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Fabrication of novel fiber reinforced aluminum composites by friction stir processing

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ABSTRACT

In this study, chopped and attrition milled high strength carbon, E-glass, and S-glass fibers have been used as the reinforcing agents in an aluminum alloy (Al1100) considered as the matrix. The Surface Metal Matrix Composites (SMMCs) then are produced by Friction Stir Processing (FSP). Tensile and micro-hardness examinations represent a magnificent improvement in the hardness, strength, ductility and toughness for all of the processed samples. Scanning Electron Micrographs reveal a proper distribution of the reinforcements in the matrix and a change in the fracture behavior of the FSPed specimens. The synergetic effects of reinforcing by fibers and Severe Plastic Deformation (SPD) lead to an extra ordinary improvement in the mechanical properties.

1. Introduction

Recently, Friction Stir Welding (FSW) which is invented by TWI of UK in 1991 [1] has been employed to weld similar and dissimilar metals [2,3]. Later on, new techniques such as Friction Stir Processing (FSP) and Friction Stir Spot Welding (FSSP) have been developed [3–5]. FSP is one of the most capable solid state Severe Plastic Deformation (SPD) processes to modify the grain structure of the surface [6–8] and to fabricate Surface Metal Matrix Composites (SMMC) [9–11]. The most important objectives of this process are improvement of surface mechanical properties [12,13], enhancement of wear resistance [14–16], microstructure and grain refinement [17,18].

FSP method includes an inconsumable rotating tool which contains a pin and a shoulder. The tool inserts into the surface of flat sheet and stirs the material around pin via frictional heating. This heat is generated through the severe plastic deformation which is attributed to the material stirring around the pin [2,3]. The key parameters of FSP are the tool geometry [19,20], rotating and traverse speed [21,22], target depth and spindle tilt angle [2,3] which have significant effects on the microstructure and mechanical properties of the products. The FSP is successfully used to fabricate Al based SMMCs with various reinforcements. The applied reinforcements were hard carbide particles such as TiC and SiC [18,23], carbon nanotubes [24,25], Al_2O_3 [26–28], etc.

Bauri et al. [18], used FSP effectively to homogenize the TiC particles distribution in Al based in situ composites. A single pass FSP could break the particles segregation from grain boundaries. Two passes of FSP improved TiC particles distribution and refined grain structure, remarkably. The novel feature of FSP is that ductility was not compromised while the strength and hardness improved after FSP.

Wang et al. [23], used FSP to fabricate bulk dispersal SiCp-reinforced aluminum metal matrix composite. An excellent bonding between SiCp particles and base metal obtained by FSP. The microhardness of MMCs could reach to the amounts 10% higher than the one of the base metal.

Izadi and Gerlich [24] continued Lim et al.'s work [25] by fabrication of CNT/aluminum composites through multi pass FSP. They dispersed high volume fraction (> 50%) of CNT through three pass of processing. The results showed that FSP could embed nanotubes in the lamellae regions of the Al-alloy stir zone. They also found that increasing the rotational speed and increasing the tool shoulder penetration depth could improve the distribution of nanotubes in the Al-alloy matrix.

Zahmatkesh et al. [26] produced Al–10% Al_2O_3 surface nanocomposite on a 2024 aluminum substrate. The Al–10% Al_2O_3 powder was sprayed on the Al2024 sheet by atmospheric plasma and then subjected to friction stir processing. A uniform distribution of nanoparticles was achieved after FSP and also, wear rate of the surface nanocomposite was reduced. They also could have

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refined Al2024 grain structure through FSP [27]. The results of their study represented that FSP could improve hardness and wear resistance. The process also, reduced friction coefficient by approximately 30% and wear rate by an order of magnitude.

Mazaheri et al. [28] discussed that FSP could develop a uniform distribution of Al_2O_3 particles in A356 matrix which improved the mechanical properties of specimens. They also suggested grain refinement, work hardening and Orowan mechanism to strength the A356 by Al_2O_3 during FSP.

Raaft et al. [29] changed the rotational to traverse speed ratio in order to study their effect on the hardness and wear properties of A390/graphite and A390/Al_2O_3 surface composites. They found that increasing the rotational speed could lead to more homogenous distribution of reinforcement, higher hardness and lower wear damages where traverse speed had less significant influence on the hardness of the composite layer than the tool rotational speed. The A390/Al_2O_3 surface composites exhibited higher hardness than the A390/graphite surface composites. The A390/Al_2O_3 surface composites exhibited lower wear rates than the A390/graphite surface composites.

Miranda et al. [30] studied on the three different strategies to impose SiC and Al_2O_3 reinforcement into the surface of the commercially pure aluminum. The three techniques: a square shaped groove packed with reinforcement particles, the pre-deposition of a uniform layer of particles prior to FSP with a non consumable tool, and the last one consisted of a consumable rod in aluminum drilled with holes placed in different positions along a radial line filled with reinforcing particles were used. It has been showed that the packing of reinforcements in square shaped groove could increase the composite layer thickness. The consumable rod approach allowed soundly deposition of composite layer while avoiding FSP tool wear problem.

Table 1
Chemical composition of 1100 Al alloy (±0.1%).

Element	Al	Cu	Zn	Other elements	Standard error
Percentage	>0.95	<0.15	<0.09	<0.1	±0.01

FSP technique also was applied to synthesis AA6082/TiC surface composite in order to analyze the effect of TiC particles and FSP on the microstructure, mechanical and the wear behavior by Thangarasu et al. [31]. They reported that the TiC particles significantly influenced the area of the composite, grain size of matrix, microhardness, UTS and wear behavior of the AA6082/TiC composites. The process could distribute TiC particles fairly homogenous in the composite irrespective of the volume fraction. Both the microhardness and the UTS increased when the volume fraction of TiC particles was increased. The TiC particles also increased the stiffness of the matrix and reduced the formation of voids. The particles also reduced wear rate and changed the adhesive to abrasive mechanism.

In the current study aluminum matrix SMMCs reinforced with carbon and glass fibers (chopped and milled) are fabricated trough FSP to enhance the mechanical properties. An appropriate bonding between reinforcement and Aluminum matrix and uniform distribution of reinforcement is observed which is consistent with other studies [18,23]. No other studies have used the carbon or glass fibers as the reinforcement in the FSP. These fibers are more economical and easy to use than other conventional reinforcements such as carbon nanotubes [24,25]. Unlike the most other studies, the both strength and ductility were increased in these Al/chopped or milled fibers surface composites. The thin square grooves are made along the aluminum specimens and the reinforcements are placed into the slots and then followed by friction stir processing.

Table 2
The raw fibers properties (ASTM E08).

Fiber	Type	Density (±0.1 g/cm^3)	Tex (±50 g/km)	Tensile strength (±10 MPa)
E-glass	CAMELYAF	2.55	2400	480
S-glass	LBIE HS4C	2.45	1200	1600
Carbon	TORAYCA T700S	1.81	700	2900

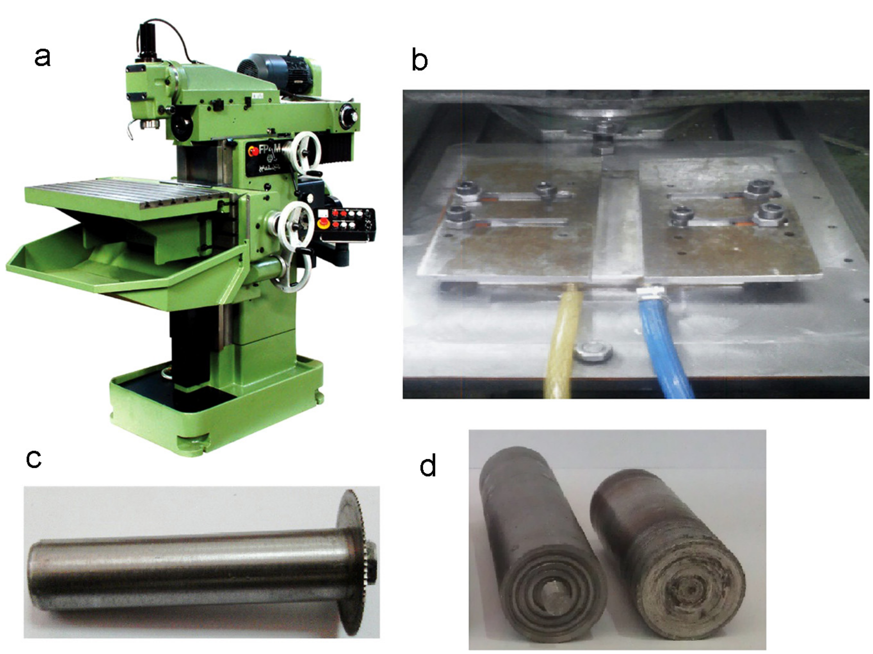

Fig. 1. (a) The universal milling machine which is used for FSP, (b) attributed fixture, (c) radial cutting saw which is used for milling the slots, (d) tool for closing the slots (right) and cylindrical FSP tool (left).