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Microstructure and wear characterization of aluminum matrix composites reinforced with industrial waste fly ash particulates synthesized by friction stir processing

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ABSTRACT

Fly ash (FA) is a waste product of coal combustion in thermal power plants which is available in massive quantities all over the world causing land pollution. This paper reports the characterization of AA6061 aluminum matrix composites (AMCs) reinforced with FA particles synthesized using friction stir processing (FSP). The volume fraction of FA particles was varied from 0 to 18 in steps of 6. The prepared AMCs were characterized using optical microscopy (OM), scanning electron microscopy (SEM) and electron backscattered diagram (EBSD). The wear rate was estimated using a pin-on-disc wear apparatus. FA particles were observed to be distributed homogeneously in the AMC irrespective of the location within the stir zone. The EBSD micrographs revealed remarkable grain refinement in the AMC. The incorporation of FA particles enhanced the microhardness and wear resistance of the AMC. The strengthening mechanisms of the AMC were discussed and correlated to the observed microstructures. The wear mechanisms were identified by characterizing the wear debris and worn surfaces.

1. Introduction

Aluminum alloys reinforced with various ceramic particles, universally known as aluminum matrix composites (AMCs) have become the focus of the current materials era due to their superior properties such as light weight, high wear resistance, low thermal expansion, high strength to weight ratio etc. AMCs are progressively phasing out aluminum alloys in a wide range of applications in automotive, aerospace, marine and nuclear industries [1–3]. Although industries gaze to exploit the benefits of AMCs, it still remains a daunting task to produce AMCs possessing all desirable properties at an economical price. The production cost of AMCs can be controlled if inexpensive reinforcements such as fly ash (FA) and natural minerals are used. FA is reasonably an economical reinforcement compared to conventional reinforcements such as silicon carbide (SiC), aluminum oxide (Al_2O_3), titanium carbide (TiC) and boron carbide (B_4C). The combustion of coal in thermal plants around the world releases FA as a byproduct in massive quantities which goes as a waste causing environmental impact. Incorporating FA to produce AMCs is a sensible way to reduce the cost of AMCs and land pollution [4–7].

Several researchers attempted to produce and characterize AMCs reinforced with FA particles using liquid metallurgy and solid state methods in the past decade [8–17]. Sobczak et al. [8] characterized the interfacial reaction products in Al/FA AMCs prepared using hot pressing. Rohatgi et al. [9] synthesized A356/FA AMCs using pressure infiltration and reported the compressive behavior. Wu et al. [10] measured the damping properties of AA6061/FA AMCs prepared using squeeze casting. Rajan et al. [11] prepared A356/FA AMCs using stir casting and compo casting methods and evaluated the effect of processing method on the distribution FA particles in the aluminum matrix. Sudarshan and Surappa [12] shed light on the compressive and damping behavior of A356/FA AMCs formed using stir casting followed by hot extrusion. Kumar et al. [13] studied the high temperature dry sliding wear behavior of AA6061/FA AMCs developed by powder metallurgy subjected to hot extrusion. Marin et al. [14] investigated the electro chemical behavior of Al/FA AMCs obtained by powder metallurgy. Murthy et al. [15] fabricated AA2024/FA nano AMCs using ultrasonic cavitation and analyzed the microstructure and mechanical properties. Kumar et al. [16] reported the tensile and fracture behavior of AA4026/FA AMCs produced by stir casting. Selvam et al. [17] reported the microstructure of AA6061/FA AMCs made by compocasting.

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Table 1
Chemical composition of AA6061 aluminum alloy.

Element	Mg	Si	Fe	Mn	Cu	Cr	Zn	Ni	Ti	Aluminum
wt.%	0.95	0.54	0.22	0.13	0.17	0.09	0.08	0.02	0.01	Balance

The literature survey revealed that it is possible to produce AMCs reinforced with various types of FA particles using several techniques which include stir casting, compo casting, squeeze casting, powder metallurgy etc. But those production methods were always associated with multiple defects such as porosity [10,12,13], voids [9], particle clusters [15], inhomogeneous distribution [16] and brittle intermetallics owing to interfacial reaction [8,11]. Those defects diminish the mechanical and tribological properties and reduce the performance of Al/FA AMCs during service. Further, the wettability of FA particles with molten aluminum is poor which requires treatment of FA particles [12,15] or addition of wettability agents [11] leading to an increase in the cost of the AMC. The poor wettability weakens the interfacing bonding between the aluminum matrix and the FA particles limiting the load bearing capacity of the AMCs. Therefore, development in production method is crucial to exploit the advantages of low cost Al/FA AMCs.

Friction stir processing (FSP) is a promising method to produce surface and bulk AMCs and gained more attention in the last five years [18, 19]. FSP is capable of overcoming the short comings of casting and powder metallurgy routes. Mishra el al. [20] conceived an idea to use FSP to create AMCs. The working principle of FSP was derived from friction stir welding (FSW) which was invented at The Welding Institute (TWI) in 1991. FSP induces severe plastic deformation and material flow due to the frictional heat and translation of material across the tool. The ceramic particles are packed along the FSP direction by applying any one of the methods which include straight groove, V groove, circular holes etc. The rotating action of the tool and plasticized material flow mix with the packed ceramic particles to form the composite. AMCs produced at optimized FSP parameters will be free of porosity, clusters and interfacial reaction. Moreover, FSP is not sensitive to the type of ceramic particles commonly employed in engineering applications. Hitherto, FSP has been successfully employed to produce AMCs reinforced with SiC [21], Al_2O_3 [22], TiC [23], Si_3N_4 [24], Ni [25], CNT [26], NiTi [27], TiN [28] and solid lubricants [29,30].

The structure and properties of Al/FA AMCs produced using FSP is not reported in literatures. Hence, the objective of the this research work is to synthesize AA6061/FA AMCs using FSP and characterize the evolution of microstructure, distribution, micro texture and sliding wear behavior. Aluminum alloy AA6061 is extensively used in industries and possesses good castability, weldability, reasonable strength and corrosion resistance [31].

2. Experimental procedure

Aluminum alloy AA6061 plates of size 100 mm x 50 mm x10 mm were used for this research work. The chemical composition of aluminum alloy AA6061 is presented in Table 1. A groove of 5.5 mm deep was made along the centre line of the plates using wire cut electrical discharge machining (WEDM) and compacted with FA particles. The average size of FA particles used in this work was 2 μm. SEM micrograph of FA particles is shown in Fig. 1a and b. A pinless tool was initially used to cover the top of the groove after filling with FA particles to avoid the particles from scattering during FSP [32]. A tool made of HCHCr steel having threaded pin profile was used for the present study. The tool had a shoulder diameter of 18 mm, pin diameter of 6 mm and pin length of 5.8 mm. FSP was carried out on an indigenously built FSW machine. The process parameters employed were: tool rotational speed = 1600 rpm; traverse speed = 60 mm/min and axial force = 10 kN. The process parameters were adopted from Rejil et al. [33] which were optimized to yield desirable distribution of second phase particles without macroscopic defects in the FSP zone. The FSP procedure to produce the composite is available elsewhere [32]. Two passes were applied in opposite directions to achieve better distribution of FA particles. FSP was processed on three such plates by varying the width of the groove (0.4, 0.8, and 1.2 mm) to have four levels of volume fraction of FA particles (0, 6, 12, and 18 vol.%). Zero volume fraction refers to unprocessed aluminum alloy AA6061. The theoretical and actual volume fractions of FA particles were calculated as reported by Sathiskumar et al. [34].

Specimens were obtained by cutting the friction stir processed plates at its centre perpendicular to the processing direction. They were polished as per the standard metallographic procedure and etched with Keller's reagent. The digital image of the macrostructure of the etched specimens was captured using a digital optical scanner. The microstructure was observed using a metallurgical microscope, scanning electron microscope (SEM) and electron backscattered diffraction (EBSD). Selected samples were electro polished using a mixture of perchloric acid and methanol to observe micro texture using EBSD. The microhardness was measured using a microhardness tester at 500 g load applied for 15 seconds at various locations in the composite.

The sliding wear behavior of AA6061/FA AMCs was evaluated using a pin-on-disc wear apparatus (DUCOM TR20-LE) at room temperature according to ASTM G99-04A standard. Pins of size 6 mm x 6 mm x 40 mm were prepared from the FSP zone by WEDM. The wear test was conducted at a sliding velocity of 1.0 m/s, normal force of 20 N and sliding distance of 3000 m. The polished surface of the pin was slid on a hardened chromium steel disc. A computer aided data acquisition system was used to monitor the loss of height. The volumetric loss was computed by multiplying the cross sectional area of the test pin

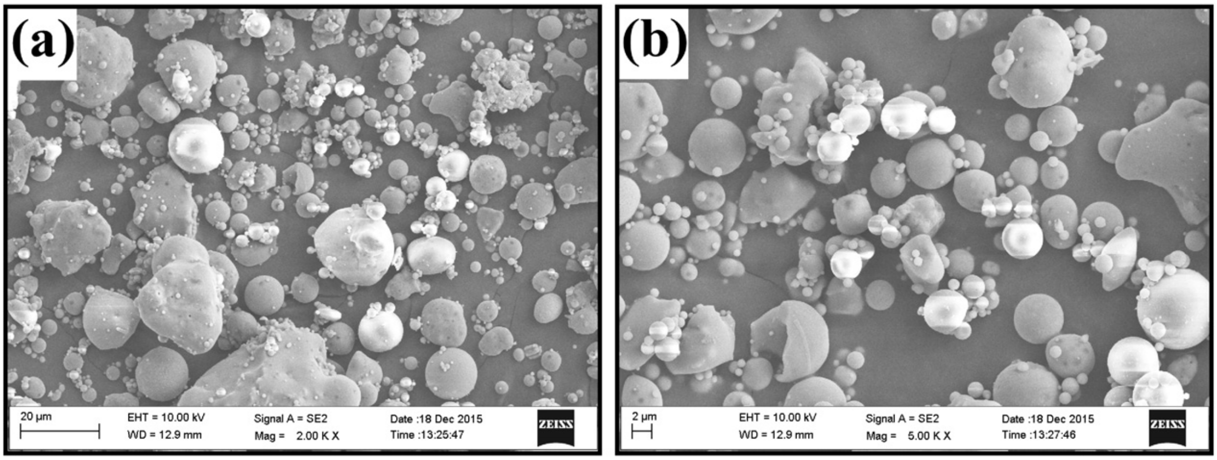

Fig. 1. FESEM micrograph of fly ash particles at magnification; (a) 2000x and (b) 5000x.