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Low cost metal matrix composites based on aluminum, magnesium and copper reinforced with fly ash prepared using friction stir processing

Isaac Dinaharan*, Esther Titilayo Akinlabi

Department of Mechanical Engineering Science, University of Johannesburg, Auckland Park Kingsway Campus, Johannesburg 2006, South Africa

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ABSTRACT

Fly ash (FA) is a cheaper reinforcement which will bring down the production cost of metal matrix composites (MMCs). This paper reports FA reinforced MMCs based on aluminum alloy AA6061, magnesium alloy AZ31 and copper. The composites were synthesized using the novel and latest method friction stir processing (FSP). The microstructure was examined using optical microscopy, scanning electron microscopy (SEM) and electron back scattered diffraction (EBSD). A homogenous distribution of FA particles was observed in all the composites. The severe plastic deformation of the process caused fracture of FA particles. The grains were refined remarkably in the composites due to dynamic recrystallization and pinning effect. The reinforcement of FA particles enhanced the microhardness of the composites. The strengthening mechanisms were discussed.

1. Introduction

Fly ash (FA) can be used as an effective reinforcement for metal matrix composites (MMCs) to reduce land pollution and negative environmental impact [1]. MMCs are produced using several methods which are not limited to powder metallurgy, stir casting, compo casting, squeeze casting etc. Those methods were used by researchers to produce MMCs reinforced with FA particles with matrix material as aluminum alloys, magnesium alloys and copper [2–4]. FA particles was successfully reinforced into various monolithic alloys to prepare MMCs. Nevertheless, several defects such as porosity, agglomeration, inhomogeneous distribution, poor interfacial bonding, interfacial reactions and decomposition of FA particles were observed. Those defects took a toll on the mechanical properties and the performance of the MMCs.

Friction stir processing (FSP) is a novel and latest method to produce high performance MMCs with minimum or no defects encountered in other production methods [5]. FSP was derived from the working principles of friction stir welding (FSW). FSP utilizes the frictional heat generated by the rubbing of the tool with the metallic material to make it plasticized. Preplaced reinforcement particles are subsequently mixed with the plasticized matrix material due to the rotating pin. The material flow across the tool movement is consolidated by applying an axial force. The material matrix never melts and the composite is produced in solid state. The density variation between the matrix material and the reinforcement particle does not alter the final distribution of reinforcement particles in the composite. Further, FSP is an economical process with minimum energy consumption [6,7].

FSP was successfully used to produce MMCs based on aluminum [5], magnesium [7], copper [8], steel [9] and titanium [10]. However, literature on MMCs reinforced with FA particles using FSP are scantly. Dinaharan et al. [11] demonstrated that FA particles can be successfully reinforced into aluminum alloy AA6061 using FSP and properties can be improved. The objective of the present work is to develop MMCs based on aluminum, magnesium and copper reinforced with industrial waste FA particles and investigate the microstructural features.

2. Experimental procedure

Rolled plates of aluminum alloy AA6061, magnesium alloy AZ31and pure copper were employed for this work. The breadth and length of the plates were respectively 50 mm and 100 mm. The plates were machined at the middle along the length direction using wire EDM to create a groove for packing the FA particles. The groove dimensions correspond to 18 vol% of reinforcement particles. The volume fraction was estimated based on the ratio between the area of the groove and the cross sectional area of the tool pin [12].The groove was carefully packed with FA particles (~ 5 μm) to the brim. Fig. 1 represents the SEM micrograph of the FA particles. FA particles were collected from Thermal Power Station, Tuticorin, INDIA. Most of the FA particles display solid spherical shape which is categorized as precipitator type of FA. FSP was accomplished using an indigenously built FSW machine (M/s RV Machine Tools, Coimbatore, INDIA). The experimental conditions are shown in Table 1. The process parameters were chosen

* Corresponding author.
E-mail addresses: dinaweld2009@gmail.com (I. Dinaharan), etakinlabi@uj.ac.za (E.T. Akinlabi).

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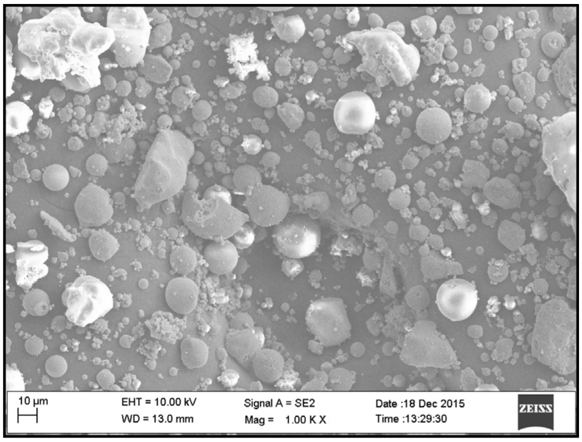

Fig. 1. FESEM micrograph of fly ash particles.

based on literature and author's past experience to yield a uniform distribution of reinforcement particles across the stir zone. A detailed FSP procedure is available in literature [6,7] and schematically shown in Fig. 2.

Specimens for microstructural characterization were machined perpendicular to the friction stir processed plates. They were mounted, polished and etched. The etched specimens were observed using an optical microscope (OLYMPUS BX51M), field emission scanning electron microscope (CARL ZEISS-SIGMAHV) and electron backscatter diffraction (EBSD). EBSD was carried out in a FEI Quanta FEG SEM equipped with TSL-OIM software. The microhardness was measured using a microhardness tester at 500 g load applied for 15 seconds at various locations in the composite.

3. Results and discussion

3.1. Microstructure

Fig. 3 presents representative optical micrographs of aluminum, magnesium and copper MMCs reinforced with FA particles. It is clear from those micrographs that the FA particles are spread across the metallic matrix. FA particles are distributed in all areas of the micrographs. Liquid metallurgy processing methods such as stir casting is prone to segregation of reinforcement particles along the grain boundaries [2]. The solidification related phenomenon creates segregation due to density gradient between metallic matrix and the reinforcement. On the contrary, there is no segregation of FA particles in the micrographs in any of the composites. This can be attributed to the nature of the FSP method which does not involve solidification. The composites are formed by severe plastic deformation in solid state. Absence of matrix material melting discards the effects of solidification. The possibility of free movement of the reinforcement particles due to density gradient within the plasticized material prior to forging is absent. Therefore, FA particles did not segregate in the composite. The distribution of FA particles in the composite is fairly homogenous. All particles are separated sufficiently. There are no agglomerations or regions of the matrix unreinforced with particles known as particle free regions. The homogenous distribution is a result of effective stirring action of the rotating tool. The available stirring action is influenced by the major process parameters such as tool rotational speed and traverse speed [5]. It can be said that the adequate stirring of the tool was present under the chosen experimental conditions. A homogenous distribution is essential to obtain enhanced properties as well as isotropic properties. Although, grain boundaries are not clearly visible in the optical micrographs (Fig. 3), the distribution can be counted as intragranular due to the absence of segregation. There are possibilities that some particles might have seated on the grain boundaries.

FSP method depends upon the severe plastic deformation of the metallic matrix to produce the composite. Hence, the material experiences very large strains. It is reported that the strain developed during FSP is several fold higher to the strain in other severe plastic deformation processes [5]. The matrix usually observes this high strain and deforms plastically. But, the reinforcement particles cannot absorb the entire strain and undergoes a change in shape and size. A comparison between the initial morphology (Fig. 1) of the FA particles and after FSP (Fig. 3) helps to assess any change in shape and size. It is obvious from the comparison that several FA particles underwent a change in shape and size. Many FA particles could not withstand the high plastic strain and rigorous stirring action of the rotating tool. As a result, FA particles broke up during FSP. The spherical shape is almost lost in all the MMCs. Few spherical particles are observed (Fig. 3a) in aluminum MMC. Commonly, ceramic particles having irregular polygonal shape are vulnerable to fragmentation [13]. There are no sharp corners or completely irregular shapes in the morphology of FA particles. However, FA particles broke up due to the severe plastic strain. This can be attributed to the deformation behavior of FA particles which cannot deform in the similar manner to that of the metallic matrix. Fragmentation of FA particles produces large amount of smaller debris. It is interesting to notice that no agglomerations of debris are seen around larger particles. This observation suggests that the fragmented debris also mixed well with the plasticized matrix material and formed the composite. A variation in change in shape and size may lead to functionally graded regions within the composite. The flow stress to plasticize magnesium and copper is relatively higher compared to that of aluminum alloy. Therefore, the fragmentation is well pronounced in magnesium and copper MMCs. The fragmentation cannot be compared to decomposition of FA particles which are encountered during liquid metallurgy processing methods [2]. A change in composition occurs after decomposition. But the composition of FA particles remains same subsequent to fragmentation.

Grain boundary maps of the developed composites superimposed from the EBSD images are presented in Fig. 4. The quantitative analysis of grain size before and after FSP is furnished in Table 2. The grain boundary maps of as-received metallic plates are not given due to space limitation. It is evident from the micrographs and the tabulated results that all the matrix materials experienced intense grain refinement. The grain refinement can be related to the following factors. The frictional heating coupled with the intense severe plastic deformation lead to dynamic recrystallization [5]. It is agreed in literature that materials with high stacking fault energy undergo continuous dynamic recrystallization and vice versa. Since, aluminum has high stacking fault energy; it might have experienced continuous dynamic recrystallization. Magnesium and copper might have undergone discontinuous

Table 1
Experimental conditions.

Matrix	Tool design				Process parameter		
	Shoulder diameter (mm)	Pin diameter (mm)	Pin length (mm)	Material	Rotational speed (rpm)	Traverse speed (mm/min)	Axial force (kN)
AA6061	18	6	5.8	HCHCr	1600	60	10
AZ31	18	6	5	HCHCr	1200	40	10
Cu	24	6	4.5	H13	1000	40	10