

Composites Prepared via Friction Stir Processing Technique: A Review



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ABSTRACT

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This review article investigates the mechanical and tribological properties of metal matrix composites (MMCs) prepared through friction stir processing technique. MMCs are developed materials with enhanced mechanical properties, exhibits their application in automotive and aerospace industries. The limitations of liquid metallurgical route can be reduced by using Friction Stir Processing (FSP) technique. FSP, a developed methodology technologically advanced by friction stir welding process is reviewed to fabricate the MMCs. In FSP, a hole or groove is made in the alloy. Reinforcement filled in the groove or hole are distributed in the matrix material by the FSP tool. Heat produced between the tool and the surface tends to the grain refinement. Owing to grain refinement, mechanical and wear properties of the composites are enhanced. In this review article, mechanical and wear behavior of the composite developed through FSP method are reviewed, which will help the researchers and industrial societies to fabricate the composite of required enhanced properties.

1. INTRODUCTION

Aluminum and its alloys have achieved extensive acceptance in different technological uses due to their specific high strength to weight ratio. The composites were formed when alloys were reinforced with ceramics like SiC, TiC, ZrO₂ and B₄C [1] etc. Figure 1 shows different types of composites formed by reinforcing different materials.

Composites have got improved mechanical and wear characteristics as compared to base alloy. Mechanical, wear and tribological properties of the fabricated composites were

investigated by various researchers. The limitations of MMCs observed was the loss of ductility, which limits its application. Various processing techniques like mechanical stir casting, powder metallurgy, electromagnetic stir casting etc. are present in the current scenario [2-4]. Friction stir welding (FSW) was developed by The Welding Institute (TWI) at UK in 1991 as a solid-state joining process. Friction stir processing is newly emerged technique developed through FSW to develop surface composites. FSP technique is unable to fabricate bulk composites [5].

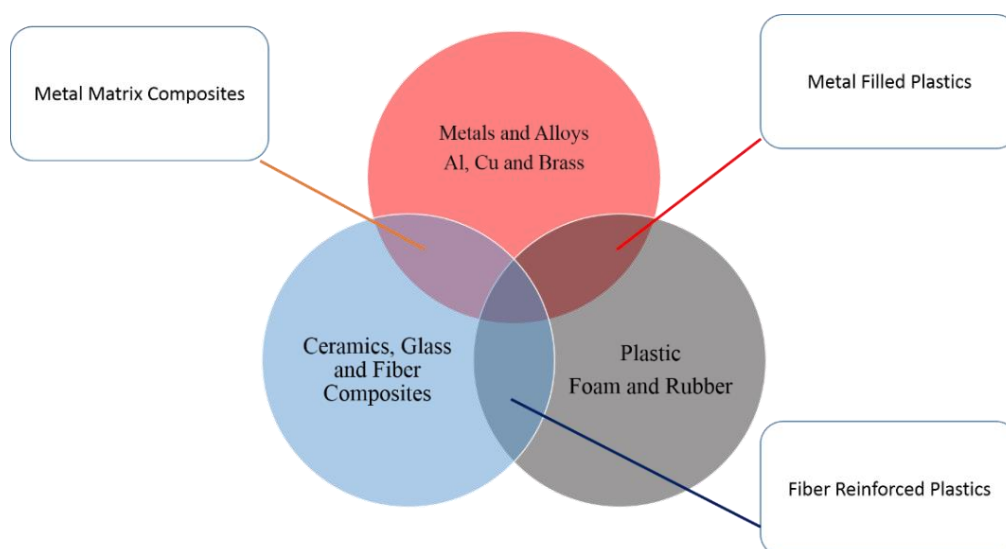


Figure 1. Composite formation with different reinforced materials

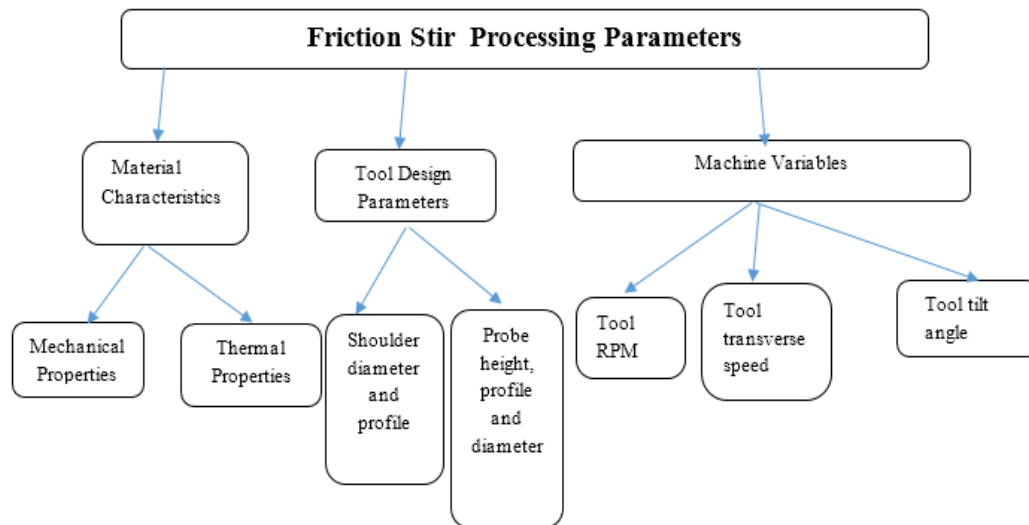


Figure 2. Classification of FSP process parameters

In FSP, non-consumable rotating tool is stirred above the specimen. The applied axial force on the tool had produced the interaction between the developed sample and tool, had resulted the heat formation. The reinforced particle works as a grain nucleating site inside the solidifying specimen which obstruct the grain growth of the aluminum alloy. Thus, a consistent decrease in grain size with increased reinforcement of uniformly distributed reinforced particles was observed [5]. Secondly, FSP technique leads to intense plastic deformation that neutralizes the pinning effect. The occurrence of pulled out and fractured particles accept proof to better have interfacial bonding. The heat produced from FSP tool inclines to plastic flow of material. Plastic flow of material leads to grain refinement. Generally, reinforcements were filled by two techniques in the base alloy. One was by drilling a hole and the other by cutting a groove in the base alloy. The classification of FSP process parameters is shown in Figure 2.

2. APPROACH FOR INVESTIGATING THE LITERATURE

This review article has been prepared on the analysis of published research work (from 2014 to 2018) on the fabrication and evaluation of mechanical properties of FSPed composites. This literature review is accompanied as a content investigation in which the mechanical properties of FSPed composites are evaluated. The main source of collecting literature survey was (1) review articles (2) conferences (3) theory and notes of FSP and (4) research articles. In this review article, the assessment of FSP methodology to fabricate the composite is discussed. The literature section is categorized into two sections. The first section includes microstructural and mechanical properties while the other section deals with tribological behavior of the composites. The results of hardness, tensile and wear test obtained by various researchers is evaluated in the tabular form. The detailed summary of the research work is reported in the next sub section.

2.1 Microstructural and mechanical properties of FSPed composite

Arab et al. [6] investigated the yield and tensile strength of

Al 1100/E glass, S glass and carbon reinforced composite fabricated through FSP method. Al 1100/S glass composite had maximum yield strength (75 MPa) and tensile strength (130 MPa) in comparison to E glass and carbon reinforced composites.

Sharma et al. [7] observed the microstructural and mechanical properties of AA 2014/SiC composite by FSP. Experimental results revealed that change in grain size of microstructure from thermo mechanical affected zone and stirred zone was observed. The maximum hardness of 150 HV was found for AA 2014/SiC composite. FSPed AA 2024/SiC composite was fabricated by Hosseinzadeh et al. [8] to investigate the mechanical properties. The hardness and yield strength were enhanced by 50% and notable 240%. Yang et al. [9] investigated the microstructural and mechanical properties of AA 2024/Al₂O₃ composite prepared through FSP. The micro hardness was improved to 155 Hv and tensile strength of cold sprayed composite was improved by FSP method.

Sahraeinejad et al. [10] prepared Al 5059/ Al₂O₃, SiC and B₄C reinforced composite by FSP technique to observe the microstructural and mechanical properties. Al₂O₃ reinforced composite had better grain refinement in compare to SiC and B₄C particles. Al 5359/B₄C composite had higher tensile and yield strength with reduced ductility as compared to Al₂O₃ and SiC reinforced composite. The ball milling and particle size effect on FSPed Al5083/Ni surface composite was evaluated by Kumar et al. [11]. The particle's size of 10 μm was refined by ball milling, had got uniform distribution of the reinforcement. The ductility and hardness of Al5083/Ni composite was reduced as compared to received Ni particles. Bauri et al. [12] investigated the optimum tool rotation speed and transverse speed to prepare defect free stir zone of Al 5083/Ni surface composite prepared through FSP. The minimum 1,200 rpm of tool rotational speed and 0.4 mm/sec of transverse speed was required to incorporate Ni particles. During recrystallization of the matrix, the grain size was abridged from 25 to 3 μm.

Huang and Shen [13] fabricated Al 5083/Ti composite via FSP to investigate the mechanical properties of composite under air and water processing environments. Finer recrystallized grain in the composite was accomplished due to influence of cold water on it, had increased the tensile and yield strength. Papantoniou et al. [14] studied the microstructural properties of AA 5083/MWCNT composite

prepared through FSP. Optical microscopy and scanning electron microscope were used to observe the microstructural behavior of the prepared composite. It was observed that the distribution of micro hardness was perpendicular to the transverse speed of FSP tool.

Kishan and Devraju [15] prepared Al 6061/nano TiB₂ composite by FSP technique to observe the microstructural properties. The micro hardness of the composited was improved to 132 Hv as compared to base alloy having 104 Hv. The decrease in tensile strength was observed due to accumulation of TiB₂ particles [15]. Dinaharan and Akinlabi [16] prepared FSPed composite made of AA 6061, AZ31 and Cu alloy incorporated with fly ash. The plate of 10 × 50 mm was used to make a groove. The groove was filled with fly ash particles of size 5 µm. The optical micrograph results revealed uniform dispersal of reinforced content. The nature of FSP that is plastic deformation in solid state had reduced the free movement of reinforced FA particles. The operative stirring action of FSP tool had avoid the agglomeration of FA particles. The micro hardness of AZ31/FA composite was obtained to be 110.29 VHN.

Dhayalan et al. [17] developed AA 6063/SiC-Gr composite by FSP method to observe the microstructural properties. Optical microscopy results revealed that stirred zone had maximum refined grain structure as compare to heat affected or transition zone. The maximum micro hardness of AA 6063/SiC surface composite was improved to 62 Hv. Rathee et al. [18] fabricated AA 6063/SiC composite via FSP to investigate the influence of groove width to pin diameter on the mechanical characteristics. The ratio (w/d) of 0.5 was obtained to yield defect free composite. The micro hardness and tensile strength were improved to 80 Hv and 175 MPa. The influence of multi pass FSP on AA 6063-T6Al /SiC composite was evaluated by Gangil et al. [19]. With the increase in number of passes, finer recrystallized grain structure was observed. Abraham et al. [20] prepared AA 6063/SiO₂ composite via FSP methodology to investigate the micro hardness and wear properties. The micro hardness of stir zone was improved to 135 Hv at 18 vol. % SiO₂. The refinement of grain size has increased the micro hardness of surface composite. The wear rate of the composite was reduced to 258×10^{-5} mm³/m at 18 vol. %.

FSPed Al 6082/Mo composite was developed by Selvakumar et al. [21]. The UTS was improved to 305 MPa at 18 vol. % while ductility was reduced by 24 % for Al 6082/Mo composite. Selvakumar et al. [22] prepared AA 6082/ stainless steel composite through FSP to enhance the ductility. SEM results revealed that no any particle free region was observed in the stirred zone. The UTS was improved to 293 MPa at 18 vol. % while ductility was measured to be 17% at 18 vol. %.

Du et al. [23] fabricated Al/Al₂O₃/CNTs composite by FSP method to investigate the microstructural properties. Grain refinement had resulted in the improvement of the mechanical properties of Al/ Al₂O₃/CNTs composite. 108.4 HV and 263 MPa was the micro hardness and tensile strength for the prepared composite. Microstructural and mechanical properties of FSPed Cu/Rice husked ash composite was investigated by Dinaharan et al. [24]. Strong interfacial bonding was formed between Cu matrix and the rice husked ash particles. The micro hardness was found to be 105 VHN. The wear rate was reduced to 5.3×10^{-3} mm³/m by incorporating 18 vol.% of the particles. Kurtyka et al. [25] investigated the mechanical characteristics of A 339/SiC composite prepared through FSP method. The compressive

strength was maximum in advancing side. 30% increase in hardness and 40 % increase in compressive strength was obtained.

2.2 Tribological behavior of FSPed composite

Janbozorgi et al. [26] investigated the mechanical and wear characteristics of A413/SiC and A413/SiC/ MoS₂ composite prepared through FSP. MoS₂ lubricant contents had reduced the micro hardness of the A413/SiC/ MoS₂ composite. This was due to reduced hardness of MoS₂ lubricant. 105 Hv was the maximum hardness for non-lubricated A413/SiC composite. The wear loss was reduced with lubricating SiC particles by MoS₂.

Golmohammadi et al. [27] prepared A 413/Ni surface composite by FSP method to observe the mechanical and wear characteristics. Three pass composites had got higher micro hardness of 80 Hv as compared to casted or single pass composite. Wear resistance was improved for three pass composites in comparison to casted or single pass composite. Esfahani et al. [28] investigated the wear properties of Al 1050/Fe surface composite fabricated via FSP. Two pass FSP had improved the grain size of the stirred zone composite. 70 VHN was the micro hardness found in the nugget zone. Fe particles in the surface of Al 1050 alloy had better wear resistance in comparison to Al 1050 alloy.

Abreu et al. [29] developed AA 2024/SiC composite by FSP method to investigate the tribological properties. The presence of SiC content had amplified the micro hardness of AA 2024/SiC composite to 145 Hv. The wear rate was reduced in the processed zone to 2.64×10^{-4} mm³/Nm. Yuvaraj et al. [30] examined the tribological characteristics of Al 5083/B₄C micro and nano surface composite prepared through FSP technique. The micro hardness of nano composite was enhanced to 122 Hv, having three number of passes. Wear resistance of nano composite was increased due to hard B₄C particles embedded in the surface of Al 5083 alloy. Kumar et al. [31] evaluated the wear characteristics of Al 5083/W composite developed through FSP method. The groove of 60×2×1.5 mm was made on Al 5083 plate, having thickness 10 mm. Tungsten particles of 10 µm were kept in the groove. FSP tool was rotated at 1,200 rpm having transverse speed of 2 mm. Uniform distribution was observed in the microstructure. EDM was used to cut the wear test samples of diameter 8 mm and height of 10 mm. Wear rate was less in comparison to base and FSPed alloy under different loading conditions. Mirjavadi et al. [32] studied the mechanical and wear behavior of AA 5083/ZrO₂ composite prepared through FSP. Composite having 8 passes had got the maximum grain refined structure, with micro hardness of 140 Hv. Wear rate was also reduced for composite prepared through 8 number of passes. Jain et al. [33] investigated the mechanical and wear properties of AA5083-B₄C/SiC/TiC composite prepared by FSP. Experimental results concluded that the tensile strength and micro hardness was improved to be 349 MPa and 132.56 ± 2.52 Hv for AA 5083/B₄C composite as compared to AA 5083/ SiC/ TiC composite. 18×10^{-5} mm³/Nm was the minimum wear rate for AA 5083/B₄C composite.

The effect of process parameters on the stirred zone for FSPed Al 5456/BNi₂ composite was investigated by Esmaily et al. [34]. 10 mm/min was the best tool transverse speed to avoid agglomeration of BNi₂ particles. The tool having speed of 30 mm/min had uniform distribution of reinforced particles, along with fine grain structure. V shape and step groove had got

more uniform distribution in comparison to square groove. The maximum hardness was achieved to be 120 HB in the stirred zone for Al 5456/BNi₂ composite.

Rao and Rao [35] evaluated the wear behavior of AA 6061/TiB₂ composite prepared by FSP. The micro hardness was enhanced to 135 HV. TiB₂ reinforced composite had minimized the wear resistance of the AA 6061/TiB₂ composite. Kishan et al. [36] investigated the tribological behavior of Al 6061/nano TiB₂ composite prepared via FSP method. The depth of prepared nano surface layer was 3863.83 µm. The micro hardness of the prepared composite was improved to 132 Hv. 4 vol. % of nano TiB₂ composite exhibit the maximum wear resistance as compared to 2 or 6 vol. % of TiB₂ nano particles [36].

The influence of transverse speed AA 6082/TiC composite fabricated through FSP technique was evaluated by Thangarasu et al. [37]. The area of stirred zone was reduced by the increase of transverse speed. Non uniform dispersal of TiC content was observed at higher transverse speed. The maximum micro hardness was found to be 135 HV at 80 mm/min with minimum wear rate of 412x10⁻⁵ mm³/m at 80 mm/min. Thangarasu et al. [38] fabricated AA 6082/TiC composite through FSP technique to investigate microstructural and mechanical properties. The maximum micro hardness and UTS was found to be 149 HV and 222 MPa by incorporating 24 vol.% of TiC particles. The wear rate was reduced with the increased volume % of TiC particles [38]. The empirical relationship was by Thangarasu et al. [39] to evaluate the mechanical and wear characteristics of AA 6082/SiC, Al₂O₃, TiC, B₄C and WC composite prepared via FSP. TiC reinforced composite had maximum micro hardness of 115 Hv and, minimum wear rate as compared to SiC, Al₂O₃, B₄C and WC particles. Thangarasu et al. [40] investigated the wear properties of AA 6082/TiC composite by FSP method. Increased wt % of TiC content had improved the wear resistance, found to be 0.00303 mg/m at 22 vol. %.

Ambigai and Prabhu [41] performed the experiment to observe the tribological behavior of Al/B₄C micro/nano composite fabricated through FSP. The wear characteristics were observed on pin-on disc machine. The mass loss, volume loss, wear rate and coefficient of friction were investigated for different loading and sliding distance conditions. It was observed that Al/B₄C nano composite had less wear loss as compared to Al/B₄C micro composite. ANOVA had depicted that normal load had maximum influence on the wear property. The increase in normal load had reduced the coefficient of friction due to development of tribo layer on the contact of surface [41]. Bhat et al. [42] prepared Al /Fe composite through FSP to evaluate the microstructure and creep behavior. Experimental results revealed that FSPed zone had uniform reinforcement of Fe particles. High degree metastability had led the poor creep resistance on the stirred zone.

Rajan et al. [43] developed AA 7075/TiB₂ composite via FSP technique to investigate the mechanical characteristics. Excellent interfacial bonding between TiB₂ and alloy had strengthened the mechanical properties of AA 7075/TiB₂ composite. The maximum micro hardness and UTS was obtained to be 160 VHN and 340 MPa. Wear rate was reduced for FSPed AA 7075/TiB₂ composite. Wear properties of FSPed Al 7075/B₄C composite was evaluated by Rana et al. [44]. The groove of 100×1.2×2.5 mm was made in Al 7075

plate through shaper machine. B₄C particles of 12-15 µm were incorporated in the groove. FSP tool of WC-Co (12%) was rotated at 545 rpm having tool tilt angle of 30. Lowest transverse speed has uniform dispersal of B₄C particles in the nugget zone. Increased transverse speed had reduced the micro hardness of the composite. This was due to reduced stir time and insufficient time for grain refinement of the particles. Kumar et al. [45] observed the mechanical properties of Al 7075/SiC micro and nano composite fabricated through FSP. Tensile strength was improved up to 190 % in nano composites. Nano composites possess better wear resistance in comparison to micro reinforced composites. Eskandari and Taheri [46] fabricated Al 8026/TiB₂/ Al₂O₃ hybrid nano composite via FSP to evaluate the micro hardness. Micro-hardness was enhanced to 175 Hv, as compared to base alloy having 85 Hv.

Zangabad et al. [47] prepared Al/Al₃Ti/MgO hybrid nano composite by FSP route to observe the fatigue fracture. Optical microscopy results revealed homogeneous distribution of reinforced particles. Increased TiO₂ content had increased the tensile and yield strength. Hard inclusions had strengthened the fatigue strength of the composite. Azizieh et al. [48] prepared Al/Al₂Cu nano composite through FSP to investigate the micro structural and wear properties. Experimental results concluded that the micro hardness was increased with the increase in number of passes up to an extent. The micro hardness was improved to 53 Hv at tool rotation speed of 1120 rpm, transverse speed of 56 mm/min and 4 passes of FSP.

3. ADVANTAGE OF FSP METHOD

FSP had got advantages when two materials were mixed by solid state processing route. Through FSP, the microstructural refinement, densification and homogeneity was obtained [49]. FSP helps to modify the materials without porosity and casting defects, generally generated in liquid metallurgical route. For example, FSP can simply modify the form of a piece sheets metal with the enhancement of mechanical and wear properties, where before it had to be melted down before and put into a mold to cool and form the sheet. The microstructural, mechanical and tribological characteristics of the stirred zone can be precisely monitored by selecting the FSP parameters and tool design [50]. The same sheet of metal can be changed to fit different conditions with the suitable alteration of the tool design. FSP has proved to prepare metallic alloys bendable as for example an alloy altered with FSP would be capable to bend to 35 degrees as before it could only bend to eight degree.

4. APPLICATION OF FSP TECHNIQUE

The FSP was used to improve the mechanical properties by using other metals or alloys for support and enhancement of the first. This was favorable route for the automotive, armors, defence and aerospace industries where new material was to be established with improved wear resistance, creep, and fatigue [51]. Examples of composites successfully developed using the FSP technique includes AA 6082/ stainless steel, AA 6082/TiC, AA 6063/SiO₂, Al5083/Ni, Al 5083/Ti and AA 7075/TiB₂ etc.

5. SUMMARY AND FUTURE SCOPE

From the review of different range of previously reported work, it is clear that lots of work have been reported on FSP over the last several years. The main reason for this interest was significant improvement on mechanical and tribological properties with addition of different reinforcement through solid metallurgical route. Table 1 shows the summary of previously reported work on composite fabrication by using the FSP technique. Figure 3 shows the summary of percentage contribution of research work reported related to the mechanical and wear properties. It can be clearly seen that the major focus of researchers were to evaluate the hardness, tensile strength and wear rate of the composite fabricated via

FSP. However it was noticed that very less work have been reported related to other important mechanical properties like fatigue strength, creep and compressive strength etc. Eighty percent of the mechanical components were failed due to the fatigue failure. So more work related to fatigue behavior are required to understand the effect of reinforcement on fatigue strength of aluminium composite. Figure 4 shows the summary of percentage contribution of research work on different reinforcement particles for the fabrication of composite. It can be observed that most of the research works were carried out by using SiC, B₄C, TiB₂ and TiC. From the reported work, it was observed that the mechanical and tribological properties of aluminium was maximum by B₄C reinforcement.

Table 1. Summary on Composite Fabrication using FSP

S.NO.	Authors	Al Matrix / Reinforcement	Properties Evaluated	Micro Hardness	Prominent Results
1	Arab et al. [6]	Al 1100/E glass, S glass and carbon	Mechanical Properties		Al 1100/S glass composite had yield strength of 75 MPa, and tensile strength of 130 MPa.
2	Sharma et al. [7]	AA 2014/SiC	Mechanical Characteristics	150 HV	Change in grain size of microstructure from thermo mechanical affected zone and stirred zone was observed.
3	Yang et al. [9]	AA2024/Al ₂ O ₃	Mechanical Properties	155 HV	Maximum hardness was obtained on stir zone. Tensile property of cold sprayed composite was enhanced with FSP.
4	Sahraeinejad et al. [10]	Al 5059/ Al ₂ O ₃ , SiC and B ₄ C	Mechanical Properties		Al ₂ O ₃ had better grain refinement. B ₄ C reinforced composite had improved tensile and yield strength with reduced ductility.
5	Kumar et al. [11]	Al 5083/Ni	Influence of reinforced particle size was evaluated		Particle size of 70 µm had accumulation of Ni particles, leads to fracture during FSP.
6	Bauri et al. [12]	Al 5083/Ni	Mechanical Characteristics	91 HV	Recrystallization of the matrix had refined the grain size from 25 to 3 µm. Minimum 1,200 rpm of tool rotation speed and 0.4 mm/sec of TS was required to incorporate Ni particles.
7	Huang and Shen [13]	Al 5083/Ti	Micro structural Properties		Cooling effect of water had refined the grain size of the composite. Water FSPed had maximum tensile strength of 423 MPa.
8	Kishan and Devraju [15]	Al 6061/nano TiB ₂	Mechanical Characteristics	104 HV	Decrease in tensile strength was found due to accumulation of nano TiB ₂ particles.
9	Dinakaran and Akinlabi [16]	Al, Mg, Cu/Fly Ash	Mechanical Characteristics	125,110 and 170 VHN	Uniform Distribution of Fly Ash is found in Al, Mg and Cu Matrix.
10	Dhayalan et al. [17]	AA6063/SiC-Gr	Characterization Property	62 HV	Uniform dispersal of reinforced particle was observed.
11	Rathee et al. [18]	AA 6063/SiC	Mechanical Properties	80 HV	Tensile strength was improved to 175 MPa.
12	Abraham et al. [20]	AA 6063/SiO ₂	Micro structural and Wear properties	135 HV	Micro hardness was increased with the increase of SiO ₂ content. Wear rate was reduced by 258x10 ⁻⁵ mm ³ /m at 18 vol. % of SiO ₂ particles.
13	Selvakumar et al. [21]	Al 6082/Mo	Characterization Property		No accumulation of Mo particle was observed. Tensile strength was improved to 305 MPa at 18 vol.% of Mo particles.
14	Selvakumar et al. [22]	AA 6082/ stainless steel	Mechanical Characteristics		The UTS was improved to 293 MPa at 18 vol. % while ductility was measured to be 17% at 18 vol. %.
15	Du et al. [23]	Al/ Al ₂ O ₃ /CNTs	Mechanical Characteristics	108.4 HV	The tensile strength of Al/Al ₂ O ₃ /CNTs composite was found to be 263 MPa.
16	Dinakaran et al. [24]	Cu/Rice husked ash	Mechanical and Wear Properties	105 VHN	The wear rate was reduced to 5.3x10 ⁻³ mm ³ /m by incorporating 18vol. % of the RHA particles.

17	Kurtyka et al. [25]	A339/SiC	Micro structural and Mechanical Properties	117.3 HV	The compressive strength was improved to 40% and 30 % for hardness.
18	Janbozorgi et al. [26]	A413/SiC	Tribological Properties	105 HV	The wear loss was reduced with lubricating SiC particles by MoS ₂ .
19	Golmohammadi et al. [27]	A413/Ni	Mechanical and Wear Characteristics	80 HV	Wear resistance was improved for three pass composites in comparison to casted or single pass composite.
20	Esfahani et al. [28]	Al 1050/Fe	Tribological Properties	70 VHN	Fe particles had improved the wear resistance.
21	Abreu et al. [29]	AA 2024/SiC	Tribological Properties	145 HV	SiC particles had increased the micro hardness. Wear rate was reduced in the processed zone.
22	Yuvraj et al. [30]	Al 5083/B ₄ C micro- and nano particles	Tribological Properties	116 HV and 124.8 HV	Nano particles had enhanced the micro hardness in compare to micro particles.
23	Kumar et al. [31]	Al 5083 /W	Wear characteristics	126.7 HV	Adhesive wear mechanism was observed at low loads. 5X10 ⁻³ mm ³ /m was the wear rate for Al 5083 /W composite.
24	Mirjavadi et al. [32]	AA 5083/ZrO ₂	Mechanical and Wear Properties	140 HV	Composite having 8 passes had got the maximum grain refined structure.
25	Jain et al. [33]	AA5083-B ₄ C/SiC/TiC	Mechanical and Wear Properties	132 HV	18x10 ⁻⁵ mm ³ /Nm was the minimum wear rate for AA 5083/B ₄ C composite.
26	Esmaily et al. [34]	Al 5456/BNi ₂	Mechanical characteristics	120 HB	V shape and step groove had got more uniform distribution in comparison to square groove.
27	Rao and Rao [35]	AA 6061/TiB ₂	Wear Properties	135 HV	The wear resistance of AA 6061/TiB ₂ composite was improved.
28	Kishan et al. [36]	Al 6061/nano TiB ₂	Mechanical Properties	132 HV	4 vol. % of nano TiB ₂ composite exhibit improved mechanical properties.
29	Thangarasu et al. [37]	AA 6082/TiC	Mechanical and Wear Properties	135 HV	The micro hardness was found to be 135 HV at 80 mm/min with the wear rate of 412x10 ⁻⁵ mm ³ /m.
30	Thangarasu et al. [38]	AA 6082/TiC	Micro structural Properties	149 HV	Tensile strength was improved to 324 MPa at 24 vol% of TiC particles. Wear rate was reduced to 300x10 ⁻⁵ mm ³ /m for AA6082/24 vol.% TiC particles.
31	Thangarasu et al. [39]	AA 6082/SiC, Al ₂ O ₃ , TiC, B ₄ C and WC	Mechanical and Wear Characteristics	105, 85, 115, 108 and 85 HV	TiC reinforced composite had maximum micro hardness and minimum wear rate in comparison to SiC, Al ₂ O ₃ , B ₄ C and WC particles.
32	Thangarasu et al. [40]	AA 6082/TiC	Wear Properties		The wear resistance was improved to be 0.00303 mg/m at 22 vol. %.
33	Ambigai and Prabhu [41]	Al/B ₄ C	Wear Characteristics		Nano B ₄ C particles had got less wear rate as compared to micro B ₄ C particles.
34	Bhat et al. [42]	Al /Fe	Microstructural Properties		High degree of metastability leads to poor creep resistance.
35	Rajan et al. [43]	AA 7075/TiB ₂	Micro structural and Mechanical Properties	160 VHN	Intergranular distribution of reinforced particles was observed. Wear rate was reduced to 98 mm ³ /m for AA7075/9wt%TiB ₂ .
36	Rana et al. [44]	Al 7075/B ₄ C	Wear Properties	112 HV	Micro hardness was increased with the increase of transverse speed. Lower transverse speed leads to uniform dispersa of reinforced particles.
37	Kumar et al. [45]	Al 7075-2% SiC micro- and nano particles	Mechanical Properties	101 HV, 121 HV	Nano SiC particles had got less wear rate as compared to micro SiC particles. Less wear loss was observed for prepared nano composite.
38	Eskandari and Taheri [46]	Al 8026/TiB ₂ /Al ₂ O ₃	Mechanical Properties	175 HV	Micro hardness was doubled for the fabricated hybrid composite.
39	Zangabad et al. [47]	Al/Al ₃ Ti/MgO	Fatigue Behaviour		Fatigue strength was improved to 33% by incorporating 3.5 vol. % of TiO ₂ particles.
40	Azizieh et al. [48]	Al/Al ₂ Cu	Microstructural and Wear Properties	53 HV	Increased number of passes had refined the grain structure.

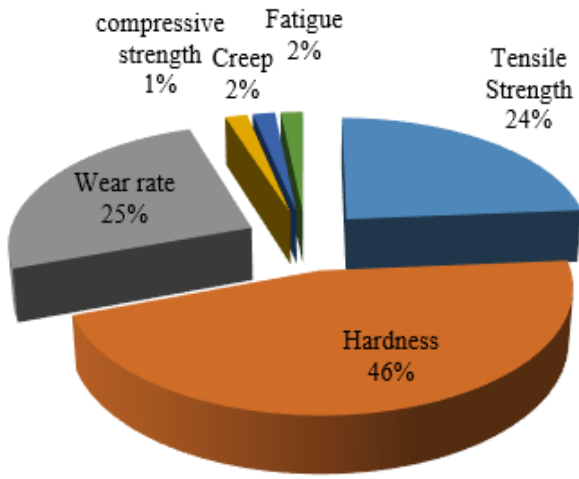


Figure 3. Summary of percentage contribution of research work on mechanical properties

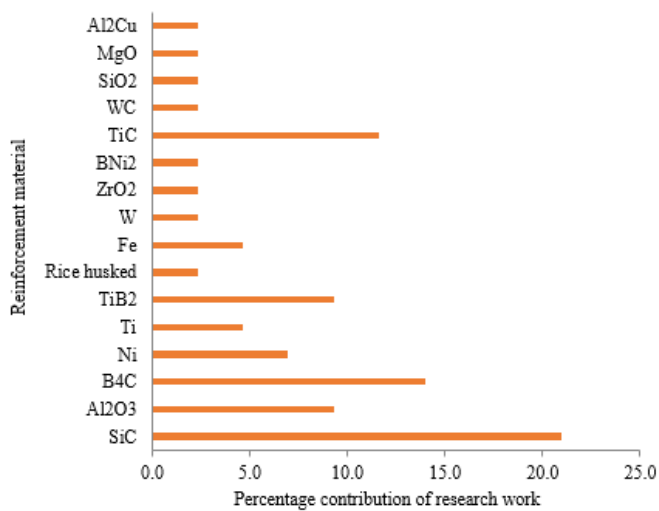


Figure 4. Summary of percentage contribution of research work on reinforcement particles

6. CONCLUSION

FSP has been positively developed as a composite manufacture technique. The main problem in generation of ex situ composites wherein the reinforcement is added externally to the material is the accumulation of reinforced particles. FSP leads to plastic strain, can shear the metal powders and break the oxide film around the reinforced particles. This intimates the contact between the matrix and the reinforcement to form the reaction. The chance of formation of clusters of reinforced particles can be abridged by suitable selection of an FSP tool shoulder diameter, pin diameter and tilt angle, mainly accountable for the generation of frictional and shear force. Pretreatment of the reinforced particles to improve wettability, together with multi pass FSP, offers another substitute to avoid cluster formation of reinforced particles in the FSP nugget zone. Heat generated between the tool and the surface is an important factor to produce defect free surface composite. Increased friction coefficient may lead to stick the work piece and the tool shoulder while reduced friction coefficient may not generate the heat required to make the material soft. Reinforcements acting as pinning sites refined the grain structure and thus improving the mechanical and wear

properties of the surface composites.

Thus, the effective use of the FSP technique in generating composites firmly creates it in the field of composite fabrication. Further research determinations in this field and better understanding of the process features can pave the way for the commercial success of the FSP technique.

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