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An Overview of Recent Development and Application of Friction Stir Processing Technique

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Abstract: In current scenario, friction stir processing (FSP) is used for the development of surface composite. This process improves the grain refinement, which refines the localize grain size of the material near the stir zone. Owing to grain refinement, tensile strength and hardness of the material are significantly improved. Several studies have been reported related to research work performed by various researchers on FSP in the archival literature. The main emphasis of this study is to evaluate the mechanical properties investigated by the various researchers. This article presents the summary of research work performed on different types of material, reinforcement material used for the development of composite and application of FSP process.

Keywords: Friction stir processing, mechanical properties, matrix material, reinforcement material.

1. Introduction

Nowadays, friction stir processing (FSP) is used to develop the surface composite. From various archival literatures, it was observed that due to the reinforcement of ceramic particles, mechanical properties of the developed composite was significantly improved. The frequently used ceramic particles are B_4C, TiB_2, and Al_2O_3 etc [1-3]. Initially FSP was originated from the friction stir welding (FSW) process. FSP is a solid-state manufacturing process, which had enhanced the tensile strength and hardness of the fabricated material without significant reducing its toughness of the material. The concept of frication stir welding was introduced by Welding Institute (TWI) in 1991 [4-6]. In FSW process, frictional heat is generated between the joining metal sheets due to rotation of the tool, and results the softening of the material. In FSP process, ceramic particles are filled in the grooves made by milling machine. FSP tool is introduced into the edges of plates and moves in the transverse direction. Owing to heat generated by friction, matrix material was softened and mixed with the ceramic particles. In this process, grain size is further refined by strain hardening phenomena. Currently, FSP process is used to developed high strength and light weight material in automotive industries [7-9]. It has an advantage that depth of cut can be controlled through changing the length of tool pin. From archival literature it can be concluded that the reinforcement particle are evenly distributed near the stirred zone[10-12].

The review of microstructural evolution for Al alloys on FSP/FSW was done by Heidarzadeh et al.[13]. The growth of textures, grain structures, phase transformations and phases was observed during the processing or welding of similar or dissimilar alloys. The several mechanical properties of alloy enhanced with FSP were studied by Chaudhary et al. [14]. Butola et al.[15] have reviewed FSP technique to fabricate the composite. Khan et al. [16] have reviewed FSP technique to fabricate the nano composites. Review on FSW focusing on friction based welding processes was done by Kumar et al. [17].

FSP has emerged as most promising process for improvement of metal properties in automotive and aerospace industries. This process provides modification of microstructural, mechanical, tribological, ballistic behavior and other specific properties by thermodynamic processing of selective locations on metal surface.

The novelty of the article lies in fact that very few articles are published that has covered the recent published articles for the duration of seven years. Results, process parameters are given in tabular form will help the industry persons to know the results of various experiments at a glance. Several review articles are available related to FSP process. The main emphasis of this article is to present the methodology adopted by various researchers. The main industrial application of FSP includes the fabrication of surface composite by intermixing of two different materials by plastic deformations such as Al 6061/TiC, Al 7075/Al_2O_3, Al 5083/SiC etc. Refinement of grains or second phase particles of alloys at microstructural level by recrystallization and grain growth had occurred. Significant improvement of YS, UTS, micro hardness, wear resistance the composite was observed. FSP provides solid state processing of surface composite with full control of process parameters in comparison with existing processing techniques which are based on liquid phase processing. Due to limited formability of Al and Mg at room temperature, it is very hard to change body shape according to need but FSP can increase formability of these elements after 200°C which is a major significance of FSP for industrial applications. The next section highlights the state of art related to FSP process.

2. State of art

Several experiments on FSP methodology had been performed earlier to fabricate composite. In this article, different composites fabricated through FSP had been discussed. The parameters used are given in Table 1 with the prominent finding is discussed at the end of article.

Kumar et al.[18] have developed Al 5083/W composite using FSP technique to examine the tensile behavior. EBSD and SEM study shows that tungsten and Al5083 have strong interfacial bonding. Results revealed that due to the reinforcement of tungsten hardness of Al5083 alloy was improved by 55%. Sudhakar et. al. [19] have developed AA 7075/B_4C composite via FSP process to evaluate the hardness properties. The range (30-60 µm) of particle size of B_4C was used for the preparation of surface composite. Due to the reinforcement of B_4C hardness of AA7075 was improved from 90 BHN to 260 BHN.

Yuvaraj et al.[20] have highlighted the impact of number of passes on mechanical properties of the Al 5083/ B_4C composite developed through FSP process. The manufactured surface composite had 60% greater hardness in comparison to Al 5083 alloy. It was also observed that ultimate tensile strength and wear properties significantly improved. Kumar et al. [21] have fabricated Al 7075/SiC composite by frication stir processing to compute the mechanical properties of Al 7075/SiC composite. Results depicted that due to the reinforcement yield strength and tensile strength of Al7075 alloy was enhanced by 30% and 71% respectively. The grain size of stirred zone of the surface composite was refined and resulting improved hardness of the material.

Rajan et. al.[22] have generated AA7075/TiB_2 surface composite through situ reaction of inorganic salts with molten aluminium to examine the wear behavior of the material. The value of wear rate was calculated at a sliding velocity of 1.5m/s with normal force of 25 N and sliding distance of 300 m. Results of SEM analysis proves that particles of TiB_2 were uniformly distributed in the stirred zone. The grain size of the fabricated composite was refined. Zhang et al. [23] have observed the influence of energy input throughout FSP on mechanical characteristics and microstructure of CNTs reinforced composite. During FSP energy input was used in three range low, medium and high. However, feed rate was used in the range of 30 to 50 mm/min. Microstructure observation analyzed that CNTs were effectively amalgamated into the matrix material.

Nazari et al. [24] have elucidated the influence of number of passes on mechanical behavior of AA 6061/Graphene/TiB_2 nano-composite manufactured by FSP process. The hardness AA 6061/Graphene/ TiB_2 nano-composite was improved to 90 HV. S et al.[25] developed AA 7075/$SrCO_3$ composite via FSP. Uniform dispersal of fine fragmented content had improved the micro-hardness of AA 7075/$SrCO_3$ composite by 50 %. It was observed that tensile strength of the surface composite was reduced by 3.2%. Figure 1 illustrates the classification of process variable used for the FSP process.

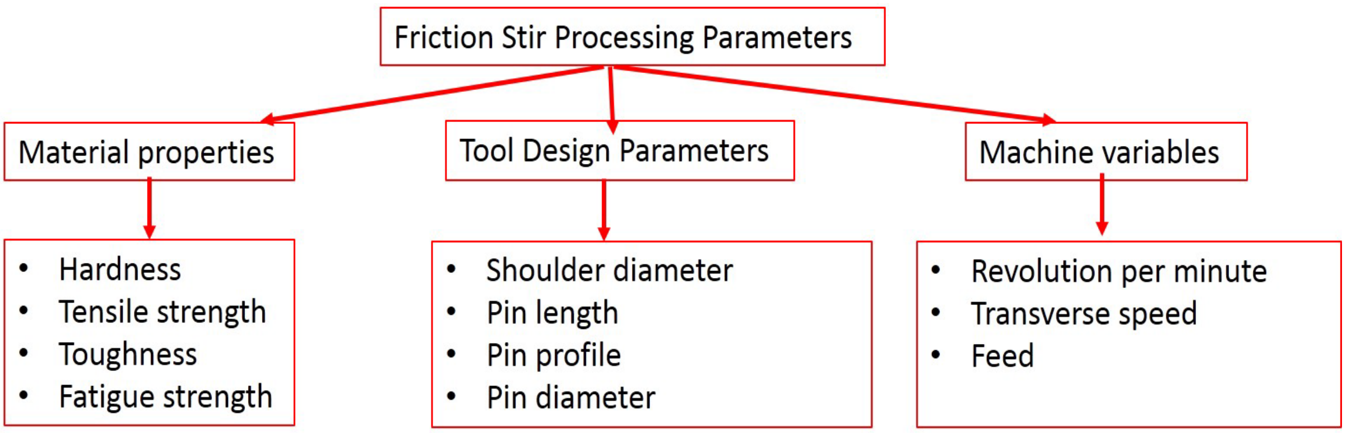

Figure 1. Categorization of FSP process variables.

Deore et al. [26] have evaluated the ageing treatment on mechanical behavior, wear behavior and microstructure of AA 7075/ MWCNTs surface composite prepared via FSP. It was observed that toughness enhanced from 15.8KJ to 27.5KJ. Results revealed that micro-hardness was improved by 76% by reinforcing SiC content. Wear loss was reduced from 8.57 mg to 5.49 mg for AA 7075/ MWCNTs composite. Jain et al. [27] have prepared mono and hybrid composite by FSP reinforcing 98% pure CNTs in Al 5083 alloy. The hardness and tensile strength of Al 5083-SiC/CNTs composite was 112.50-118.12 VHN and 361 MPa. Bourkhani et al.[28] have manufactured AA 1050/Al_2O_3 surface composite via FSP process to observe the mechanical properties and microstructure of composite. Studies revealed that mechanical properties, grain refinement and homogeneity depend on the number of passes run for the fabrication of composite.

Dinaharan et al. [29] have prepared AA 6061/Al_2Cu composite by FSP to investigate the ultimate tensile strength and yield tensile strength of the fabricated composite material. The value of ultimate tensile strength and yield tensile strength were found to be maximum of 280 MPa and 168 MPa respectively. Tang et al.[30] have developed AA 1060/SiC composite through FSP by newly designed multi-pin tool and traditional single pin tool. Uniformity of SiC particle and degree of refinement was improved by using multi-pin tool, in comparison to single pin tool. Single pin tool had reduced the friction coefficient and wear rate of AA 1060/SiC composite and enhanced the micro-hardness.

Abraham et al. [31] have prepared AA 6063/V surface composite through FSP process to investigate the micro-structural characteristics. V content had enhanced the tensile strength with reduced ductility of composite. It was observed that dispersion of V content was homogeneous in the stirred zone. Khorrami et al. [32] have observed the mechanical behavior, i.e. FSP. UTS, YS and hardness of Al 1050/ SiC surface composite. The value of ultimate tensile strength, yield strength and hardness was found to be 95 MPa, 65 MPa and 45 HV respectively.

Pol et al.[33] have fabricate the 7005/TiB_2-B_4C hybrid composite to observed the ballistic properties of the material. The value of hardness was found to be 70 HV. Fotoohi et al. [34] have developed Al-Al3Ni/TiC surface composite through FSP process to evaluate the mechanical behavior. The value of micro-hardness and tensile strength were found to be 70HV and 179 MPa respectively. Mehta et al. [35] have investigated the wear behavior of Al 6061 /B_4C composite produced through FSP. 72.15% less wear as compared to base alloy was found in prepared composite. The micro-hardness of Al 6061 /B4C composite was improved to be 85-88Hv, greater in comparison to Al 6061 alloy, possessing 40-50Hv.

Jalilvand et al. [36] have prepared A356/ Al_2O_3/ SiO_2 composite through FSP to observe the mechanical characteristics. The maximum hardness of A356/ Al_2O_3/ SiO_2 composite was enhanced to 110HV, as compared to base alloy having, 70HV. The influence of FSP on corrosion behavior, microstructure and wear of Al6061/SiO2 surface composite by Barati et al.[37]. Abraham et al. [38] have developed AA 6063/ SiO_2 composite via FSP to study the mechanical behavior of the composite. Experimental result revealed that the micro-hardness was improved to 135 Hv at 18 vol. % of quartz particles with reduced wear rate of 258×10^{-5} mm^3/m at 18 vol. % of quartz particles.

Rana et al. [39] have observed the mechanical properties of Al7075/ B_4C composite fabricated via FSP. Test result concluded that average hardness of composite was 75 to 88 Hv. Arora et al. [40] have investigated the fabrication of Al/Mo composite through FSP. Mo particles were fully dispersed in Al matrix with the improvement in mechanical properties. Rathee et al. [41] have elucidated the process parameter optimization of AA6061/SiC surface composite fabricated through FSP. Investigations concluded that maximum hardness of composite in the nugget zone was higher, 116 Hv in comparison to AA 6061 alloy, having 94 Hv. Figure 2 shows the schematic layout of FSP process.

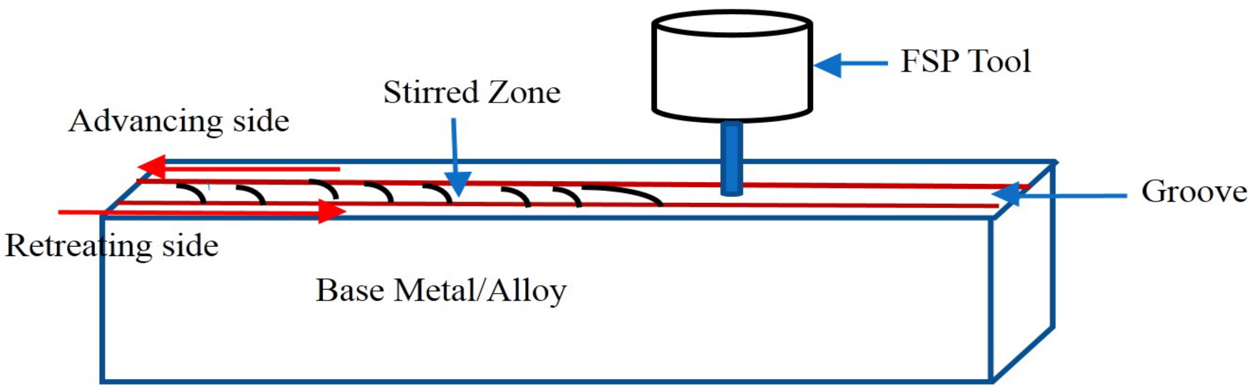

Figure 2. Schematic layout of FSP process

Thangarasu et al. [42] have developed AA 6082/ TiC composite by FSP method to observe mechanical properties. Micro hardness, UTS and wear rate of AA 6082/ TiC composite was found to be 149 Hv, 382 MPa and 303×10^{-5} mm^3/m by reinforcing 24 vol. % of TiC content. Zangabad et al. [43] have explained the evaluation of microstructure and fatigue properties of Al 5052/Al3Ti-MgO hybrid nano composite fabricated through FSP. Investigation results revealed that YS and UTS of composite after FSP were significantly enhanced.

Manochehrain et al.[44] have investigated the fabrication of nano layered Ti_3AlC_2 max phase and A356 alloy via FSP. Test result revealed that micro hardness and tensile strength of composite was improved to 87 Hv and 184 MPa, as compared to A356 alloy having, 68 Hv and 112 MPa. Kishan et al. [45] have elucidated the tribological and mechanical properties of Al6061/TiB_2 surface composite through FSP. Test result concluded that with the reinforcement of 35 nm sized TiB_2 particle in Al 6061 matrix, the micro hardness of composite was enhanced to 130 Hv, in comparison as compared to Al 6061 alloy, having 104 Hv. High wear resistance was found for Al 6061/4 vol. % TiB_2 composite.

Huang et al. [46] have developed Al5083/Ti composite through FSP to study the mechanical properties. A dynamic recrystallization was responsible for the ultra-fine grain formation in the stirred zone. Experiment concluded that YS and UTS of composite after FSP was improved to 78 MPa and 153 MPa. Sharma et al. [47] have investigated the effect of multiple channel reinforcement filling strategy in the fabrication of Al 6061/GNP surface composite through FSP. Result concluded that UTS and hardness of the composite was increased by 28 and 84 %. Prabhakar et al. [48] have described the mechanical and corrosion properties of Al 5083/CNT composite prepared by FSP. Test concluded that dispersion of CNT in stir zone was not uniform and micro-hardness of composite was found to be increased by 25 % as compared to base alloy Al 5083.

Yang et al. [49] have performed FSP in the fabrication of cold sprayed AA 2024/Al_2O_3 and analyzed the microstructural and mechanical properties. Nano indentation test result revealed that hardness and elastic modulus of cold sprayed AA 2024 particle was decreased before FSP. After FSP the UTS and elongation of composite was improved by 25.9% and 27.4%. Hosseinzadeh et al. [50] have explained the high temperature characteristics and microstructural evaluation of Al2024/SiC composite through FSP. Experimental result concluded that hardness and YS of Al2024/SiC composite was improved by 50 and 240% with the reduction of ductility by 4%. Butola et al. [51] fabricated AA 7075/ B4C composite via FSP to evaluate the mechanical properties. Optimum results were obtained at tool rotational and traverse speed of 800 rpm and 60 mm min^{-1}. Optimization of FSP parameters for AA 7075/ B4C composite using Taguchi and GRA was also done by Butola et al. [52]. Salahan et al. [53] performed FSW on AA7075 alloy and compared the experimental results with ANN. Experimental results were validated with ANN. Butola et al.[54] compared RSM with ANN to predict tensile characteristic of FSPed composite. ANN results revealed better predictive capacity in comparison to RSM. Bector et al.[55] fabricated AA 6063/ B4C composite via multi pass FSP. Specimen having three number of passes showed best results. Bector et al. [56] evaluated the hardness of AA 6061/Al2O3 composite via ANN. ANN results were close to experimental results. Optimization of process parameters for Al/SiC/aloevera composite was performed by Butola et al. [57]. Sahdeo et al. [58] performed FSP on 5053 alloy and evaluated the influence of process parameters using ANSYS.

Akshay et al. [59] have observed the mechanical behavior of Al 6061/BN surface composite prepared via FSP. Mechanical properties of composite were significantly increased. Khan et al.[60] have investigated the effect of inter-cavity spacing in the fabrication of Al5083/B_4C/CNTs surface nano composite through FSP. For analysis of metal loss in cavity, single pass approach was adopted. Result revealed that tensile strength and hardness of composites containing B4C particles at 10 mm spacing was improved by 41% and 20% .

Zhang et al. [61] have observed the microstructural and mechanical evaluation of Al 6061/ ZrB_2 nano composite through FSP. Result concluded that ZrB_2 nanoparticles where successfully fabricated by 4-pass FSP of in situ nano composite. The yield strength of nano composite was found to be 138-153 MPa. Cao et al. [62] have investigated the tribological and mechanical behavior of in situ carbon fiber AA 5052/ Al4C3 composite via FSP. Experimental results revealed that carbon fiber was homogeneously dispersed in large volume, where no layer was detected. Hardness, UTS and elongation of composite was increased by 46.8%, 18.6% and 13% respectively while wear volume loss was reduced by 70%. Kumar et al. [63] have elucidated the mechanical and corrosion behavior of Al7075/TiC surface composite fabricated through FSP. Experimental results concluded that grain size of the composite was reduced with improved mechanical properties.

3. Summary and discussion

Development of composite through FSP is an interesting area of research in the last two decay. Several studies related to influence of various process variables on mechanical and surface properties have been reported. From the archival literature it can be concluded that FSP process parameters have significant influence on mechanical properties and surface properties of the developed composite through FSP process. These studies summarize the tools dimension, matrix material, reinforcement material and process parameters used by researcher. Table 1 & 2 gives the description of various composite prepared through FSP process. Figure 3 shows the microstructure of stirred zone and thermo mechanical affected zone where B_4C particles are uniformly distributed in the Al 6063 alloy. Figure 4 shows the summary of recent trend of research work performed by researchers related to FSP process. However, this graph was plotted based on the sample size used in this research article only. It indicates that the interest of researchers is increasing very rapidly in this area due to low fabrication cost and environment friendly. Figure 5 shows the summary of reported work of different aluminium used in this research article. It shows that percentage of research work performed was maximum on Al6061 alloy due to low cost and better machinability. Pure Al6061 alloy is less in used due to low tensile strength and poor hardness properties. However, due to reinforcement of ceramic particle its mechanical properties significantly improved and suitable of the automatable and aerospace industries for light weight and high strength material. Figure 6 demonstrates the summary of reported work of different reinforcements used by the researchers for the development of surface composite through FSP process. It can be concluded that most of the research work were performed by using SiC, Al_2O_3, TiB_2, TiC, B_4C and CNTs. However, very less work have been reported on related to other ceramic particles like reinforcement of MgO, W, V and Gr etc. By the use of these reinforcements in aluminum alloy, new mechanical and tribological properties can be evaluated in future work.

Table 1**:** Summary of tool dimension and process parameters used by various researchers

Composites	**Tool Used**	**Tool Dimension**	**Groove Dimension**	**Process Parameters**	**Remark**	**Reference**
Al5083/ Al-W	Hardened steel tool	Pin dia-3.5mm, Pin length-4mm Shoulder-15mm	Depth-2mm Width-1.5mm Length-60mm	Tool rotational speed-1200rpm Tool Transverse speed-24mm/min	Good interfacial bonding between alloy and reinforcement.	18)
AA7075/B_4C	Flat steel tool with pin	Pin dia-7.62mm. Pin length-98mm		Tool rotational speed-750 -1200 rpm. Longitudinal feed rate-30 50mm/min.	Hardness = 260 BHN	19)
Al5083/B_4C	H-13 hardened steel tool	Pin dia-M6*1.0. Pin length-5mm. Shoulder-18mm	Depth-3mm Width-1mm	Tool rotational speed-1000 rpm. Tool Transverse speed-25mm/min.	Hardness was improved by 60%.	20)
Al7075/SiC	Specially designed tool	Pin dia-6mm. Pin length-4mm. Shoulder dia-25mm	Length-60mm Width-45mm Depth-6mm	Tool rotational speed-720 to 1025rpm. Tool Transverse speed-25 to 100mm/min.	Yield strength was improved by 60%.	21)
AA7075/TiB_2	HCHCr steel tool	Pin dia-6mm. Pin length-5.8mm. Shoulder dia-18mm.	Length-100mm. Width-50mm. Depth-8mm.	Tool rotational speed-1200rpm. Tool Transverse speed-50mm/min.	Reduction in wear rate was found.	22)
Al1060/CNT	Steel tool with pin	Pin dia-4mm. Pin length-5mm.	Length-150mm. Width-100mm.	Tool rotational speed-1500rpm. Tool Transverse speed-25-100mm/ min.	Uniform dispersal of CNT was observed.	23)

AA 6061/TiB_2	Hardened steel tool	Pin dia-6mm. Pin length-3mm. Shoulder dia-18mm.	Length-100mm. Width-50mm.	Tool rotational speed-1000rpm. Tool Transverse speed- 340 mm/min.	Hardness = 90 HV	24)
AA 7075/$SrCO_3$	Steel tool with pin.	Pin dia-6mm. Pin length-5mm. Shoulder dia-18mm.	Length-130mm. Width-4mm. Depth-4mm.	Tool rotation speed-1200 rpm. Tool Transverse speed- 20mm/min.	Tensile strength was reduced by 3.2%.	25)
AA 7075 /SiC	W-1% La2O tool.	Pin length-3mm. Shoulder dia-20mm.	Cylindrical hole; Dia-2mm. Depth-3mm.	Tool rotational speed-800rpm. Tool Transverse speed- 60mm/min	Toughness 2705 KJ	26)
Al 5083/CNTs/SiC	Hardened steel tool.	Pin length-150mm. Width-80mm. Depth-6mm.	Width-1mm. Depth-2.5mm.	Tool rotation speed-1600 rpm. Tool Transverse speed- 20 mm/min.	Hardness = 112 VHN Tensile strength = 3610 MPa	27)
AA 1050/Al_2O_3	Hardened steel tool.	Pin dia-6mm. Pin depth-5mm. Shoulder-20mm.	Width-1mm. Depth-3mm.	Tool rotation speed-1180 rpm. Tool Transverse speed-80 mm/min.	Uniform dispersal of the reinforcement.	28)
AA 6061/Al_2Cu	TSL- OIM software	Pin length-40mm. Pin width-7mm. Pin deth-6mm.			UTS = 280 MPa YTS = 168 MPa	29)
AA 1060/SiC	Hardened steel tool with pin and shoulder	Pin dia-6mm. Shoulder dia-22mm.		Tool rotational speed-950rpm. Tool transverse speed- 40mm/min	Single pin tool had reduced friction coefficient.	30)
AA 6063/V	Hardened steel tool.	Pin length-30mm. Pin width-4mm. Pin depth-4mm.	Length-1.2mm. Width-505mm. Depth-100mm.		Tensile strength was enhanced.	31)
Al 1050/SiC	Hardened steel tool	Pin dia-3mm. Pin depth-2.1mm Shoulder dia-12mm.	Length-1mm. Width-2mm.	Tool rotation speed-1200rpm. Tool Transverse speed-50mm/min.	UTS = 95 MPa YS = 65 MPa Hardness = 65 Hv	32)
AA 7005TiB_2-B_4C	Hardened steel tool	Pin length-4mm. Pin dia-6mm. Shoulder		Tool rotational speed-750rpm. Tool Transverse speed-50mm/min.	Hardness = 70 Hv	33)

		dia-18mm.				
AA1050/ Al_3Ni/TiC	Hardened steel tool	Shoulder dia-18mm. Cylindrical pin dia-6mm. Cylindrical pin length-5mm.	Hole dia-2mm. Hole depth-3mm. Intervals between two holes-1mm.	Tool rotational speed-1400rpm. Tool Transverse speed-40mm/min.	Hardness = 70 Hv Tensile strength = 179 MPa	34)
Al 6061/B_4C	Tungsten carbide	Cylindrical pin dia-6mm. Cylindrical pin length-6mm.	Length of slot-2mm. Width of slot-2mm.	Tool rotational speed-545rpm. Tool Transverse speed-50mm/min.	Hardness = 85-88 Hv	35)
AA 356/Al_2O_3+SiO2	Hardened steel tool	Shoulder dia-16mm. Pin dia-4mm. Shoulder length-60mm. Pin length-4mm.		Tool rotational speed-500-1500rpm. Tool Transverse speed-56-112mm/min	Hardness = 110 Hv	36)
Al6061/Al_2O_3/SiO_2	M2 steel	Pin dia-6mm Pin length-5.8mm Shoulder 18mm	Depth-2mm Width-1mm	Tool rotational speed -1150rpm Transverse speed=31.5mm/min	Fine grain structure was formed.	37)
AA 6063/TiC/	HCHCr steel tool	Pin dia- 6mm Pin length-5.8mm Shoulder =18 mm	Depth-5.5mm Width-1.2mm	Tool rotational speed -1600rpm Transverse speed=60mm/min	Hardness = 135 Hv	38)
Al 7075/TiB_2	M2 steel		Depth-2.5mm With-1.21mm Length-100mm	Tool rotational speed 545 rpm Transverse speed-50mm/min	Hardness = 88 Hv	39)
Al-Mo	High speed steel	Pin dia- 6mm. Pin length 2.5mm, Shoulder-20mm	Depth-0.5mm Width-2mm	Tool rotational speed -840rpm Transverse speed=40mm/min	Uniform dispersal of Mo content.	40)
AA 6061/SiC	H-13 steel	Pin dia 6mm, Pin length-2.5mm, Shoulder-20mm ,	Depth-2mm Width-2mm	Tool rotational speed –rpm Transverse speed=mm/min	Hardness = 116 Hv	41)
AA 6082/TiC	HCHCr steel tool	Pin dia 6mm, Pin length-5.5mm, Shoulder18mm,	Depth-5mm Width-1.6mm	Tool rotational speed -1200rpm Transverse speed=60mm/min	Hardness = 149 Hv Tensile strength = 382 MPa	42)
AA 5052/Al-MgO/	H13 steel tool	Pin dia 12mm,	Depth-5mm	Tool rotational speed -1200rpm	YS and UTS was improved.	43)

Al_3Ti			Width-1.2mm	Transverse speed=100mm/min		
A 356/Ti_3AlC_2	H13 steel tool	Pin-dia 3.6mm Pin length-4mm Shoulder-18mm	Depth-3mm Width-1mm	Tool rotational speed -1000rpm Transverse speed=112mm/min	Hardness = 87 Hv Tensile strength = 114 MPa	44)
AA 6061/TiB_2				Tool rotational speed -1120rpm Transverse speed=40mm/min	Hardness = 130 Hv	45)
AA 5083/Ti	Hardened Steel tool	Pin-dia 5mm Pin length 4mm Shoulder 18mm	Hole Depth- 4mm Hole dia-1.5mm	Tool rotational speed -1400rpm Transverse speed=40mm/min	YS = 78 MPa UTS= 153 MPa	46)
Al 6061/GNP	Steel tool	Pin-diameter 6mm Pin Hight 4mm Shoulder 24mm	Width 0.65-1.95mm Depth 3mm Length 120mm	Tool rotational speed -1400rpm Transverse speed=40mm/min	UTS and hardness was improved.	47)
AA 5083/CNTs	Pinless steel tool		Depth- 2mm Width-1mm	Tool rotational speed -1800rpm Transverse speed=25mm/min	Hardness was improved by 25 %.	48)
AA 2024/Al_2O_3	H13 Steel tool	Pin-dia = 3 mm Pin length= 2.9mm Shoulder =10mm	Length-150mm Width-100mm	Tool rotational speed -1500rpm Transverse speed=100mm/min	UTS and elongation was enhanced by 25.9% and 27.4 %.	49)
AA 2024/SiC	Hardened steel tool	Pin-height-5mm Pin length 2.65mm Shoulder14mm		Tool rotational speed -1600rpm Transverse speed=40mm/min	Hardness was improved by 50%.	50)
Al 6061/BN	RV machine tool	Shoulder dia-25mm Probe dia-12mm	Length-150mm Width-150mm Thickness-8mm		Improvement in mechanical properties.	59)
Al 5083/B_4C				Tool rotational speed -750 rpm Transverse speed=16 mm/min	TS and hardness was enhanced by 41 % and 20 %.	60)
Al 6061/ZrB_2	H13 steel tool	Pin shoulder -15mm Root-5.5mm	Length-180mm Width-100mm Thickness-7mm	Tool rotational speed -1200 rpm Transverse speed=50mm/min	Yield strength = 138-153 MPa	61)

AA 5052/Carbon fiber	Hardened steel tool	Shoulder dia-20mm Probe dia-7.5mm	Length-300mm Width-15mm Thickness-1mm	Tool rotational speed -1000rpm Transverse speed=100mm/min	UTS and hardness was enhanced by 18.6 % and 46.8 %.	62)
Al 7075/TiC	H13 steel tool	Pin dia larger end 8mm , Pin dia small end 6mm Shoulder 24mm	Depth-3.4mm Width-0.5-1.5mm	Tool rotational speed -1200rpm Transverse speed=30mm/min	Improvement in mechanical properties was found.	63)

Table No. 2 Summary of results achieved by the various researcher.

Author Name	**Alloy**	**Reinforcement**	**Properties investigated with results**		**Reference**
Arab et al.	Al 1100	S glass, E glass and high strength Carbon	Mechanical Characteristics	Hardness = 49 VHN	64)
Zhao et al.	Al 1060	AZ31B	Mechanical properties	Failure load of 9.25 KN was observed.	65)
Azizieh et al.	AA 1100	Al_2Cu	Mechanical Characteristics	Improvement in mechanical property was found.	66)
Sharma et al.	AA 2014	SiC	Mechanical characteristics	Hardness =150 Hv.	67)
Mohamadigan-graj et al.	A 390	SiC	Mechanical characteristics	Hardness = 155 Hv	68)
Vijayavel et al.	LM 25	SiC	Effect of tool velocity	Influence on mechanical property.	69)
Kurtyka et al.	A339	SiC	Mechanical characteristics	Compressive strength was improved by 40 %.	70)
Golmohamma-di et al.	A413	Ti	Mechanical characteristics	Hardness = 85 Hv	71)
Prasad et al.	A 356	Flyash + Red mud	Mechanical Properties	Improve in hardness, UTS	72)
Bauri et al.	Al 5083	Ni	Hardness and Tensile Strength	Hardness = 91 Hv	73)
Kumar et al.	Al 5083	Ni	Influence of particle size on the microstructure	Grain size was reduced.	74)
Rao et al.	Al	TiB2	Characterization	Uniform distribution	75)
Huang and Shen	Al 5083	Ti	Micro structural and mechanical characteristics	YS= 263 MPa	76)
Sahareinejad et al.	Al 5059	Al_2O_3, SiC, B_4C	Comparison of Al2O3, SiC and B4C reinforced particles	Al 5059/B4C composite had tensile strength.	77)
Kishan and Devraju	AA 6061	TiB2	Mechanical properties	Hardness = 132 Hv	78)
Du et al.	Al 6061	Al_2O_3/CNT	Mechanical characteristics	Hardness = 263+3 MPa	79)

Daneshifar et al.	Al	Si/Mg_2Si	Mechanical properties	Hardness was improved by 15%.	80)
Ni et al.	Al 6061	NiTi	Mechanical properties	Damping coefficient = 23.6x10-3K-1.	81)
Bharti et al.	Al 5052	ZrO_2	Micro-hardness	Improvement in micro hardness.	82)
Dinaharan et al.	AA 6062	TiC/ Al_2O_3/TiC/	Mechanical and wear properties	Hardness = 115 HV.	83)
Selvakumar et al.	AA 6082	Mo	Mechanical characteristics	Tensile strength =305 MPa.	84)
Selvakumar et al.	AA 6082	Stainless Steel	Mechanical properties	Tensile strength = 293 MPa.	85)
Srivastava et al.	A 359	Si3N4	Mechanical and wear characteristics	Hardness = 125 HRB	86)
Kumar et al.	Al	Bagasse and graphite	Mechanical characteristics	Improved mechanical properties	87)
Marini et al.	AA 6061	RHA	Wear characteristics	Wear =0.97 × 10^3 mm^3/Nm.	88)
Kumar et al.	Al 6063	B_4C	Mechanical characteristics	Micro hardness was improved by 30%	89)
Srivastava et al.	A359	Si_3N_4	Microstructure and fractography	Tensile strength = 479 MPa Hardness = 119 HRB	90)

Kumar et al. [89] have fabricated Al 6063/B_4C surface composite via FSP. Microstructural results revealed microstructural uniform dispersal of B_4C content in the surface and tend to improve the micro hardness of the fabricated composite. Figure 3 shows the microstructure of stirred zone and thermo mechanical affected zone where B_4C particles are uniformly distributed in the Al 6063 alloy.

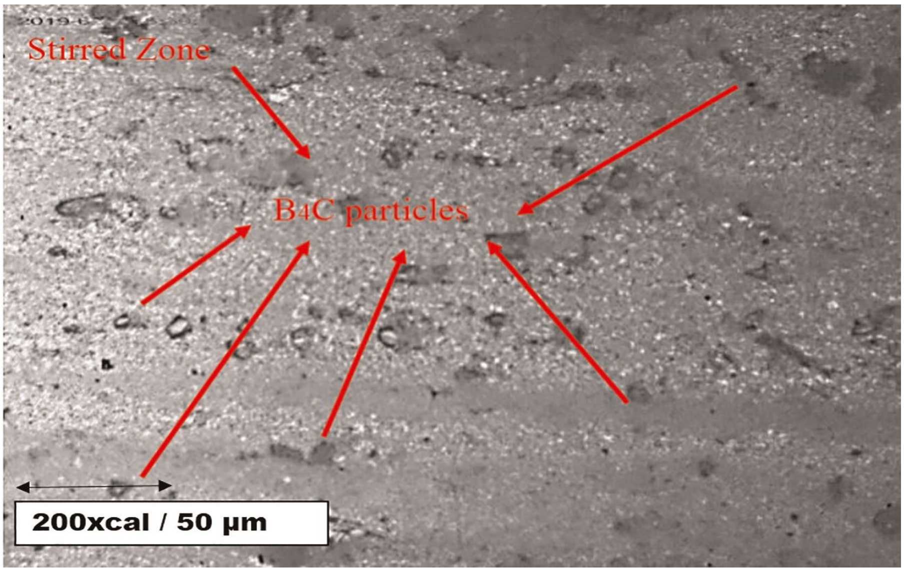

Figure 3. Microstructure of the stirred zone of the prepared composite[89]

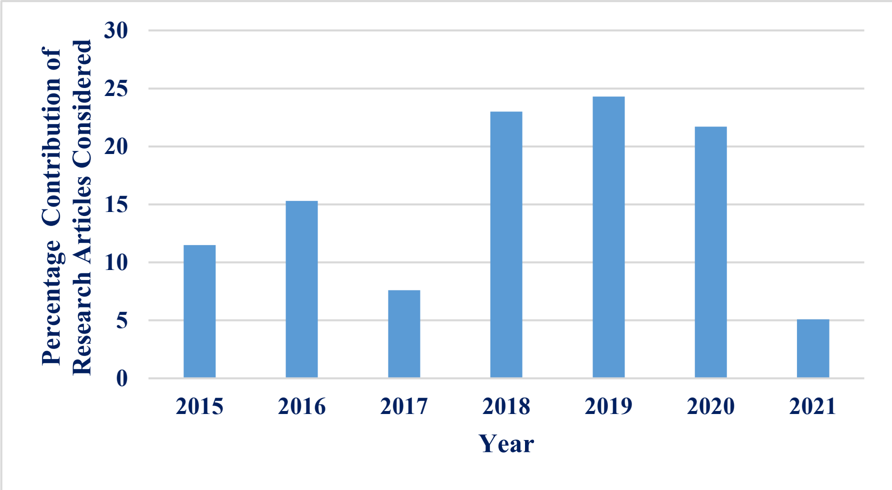

Figure 4. Year wise contribution of reported work in this review article.

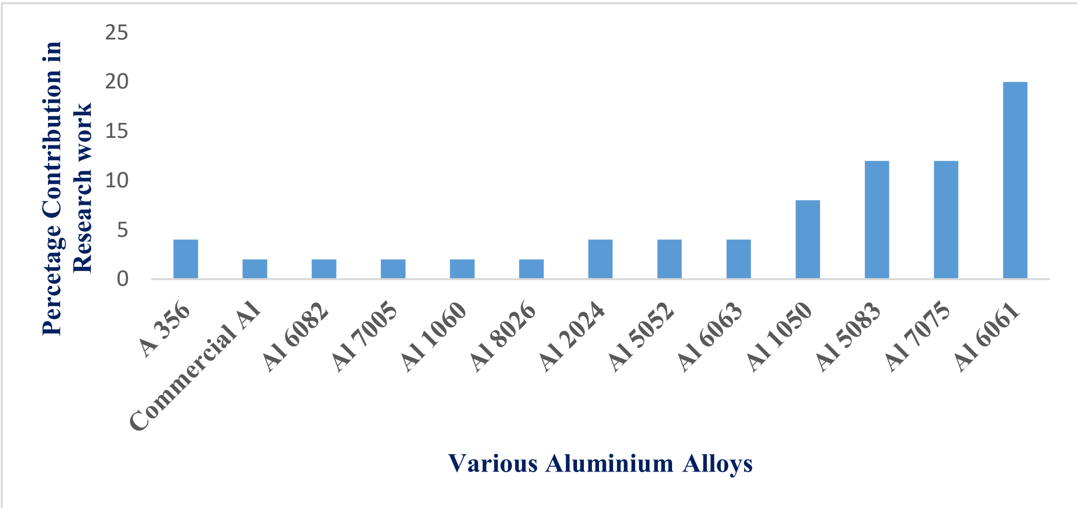

Figure 5. Percentage contribution of aluminum alloys in this review article.

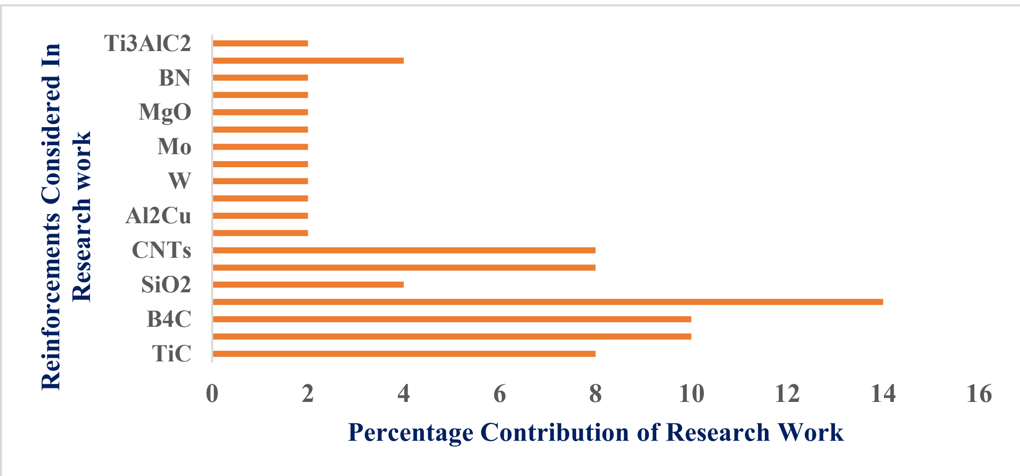

Figure 6. Percentage contribution of reinforcements in this review article.

4. Research gap

In spite of all the advantages over fusion-based techniques like stir casting, FSP has several challenges to overwhelmed before its vast application. Agglomeration, porosity, scattering of reinforcement is a severe problem. Through FSP, ductility along with tensile strength can be simultaneously improved. However, on changing certain process parameters, more improvement in mechanical properties can be observed with the mixing of two or more reinforcements.

5. Future scope

Through the literature survey, it can be concluded that FSP was a successful technique to fabricate the composite. However an effort may be placed to use Friction stir based additive manufacturing technique, a new novel method and an advancement of FSP technique to fabricate a composite up-to certain layers. The mechanical properties can be observed by manufacturing the composite with two FSP and friction stir additive manufacturing technique. The difference in their microstructural and mechanical properties can be evaluated.

6. Conclusion

Throughout friction stir processing, thermal exposure along with intense plastic deformation generates refinement of matrix grains, the disintegration of closure of porosity, the dissolution of precipitates and coarse dendrites. This develops to form a defect free composite material. The successful application of FSP in producing the composite with fine-grained structure had enabled it to be used in automotive sectors. FSP is environment friendly, versatile and energy efficient methodology to fabricate magnesium/aluminium metal matrix composite. More investigation efforts along with the understanding of the FSP method can improve the number of applications. By altering the tool design and process parameters, more significance results of FSP methodology can be obtained. Friction stir processing technique has enabled to improve the ductility and grain refinement without heat treatment process. Mechanical stability, process parameters, fabrication cost and tool wear are the key aspects which must be considered before preparation of the composite.

Declaration of conflicting interest

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