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Review Article

A Study on Microstructural Behaviour and Mechanical Properties of Composites Fabricated by Friction Stir Processing

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Being a green manufacturing technique, FSP could be viewed as the most important advancement in the field of metal joining and composite fabrication. In the current scenario, it is required for any production technique that,it should be efficient, versatile and environment friendly. Nowadays surface composites are the most suitable materials for industrial purposes and for its fabrication, the most evolving production technique is FSP. Surface properties can be enhanced by using this technique such as strength, hardness, corrosion resistance, ductility, abrasion wear, formability, fatigue etc. Earlier, it was used to fabricate the composite of mainly aluminium and magnesium-based alloys, but now this technique can be used on steel, titanium, and other metal alloys also. Nowadays various research has been going on in the field of metal foam fabrication which is fabricated by mixing the base material with the blowing agents and the surface properties of the metal foam is better than the surface composites in term of hardness, strength, fatigue life, etc. The current review has classified to discuss the effect of the process parameters, geometry and material of the tool, reinforced particles, microstructural behaviour and surface properties of the composites and metal foam.

Keywords: Friction stir processing, Surface composite, Metal foam, Metallurgical and microstructural properties

1 Introduction

Friction Stir Processing is the technical variant of the friction stir welding, invented at The Welding Institute, Cambridge (U.K.) in 1991[1-3]. It is a solid state joining process whose working principle is very basic in which a non-consumable spinning tool with specially built pin is being used for the processing[4-5]. In this process plastic flow of material could be seen and between the tool and the workpiece, frictional heat is generated which softens the base material[6]. In the technique, a non-consumable spinning tool consisting of a shoulder and probe, with some restrictions in dimensions, is used for the processing. A downward force is applied to the tool shoulder during the rotation of the tool so that the tool probe could be inserted into the base material and the tool shoulder touches the surface layer of the material. FSP tool, during the rotation, allows controlled surface depth alteration and microstructural enhancement[7]. The current application of friction stir processing can be seen in various fields such as composite fabrication, grain size refinement, microstructural enhancement etc[8-9]. Nowadays this technique is also used for metal foam fabrication. The schematic diagram of friction stir processing is shown in Fig. 1.

The FSP method requires extreme deformation and mixing of material particles. FSP/FSW can be considered as a hot working process as it can attain a peak temperature of 80% of the melting point of a base temperature. Most of the experiments in FSP have been carried out in the aluminium alloys fabrication industry[10]. This technique can be used even for the joining and processing of non-weldable Al series such as Al2XXX, Al6XXX, and Al7XXX, etc with low processing cost and high performance joint[11]. Application of FSP can also be seen in the modification of various mechanical properties that are not restricted to corrosion resistance, ductility/elongation, static mechanical properties, fatigue properties, static mechanical properties, hardness, etc. This technique can also modify the material's machining ability such as the formability of the material[10].

Firstly FSP technique was used for surface modification and microstructural refinement of Al and Mg alloys; later the technique was also used for copper[12], steel[13] and titanium alloys[14]. The FSP technique had been developed mainly for aluminium based alloys in which various reinforcing particles such

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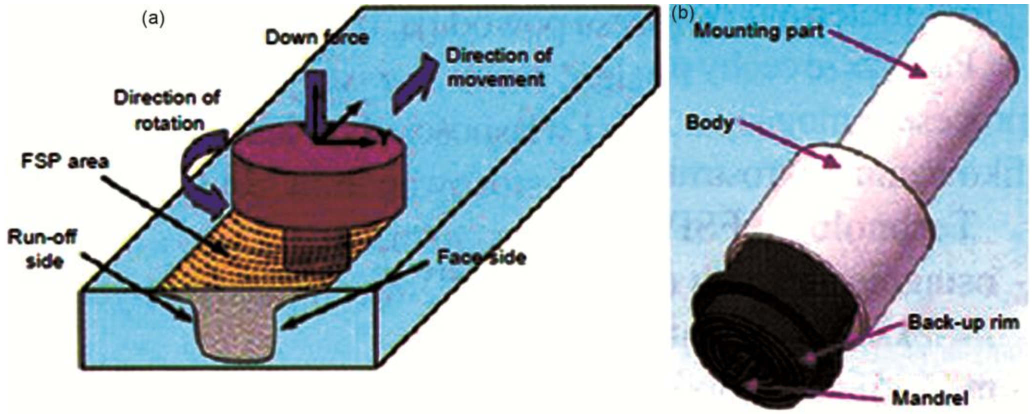

Fig. 1 — (a) Schematic diagram of Friction Stir Processing, and (b) Friction Stir Processing Tool[24].

as SiC, TiO_2, Al_2O_3 etc were used[4]. Now a days Friction Stir processing is used for magnesium, steel, copper, titanium based alloys and their mechanical and microstructural behaviour are studied[15-16]. Current advancements in the field of FSP are discussed in this review. This is supported by the analysis on process parameters of FSP, tool geometry and its effect, composite fabrication and its microstructural behaviour, enhancement of mechanical and electrical properties, and the metal foam fabrication by FSP. The work is summarized by the defects and the future scope in the field of Friction Stir Processing.

2 Materials and Methods

2.1 Process parameters

Process parameters of FSP play a crucial role in the fabrication and surface composite properties. During the discussion of process variables, three major areas need to be discussed: machine Variables, material properties and tool design variables[17-18]. Under these major areas, various sub areas can affect the properties of fabricated surface composites[19]**.**

These parameters govern the hardness, yield strength, tensile strength, etc of the fabricated composite. Thermal properties of the material are also governed by these process parameters as the peak temperature during the processing could be predicted by the various machining parameters. Heat loss of the material during the processing majorly depends upon the thermal conductivity of the material; if thermal conductivity is high, a large amount of heat loss would occur and high conductivity material also required high heat input[20-21]. So backing plate could be used in FSW/P to manipulate the heat loss during processing[22]**.** Figure 2 illustrates the various FSP process variables.

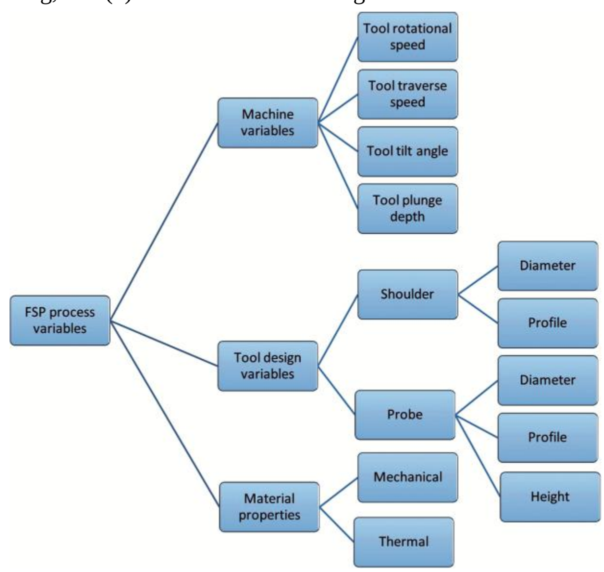

Fig. 2 — FSP process variables[19].

2.1.1 Machine variables of Friction Stir Processing

The main machine variables are tool rotational speed and tool transverse speed as these produce the frictional heat between the workpiece and the tool[23]. The tilt angle of the tool and tool plunge depth also affects the stir zone of the material. Contact between the workpiece and the tool generates frictional heat which produces plastic deformation in the base material. Heat input during the processing in the stir zone creates microstructural and tribological evolution in the base material which also enhances the mechanical properties of the material[1]. The volume of heat insertion in the stir zone depends upon the tool rotational and tool travel speed. The selection of the tool speed primarily depends upon the properties of the material selected[25].

2.1.1.1 Effect of tool speed (Tool rotational and travel speed)

The rotation rate of the tool and travel speed decide the heat input in the stir zone of the fabricated composite[19]. The lesser the heat input, the higher would be the value of grain refinement and vice-versa but the higher value of heat input is required for the plasticization of the base material[26]. The processing speed of the material depends upon numerous factors such as tool geometry, type of alloy, penetration depth, etc[27]. For AA2219 three different rotational speeds had been used for the friction stir processing and it was concluded that a high rotational rate was required for high heat input and stirring action in the stir zone[28]. Hangai et. al.[29] studied the impact of tool rotation rate on morphology and porosity of Al 1050 which was processed by friction stir method. Different mechanical properties were examined on various rotational rates during the processing. It was estimated that better mixing of reinforced particles can be achieved at a higher tool rotation rate as tool rotation is the basic parameter of friction stir processing[30].

Devaraju et. al.[31] had examined the effect of tool rotational rate and reinforcement on mechanical and wear characteristics of aluminium hybrid composite was, in which SiC and graphite were taken as reinforcement particles and Taguchi technique was used to optimize the tool rotational rate. The fabricated hybrid composite was examined by optical microscopy in which it was revealed that the microhardness of the material was improved due to the uniform dispersal of the SiC particles and wear resistance could be improved by mixing the graphite flakes in the base material**.** Thermal models for various alloys were also developed and it was concluded that for high melting point alloys, high heat input was required[32]. Srivastava et. al.[33] studied the effect of cooling medium on stir zone and multi-pass FSP produced more uniform surface composite. Nano SiC particles and graphite were selected as reinforced particles and multi pass FSP distributed reinforced particles more uniformly in the metal matrix and the cooling environment refines the grain structure and mechanical properties of the surface composite. Srivastava et. al.[34] had optimized the process parameters was also done for the fabrication of surface composite by using the Taguchi technique. In this experiment, Al 6063 was selected as a base material in which SiC was added as reinforcement. It was concluded that better mechanical properties of the surface composite were obtained corresponding to tool rotational rate of 1400 rpm, tool transverse speed of 40 mm/min, and tilt angle of tool tip as 2.5º. Approximately 46% improvement in microhardness was also reported**.**

Tool rotation and tool transverse speed also influence the dispersion of reinforced particles in the base material. Higher the value of tool rotational rate and transverse rate, more uniform will be the dispersion of SiC particles in AA1050 surface composite[35]. Chen et. al.[18] had analysed about the fabrication of Al-CeO_2 surface composite and it was found that a lower tool rotational rate was more suitable because of the exothermic reaction during the processing. Rathee et. al.[36] investigated the effect of Groove dimensions on the base material and the mechanical and microstructural properties of Al6063/SiC friction stir processed surface composite. An experimental study was done with 5 grooves of different dimensions which were cut and processed by friction stir technique with constant process parameters and it was concluded that 0.5 w/d ratio is most optimum for developing a high volume percentage of Al6063/SiC surface composite. Heidarpour et. al.[37] performed the same experiment on Al 6061 and optimized the process parameters of FSP for microstructural advancement by using the same reinforced particles. Three process parameters, namely, tool rotational speed, tool transverse speed and tilt angle with three levels were chosen. Taguchi L9 orthogonal array was used to get the optimum value. It was concluded by using signal to noise ratio (S/N ratio) analysis that maximum microhardness could be achieved when tool rotational speed, transverse speed and tilt angle were taken as 1400 rpm, 50 mm/min and 2.5º respectively**.** Table 1 summarizes the effect of tool rotational and transverse speed on the composites.

2.1.2 Tool design variables

Tool design i.e. tool pin profile and tool material also influence the uniform mixing of the reinforced particles in the processing zone which affects the mechanical properties of the fabricated composite.

2.1.2.1 Tool material and geometry

Tool material and its geometry play a very important role in the field of friction stir processing/welding. As discussed earlier there are two key parts of the tool: Tool pin and tool shoulder. FSP tool has to perform two major functions during the processing: (a) localized heating between the base material and the tool shoulder (b) flow of material[52]. Three different types of tools could be used in FSP/FSW: fixed tool,

Table 1 — Effect of Tool rotation and transverse speed on the fabricated composite

Material	Tool Rotational Speed	Tool Transverse Speed	Result
Cu/SiC[12]	900 rpm	40mm/min	Microhardness of Cu/SiC composite increases upto 58%; The grain size of the composite reduces remarkably after multi-pass FSP.
AA5083/AA6351[38]	650 rpm 950 rpm 1300 rpm	60mm/min	UTS of 273 MPa was found to be maximum at 950 rpm rotational speed; Grain size also reduced significantly at the 950 rpm rotational speed.
AZ91/SiC[39]	710 rpm 900 rpm 1120 rpm 1400 rpm	Transverse speed varied from 12.5—80 mm/min.	The grain size of the stir zone reduces from 150-7.17µm. The hardness of the material increases from 63 to 96 Hv.
AA7021-T53[40]	900 rpm 1400 rpm	40mm/min 16mm/min	Heat input in the stir zone increases with the increase of the rotational speed and heat input in the stir zone decreases with the increase of the transverse speed.
AA6061[41]	2250 rpm 2500 rpm 2750 rpm	10mm/min 15mm/min 20mm/min	The maximum value of tensile strength of welded region was found at the 2750 rpm rotational speed and 15mm/min travel speed.
AZ61/TiC[42]	850 rpm	25mm/min 100mm/min 170mm/min	A good dispersion of TiC was found with the tool rotation rate of 850 rpm and travel speed of 25mm/min. Grain sizealso reduced significantly with the same combination.
AA6061/SiC nanocomposites[43]	800 rpm 1000 rpm 1250 rpm 1600 rpm	40mm/min 80 mm/min 125mm/min 160mm/min	Maximum tensile strength in the stir zone was found with the 1600 rpm rotational speed and 40mm/min travel speed. It was also concluded that rotational speed is the most influential factor having a percent contribution of 43.7%.
Al 5059/ Multi-wall Carbon nanotube[44-45]	1130 rpm	30mm/min	The hardness of the composite increases upto two times from 84 Hv to 169 Hv after 3 passes of FSP.
Cu/SiC[12]	900 rpm	40mm/min	Hardness, Tensile Strength, and friction coefficient behaviour of the material enhanced remarkably after 8 passes of FSP.
AA2009/SiC[46]	600 rpm	50 mm/min	Longitudinal and transverse tensile strength of the composite enhanced from 82% to 95%.
AL 6061-T651/NiTip[47]	600rpm	100mm/min	Lower tensile strength and higher elongation can be seen in the fabricated composite.
AA5083/SiC[48-49]	1000rpm	25cm/min	The hardness of the material increased upto 5.15 GPa on the retreating side and 1.05 GPa on the advancing side and the wear rate was reduced upto 13%.
High-Density Polythene/Nano clay particles[50]	900 rpm	160mm/min	62% increment was seen in the friction stir processed polymer. Modification in surface properties was also seen in polymer composite.
AZ31 Mg/SiC[9]	900 rpm	160mm/min	The grain size of the fabricated composite decreased from 16.57 micro meter to 1.25 micrometer, the microhardness of the material enhanced from 57.77 Hv to 115.51 Hv and the p low width of AZ31 with SiC also decreased from 620 µm to 410 µm.
AZ91 Mg/SiC[39]	1400 rpm	80mm/min	The hardness of the fabricated composite was increased from 63 to 96 Hv and grain size was reduced from 150 to 7.17 µm.
Al1050/SiC[35]	500 rpm 700 rpm 1000 rpm	15mm/min 20mm/min 30mm/min	Microhardness of the fabricated composite was enhanced upto 2 times and maximum hardness was evaluated at the combination of rotation and travel speed of 1000 rpm and 15 mm/min.
WE 43/ Nano TiC[51]	500 rpm 700 rpm 1000 rpm	15mm/min 20mm/min 30mm/min	Significant reduction in Grain size of the Mg alloy from 22.42 to 6.6 micrometer; microhardness was increased upto 180 Hv and degradation rate of processed Mg was 45% lesser than the unprocessed Mg.

Table 2 — Properties of high melting point materials[6,60-62].

Properties Materials	Melting point/K	Tensile strength/MPa	0.2% proof stress/MPa	Elongation/%	Hardness/HV
Ir	2720	500	90	6	200
Re	3459	1131	317	24	280
Mo	2896	481	441	50	160
W	3695	588	539	0	360
Nb	2742	275	206	30	30
Ta	3293	206	177	40	70
Hf	2504	444	230	23	160

adjustable tool, and self-reacting tool. In a fixed tool, the shoulder and probe are made up in one piece and the tool probe length remains uniform during the whole process as this type of tool probe is used to process the material of uniform thickness. An adjustable tool,
and probe are made up of different materials. Tool probe can be changed during the process as per the requirement of the design. But a back anvil is required in these tools. The self-reacting tool is made up of three components, namely a top shoulder, probe, and a bottom shoulder. This tool does not require any backing anvil[53]. Material gets plasticized when it gets processed by friction stir method. The tool geometry, as well as the rotational and transverse speed of the tool, affects the amount of heat generation between the workpiece and the tool[38, 54].

For FSP/W, tool material with high wear resistance and high strength is required. Tool material used for FSP/W need to have some particular characteristics such as hardness, roughness, wear strength, non-reactivity with the workpiece at a higher temperature[6]**.** Tungsten alloy[55], Molybdenum alloy[56], various ceramic materials, and other super hard materials (Nb, Ta, Hf) having melting point greater than 2273 K were found suitable and fulfil the requirements for the tool[57]. Some typical characteristics of the high melting point materials are mentioned in Table 2.

Miyazawa et. al.[6] had designed Iridium (Ir) based tool specifically for friction stir processing. The stir zone of Al 6061 alloy. Tool pin profile performs a very important role in the quality of the weld. Five different types of pin profile: triangular, square, straight cylindrical, tapered cylindrical, and threaded cylindrical— with three diameter sizes were used for the weld fabrication. The macroscopic investigation was done and tensile properties have also been evaluated and it was found that square profile pin was most appropriate for mixing purpose and in comparison to the other pin profiles, it produces mechanically sound and metallurgically defect-free weld[28, 58]. Figure 3 shows the various tool design. The effect of tool material and tool geometry on the performance of FSP is reported in Table 3.

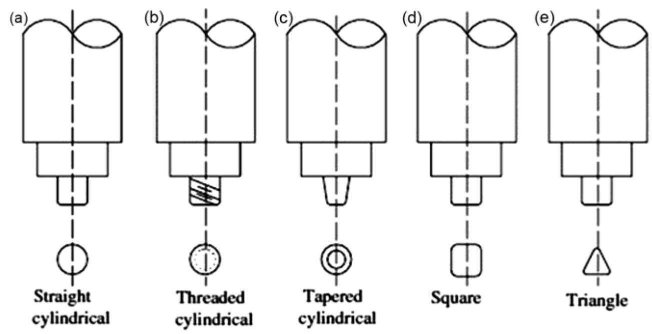

Fig. 3 — Various types tool design[28, 59].

3 Results and Discussion

The applications of FSP can be seen in the fields of composite fabrication, microstructure modification, Mechanical properties improvement, etc. Nowadays, one of the most promising applications of the FSP is metal foam fabrication. The details of various applications are discussed in the following sections.

3.1.1 Composite fabrication by FSP

During the fabrication of composite, initially, the reinforced particles are inserted inside the base material and then the processing starts. There are various approaches to create the matrix in the material.

3.1.1.1 Slit filling method

In this technique, a slit/groove having prescribed width and thickness is being cut on the base material and then the groove is filled with the reinforced particles. After filling the groove, FSP is applied over it, and because of the rotational and transverse speed of the tool frictional heat is generated and reinforced

Table 3 — Effect of tool material and geometry on fabricated composites

W/P Material	Tool Material	Tool Geometry	Process Parameters	Conclusion
Al6111-T4[63]	H13 Steel	SD:10mm SS: Flat PL: 0- 1.6mm	RS: 2000rpm	Better weld quality achieved with pinless tool
Al 7020-T6[64]	Steel	SD:10-20 mm, Flat PD: 3-8mm, PL: 4.2mm, PS: Frustum and straight circular,	RS: 1400rpm TS: 80mm/min	Joint efficiency achieved 92%
Al 7075-T7351[65]	Uncoated MP159 Steel tool (Dievar) MP 159 pjn with H13 shoulder	PS: Threaded	RS: 190-457rpm TS: 0.3-1.4mm/min	Surface scaling and voiding problems
Al 7075-T7351[66]	Uncoated MP159 Steel tool (Dievar) MP 159 pjn with H13 shoulder	PS: Trivex, Triflute	RS: 394-457rpm TS: 300-540mm/min	UTS achieved 477-488MPa
Al-5754[67]	H-13 Steel	SD: 12 mm; SS: concave, convex, flat; PD: 5 mm; PS: Threaded Cylindrical PL: 1.6 mm	RS: 1500rpm TS: 20mm/min	Static strength for concave shoulder was 3550N, for flat shoulder was 3400 N and for convex shoulder was 3080 N.
Al7020-T6[68]	High Carbon steel	SS: concave, SD: 13 mm, PS: Straight Circular and tapered circular with 3 flats, PL: 3.19 mm, PD: 5 mm	RS: 300-1620 rpm TS:100-900 mm/min	Flat pin deposited the material on the advancing side of the rotation and this effect is decreased in the tapered pin with 3 flats
Al6082-T6[69]	56NiCrMoV7-KU	SS: scroll, cavity and fillet, PD: 1.7 mm; PS: Straight Circular PL: 1.2 mm	RS: 1810 rpm TS:460 mm/min	Joint efficiency was found 76%
Al1050-H24 Al6061-T6 Al5083-O[70]	H13	PS: Straight Circular, Straight circular with thread, Triangular PL: 4.7 mm	RS: 600-1500 rpm TS:100-700 mm/min	Maximum UTS was found at the circular threaded probe. The shape of the tool does not influence the mechanical and microstructural characteristics at a lower tool rotational rate.
Al6061-T6[71]	H-13 Steel	PS: Straight Circular, PD: 7.1mm, PL: 1.8-7.1 mm	RS: 650 rpm TS:200 mm/min	Longitudinal force increases with the pin length.

particles get diffused inside the base material. Mishra et. al.[4] used this technique for Al5083 in which SiC was used as a reinforcement to fill the slit which was cut over the base material. Later on, this technique was used by various other researchers. Rathee et. al.[72] used the groove cutting technique on Al6063 as a base material with SiC particles as reinforced particles. A slit of width 2 mm was cut on the base material and the FSP technique was applied over it. The single pass and multi-pass FSP technique can be applied to the base material for the mixing purpose of reinforced particles on the base material. Figure 4 illustrates multi pass FSP with groove filling technique.

3.1.1.2 Drill Hole Technique

In this technique multiple holes in a random manner are drilled on the base plate, reinforced particles are filled in these holes and then the FSP technique is applied over the plate. Bauri et. al.[11] used this technique for Al 1100 in which Ni Ti was used as reinforcement. Multiple holes were drilled of diameter 1.6 mm and depth of 76mm over the plate. These holes were made in such a manner so that all the holes could be covered in FSP single pass. The Centre distance between the holes was in such a manner that the shoulder of the tool can rotate easily. The holes were packed with the NiTi particles and the tool started rotating over the hole**.** Figure 5 depicts a drill hole method.

3.1.1.3 Powder metallurgy technique

In this technique precursor of metal and reinforced particles are prepared by using the conventional powder metallurgy method. This technique involves blending and mixing of metal matrix and reinforced

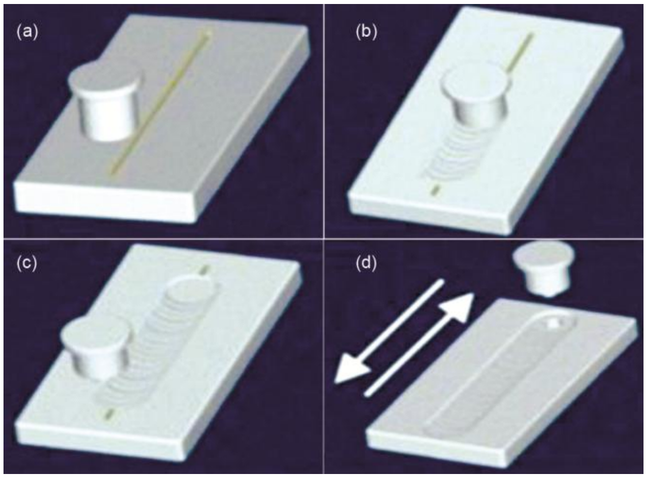

Fig. 4 — Schematic Diagram of Multi-pass FSP Technique with groove filling technique, (a) Tool and Workpiece positioning, (b) Friction Stir Processing during 1st pass, (c) Tool after completing 2nd pass, and (d) Tool after completing multi-pass for FSP[11].

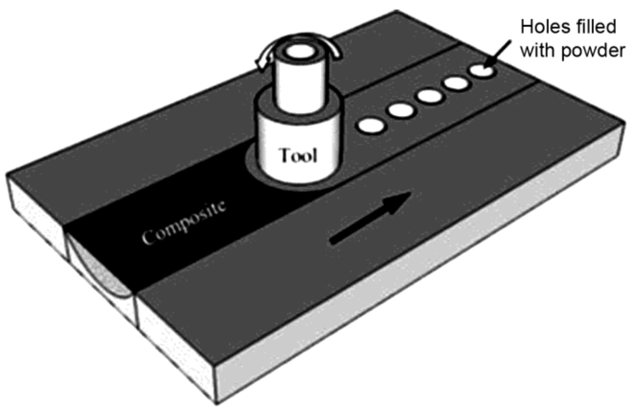

Fig. 5 — Schematic diagram of Drill-Hole method[11].

particles by compaction and sintering. Then FSP technique is applied to the sintered precursor. After the application of FSP reinforced particles are distributed uniformly in the base material[73].

When the tool is traversed on the workpiece, frictional heat is produced between the contact of the workpiece and the tool which results in deformation in the plastic of the material. This technique can be used for the joining purpose of similar as well as dissimilar material.

Friction Stir Processing can be applied for the surface composite fabrication. Composite fabricated by FSP exhibits better reinforced particles dispersion and its mixing in the stir zone. It occurs due to the significant frictional heating and grain refinement of the material. Commonly used reinforced particles are SiC, TiO_2, B_4C, Al_2O_3, TiC, and carbon nanotubes, etc[19]**.** FSP has various advantages including solid state microstructural refinement and improvement in mechanical properties by optimizing the process parameters such as pin profile, pin plunge depth, tool rotation rate, tool transverse speed, etc. Mishra et. al.[4] had implemented this technique for surface modification of Al5083 by using SiC particles and the microhardness of the composite material was obtained as 173 HV which is approx. double of the hardness of Al 5083 alloy. Kurt et. al.[35] had experimented with grain refinement of Al 1050/SiC surface composite in which SiC particles were kept on the base material surface and the tool was rotated in anticlockwise direction with the different rotation speed of 500, 700, and 1000 rpm and the transverse speeds were 15, 20 and 30 mm/min. Microhardness and Vickers hardness tests were performed on the specimen and different results were attained**.** With higher rotational speed and lower transverse speed good dispersion of reinforced particles and better hardness of the material can be achieved[18] and used SKD61 steel tool for the processing of AZ31. The surface composite was fabricated by adding SiC reinforced particles in which steel tools were used for the processing. On the prepared test piece, microstructural evaluation and hardness test were done and it was reported that grain size of the base material decreases and hardness increases with the increase in the transverse speed. The composite possesses increased Young's modulus (88 ± 8 GPa), good compressive ductility with the reasonably good compressive strength (450 MPa yield strength and 650MPa ultimate strength). Morisada et. al.[74] used multi-walled carbon nanotube as a reinforced material for the fabrication of Mg based composite by using friction stir processing route. In this study amount of dispersion of the particles varied based on the speed of the tool and after the processing it was found that the microhardness of the composite was 78Hv, roughly double of the base material AZ31

Some of the composites like Al 6061 and Al5083 were fabricated in which nano-ceramic particles were used as the reinforcement. Yang et. al. had performed Optical microscopy and Vicker's hardness tests on the composite for investigating the effect of axial forces and number of passes of FSP on the base material[75]. It was concluded that the composite region increases if the axial forces and number of passes of the FSP increase, and it was also found that nanoparticles have not left any major effect on the macro hardness of Al 6061 material**.** Muthukumar et. al.[76] used novel direct particle injection tool for FSP for the insertion of reinforced particles. TiC was selected as reinforced particles whereas Al alloy was taken as a base material. A unique technique was selected for the insertion of reinforced particles in the material by using a spring attached with the plunger of the tool. The microstructural investigation was done and it was found that the thickness of the composite layer was 0.34 mm and the hardness of the material was enhanced from 68 to 135 Hv**.** Figure 6 demonstrates the use of the spring attached FSP tool.

Heidarpour et. al. proposed his studies in the field of surface composite fabrication and its characterization in which WC-Al_2O_3 is inserted in Al 5083 and its microstructural, hardness, and wear properties were evaluated. Multipass FSP was applied for composite fabrication and finally, it was concluded that the microhardness of the composite increased upto 101 Hv whereas the microhardness of the base material was 65Hv[77]. In the microstructural evaluation of the stir zone, equiaxed fine grains with no defects were found. During the wear test evaluation, the wear rate decreased considerably after the processing. Rana et. al.[78] had also used the same technique for the fabrication of surface composite in which Al7075 was taken as base material and B_4C was selected as reinforced particles and examined the wear properties of the composite. Various combinations of tool rotational rate, transverse speed, and the number of passes had been taken for the experiment. By using a non-consumable tool, hardness could be improved upto 70% whereas wear rate was improved upto 100%. A cylindrical shaped tool profile was chosen for the processing. In this experiment, it was concluded that transverse speed had a less significant role in particle dispersion and microhardness enhancement. Barmouz et. al.[50] had used nano clay particles for the fabrication of surface composites. Nano clay particles were dispersed on Cu material and mixing was done by using FSP. SEM, TEM, and X-Ray Diffraction revealed that the microhardness of this high density polyethylene nanocomposite had improved upto 62% induced with high thermo-mechanical stresses. Barmouz et. al.[12] had used same base material was used with SiC reinforced particles by using multi-pass FSP to evaluate the microstructural, mechanical, and electrical behaviour of the composite. SEM and optical microscopy results proved that refined grain structures were developed in the surface composite. Further, it was concluded that the electrical resistivity of the Cu was enhanced, the frictional coefficient of the material was reduced and tensile properties were improved significantly. Barmouz et. al.[79] had also studied the role of process parameters were also evaluated on microstructural, mechanical, wear, and tensile behaviour of surface composite. In this experiment Cu was used as a base material and SiC particles were dispersed over the surface. It was concluded with this experiment that higher the speed of tool rotation, poorer the dispersion of the SiC particles. The wear properties of surface composite were improved by adding more SiC particles.

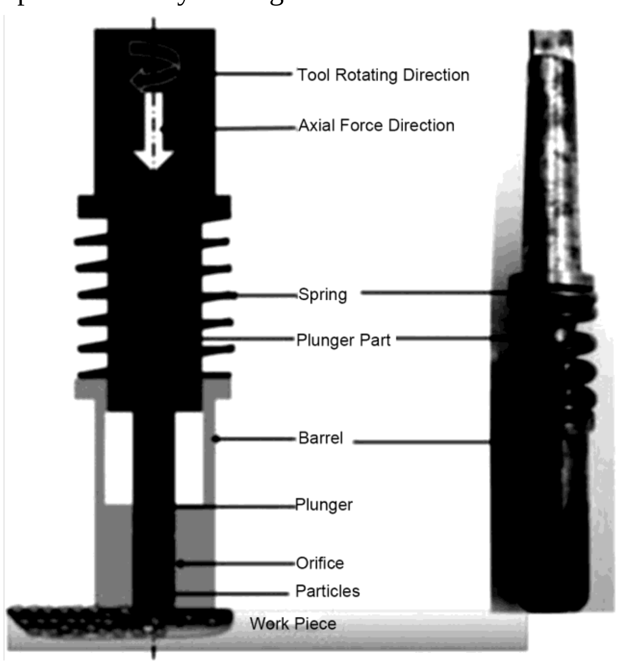

Fig. 6 — Spring attached FSP tool[76].

3.1.2 Microstructural Enhancement by using FSP

It is usually considered that the grain refinement occurs due to dynamic recrystallization[8,80]. This technique was applied on Mg alloy and produced a highly formable Mg alloy plate[81]. Sato et. al.had experimented on AZ91D Mg alloy[82]. Multipass FSP was done on the base material and produced a fine and homogeneous microstructure of grain size 2.7µm**.** Ma et. al.[83] had modified the surface of A356 was done with the help of friction stir processing. Si particles were distributed homogeneously in the A356 plate. After the processing, porosity defect could be eliminated from the base material and refined grain structure with Si particle was found**.** Ma et. al.[84] used FSP for the microstructural modification of As-Cast Al-Si-Mg Alloy. In this research, the impact of tool geometry and FSP parameters on base material was evaluated and it was concluded that mechanical and metallurgical properties of the base material were enhanced. Hsu et. al.[85] produced ultra fine grains of Al-Al_2Cu composite fabricated by FSP in which Al_2Cu particles were distributed uniformly on Al base plate. In the processing of Aluminium plate, the rotational speed was 700 rpm and transverse speed was taken as 45mm/min. After the completion of the process microstructural evaluation was done and in the cross-section of the material, a typical onion ring type microstructure was seen. The hardness of the material increases from 80 Hv to 160 Hv after the processing. Najafi et. al.[86] applied FSP on magnesium alloy for the improvement of its metallurgical behaviour. The process was applied on AZ31 magnesium alloy in which SiC_p was used as a reinforced particle. A comparative study was done on the microstructural study with and without the SiC particles. While examining the stir zone it was found that Sic particles were mixed uniformly by using FSP and grain size was larger when FSP was done without SiC particles. The hardness of the base material was also increased up to two times. Su et. al.[87] had optimized process parameters of FSP. Different mechanical and microstructural properties were exhibited at various process parameters while conducting FSP tests on 2 mm thick Ti-6Al-4V sheets. Better tensile strength and ductility were seen in the processed material. Figure 7 shows microstructure of a friction stir processed specimen. Figure 8 depicts optical micrograph of stir zone of a sample with different process parameters.

Better surface resistance could also be exhibited after the processing. Raaft et. al.[88] had fabricated composite of A390/Al_2O_3 and A390/graphite and the wear and mechanical properties were evaluated. In microstructural evaluation, it was found that the reinforced particles dispersed heterogeneously in the base material. Nascimento et. al.[89] had made a comparative study of two different friction stir processed Al alloy i.e. AA7072-T6 and AA5083-O. In this study, two different surface modifications were done. In VFSP, modification of the full thickness was

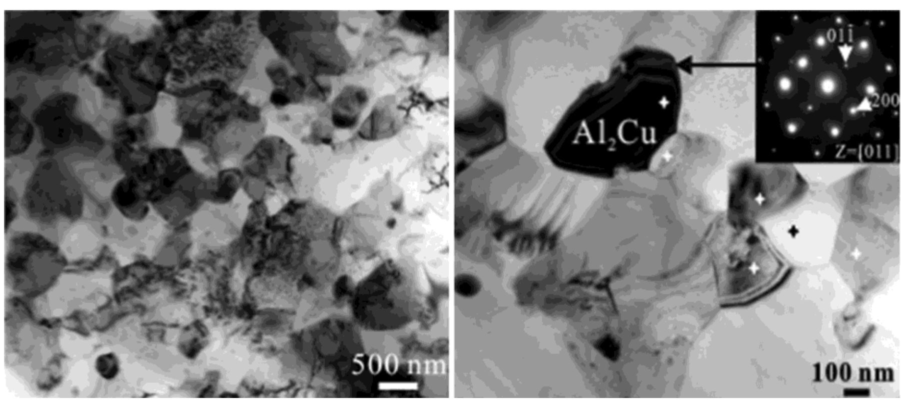

Fig. 7 — The microstructure of Friction Stir Processed specimen by TEM[85].

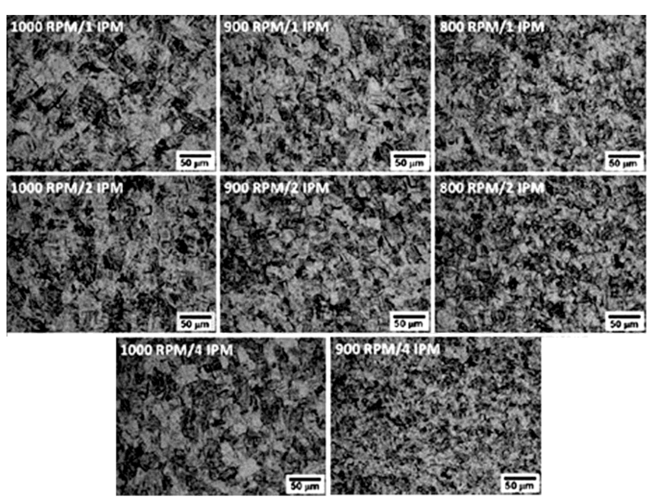

Fig. 8 — Optical micrograph of stir zone of a sample with different process parameters[87]

done; and in SFSP, the modification was done upto a depth of 2 mm. After the surface modification, a significant amount of increment in material formability and grain size refinement was observed**.** Bauri et. al.[90] had investigated microstructure of Al-TiC composite which was prepared by FSP route. In the proposed study, the reinforced particles were distributed more homogenously by using FSP. A further microstructural investigation was also done by single-pass and multi-pass FSP on the base material. It was found that two-pass FSP eliminated the casting defects from Al alloy matrix and also refined the grain size. Uematsu et. al.[91] had examined the fatigue behaviour of magnesium alloy AZ91was examined and microstructural modification was done by FSP. Processing was done by a cylindrical threaded tool with 800 rpm rotational speed and 500mm/min transverse speed. It was found that crack resistance of the surface enhanced and the improvement in the fatigue behaviour of the material took place**.**

Khodabakshi et. al.[92] analysed that heat treatment also affects the mechanical and microstructural behaviour of Al-Mg-TiO_2 nanocomposites was also studied. The annealing technique was used for heat treatment. Nanocomposites were annealed at a temperature upto 500ºC for 1-5 hr in the air. After prolonged heating at 500ºC, irregular grain growth could be observed and significant improvement in mechanical properties was found when the nanocomposite was annealed at 400ºC for 3 hours. Rathee et. al.[93] had made a comparative study on the composite fabricated by the dispersion of micro SiC particles and nano-SiC particles and it was concluded that nano-SiC exhibited higher microhardness and ultimate tensile strength than micro-SiC surface composite when multipass FSP applied on the material.

3.1.3 ***Metal foam fabrication by FSP***

Nowadays application of FSP can be seen in the fabrication of foamable precursor in which blowing agent and stabilizing agents are mixed in the base material by using the principle of FSP. In base material, stabilizing the pore structure is the main purpose of a stabilizing agent. These materials get mixed easily in the base material because of the high rotational speed of FSP.

Hangai et. al.[94] used FSP for the fabrication of dissimilar metal aluminium foam i.e. A1050-A6061. For the foaming of the dissimilar materials, initially it is required to fabricate its precursor by the FSP route. Various tests were performed to find out the change in Mg content in the joining region by using an electron probe micro analyser. In the current study, Al_2O_3 is used as a stabilizing agent and TiH_2 is used as a blowing agent. A cylindrical shaped tool with a screw probe was used for the friction stir processing**.** Hangai et. al.[95] also analysed the porosity and compression behaviour of different materialsafter the foaming. FSP was performed on ADC12 aluminium alloy die casting without using the blowing agent. ADC12 aluminium alloy die-casting was used as a base material which contains gas pores in the large amount. FSP route was selected for foam fabrication and its porosity and compression properties were investigated. ADC12 having a porosity of 50-77% had been fabricated effectively in this study and it was concluded that higher energy absorption capacity and low compression stress exhibited in foam fabricated with blowing agent whereas the foam fabricated without blowing agent showed higher energy absorption capacity and high compression stress. After fabricating the three layers of ADC 12 foams with 1-0-1% and 0-1-0% TiH2 and performing the compression tests on foams and it was concluded that the foam layer with 1% blowing agent deformed first than the layer with 0% foam[96]. Fig. 9 and Fig.10 depict the compression deformation images of three-layered foams.

Papantoniou et. al.[97] used nano- γ- Al_2O_3 particles for the fabrication of localized composite metal foam in which AA5083was used as a base material and then its microstructural characterization was studied. In

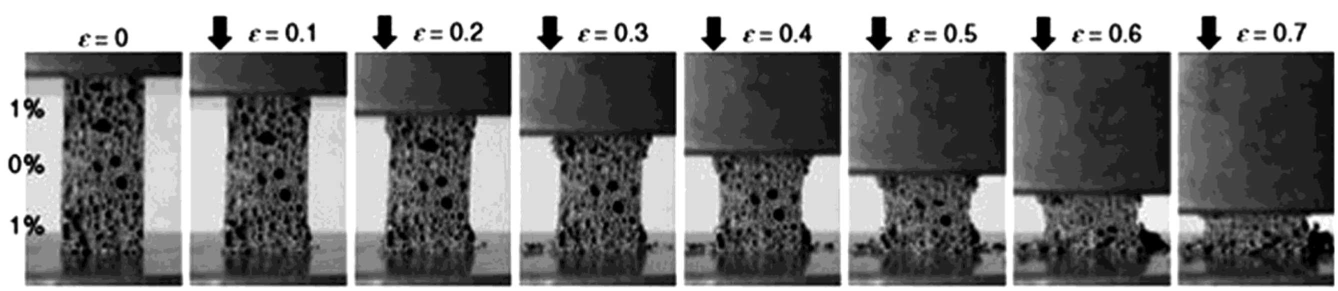

Fig. 9 — Compression deformation images of 1-0-1% TiH_2 foam types[96].

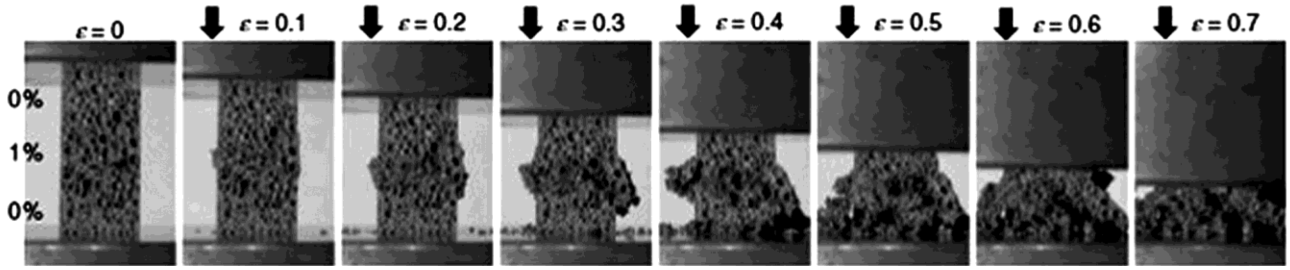

Fig. 10 — Compression deformation images of 0-1-0% TiH_2 foam types[96].

Table 4 — Effects of blowing agents on the fabricated foams

Base Material	Blowing Agent	Conclusions
Al alloys (6061,7075,2021, 5083,1050 etc)[94,101]	TiH_2	Higher porosity with higher compressive strength, Hardness gets doubled whereas the density of the fabricated foam reduces significantly.
AlMg4.5 and AlSi9Cu3[102]	$CaCO_3$	Low-cost Foaming Agent, Pores generated are very regular and the density of the fabricated foam is quite low as compared to the foam fabricated by the conventional blowing agent.
Al2024[98]	Methyl Hydro Siloxane	The energy absorption capacity of the fabricated foam increases upto 80%.

this study, grooves are made on the base metal for integrating the foaming agent with the stabilizing agent. γ- Al_2O_3 is used as a stabilizing agent in place of conventional stabilizing agents like Al2O3 and TiH_2. On analysing the microstructure and porosity evolution it was found that a porosity of 60% having a pore diameter in the range of 0.2 to 3.3 mm can be attained.

Novel polymeric blowing agents can also be used to produce a foaming effect in aluminium alloys. Polymeric agents are more environment friendly and create more porosity inside the base material as compared to conventional blowing agents. Madhu et. al.[98] used methyl hydro siloxane, a polymeric agent, was used for the fabrication of Al 2024 foam. Friction stir process was done for dispersion of polymer followed by pyrolysis process at temperatures of 500–640°C. Results had shown, at a temperature of 560°C, relative density gets a minimum of 0.65. A compression test was performed on the heat-treated Aluminium foam and it was found that in comparison to the processed foam, energy absorbed by the aged foam increased approx. 80%.

Instead of conventional TiH_2, Calcium carbonate as a foaming agent was used because the decomposition of $CaCO_3$ releases CO_2 gas which forms pores inside the material. Several studies were done for the same in which Al alloy is used as a base material. The studies concluded that grain size of calcium carbonate decreases the relative density, increases the porosity of the foam, and also increases the number of pores per inch[99]. Azizieh et. al.[100] fabricated nanocomposite magnesium based foams by using FSP. The impact of the weight ratio of TiH_2 to Al_2O_3, foaming temperature, number of FSP passes on the pore distribution and porosity were identified. Rajak et. al.[101] used the same process with the same process parameters was applied for the characterization of Aluminium alloy foam (Al-Si7Mg) in which TiH_2 was used as a blowing agent, it was concluded that the blowing agent stabilized the pores with a diameter of 1.2 mm.

Recently a study was done in which heat produced by friction stir processing (FSP) on a steel plate was used for the foaming purpose of the aluminium precursor in place of conventional furnace heating. Hangai et. al.[103] applied the same technique on Al 1050, used as a base material, and the precursor of the same was fabricated by using transverse speeds of the tool as 10 mm/min, 20 mm/min and 30 mm/min. It was concluded during the study that uniform temperature distribution is required to achieve a larger and finer pores structure and a less conductive material is required for the generation of friction heat so that a large amount of heat could be introduced in the precursor**.** Table 4 reports the effects of differet blowing agents such as TiH_2[104], $CaCO_3$[102], and methyl hydro siloxane[98] on the fabricated foams.

4 Conclusion

FSP/W is a very vigorous process that is being used quite extensively in the field of composite fabrication, surface, and microstructural properties enhancement, foam fabrication, etc. The fabricated materials possessing such peculiar characteristics are mainly used in the aerospace industry because of their higher mechanical properties including strength to weight ratio. FSP/W technique could be used on all Aluminium series i.e. 1XXX to 8XXX. This process is very much attractive because of its better-quality results, cost-effectiveness, environment friendliness, less time consuming, etc. Foam fabrication is a very attractive application of this process because of its properties as the material is very lightweight and could be widely uses in space industries also. To this end, further research can be done by varying the reinforced/ blowing agents for the base material and the technique can also be used on the harder materials such as Ti, Ni, steel, etc by varying the tool design and material.

5 Future Scope of Research

FSP/W is a versatile solid-state technique for various purposes such as composite fabrication, microstructural enhancement, grain refinement, metal foam fabrication, etc. Nowadays demand for light weight structures with exceptional properties is increasing rapidly. This technique is the latest in the field of production and the composite fabricated by this process exhibits wear and corrosion resistance as well as high hardness. Various studies have been carried out successfully in the field of surface composite, hybrid composite fabrication by using different reinforced particles, carbon nanotubes, nano-particles, etc; but comparatively fewer studies were seen in the field of metal foam fabrication which opens a vast area of research for the researchers. Thermal management of the stir zone is also one of the most interesting areas. To achieve the same, both thermal boundary conditions and temperature control are required. To regulate the temperature in the stir zone thermocouples can be attached to the tool shoulders.

Tool material and tool geometry also form a wide area of research in the field of FSP/W. Different pin geometries have been used such as cylindrical, square, threaded cylindrical, triangular, etc during the FSP/W and by using these tools uniform particle dispersion was seen in the microstructural studies. Dispersion of the particles could be improved by providing threads on the face of the tool shoulder also. Tool wear is an essential issue to discuss around FSP/W. Generally, it was seen that for the tool material, high-speed steel was taken, but under the condition of the high rotational speed of the tool for hard materials, it gets worn out. So different materials such as polycrystalline CBN, tungsten-based alloy materials can be recommended for the processing or welding of harder materials. Recent advancements of FSP/W could be seen in the field of joining of dissimilar materials and some harder materials such as steel, copper**,** titanium alloys, etc.

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