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REVIEW ARTICLE

A critical review of recent progress in the fabrication of composite material via friction stir processing

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Abstract

A fast-developing novel solid-state technology for composites manufacturing is friction stir processing (FSP). It involves surface modification, which allows for successful surface property adaptation via solid-state plastic deformations. When FSP started, it was mostly used to make metal matrix composites from light metal alloys like aluminium. Manufacturing composites made from various nonferrous and ferrous metal alloys and polymers has recently given it a more attractive role. FSP has been a ground-breaking method for creating functionally graded systems/surfaces (FGS) of a metal matrix in addition to composite manufacturing. The entire FSP process, in which reinforcement particles are incorporated into the base matrix to create composites and FGS, is covered in this article. It provides a comprehensive evaluation of recent breakthroughs in the fabrication of FGS and the effects of various types of reinforcing particles on composites' properties. Several pressing problems, difficulties, and upcoming tasks are methodically addressed.

1. Introduction

Composites are a particular category of engineering materials that are created by combining two or more unique engineering components with the proper processing method. At the interface borders, there is a distinct separation between the components. Base matrix and reinforcing particles are the two different types of component materials [1-4]. Base matrices can take many forms, such as metals, polymers, or ceramics. These three categories of reinforcement are also possible. Materials created for functional uses are classified as functionally graded systems (FGS) [5, 6]. Fractional volume, orientation, density, material shape, and size are a few examples of the diverse FGS properties that result in these systems' customized operation. With the funding assistance of the National Aeronautics and Space Administration (NASA), Wayne Thomas created the relatively new joining technique known as friction stir welding (FSW) in 1991 [7]. The initial goal of this procedure was to lighten orbital spacecraft, and the work was only done with aluminium alloys [8-10]. Over time, though, the use of friction stir welding expanded, and tool materials also changed. Lead, nickel alloys, zinc, stainless steel, mild steel, titanium, and copper and their alloys are among the materials utilised for welding by this method [11-14]. In contrast to conventional metallic materials, composite materials with a metallic matrix are greatly desired [15]. The composite materials are stronger and lighter in weight. By dispersing micro- or nano-sized reinforcement particles (RPs) in a base matrix using a variety of processes [16], such as lasers, electron beam irradiation, spray deposition, injection moulding, powder metallurgy, diffusion bonding, etc., composites are traditionally made. Almost all standard techniques involve fabricating composite materials in a liquid state at a high temperature, creating unfavourable phases

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between the substrate and reinforcement and intermetallic interactions. Energy from the core production processes is also wasted during value additions when melting. These flaws make it necessary to fabricate composites and adjust surface properties, both of which can be done at temperatures below the melting points of the base matrix [17, 18]. Its goal should be to improve and optimize composites and FGS manufacturing and design processes. In addition to being extraordinarily practical and using no filler material, friction stir welding is also environmentally benign [19, 20]. Since the interface reduces the development of brittle compounds, this technique can enhance the mechanical qualities of the joint, such as strength. Friction and plastic deformation between non-consumable tools and work parts result in localized heating [21, 22]. Heat and friction are created by the relative motion of the tool and the work. Using plastic atomic diffusion, this heat is exploited to combine various materials. About 80% of the material's melting point to be welded is reached by the heat generated [23-27]. The friction stir welding technique transforms mechanical energy into thermal energy without using heat from any external sources to create the weld. The groove technique entails cutting a groove on the plate surface with specific dimensions [28]. The RPs are then stuffed into the groove and squeezed there. The pinless tool is used to seal the groove hole after packing RPs. After that, FSP is carried out using a unique tool with a pin. Fig. 1 depicts the common procedures used in the groove approach. However, by covering the groove mouth with a thin piece of tape, the degree of sealing the groove mouth can be prevented [29-32].

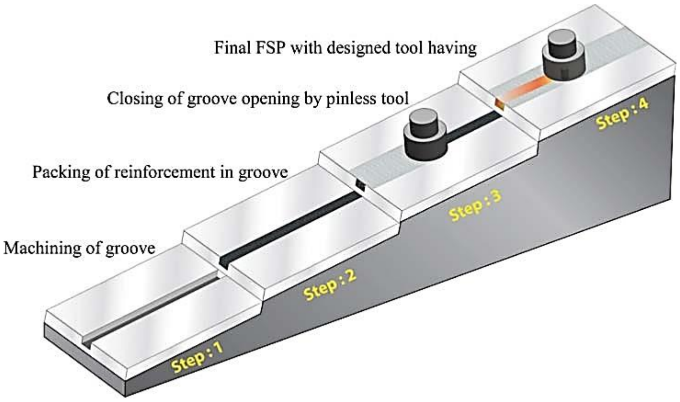

Figure 1. Steps in SCs fabrication using groove technique [33].

The process of fabricating composites using FSP can be summed up as follows. Due to the heat of friction created by the rotating tool and work material during FSP [34], the material of the workpiece softens and turns plastic. The heated tool's stirring motion blends the RPs and BM. Material is forged beneath the shoulder as the spinning tool travels, producing a processed zone [35]. The production of composites is thus finished. This process results in a significant reduction in grain size (Fig. 2), primarily due to the interaction between plastic deformation, DRX, and the pinning effect of RPs [36, 37]. Fig. 3a shows a microscopic picture of an Al5083 alloy BM with 21 mm-long grains that were reduced to 6.31 mm following a straightforward FSP without using RPs (see Figure 3b). Adding CNTs caused the grain size to be further lowered to 3.98 mm (see Figure 3c) [38].

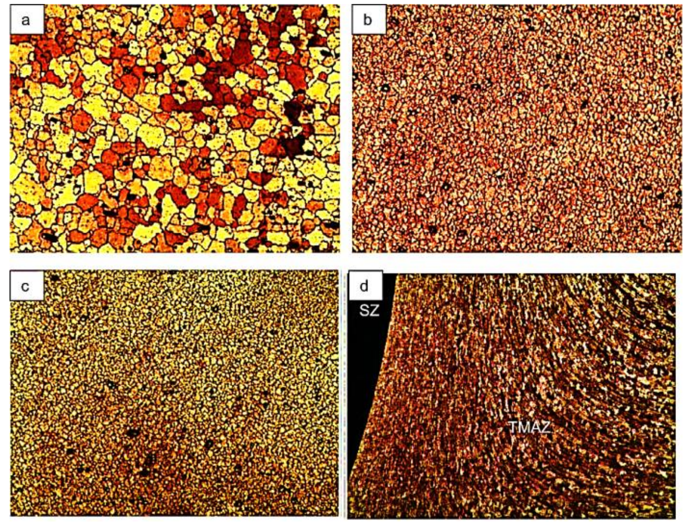

Figure 2: Microscopic images showing grain sizes of: (a) base material; (b) after FSP without RPs; (c) after FSP with CNTs as RPs); and (d) interface of composite with upward flow pattern [38].

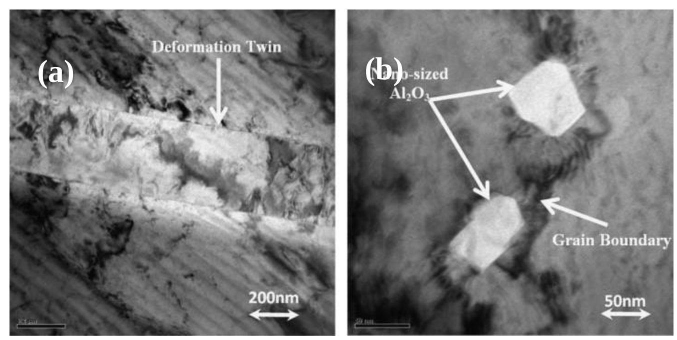

Figure 3: TEM microstructure of Ti/Al_2O_3, (a) deformation twin in the Ti-20n-0.8 sample, (b) pinning of grain boundary by two nanoparticles [39].

The increase in tensile strength of surface composite and related factors are explored here in terms of individual qualities. It is a well-known fact that FSP refines granular size during composite production through recrystallization and the pinning effect. The pinning effect is a phenomenon in which RPs limit grain development upon recrystallization (see Fig. 3) [39]. Smaller-sized RPs prevent grain boundaries (GBs) from moving if resting on them. If the particles are inside the grains, these small-sized RPs also limit the dislocation movement, improving strength. The white particles in the illustration are SiC particles, and the black lines are GBs. During tensile testing, dislocations migrate toward grain interiors with rising tensile stresses. RPs may limit the slide. Higher stresses are required to facilitate material deformation because dislocation lines create a loop around RPs, increasing the dislocation density [40-43].

Table 1: Effect of process parameters on mechanical properties of FSWed joints

Ref.	Title of paper	Author	Input parameters	Finding
[44]	Self-optimization in tool wear for friction-stir welding of Al 6061_/20% Al_2O_3 MMC	Prado, R.A., et al (2003)	welding speed , tool shape	Result shows that tool wear decreases on increasing welding speed
[45]	CDRX modelling in friction stir welding of aluminium alloys	Fratini,L., Buffa,G. (2005)	Tool rotational speed and traverse speed	A linear regression based an inverse identification approach was used in order to develop the proper material characterization.
[46]	Fracture and mechanical properties of friction stir spot welds in 6063-T6 aluminum alloy	Jonckheere, C.,et al. (2012)	tool pin diameter, plunge rate	A hooking effect at the tip of the natural notch existing in spot welds, as well as joint line remnants distributed along the thermomechanical affected zone and through the weld, was observed on non-broken samples
[47]	Friction stir welding characteristics of 2219-T6 aluminum alloy assisted by external non-rotational shoulder	Liu, H. J., Li,J.Q., (2012)	Non-rotational shoulder dia., welding speed	Microstructures and Vickers hardness distributions showed that this new welding process is beneficial to improving the asymmetry and inhomogeneity, especially in the weld nugget zone. The maximum tensile strength was up to 69 % of the base material.
[48]	Influence of shoulder geometry on microstructure and mechanical properties of friction stir welded 6082 aluminium alloy	Scialpi,A., et al. (2007)	Shoulder geometries	The investigation results showed that, for thin sheets, the best joint has been welded by a shoulder with fillet and cavity.
[49]	An experimental investigation on friction stir welding of AZ31B magnesium alloy	Padmanaban (2011)	tool rotational speed, welding speed, and axial force	Joints fabricated using a tool rotational speed of 1,600 rpm, a welding speed of 0.67 mm/s, and an axial force of 3 kN yielded superior tensile properties compared to other joints. Fatigue properties less than base metal.
[50]	3D modeling of material flow in friction stir welding under different process parameters.	Zhang, H.W. et al. (2007)	tool rotation speed , welding speed and axial force	It seems that there is a quasi-linear relation between the change of the axial load on the shoulder and the variation of the equivalent plastic strain. The material flow can be accelerated with the increase of the translational velocity and the angular velocity of the pin.
[51]	Defects formation procedure and mathematic model for defect free friction stir welding of magnesium alloy	Zhang, H., et al (2006)	welding speed and welding rate	The pore firstly occurred near the welding line at relatively low welding speed, but move into advancing side and up part of the weld when continues to increase the welding speed. Faster the welding speed is, larger the pore is.
[52]	An Experimental Study On The Effect Of Welding Parameters On Mechanical And Microstructural Properties Of Aa 6082 FSWed Butt Joints.	Raghu Babu,G., et al. (2008)	tool rotational speed, welding speed, and axial force	The tensile strength of the joint is lower than that of the parent metal. And it is directly proportional to the travel / welding speed.
[53]	Mechanical and thermal modelling of Friction Stir Welding	Heurtier,H. , et al (2005)		The semi-analytical model can be used to obtain the strains, strain rates, and estimations of the temperatures and micro-hardness in the various weld zones
[54]	Theoretical and experimental investigation into friction stir welding of AA 5086.	Aval,H.J., et al. (2011)	Tool rotation speed , welding speed	Work-hardened and annealed conditions, can significantly affect the final microstructures and mechanical properties of welded alloy.
[55]	Enhancing mechanical properties of friction stir welded 2219Al-T6 joints at high welding speed through water cooling and post-welding artificial ageing	Zhang Z., et al. (2016)	welding speed, water cooling and air cooling conditions, post welding artificial ageing	A combination of high welding speed and post-welding artificial ageing is proven to be the optimal path to improving the mechanical properties of FSW2219Al-T6 joints, with a maximum joint efficiency of 91% obtained.
[56]	Friction stir spot welding of low-carbon steel using anassembly-embedded rod tool	Hsieha M.J., et al. (2015)	Tool rotation speed, downward force	The failure load fora 4 mm thick upper plate using the AER tool is still greater than that for a thinner plate using the plain tool. The strong bonding mechanism using the AER tool could be explained by diffusion reaction at a high interface temperature with a deep TMAZ.
[57]	Impact & improvement of tool deviation in friction stir welding: Weld quality & real-time compensation on industrial robot	Guillo.M, Dubourg (2016)	Rotational speed, traveling speed, tilt angle	This paper shows that a robot with an embedded real time algorithm for the compensation of the lateral tool deviation can reproduce the same FSW quality as a gantry-type CNC system.

[58]	Role of friction stir welding - Traveling speed in enhancing the corrosion resistance of aluminum alloy	Nam N.D., at al. (2016)	welding speed	The study suggests that high quality and better characteristics of thin film on the surface results in high corrosion resistant alloy. This may be due to the homogeneous distribution of the impurities in the alloy by the FSW, on which homogeneous passive film was formed to enhance the corrosion resistance.
[59]	Optimizing Friction Stir Welding Parameters to Maximize Tensile Strengthof AA2219 Aluminum Alloy Joints	Babu.S., et al. (2009)	Tool pin profiles, tool rotational speed welding (traverse)	A mathematical model has been developed here to predictthe tensile strength of friction stir welded AA2219 aluminium alloy joints with a 95 % confidence level.
[60]	Optimization of friction stir welding parameters for improved corrosion resistance of AA2219 aluminum alloy joints	Rambabu et al. (2015)	tool profile (P), rotational speed (N), welding speed (S) and axial force (F)	A mathematical model was developed to predict the corrosion resistances of friction stir welded AA2219 aluminium alloy joints with 95% of confidence level. The model was developed by incorporating the welding parameters and tool profiles using statistical tools, such as design of experiments and regression analysis.
[61]	Investigation of stationary shoulder friction stir welding of aluminum alloy 7075-T651	Dongxiao. L. (2015)	Tool rotational speed (rpm), Welding speed (mm/min)	The low crack initiation energy in the heat affected zone (HAZ) can be attributed to both the presence of precipitates and the redistribution of constituent particles. The presence of precipitates in the HAZ was the major reason for the decreased tensile strength of SSFSW joint.
[62]	High strain rate super plasticity in a friction Stir processed 7075 al alloy	Mishra. R.S (1999)	traverse speed was 15 cm/min.	The present results demonstrate the feasibility of friction stir processing to produce a microstructure amenable to high strain rate super plasticity in a commercial Al-alloy
[63]	Mechanical properties and microstructure studies in Friction Stir Welding (FSW) joints of dissimilar alloy- A Review	Husain Mehdi. (2017)	2100 rpm and travel speed of 2.33 mm/s 650 rpm and a traverse speed of 203 mm/min Tool rotation rate of 300,700, 900 and 1100 rpm.	Grain structures had equiaxed and fine grains due to the recrystallization in the SZ while Nano-sized alumina particles distributed differently because of different stirring action. An average grain size as low as 1.46 μm was obtained for a particular process parameters setting.
[64]	Influences of Process Parameter and Microstructural Studies in Friction Stir Weldingof Different Alloys: A Review	Husain Mehdi (2017)	2236 rpm and travel speed of 2.33 mm/s 700 rpm and a traverse speed of 203 mm/min Tool rotation rate of 300,700, 900 and 1100 rpm.	The mechanical properties of welded joint by friction stir welding are largely dependent on the combined effect of both the composition of alloying element and processing parameter.
[65]	Development of high strength, high conductivity copper by friction stir processing	Surekha.K., et al. (2010)	Tool rotation speed - 300 rpm, Transverse speed- 50 ,100,150,200,250 mm /min	The mechanical properties viz, the yield strength, ultimate tensile strength and the elongation increased in the processed samples compared to the base metal. The hardness of the processed sample was higher than the base metal (85 HV) at all parameters and the hardnessincreased from 102 to 114 HV with the decrease in grain size.
[66]	Influences of tool pin profile on the friction stir welding of aa6061	Emamian.,s et al (2016)	TRS 800,1200, 1600 rpm, Welding speed (WS) 40,70,100 mm/min, pin profiles: cylindrical, conical (C), & square (S)	Increasing the welding speed will effect on tensile properties. Threaded shape is effectiveness on mechanical properties. Differences between peak temperatures of samples welded by different pin profiles are very little and not significant. However, square pin profile produced higher temp.

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