Association of Metallurgical Engineers of Serbia
AMES

Scientific paper
UDC: 669.719.018.25

MECHANICAL BEHAVIOUR OF AL-MG-SI MATRIX COMPOSITES REINFORCED WITH ALUMINA AND BAMBOO LEAF ASH

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Received 13.01.2013
Accepted 29.03.2013

Abstract

The mechanical behaviour of Al-Mg-Si alloy matrix composites reinforced with alumina and bamboo leaf ash (BLA) has been investigated. Alumina (Al2O3) particulates complemented with 0, 2, 3, and 4 wt% BLA were utilized to prepare 10 wt% of reinforcement in Al-Mg-Si alloy matrix using double stir casting method. Micro-hardness measurement, tensile testing, fracture toughness evaluation, optical and scanning electron microscopy were used to characterize the composites. It was observed that 4.7, 9.32, and 14.3 % reduction in tensile strength was obtained for the composites containing 2, 3, and 4 wt % BLA, respectively. Although there was still a decrease in specific strength and hardness with increase in BLA content, the reductions are less than 9 % for a 40 % reduction of alumina as obtained in the hybrid composite containing 6wt % alumina - 4 wt % BLA. The hybrid composites containing 2 and 3 wt % BLA exhibited a superior elongation in comparison to the single reinforced Al-Mg-Si/ 10 wt % alumina composite, while all hybrid composite compositions exhibited a superior fracture toughness compared to the single alumina reinforced composite.
Keywords: stir casting; bamboo leaf ash; hybrid composites, mechanical behaviour; alumina; Al-Mg-Si alloy

Introduction

There is a growing interest in exploring low-cost options for the development of aluminium matrix composites (AMCs) with the hope of still maintaining their high performance levels in service applications [1]. AMCs are the most versatile of the metal matrix composites because of number of factors which include ease of processing, relatively low cost of Al matrices in comparison with other competing metal matrices (Cu, Ti, Mg), good combination of physical and mechanical properties, good high temperature properties and thermal management capability, excellent tribological

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properties, and reasonable corrosion resistance [2-5]. It is for these reasons that AMCs have found application in diverse technological areas and their influence as an engineering material is expected to continue to rise in the years ahead [6]. For example, in the automobile industry, AMCs are strongly competing with steel as material of choice for the design of a good number of components and parts [7, 8].

It has been noted that the type and characteristics of the reinforcements used in AMCs play a great role in defining the sort of properties these materials will possess [9 -10]. There has been a great number of research work devoted to understanding the influence of reinforcement parameters on the properties of AMCs [11- 13]. The search for low cost options in AMC production has lead to a number of efforts tailored at utilizing industrial and agro waste products as reinforcing materials [14, 15]. Some of the advantages of these waste products are: very low cost of processing, ready availability at little or no cost, and often lower densities in comparison with most technical ceramics (such as silicon carbide, boron carbide, and alumina), benefit in conservation and protection of the environment [16, 17]. The potentials and limitations of the use of agro wastes as reinforcements have been reported by some authors [17, 18]. A new direction in the use of agro waste ashes has been based as complementing reinforcement to either silicon carbide or alumina to develop hybrid composites [19-20]. In this regards, a number of works has been published on the potentials of the agro waste ashes as complementing reinforcements. Alaneme et al [19] reported that good casting qualities comparable with that of single reinforced alumina composites are achieved with the use of rice husk ash (RHA) and alumina as complementing reinforcements. They also reported that improved fracture toughness and comparable specific strength are achieved with the use of rice husk ash and alumina as complementing reinforcements. Alaneme and Olubambi [21] have also reported that the wear properties of these low cost hybrid composites developed with the use of RHA and alumina are comparable to that of the single reinforced alumina composite. Escalera-Lozano et al. [20] reported on the degradation characteristics of Al/SiC_p composites produced with RHA and aluminium cans. There is still the need to characterize the potentials of other agro waste ashes such as bamboo leaf ash, groundnut shell ash, and palm nut shell ash for use as hybrid reinforcement in AMCs. The present work is an effort in considering the potentials of bamboo leaf ash as complementing reinforcement in the development of high performance low-cost AMCs. The mechanical behaviour of Al-Mg-Si alloy matrix reinforced with varied weight ratios of bamboo leaf ash and alumina was studied.

Experimental

Materials

Wrought Al-Mg-Si alloy was selected as the aluminium based matrix for the investigation. Spark spectrometric analysis was used to determine the chemical composition of the aluminium alloy and the results are presented in Table 1. The reinforcements selected for the research are as follows: chemically pure alumina (Al_2O_3) particles having particle size of 28μm and bamboo leaf ashes derived from controlled burning of bamboo leaves. Magnesium was selected as wetting agent to improve wettability between the Al-Mg-Si alloy and the reinforcements during production of the composites.

Table 1: Chemical composition of Al-Mg-Si alloy

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Ni
wt %	0.4002	0.2201	0.0080	0.0109	0.3961	0.0302	0.0202	0.0125	0.0101

Sn	Pb	Ca	Cd	Li	Na	V	Al
0.0021	0.0011	0.0015	0.0003	0.0000	0.0009	0.0027	98.88

Method

Preparation of Bamboo Leaf Ash

The bamboo leaf ash processing has been described by Alaneme et al. [19]. Dry bamboo leaves (obtained within the University environs) were placed inside a perforated metallic drum (which serves as the burner) and ignited using charcoal. The bamboo leaves were left to burn completely and the ashes removed 24 hours later. The ash was then conditioned by heat-treating the ash at a temperature of 650^o C for 180 minutes. The chemical composition of the bamboo leaf ash is presented in Table 2.

Table 2: Chemical composition of the Bamboo Leaf Ash

Compound/Element (constituent)	wt. %
Silica (SiO_2)	76.4
Aluminium oxide, Al_2O_3	5.04
Calcium oxide CaO	6.68
Magnesium oxide, MgO	2.05
Potassium oxide, K_2O	5.76
Haematite, Fe_2O_3	1.82

Composites Production

The composites were produced utilizing double stir casting process performed in accordance with Alaneme and Aluko [10]. The process commenced with carrying out charge calculations to determine the amount of BLA and Al_2O_3 required to produce 10 wt% reinforcements consisting of 0:10, 2:8, 3:7, and 4:6 BLA and Al_2O_3 weight ratios respectively. Preheating of the BLA and Al_2O_3 particles at a temperature of 250^{o}C to remove moisture and improve wettability with the Al-Mg-Si alloy during melting was also performed before charging into the furnace. The Al-Mg-Si alloy ingots were charged into a gas-fired crucible furnace and heated to a temperature of 750^{o}C ± 30^{o}C (above the liquidus temperature of the alloy) and the liquid alloy was then allowed to cool in the furnace to a semi solid state at a temperature of about 600^{o}C. The temperature of the furnace was monitored using an external thermocouple. The preheated BLA and Al_2O_3 particulates along with 0.1 wt% magnesium were added at this temperature and stirring of the slurry was performed manually for 5-10 minutes. The composite slurry was then superheated to 800^{o}C± 30^{o}C and a second stirring was performed using a mechanical stirrer. The stirring operation was performed at a speed of 400rpm for 10minutes to help improve the distribution of the particulates in the molten Al-Mg-Si alloy. The molten composite was then cast into prepared sand moulds with inserted metallic chills. After fettling of the cast composites, the percent porosities in the castings were determined before mechanical testing using density measurements [10]. This method has been described in details by Alaneme et al. [19], in order to ensure that the porosity in the produced composites do not exceed 4 % which is the maximum permissible porosity levels in cast MMCs [11]. The average weight of the castings produced was 3Kg. The sample designations and the results of the percent porosity determination are presented in Table 3.

Table 3: Composite Density and Percent Porosity

Sample Designation	Weight Ratio of BLA and Al_2O_3	Theoretical density	Experimental density	% Porosity
A	0:10	2.81	2.79	0.71
B	2:8	2.74	2.72	0.73
C	3:7	2.71	2.68	1.11
D	4:6	2.68	2.62	1.49

Hardness Measurement

An EmcoTEST DURASCAN Microhardness Tester equipped with ecos workflow ultra modern software was used to evaluate the hardness of the composites. The samples for the hardness test were polished to obtain a flat and smooth surface finish. A load of 100 g was applied on the specimens and the hardness value was determined following standard procedures. Multiple hardness tests were performed on each sample and the average value was taken as a measure of the hardness of the specimen.

Tensile Testing

The tensile properties of the samples were evaluated by conducting tension test on round tensile samples machined from the composites with dimensions of 6 mm diameter and 30 mm gauge length. The tensile test was performed at room temperature (25^{o}C) using an Instron universal testing machine operated at a constant cross head speed of 1mm/s. The machined specimen dimensions and test procedures were in accordance with the specifications of ASTM E8M - 91 standards [22]. Three repeat tests were performed for each composite composition to assess reproducibility of results and hence guarantee reliability of the data generated. The tensile properties evaluated from the tensile test are: the ultimate tensile strength (σ_u), and the strain to fracture (ε_f).

Fracture Toughness (K_{1C})

The fracture toughness of the composites was evaluated in accordance with procedure prescribed by Alaneme [23]. Circumferential notch tensile (CNT) specimens were machined from the composites with gauge length of 30mm, specimen diameter of 6mm (D), notch diameter of 4.5mm (d) and notch angle of 60^o. The specimens were then subjected to tensile loading to fracture using an Instron universal testing machine at a strain rate of 10^{-3}/s. The fracture load (P_f) obtained from the tensile test was used to evaluate the fracture toughness using the empirical relations by Dieter [24]:

$$K_{1C} = P_f / (D)^{3/2} [1.72(D/d) - 1.27] \quad (1)$$

where, D and d are respectively the specimen diameter and the diameter of the notched section, respectively. The validity of the fracture toughness values was evaluated using the relations in accordance with Nath and Das [25].

Three repeat tests were performed for each composite composition to assess reproducibility and consistency of results and hence guarantee reliability of the fracture toughness values computed.

Microstructural Characterization

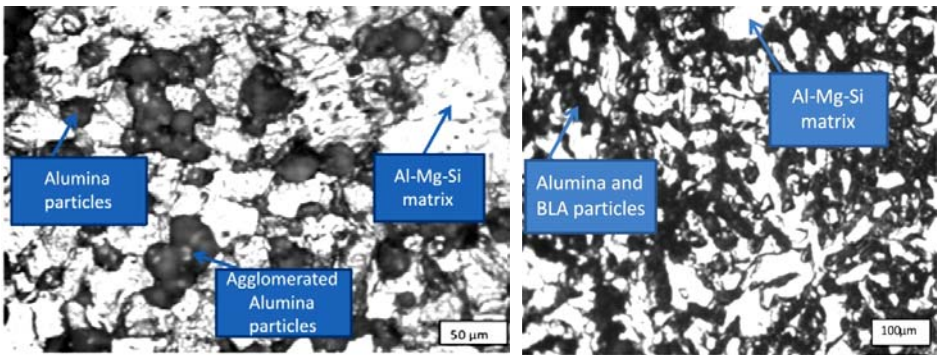
The microstructure of the composites was examined using a Zeiss Metallurgical Microscope with accessories for image analysis. The specimens for the test were metallographically polished and etched with 1HNO3: 1HCl solution before microscopic examination was performed. Further studies of the microstructural features and also determination of the qualitative chemical composition of the composites were performed using a JSM 7600F Jeol ultra-high resolution field emission gun scanning electron microscope (FEG-SEM) equipped with an EDS.

Results and Discussion

Microstructure

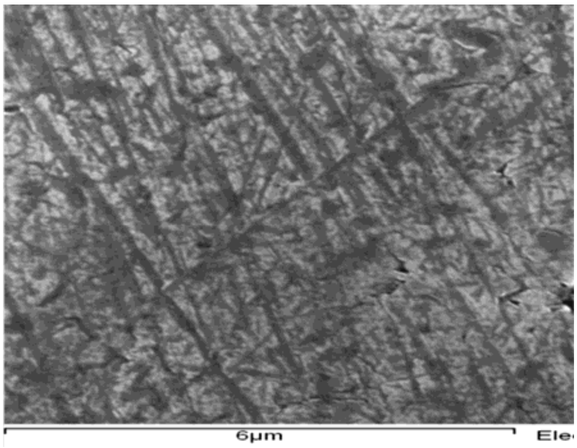
Representative microstructures of the composites produced are presented in Figure 1. From Figure 1(a) the alumina particulates dispersed in the Al-Mg-Si alloy matrix of the single reinforced composite (Al-Mg-Si/10 wt % Al_2O_3) are revealed. Figure (1b) shows the dense distribution of particulates in the hybrid composite containing 4wt % BLA-6 wt % Al_2O_3 which is due to the higher volume percent of the BLA which has very low density (0.35 g/cm^3) in comparison with alumina (3.18 g/cm^3) [19].

Representative SEM micrograph and EDS profile of the Al-Mg-Si/3wt % BLA-7wt% Al_2O_3 are presented in Figures 2(a) and 2(b). The peaks of aluminium (Al), oxygen (O), carbon (C), iron (Fe), silicon (Si), potassium (K), and calcium (Ca) confirms the presence of silica (SiO_2), alumina (Al_2O_3), potassium oxide (K_2O), calcium oxide (CaO) and ferric oxide (Fe_2O_3) which are constituents of bamboo leaf ash (Table 2).

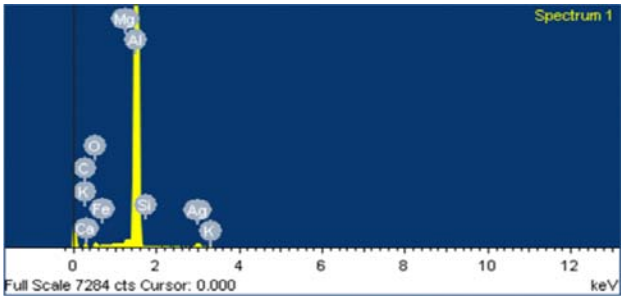


(a) *(b)*

Fig. 1. Photomicrograph of (a) the Al-Mg-Si/10 wt% Al_2O_3 composite showing the Al_2O_3 particles dispersed in the Al-Mg-Si matrix, and (b) the Al-Mg-Si/4wt% BLA-6 wt% Al_2O_3 hybrid composite showing a high density of particles dispersed in the Al-Mg-Si matrix.



(a)



(b)

Fig. 2. (a) Representative SE image photomicrograph of the Al-Mg-Si/3wt% BLA-7 wt% Al_2O_3 hybrid composite, and (b)EDS profile obtained from the Al-Mg-Si/3wt% BLA-7 wt% Al_2O_3 hybrid composite confirming the presence of Al_2O_3, SiO_2, Fe_2O_3, K_2O, C, CaO.

Mechanical Behaviour

Hardness

The hardness values of the single and hybrid reinforced composites are presented in Figure 3. It is observed that the hardness of the composites decreases with increase in the weight percent of BLA, although the least hardness (VHN -72) for the hybrid composite containing 4 wt % BLA was less than 9% in comparison with the hardness value of the single reinforced Al-Mg-Si matrix -10wt% Al_2O_3 composite. This is an indication that the addition of BLA in place of alumina only results in slight decrease in hardness of the selected weight percent of the reinforcements utilized in this research. Similar hardness behaviour was observed for Al-Mg-Si matrix hybrid composites reinforced with alumina and RHA [19]. The slight reduction in hardness is attributed to the presence of silica which is the dominant constituent in BLA (95.9 %). Silica is noted to be a softer ceramic than alumina thus an increase in the BLA content is bound to result in reduction in hardness of the hybrid composite [26]. However, it is encouraging to note that the decrease in hardness observed in the hybrid composite is less than 9 %

for a 40 % reduction in alumina by replacement with the cheap agro waste BLA. Thus the addition of BLA will not have significant effect on the hardness properties of the hybrid composite.

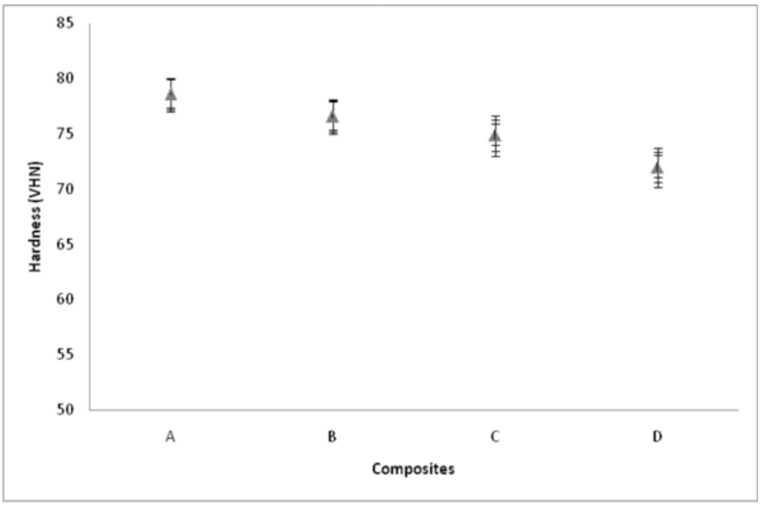


Fig. 3. Variation of hardness for the single reinforced Al-Mg-Si/10 wt% Al_2O_3 and hybrid reinforced Al-Mg-Si/BLA-Al_2O_3 composites.

Tensile Properties

The variation of ultimate tensile strength (UTS), specific strength (defined as the ratio of the UTS to the density of the composite), and elongation are presented in Figures 4 – 6. From 4 it is observed that just as in the case of the hardness results, the tensile strength of the composites decreases with increase in BLA content. For the UTS results, 4.7, 9.32, and 14.3 % reduction in tensile strength was obtained for the composites containing 2, 3, and 4 wt % BLA respectively. This trend is due to the presence of BLA which major constituent is silica. Silica is softer in comparison with alumina and has about the same elastic modulus as aluminium (60 – 70GPa) in comparison to alumina which elastic modulus is 250GPa [26]. Thus, there will be a slight reduction in the direct strengthening effect usually expected from the transfer of load from the matrix to the supposedly harder and stiffer particulates [27, 28]. However, considering the specific strength values of the composites (Figure 5), it is observed that though there is still a decrease in specific strength with increase in BLA content, the reductions are 2.24, 5.58, and 8.73 % for the composites containing 2, 3, and 4 wt % BLA, respectively. Thus the specific strength difference is less than 9% for a 40% reduction of alumina as observed in the hybrid composite containing 4 wt % BLA. This is a modest improvement compared to the maximum of 14.3 % lower UTS value obtained for 40% reduction in alumina content in the composite. This equally shows that comparable strength to weight ratios can be achieved using cheap BLA agro waste as a complementing reinforcement for the production of alumina reinforced Al matrix composites.

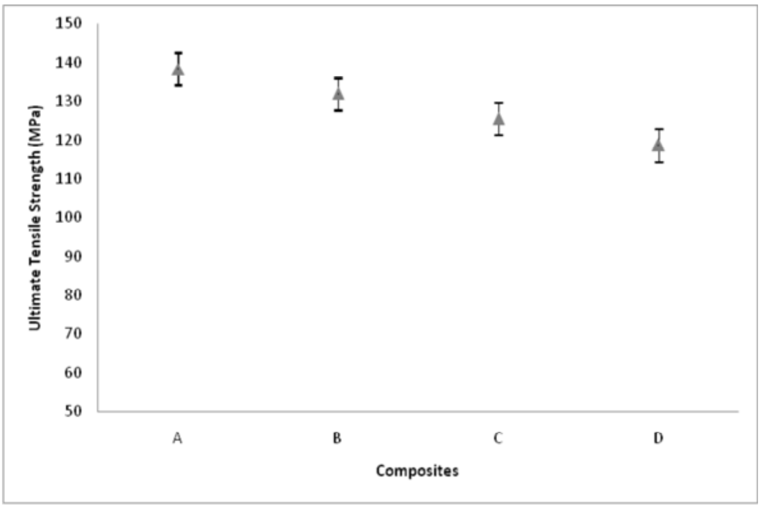


Fig. 4. Variation of tensile strength for the single reinforced Al-Mg-Si/10 wt% Al_2O_3 and hybrid reinforced Al-Mg-Si/BLA-Al_2O_3 composites.

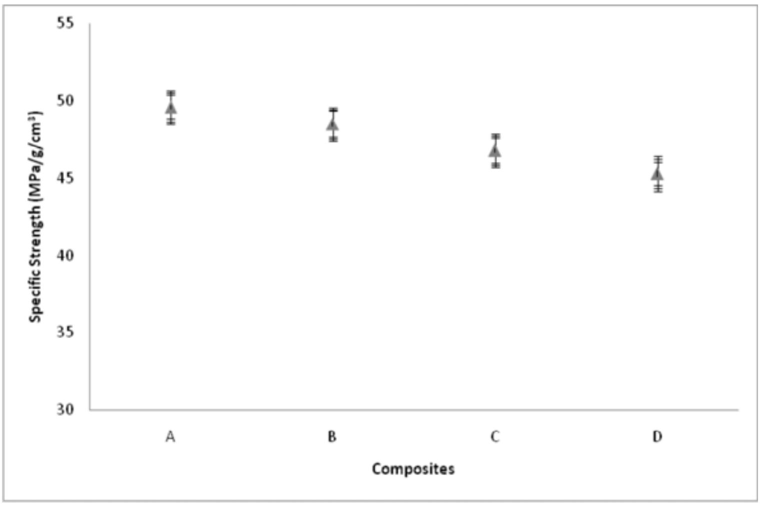


Fig. 5. Variation of Specific Strength for the single reinforced Al-Mg-Si/10 wt% Al_2O_3 and hybrid reinforced Al-Mg-Si/BLA-Al_2O_3 composites.

Figure 6 which is the plot of strain to fracture shows that the hybrid composites containing 2 and 3 wt % BLA had a superior elongation in comparison to the single reinforced Al-Mg-Si/ 10 wt % alumina composite. This indicates that the hybrid composites containing 2 and 3 wt % BLA have a superior ductility levels and a higher capacity to sustain plastic deformation in comparison with the single reinforced composite.

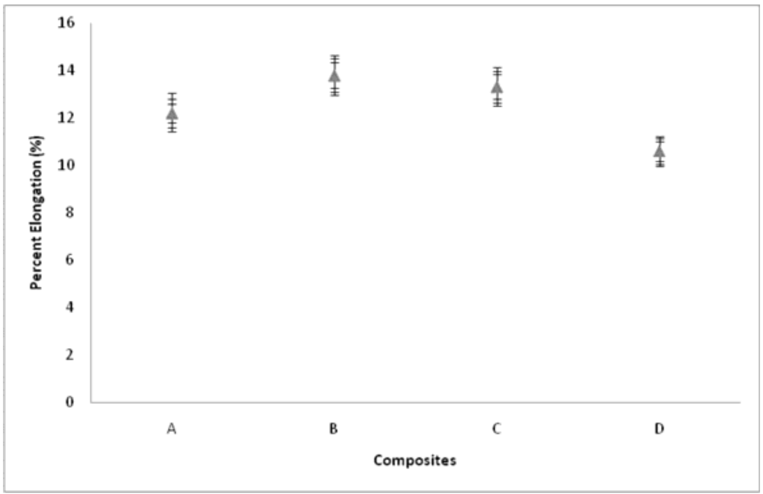


Fig. 6. Variation of Percent Elongation for the single reinforced Al-Mg-Si/10 wt% Al_2O_3 and hybrid reinforced Al-Mg-Si/BLA-Al_2O_3 composites.

Fracture Toughness

The fracture toughness values determined by the use of circumferential notched tensile (CNT) specimens are presented in Figure 7.

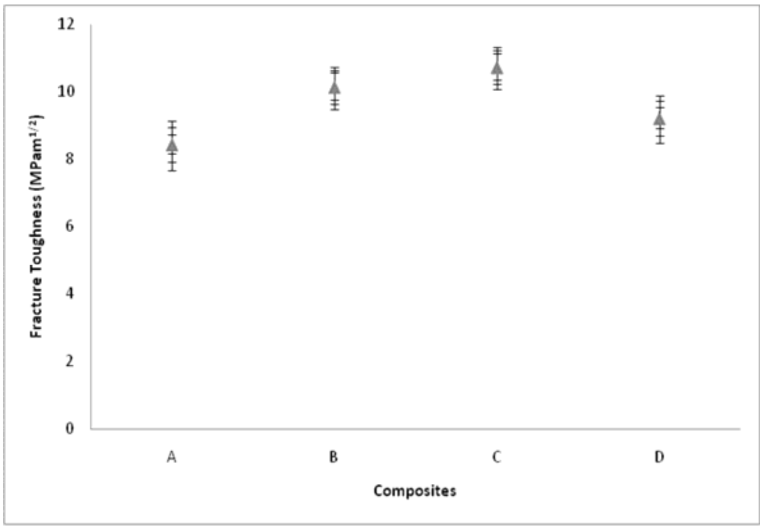


Fig. 7. Variation of fracture toughness for the single reinforced Al-Mg-Si/10 wt% Al_2O_3 and hybrid reinforced Al-Mg-Si/BLA-Al_2O_3 composites.

The values obtained were reported as plain strain fracture toughness because the conditions for valid K_{1C} (plain strain condition) were valid with the specimen diameter of 6mm when the relation $D \geq (K_{1C}/\sigma_y)^2$ [25] was utilised to validate the results obtained from the CNT testing. It is observed that the fracture toughness of the hybrid composites containing BLA were superior to that of the single alumina reinforced composite. Similar observations were made with respect to the use of RHA [19] which suggests that the use of both agro waste ashes (BLA and RHA) as complementing reinforcement to alumina does not compromise the fracture toughness of the Al-based composite. The improved fracture toughness is most likely due to the reduced amount of relatively harder and brittle alumina particles in the hybrid composites. The alumina particles like most hard and brittle ceramic particles have a higher tendency to undergo rapid crack propagation [29,30].

Conclusions

The mechanical behaviour of Al-Mg-Si alloy matrix composites containing 0:10, 2:8, 3:7, and 4:6 wt % bamboo leaf ash (BLA) and alumina as reinforcements has been investigated. The results show that:

1. The hardness of the hybrid composites decreases slightly with increase in BLA content with a maximum reduction of less than 9% observed for the Al - 4 wt% BLA – 6wt% Al_2O_3 composition(in comparison with the Al-10 wt% Al_2O_3 single reinforced composition).
2. Tensile strength reductions of 4.7, 9.32, and 14.3 % were obtained for the composites containing 2, 3, and 4 wt % BLA, respectively. On the other side, specific strengths of hybrid composites 2.24, 5.58, and 8.73 % lower were observed for the 2, 3, and 4 wt% BLA, respectively.
3. The elongation of the 2 and 3 wt % BLA containing hybrid composites were higher than that of the single alumina reinforced composite.
4. The fracture toughness of all hybrid composite compositions was superior to that of the single reinforced composite.

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