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[1.] M.O. BODUNRIN, [2,3.] O. P. OLADIJO,
[4.] O.O. DARAMOLA, [5.] K. K. ALANEME, [6.] N. B. MALEDI

POROSITY MEASUREMENT AND WEAR PERFORMANCE OF ALUMINIUM HYBRID COMPOSITES REINFORCED WITH SILICA SAND AND BAMBOO LEAF ASH

[1,4.] Dept. of Metallurgical & Materials Engineering, Federal University of Technology, Akure, NIGERIA
[2,5.] Department of Mining and Metallurgical Enginering, University of Namibia, Ongwediva, NAMIBIA
[2.] DST/NRF Centre of Excellence in Strong Materials, SOUTH AFRICA
[6.] School of Chemical & Metallurgical Engineering, University of the Witwatersrand, SOUTH AFRICA

ABSTACT: The influence of Igbokoda silica sand and bamboo leaf ash (BLA) on the porosity and wear performance of Al6063 hybrid composites was investigated. The composites were produced using a two-step stir casting technique. Different mix ratios of the silica sand and BLA reinforced aluminium composite grades were produced. Density measurements, micro-hardness testing, abrasive wear tests and SEM examination were used to evaluate the performance of the composites. The results show that the composites became less dense with increasing BLA content. Porosity increased as the quantity of BLA exceeds 2.5 wt. %, while the hardness reduced. Single reinforced Al6063-10 wt. % silica sand composite had superior wear resistance when compared to all the composites containing more than 2.5 wt. % BLA. However, hybrid Al6063-7.5 wt. % silica sand/ 2.5 wt. % BLA has slightly improved wear resistance in comparison with single reinforced Al6063-10 wt. % silica sand composite.
Keywords: bamboo leaf ash; silica sand; hybrid composites; abrasive wear; stir casting; agro waste

1. INTRODUCTION

The increasing research interest on the synthesis and characterization of discontinuously reinforced aluminium matrix composites (DRAMCs) is informed by the demand for high performance engineering materials (1). DRAMCs possess good strength –to-weight ratio, improve machine efficiency, minimise fuel consumption as well as environmental pollution. They are applicable as one of the first choice materials in automotive and aerospace industries (2). They often have superior wear resistance when compared with unreinforced aluminium alloys and are usually used for manufacturing automobile parts like brake disk, piston, cylinder liners, valves, gears, pulleys, connecting rods and engine blocks (3). Other characteristics that have extended the application of these materials from automotive and aerospace industries to marine, defence, sports and recreational firms include: isotropic mechanical properties, amenability to conventional production techniques, flexibility of obtaining tailored property combinations and possibility of using less expensive raw materials (4,5).

The use of less expensive reinforcing materials in place of conventional synthetic reinforcements such as silicon carbide (SiC), tungsten carbide (WC), boron carbide (B_4C), alumina (Al_2O_3) have received a lot of attention in the past few years especially in the developing countries (6). This is due to the limited availability and high cost of synthetic reinforcing materials. These inexpensive reinforcing materials are usually natural ceramic deposits, agro-waste and industrial waste derivatives. Fly-ash (7), red-mud(8,9), bamboo leaf ash (BLA)(10), rice husk ash (RHA)(11), bagasse ash (12,13), coconut shell ash (14) and sillimanite(15) are among the inexpensive reinforcing materials that have been investigated as single or hybrid reinforcing materials used in the development of aluminium matrix composites. Despite the increasing use of less expensive reinforcing materials, researchers are more focused on agro and industrial waste derivatives while limited attempts have been made concerning the utilization of solid minerals like granite, corundum, kaolinite among others as possible reinforcements in DRAMCs (15).

The benefits of using these derivatives apart from low cost include: availability, low density, which improves the specific strength of the composites and high percentage of silica and alumina in the chemical composition of these derivatives. Silica and alumina are among the reinforcing materials that are mostly utilized in the development of DRAMCs. It is worth mentioning that silica sand which is rich in silica can be found in large quantities in a number of deposits in Nigeria (16). Thus, it can be looked at as a possible source of less expensive reinforcing materials for DRAMCs. Several investigations have been carried out on the various silica sand deposits in Nigeria (16,17) and it has been reported that Igbokoda silica sand had about 98% silica (17). However, this abundant resource is yet to be fully harnessed. Although Igbokoda silica sand has been found to be comparable to Ottawa silica sand for geotechnical applications (17), it also has good moulding properties for foundry applications, but its suitability as a good reinforcing material for development of DRAMCs has not been investigated. According to Raw Materials Research and Development Council (RMRDC) (18), silica sand is underutilized in Nigeria and there is a need for further research to unveil the potential benefits of silica sand in the country. This research work considered the development of DRAMCs reinforced with silica sand and bamboo leaf ash. The incorporation of the BLA- an agro waste derivative, was to assess the viability of reducing the density of the composites and studying its effects on the wear performance of the composites. This was envisaged as a way of satisfying current engineering demand for lighter, stronger and affordable materials (19). The density of Igbokoda silica sand is about the same with aluminium (2.65 g/cm^3) while that of BLA is 0.35 g/cm^3. This is expected to have a significant effect on reducing the density of the composites. Wear behaviour and corrosion performance of composites are important phenomena to be carefully considered in the development composite materials as they have influence on the life span of the materials in service. The difficulty in predicting the wear behaviour of DRAMCs is ascribed to wear resistance depending on a number of extrinsic (load, sliding velocity, surface finish, environmental temperature) and intrinsic factors (reinforcement size, reinforcement type and reinforcement shape, reinforcement volume fraction and matrix microstructure) (20). In addition, reports suggesting that some DRAMCs have wear resistance that are inferior or comparable to the unreinforced alloys(20,21). This has made it necessary to investigate the wear behaviour of newly developed DRAMCs as it will provide information for material selection purposes.

Table1. Elemental Composition of Al 6063 alloy (22)

Element	Wt. %
Si	0.4002
Fe	0.2201
Cu	0.008
Mn	0.0109
Mg	0.3961
Cr	0.0302
Zn	0.0202
Ti	0.0125
Ni	0.0101
Sn	0.0021
Pb	0.0011
Ca	0.0015
Cd	0.0003
NA	0.0009
V	0.0027
Al	98.88

2. EXPERIMENTAL PROCEDURE

2.1. Materials

The materials utilised in this research work are aluminium (6063) alloy with composition shown in Table 1, silica sand and bamboo leaf ash (BLA). Al 6063 alloy with predetermined composition was supplied by Tower Aluminium Nigeria Plc.

Table 2. Chemical composition of Igbokoda Silica Sand (17)

Compound	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	CaO	K_2O	Na_2O	MgO
Wt. %	94.24	0.87	1.47	0.48	0.90	0.82	0.75	0.47

2.2. Preparation of Silica Sand

Silica sand obtained from Igbokoda, a riverine community in Ilaje area of Ondo state, Nigeria was thoroughly washed with water to remove impurities and later dried in open air for five days. Thereafter, the sand was pre-treated in the furnace at a temperature of 250 °C for 2 hours to eliminate moisture. Ball mill was used to grind the silica sand in order to reduce the particle size. After grinding, the silica sand was sieved to <75 µm using sieve shaker.

2.3. Preparation of Bamboo Leaf Ash

The bamboo leaf ash was prepared following the procedures described by Alaneme et al (22). The dried leaves were gathered from the Federal University of Technology Akure environs. The leaves were placed in a metallic drum, fired and allowed to burn completely in open air (Figure 1). The resultant ash obtained from the combustion process was allowed to cool for 24 hours before removal from the drum. The ash was then conditioned using a furnace at a temperature of 650 °C for 3 hours. The conditioned ash was sieved using a sieve shaker having different screens. Bamboo leaf ash of particle size < 50 μm was finally obtained and used as reinforcing material for producing the composites.

a) b) c)

Figure 1. a) burning dried bamboo leaf. b) as-received bamboo leaf ash. c) bamboo leaf ash after conditioning in muffle furnace at a temperature of 650°C for 3 hours.

Table 3. Chemical composition of Bamboo Leaf Ash (BLA) (22)

Compound	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	CaO	K_2O	MgO
Wt. %	75.9	1.22	4.13	0.20	7.47	5.62	1.85

2.4. Production of Composites

The composites were produced via a two-step stir casting technique described by Alaneme and Aluko (23). This involves carrying out charge calculation to determine the quantities of silica sand and BLA needed to produce 10 wt. % particulate reinforced Aluminium based composites. Weight ratios of mixed silica sand and BLA reinforcing phase produced are shown in Table 4. Al6063 alloy was charged and heated in a gas fired crucible furnace to a temperature of 750°C above the liquidus. The liquid aluminium alloy was then allowed to cool down to a semi-solid state at about 600°C. At this stage, the preheated silica sand and BLA was introduced into the molten alloy and stirred manually for 5-10 minutes. The preheating of the silica sand and BLA was done before adding to the melt to reduce dampness of the reinforcing materials and to improve wettability. The composites slurry was later superheated to a temperature of about 850°C and a second stirring was carried out mechanically at a speed of 450 rpm for 10 minutes to improve the distribution of the reinforcing particles in the matrix. The molten composites were later poured into a prepared sand mould to produce as-cast Al6063 based composites reinforced with silica sand and BLA.

Table 4. Designation of composite samples produced

No.	Reinforcement Mix Ratio	Interpretation
A	1:0	Al6063- 10wt% Silica sand
B	3:1	Al6063- 7.5wt% Silica sand/ 2.5 wt.% BLA
C	1:1	Al6063- 5.0 wt.% Silica sand/ 5.0 wt.% BLA
D	1:3	Al6063- 2.5 wt.% Silica sand/ 7.5 wt.% BLA
E	0:1	Al6063- 10 wt.% BLA

2.5. Microstructure

The as-cast microstructures of the composites were examined using a scanning electron microscope to assess the distribution of the reinforcements in the Al6063 matrix. Energy dispersive spectrometry (EDS) was also carried out to identify the elements in the composites.

2.6 .Density Measurement

The densities of the composites were determined to evaluate the porosity levels in the as-cast composites. Experimental densities and calculated densities were used to compute the percent porosity using equation 1.

$$\%\ Porosity = \{(\rho c - \rho Ex) \div \rho c\} \times 100 \qquad (1)$$

Where, ρc and ρEx are calculated and experimental densities respectively.

Experimental densities were determined by dividing the measured mass of each sample by its measured volume while calculated densities were obtained from rule of mixtures given by:

$$\rho c = wt.m \times \rho m + wt.q \times \rho q + wt.r \times \rho r \qquad (2)$$

where ρc , ρm , ρq and ρr are the densities of the composites, Al6063 matrix, silica sand and BLA respectively while wt. m, wt. q and wt. r, are weight fractions of Al6063matrix, silica sand and BLA respectively.

2.7 .Hardness Test

Samples were machined from the bulk composite materials for hardness test. The machined samples were polished to obtain a flat and smooth surface finish before the test. The tests were conducted on Vickers Microhardness Tester using diamond indenter at an applied load of 300g for 10 seconds. Five measurements were taken for each sample and the average hardness was determined. Hardness was calculated from the relation:

$$Hv = 1854.4 \times F/d^2 \quad (3)$$

where Hv is the Vickers hardness, F is the load (g) and d is the diameter of the indenter (μm).

2.8 .Wear test

The composites were subjected to dry abrasive test on a three body abrasive tester. Prior to the test, 10mm thick rectangular specimens with dimension of 75mm x 20mm were machined from each composite sample. The specimens were cleaned with acetone, dried and weighed on a high precision digital weighing balance (0.1 mg accuracy) to obtain the initial weight. Similar to Patnaik et al. (24), the abrasive tester is designed such that the flat test sample was pressed against a rotating wheel with a force of 20N by means of a lever arm. The rotating speed of the wheel was maintained at 200 rpm. Angular shaped quartz of ASF 60 grade served as the abrasive particle. The abrasive particles were introduced into the contact area between the test sample and the rotating chlorobutyl rubber wheel at a flow rate of 4.3g/s. The diameter of the chlorobutyl rubber wheel used was 228 mm and the hardness was 58 (Durometer-shore A). The abrasive wheel rotates in such a way that it's contacting face moves in the direction of sand flow. The wheel rubs the abrasive particles on the surface of the samples, creating a three body abrasive wear. At the end of each test, the specimen was removed, cleaned and reweighed to obtain the final weight. At least three tests were performed for each composite and the average values of weight loss was used to determine the volume loss and specific wear rate from the following relations:

$$Vl = (\Delta m/\rho) \times 1000 \quad (4)$$

$$Ws = \Delta m/\rho tFV \quad (5)$$

Where Vl is the volume loss (mm^3); Δm is the mass loss (gm); ρ is the density (gm/mm^3); t is the test duration (sec); F is the load (N) and V is the sliding velocity (cm/sec)

The weight loss was obtained by subtracting the final weight from the initial weight. The wear mechanisms were established by examining the surface topography of the worn surfaces of the composites using SEM- secondary electron imaging.

3. RESULTS AND DISCUSSION

3.1.Microstructure

Figure 2 shows the representative SEM photomicrographs of as-cast Samples A and E. It is observed that the reinforcements (Silica sand for sample A and BLA for sample E) are well dispersed within the Al6063 matrix. Also, it is evident that the silica sand reinforcement in Figure 2a appears to be scanty than that of BLA in Figure 2b. This is due to the higher volume percent of BLA arising from its much lower density ($0.35g/cm^3$) when compared to that of silica sand ($2.56g/cm^3$). The as-cast microstructures also reveal more pores in Al6063/ 10 wt. % BLA (sample E) when compared to Al6063/ 10 wt. % silica sand. The EDS profile in Figure 2c and 2d show peaks of aluminium, oxygen (O), silicon(Si), magnesium(Mg), potassium(k) and iron(Fe). The presence of constituents derived from silica sand and BLA (SiO_2, Al_2O_3, MgO, K_2O and Fe_2O_3) in the composite produced was confirmed by the oxygen peak.

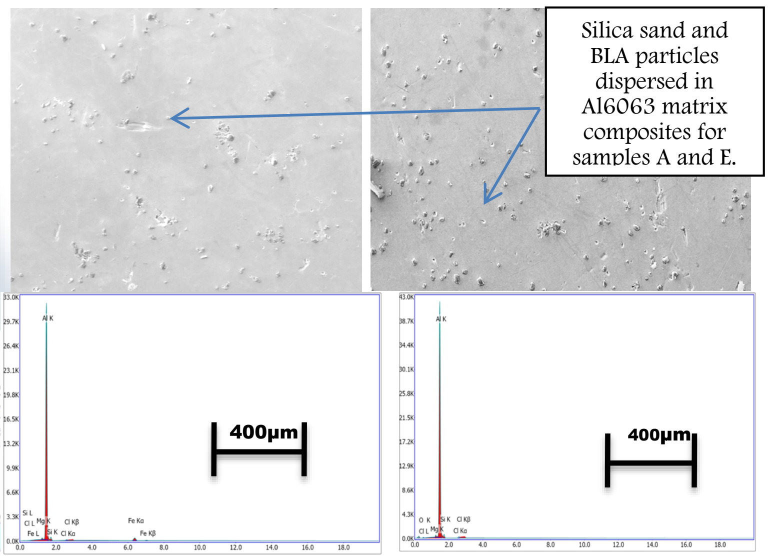

Figure 2. a) SEM photomicrograph of Sample A- Al6063/10wt. % silica sand composite b) SEM photomicrograph of Sample E- Al6063/10wt. % BLA c) EDAX profile obtained from sample A- Al6063/10wt. % silica sand composite d) EDAX profile obtained from sample E- Al6063/10wt. % BLA.

3.2.Density Measurement

Table 5 shows density, percent porosity and hardness of the single and hybrid reinforced Al6063 matrix based composites. As expected, the calculated and experimental densities of the composite reduced with an increase in BLA. This is due to the low density of the BLA ($0.35g/cm^3$) as compared with that of the aluminium alloy ($2.7g/cm^3$) and silica sand ($2.65g/cm^3$). Single reinforced Al6063 – 10wt. % silica sand composites have the highest density while Al6063 – 10 wt. % BLA has the lowest density.

Table 5. Density and Hardness of the Composites

Composite Samples		Density (g/cm^3)		Percent	Hardness
		Calculated	Experimental	Porosity (%)	(VHN)
A	Al6063- 10wt% Silica sand	2.695	2.650	1.67	64.60
B	Al6063- 7.5wt% Silica sand/ 2.5 wt.% BLA	2.638	2.610	1.06	59.86
C	Al6063- 5.0 wt.% Silica sand/ 5.0 wt.% BLA	2.578	2.510	2.64	53.28
D	Al6063- 2.5 wt.% Silica sand/ 7.5 wt.% BLA	2.522	2.454	2.68	52.24
E	Al6063- 10 wt.% BLA	2.465	2.383	3.33	50.44

The hybrid composites containing varied proportions of silica sand and BLA had their density reduced with increasing BLA content. The calculated densities for the single and hybrid reinforced Al6063 matrix composites were more than experimental densities. This suggests that the composites contain porosity.

Table 6. Effect of BLA on the density reduction and porosity of single and hybrid reinforced Al6063 -silica sand/ BLA

Samples	A	B	C	D	E
Reduction in Density (%)	-	1.5	5.2	7.55	10
Effect on porosity (%)	-	36	-58.1	-60.3	-62.2
Effect on specific wear loss (%)	-	6.25	-25	-37.5	-43.75

"- sign" represents adverse effect on the composites.

The effect of BLA on the densities and porosity of the composites was evaluated by using sample A (Al6063- 10wt% Silica sand) as a point of reference to determine how much reduction in density is obtained with increasing BLA content. As shown in Table 6, replacing 2.5wt% of silica sand of the reinforcing phase in sample B (Al6063- 7.5% Silica sand/ 2.5% BLA), a marginal reduction in density of about 1.5% was obtained, but it is worthy of note that, a reduction of 36% in porosity levels was achieved for this composite. It is thought that, the reduction in porosity can be attributed to the filling of pores by the finer BLA particles in the composites and strong interfacial bonding existed between the larger sized silica sand reinforcement and the matrix. As the amount of BLA increased from 2.5 wt. % to10 wt. % in samples E (Table 5), the density of the composites reduced by 10% but the porosity in the composites increased to 62.2% as shown in Table 6. The increase in porosity levels as BLA content increases was far higher than the reduction in density. The increase in porosity can be attributed to the increase in particle to particle contact of the BLA, which is finer in size than the silica sand particles. The particle to particle contact could have led to weak interfacial bonding between the matrix and particles and promoted residual pores in the composites. Thus in agreement with the work reported by Zuhailawati (25).

3.3. Hardness

The hardness of the single and hybrid reinforced Al 6063 based composites are shown in Table 5. It is observed that the hardness of the composites decreased with the addition of BLA. Single reinforced Al 6063-10 wt. % silica sand has the highest hardness value while Al (6063) -10 wt. % BLA has the least hardness value. The addition of 2.5 wt. % BLA in sample B reduced the hardness of the composite by 7.3%. As the content of BLA increases in the reinforcing phase, the hardness values reduced by 17.5%, 19.0% and 21.9% for samples C, D and E respectively. The reduction in hardness can be ascribed to the poor interfacial bonding and increased porosity in sample C, D and E. Also, the presence of higher percent of other BLA constituents (Al_2O_3, Fe_3O_2, MgO, K_2O) which have lower hardness in comparison to silica is likely to be responsible for the reduced hardness of the composites as the BLA content increased.

3.4. Abrasive Wear Behaviour

The variation of specific wear loss for the single and hybrid reinforced Al6063 based composites are shown in Figure 3. The result shows that the wear loss increased with increasing BLA content. The hybrid composites containing 7.5 wt. % silica sand and 2.5 wt. % BLA had the least wear loss as compared to other composites. This may be attributed to the lower porosity levels in the composites in comparison with other composites. Sample A containing 10 wt. % silica sand despite having the highest hardness value exhibited inferior wear resistance to Sample B containing 7.5 wt. % silica sand and 2.5 wt. % BLA. The variation of volume loss for the single and hybrid composites (Figure 4) in agreement with Figure 6 revealed that sample A (the single reinforced Al(6063)/10 wt. % silica sand composites) had superior wear resistance to other composites samples except sample B (7.5 wt. % silica sand and 2.5 wt. %).

The influence of hardness on the wear resistance of materials has been reported by researchers (27). Several equations and reports have established the inverse relationship between the abrasive wear rate and hardness of materials. According to Rabinowicz equation(28), the higher the hardness of materials, the lower the abrasive wear rate. This condition holds for the composites samples investigated in this research except for sample B where improved abrasive wear resistance was observed to have slightly improved compared to sample A despite having superior hardness. The introduction of 2.5 wt. % BLA in sample B improved the wear resistance of the composites by 6.25% in comparison with sample A that contains 100% silica sand. However, further increase in the amount of BLA in the reinforcing phase depleted the wear resistance of the composites. When 5.0 wt. % BLA was added to the reinforcing phase (Tables 4) the composite became less dense by 5.2% but the wear resistance was lowered to about 25%. Poor interfacial bonding between the matrix and the reinforcing phase owing to large BLA to BLA contact as BLA content increased in the reinforcing phase may likely be the reason for the drastic drop in wear resistance.

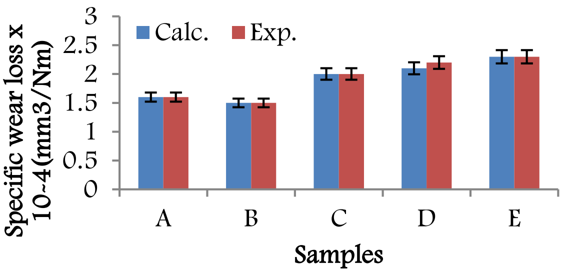

Figure 3. Variation of specific wear loss for the single and hybrid reinforced Al 6063 based composites

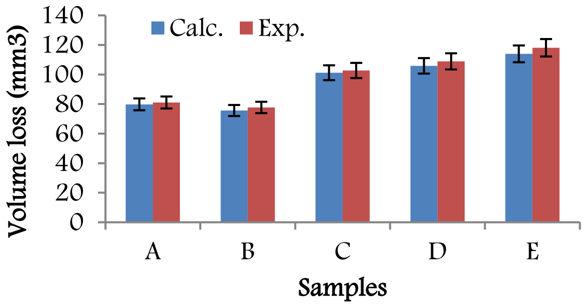

Figure 4. Variation of volume loss for the single and hybrid Al 6063 based composite

Bhansali and Mehrabian in (29) studied the three body abrasion resistance of Al2014 and Al2024 composites reinforced with alumina and silicon carbide particles. They found that the components containing Al_2O_3 particles were superior to those containing SiC. They attributed this to the superior fracture toughness of alumina to silicon carbide as well as the weak bond between the SiC and Al2024 matrix which was promoted by the formation of Al_3C_4 phase. The negative influence of Al_3C_4 phase on the properties of aluminium based composites has been reported (30,31). However, the formation of this phase is unlikely in silica sand and bamboo leaf ash reinforced Al6063 based composites due to high amount of silica contained in reinforcing materials. It has been reported that silica prevents the formation of Al_3C_4 phase in aluminium based composites(32).

Anandkumar et al. (33), investigated the effect of abrasive particle on the resistance of composite. He found that when the hardness of the abrasive particles equals the hardness of the reinforcement, grooving of the abrasive particles is interrupted by the reinforcement particle hence decreasing the wear rate. In this research, quartz (which is essentially silica) was the abrasive particle and the reinforcing materials include silica sand and BLA both containing 99% and 75% of silica respectively. It can be concluded that the improvement in wear resistance of sample A in comparison with sample C, D and E is likely due to the equal hardness of silica sand reinforcement and that of the abrasive particles. Sample C, D and E contained larger proportion of BLA which only contains 75% silica and the hardness of the other constituents (Fe_2O_3, MgO, K_2O, CaO) being lower than that of silica(34) could have resulted in the increased wear rate of these composites. Selective grooving of the BLA particles in the reinforcing phase could also be as a result of the smaller particle size of BLA.

The effects of reinforcement particle size on the wear resistance of composites have been well investigated (35,36). Al-Rubaie et al. (37), reported that reinforcement with larger particle sizes possess enhanced abrasive wear resistance than in smaller particle sizes. To understand the wear behaviour of the reinforced samples, the wear scars were examined using SEM. Figures 5a-d show the SEM images of the worn surfaces. Similar wear features (plastic deformation, discontinuous wear grooves and particle pull-out) were observed on all the samples. However, the degree of damage differs among the four samples (i.e. sample A, B, D and E).

The worn surface images of samples A and B revealed fewer and shallow discontinuous grooves and surface distortion compared to samples D and E. The worn surface images of sample A and B were also characterized by micro-cracks and fragmentation of the silica sand into smaller pieces. Particle pull-outs, plastic deformation and deep grooves are the predominant wear mechanisms observed on the worn surfaces of sample D and E. This explains why wear rate increased as the BLA content increases. The deeper plough grooves in these images (figures 5c and 5d) are evidence of poor interfacial bonding resulting from the increase in the particle to particle contact of the smaller sized BLA in the reinforcing phase. It also show that the abrasive particles (quartz) easily grooved

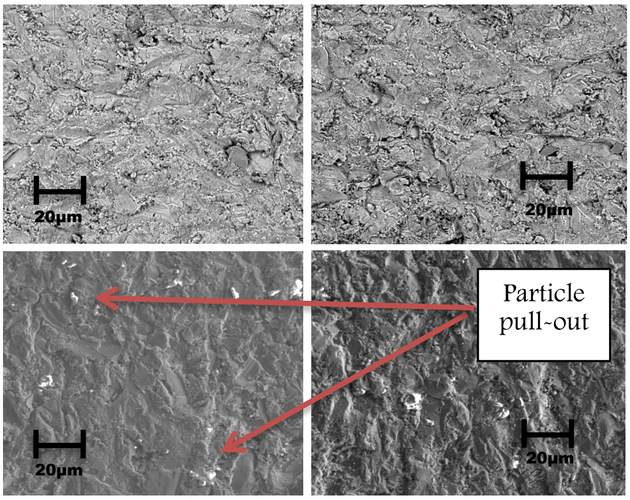

Figure 5. Secondary electron images of worn surfaces of single and hybrid reinforced Al 6063 composites
a)Al6063/10 wt. % silica sand.
b) Al6063/7.5 wt. % silica sand-2.5 wt. % BLA.
c) Al6063/2.5 wt. % silica sand-7.5 wt. % BLA.
d) Al6063/ 10 wt. % BLA

the composites (sample D and E) containing more BLA particles since they are finer and contains more constituents (Fe_3O_2, MgO, K_2O, CaO) that have lower hardness than silica. Higher magnification of the secondary electron images for sample A and B (Figures 6) revealed that the larger sized silica sand particles was able to interrupt the grooving of the abrasives particles due to strong interfacial bonding effect between the matrix and the reinforcement.

Al-Rubaie et al. (37), reported that composites containing reinforcement with smaller particle sizes are easily subjected to plastic deformation during the three body abrasive wear as compared with composites with larger particle sizes. The abrasive particles are more likely to roll in three body abrasive wear rather than sliding between the wheel and the tested specimen therefore enhance plastic deformation. This is clearly evident on the worn surfaces images for all the samples revealed surface distortion.

4. CONCLUSION

The wear behaviour of single and hybrid silica sand and bamboo leaf ash reinforced Al6063 matrix composites was investigated. The following conclusions were made from the results obtained:

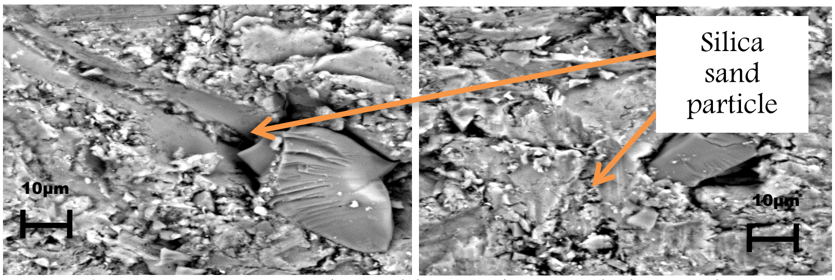

Figure 6. Micro-cracks and large silica sand observed on
a) Al6063/10 wt. % silica sand single reinforced composites and
b) Al6063/7.5 wt. % silica sand-2.5 wt. % BLA hybrid reinforced composites

» The hardness and density of the composites decreased with increasing BLA content.
» The composites became less dense with increasing BLA but the wear resistance depleted. Porosity levels increased as the BLA content exceeds 2.5 wt. %.
» Sample B containing 7.5wt. % silica sand and 2.5wt. % BLA has the lowest level of porosity and the best resistance to abrasive wear.
» The wear mechanism changed from plastic deformation and abrasive wear in sample A and B to plastic deformation, abrasive wear and particle pull out in sample C, D and E where the proportion of BLA in the reinforcing phase was higher.
» Igbokoda silica sand is a viable low cost reinforcing material that can be utilized in the development of cheap aluminium based composites. The addition of BLA to the reinforcing phase should not exceed 25% if the hybrid composite is to be used for wear applications.

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