroll TM=HCHCr steel SD=16 and 20 mm PL=3 mm PD=6.5 mm	RS=710 and 1120 rpm TS=50 and 80 mm/min TPD=0.2 mm Groove method	A new derived parameter unit stirring relates with particle distribution mechanism.	Not applicable	It is observed that the distribution of particles is depending upon particle movement mechanism.	[155]
23	AA6061/SiC	PP=Threaded cylindrical, straight cylindrical, square and triangular TM=H13 steel	RS=1250 rpm TS=80 mm/min TPD=0.42 mm Groove method	Homogeneous particles distribution is achieved on increasing pass number.	Not applicable	Lowest and highest wear resistance is obtained on using straight cylindrical and square pins	[43]

S. No.	Base material/ Reinforced material	Tool pin profile and dimension. Pin Profile (PP) Shoulder Diameter (SD) Pin Length (PL) Pin Diameter (PD) Tool Material I	Optimum Machine Variables, Reinforcement strategies	Advantages	Limitations	Results	Reference
		SD=20 mm PL=3 mm PD=6 mm				respectively.	
24	Al5083/B_4C+TiC	PP=Threaded cylindrical TM=H13 hot working tool steel SD=18 mm PL=5 mm PD=6 mm	RS=1000 rpm TS=40 mm/min Groove method	Uniform dispersion of particle exhibits in matrix at these parameters.	At lower load mild wear is observed.	Higher strength and hardness are obtained in FSPed composite specimen than the base alloy and FSPed alloy without particle reinforcement.	[153]
25	AA7075/SiC+RHA+B_4C	PP=Triangular, Circular and Square TM=H13 tool steel SD=19.95 mm PL=3.5 mm	RS=700, 1000 and 1300 rpm TS=40 mm/min TPD=0.5 mm Groove method	1. Maximum microhardness is obtained at 1000 rpm RS. 2. Most influential parameter is RS for obtaining maximum microhardness.	Influence of tool profile is less for increasing microhardness of material.	Average hardness value is increased due to incorporation of reinforcement particle.	[156]

5. Conclusion and scope

The effect of different variables of FSP techniques for the fabrication of AMMCs and the subsequent mechanical properties and microstructure of the AMMCs has been discussed in this article. Corresponding to an extensive literature survey on the published work on the effect of variables of FSP on the AMMCs, remarkable inferences concluded are listed below:

- Various researchers have found excellent microstructure, mechanical and wear properties of composite fabricated through FSP.
- At low TS maximum microhardness, wear resistance and coefficient of friction is obtained due to the mechanism of grain strengthening.
- By increasing the RS proper distribution of reinforced particles, crystallized grains were obtained due to increasing the rubbing action per unit time. Heat generation increases by increasing RS but amount of heat decreases by increment in TS because TS construe the frictional heat residing time. So competent unification of RS and TS is necessary to obtained better mechanical properties and microstructure of AMMCs.
- Pin having threaded profile fabricated more uniform distribution of RPs as compared to tool of plane shape profile.
- Numerous researchers are using groove technique for preplacement of reinforcement but some researchers reported that hole technique is more effective than groove method because in groove method material movement is higher as compare to hole method thus increasing possibility of agglomeration.
- Better distribution of RPs and refined grain structure is observed by increment in pass number which also results high microhardness and decreased wear rates of the composite.
- Despite promising results, application in industries is limited. Main issues of this development are flow of material is not very fine. Mathematical simulation models of the plasticized aluminium flow and RPs can be developed to achieve more uniform homogeneous composite. There is also a huge area remaining on properties like fatigue strength and bending of surface composite to be investigated of aluminium metal matrix composite because limited studies are available.

A complete list of abbreviations is shown in *Appendix I.*

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Conflicts of interest

The authors have no conflicts of interest to declare.

Author’s contribution statement

Abdul Jabbar Ansari: Conceptualization, data collection, writing – original draft, writing -review and editing. **Mohd. Anas:** Supervision, draft manuscript preparation.

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Abdul Jabbar Ansari is a Ph.D. Research Scholar in the Department of Mechanical Engineering at Integral University, Lucknow. He was born in 1985, Varanasi, Uttar Pradesh, India. He obtained his B.Tech (Mechanical Engineering) in 2009 and M.Tech (Mechanical Engineering) in 2014 from APJ Abdul Kalam Technical University, Lucknow. He has 8 years teaching experience. At present he is working as Assistant Professor in the Department of Mechanical Engineering at Bansal Institute of Engineering and Technology, Lucknow. He is a reviewer of scopus indexed journal. His research interest include Surface Composite, Friction stir processing and Friction stir welding.
Email: techno.abdul@gmail.com

Dr. Mohd. Anas is working as an Associate Professor in the Department of Mechanical Engineering at Integral University, Lucknow. He was born in 1981, Bahraich Uttar Pradesh India. He received his B.Tech degree in Mechanical Engineering in 2005 from U.P. Technical University, Lucknow. He obtained M.Tech in Machine Design in 2007 from Aligarh Muslim University (A.M.U.) Aligarh and completed his Ph.D. from Integral University in 2015. He has more than 30 research papers in National and International journals. He supervised more than 10 M.Tech students and 6 Ph.D. students. He is also reviewer of many scopus indexed journals. His research interest includes Finite Element Analysis (FEM), Friction Stir Processing and Surface Composite.
Email: anas@iul.ac.in

Appendix I

S. No.	Abbreviation	Description
1	AMMCs	Aluminium Metal Matrix Composites
2	APS	Atmosphere Plasma Spray
3	ASD	Advancing Side
4	FSP	Friction Stir Processing
5	FSPed	Friction Stir Processed
6	MMCs	Metal Matrix Composites
7	PMCs	Polymer Matrix Composites
8	RPs	Reinforcement Particles
9	RS	Tool rotational Speed
10	RSD	Retreating Side
11	SCs	Surface Composites
12	SEM	Scanning Electron Microscope
13	TPD	Tool Plunge Depth
14	TS	Tool Traverse Speed
15	WC	Tungsten Carbide