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RESEARCH PAPER

ASSESSMENT OF TRIBOLOGICAL PROPERTIES OF STIR CAST Al6063 ALLOY REINFORCED WITH OKABA COAL ASH

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ABSTRACT

Composite are multi-phase materials made up of matrix and reinforcement. These materials are innovated to meet the growing needs of modern industries. This paper assesses the tribological property of Al6063 alloy (AMCs) reinforced with Okaba coal ash (OCA) using the stir casting method. By using a constant speed of 1000 rpm and two different loads (250 g and 750 g) on a Taber wear apparatus, the tribological properties of the produced composite are contrasted with those of an unreinforced Al6063 alloy. The results show a reduction in wear index and the highest abrasion resistance at 4 wt.% coal ash at 500 g and 1000 rpm, as well as at 0, 2, and 6 wt.% with 8.688, 5.878, and 5.813 at 500g and 8.688, 5.878, 4.125, and 5.813 at 750g, respectively. Therefore, for all composite products compared to the base metal, there is an increase in abrasion resistance with a decrease in wear index, but this decreases when the load is increased to 750g, showing that the higher the load, the higher the wear index, which results in a reduction in abrasion resistance. As a result, the load is taken into greater consideration when using the AMCs manufactured in any engineering applications. Additionally, SEM images revealed uniform distribution of the OCA reinforcement in the matrix alloy; thereby, improving its wear resistance.

Keywords: composite; matrix; reinforcement; tribological; okaba coal ash

INTRODUCTION

Composites are multi-phase materials made up of matrix and reinforcement. These materials are created to meet the growing need for engineering utilization [1, 2]. Composites typically are two-phase materials that consist of matrix and reinforcement, which were developed to meet the demand of modern engineering thanks to the fact that they exhibit wonderful thermal properties and good mechanical characteristics including higher strength, hardness, fracture, toughness and higher resistance to wear and corrosion [3]. Properties such as resistance to heat, chemicals, and weathering can be easily attained by choosing an appropriate and suitable matrix material with the right reinforcement materials and percentage [4, 5]. The composite industries continue to evolve into using renewable materials as reinforcement in metal matrix composite development. Metal matrix composites (MMCs) as the name implies consist of a metal matrix as the base material and reinforcements. Metal matrix composites over the years have had increased demand in the automobile, marine, aerospace industries due to their fine and enhanced properties like wear resistance, toughness, lightweight, density and so on [6]. Researchers in recent years have focused more on aluminum matrix composites. Aluminum alloys are materials made primarily of aluminum with the addition of other elements. When aluminum is in molten (liquid), the elements are mixed together and cooled to form a homogeneous solid solution which is known as aluminum matrix composite (AMC) [7]. Aluminum matrix composites (AMCs) can be categorized under MMCs as they are termed as novel materials that have piqued the interest of scientists for decades [8]. AMCs have been widely used in a variety of sectors, including automobiles, airplanes, sports, manufacturing, and many more [9]. Al6063 is one of the majorly researched matrices in the 6000 series of aluminium because the matrix alloy being used has low-density, high-thermal-conductivity metal alloy with poor wear resistance [10].
It is a precipitation hardening aluminum alloy with magnesium and silicon as the main alloying constituents [9]. This alloy has excellent mechanical characteristics and weldability. It is one of the most widely used aluminum alloys for general-purpose applications. Hard metals with hard particles have a lot of potential for improving mechanical qualities including Young's modulus, yield strength, and ultimate tensile strength. In terms of mechanical qualities, reinforcements often result in increased strength and hardness, frequently at the loss of ductility [11]. Particulate AMC is made of reinforced aluminum alloy and it is produced mostly using the stir cast method [3]. The increased utilization of AMC in current and future industrial advances is referred to as new technological innovations and growing trends [12]. Particle-reinforced aluminum metal matrix composites (AMC) containing SiC and Al_2O_3 have gotten a lot of attention in recent decades due to their improved wear resistance, reduced coefficient of thermal expansion (CTE), high elastic modulus, and improved strength compared to unreinforced aluminum alloys [5]. Despite their potential applications in weight-critical components in automobile, aircraft, and defense systems, the application base of these particulate AMCs is limited by their high production costs [13]. Also, AMCs have recently been produced using a low-cost aluminum alloy reinforced with coal ash, a waste

by-product of coal combustion. To broaden the application base of this class of AMCs, it has been developed to serve as a substitute for conventional particulate AMCs in numerous applications [14]. The incorporation of coal ash into AMCs is a value-added initiative that reduces coal ash disposal costs, saves energy by reducing the amount of aluminum produced, and improves the environment [13]. For the purpose of this study, the stir casting process was used to create the aluminum matrix composite. Stir casting procedure is one of the most commonly used techniques used in the fabrication of metal matrix composites and most AMCs [3, 15]. The stir casting technique makes sure of the uniform distribution and dispersion of the reinforcement particles with the matrix material thereby granting the resulting composite good wettability and reactivity [16-21]. The use of coal in various industrial applications has increased dramatically in recent years [22-27]. Nigeria has vast coal deposits, which has interested foreign investors to patronize Nigeria since it is cheap and easily available [28]. Coals are used in firing power plants to supply electricity to the populace. Of all the coal deposits in Nigeria, Okaba coal is one of Nigeria's most commonly utilized coals because of its availability and quality [22].

A wide range of research has been performed to get aluminum matrices to sum up with several reinforcement materials for improving the strength-to-weight ratio of the matrix and also reducing the cost of production of composite [29-46]. For instance, Ikubanni et al. [17] utilized palm kernel shell ash and SiC to produce AMCs in which the tribological properties were optimized using Taguchi and Grey's relational analysis. The study demonstrated that speed had a greater impact on performance than load, which in turn had a better impact than the weight percentage of reinforcements in the composite. Using the stir casting technique, Bannaravuri and Birru [47] synthesized a composite with the matrix material A-4.5%Cu using bamboo leaf ash as the reinforcement material. The mechanical properties and tribological properties of the developed composites were strengthened compared to the unreinforced alloy. Also, Arumugam et al. [10] conducted a study on the wear behavior of an aluminum alloy reinforced with B_4C and mica particles. It was concluded that the tensile strength was nearly twice as strong as the base aluminum alloy and that there was a 30% increase in hardness. The optimization of the tribological property of Al reinforced with SiC and graphite particulates using Taguchi's method and artificial neural network was done by Stojanovic et al. [48], where the optimum conditions to attain the best tribological behaviour were obtained. Improvement of the properties such as mechanical properties was observed when fly ash, an industrial waste, was used as reinforcement in developing MMCs [13]. Ahmed & Motgi [49] also utilized nano SiC, fly ash and red mud to develop metal composites using aluminium as the matrix metal. The composites showed improved properties as investigated.

Further utilization of the ash obtained from firing power plants as reinforcement in MMCs development is limited. This study considered to utilize Okaba coal ash (OCA) as a prospective reinforcing material in Al6063 metal matrix for the synthesis of new materials. The ash was incorporated at various weight percentages. The tribological behaviour of the produced MMCs was evaluated with the inference drawn out.

MATERIAL AND METHODS

Materials

Al6063 alloy, which was utilized in this study as the metal matrix, was purchased from a vendor in Akure, Nigeria. Okaba coal ash (OCA) is the reinforcement material utilized in the production of the aluminum matrix composite. To minimize the inherent moisture, the Okaba coal was washed and then sun-dried for 72 h at room temperature. To produce Okaba coal ash, the crushed Okaba coal was then heated to 600ºC for 5 h in a muffle furnace. To increase the homogeneity of the composite, the resulting ash was subsequently sieved to a particle size below 40 µm. The chemical compositions of the metal alloy and the OCA reinforcement are presented in Tables 1a and b, respectively.

Table 1 Composition of Al6063 alloy

Element	**Al**	**Mg**	**Si**	**Fe**	**Cu**	**Cr**	**Zn**	**Ti**	**Mn**
Content (%)	96.85	0.09	0.70	0.60	0.30	0.25	0.20	0.10	0.05

Table 2 Chemical composition of Okaba coal ash [28]

Oxides	**% Composition**
TiO_2	4.11
Al_2O_3	26.02
SiO	44.8
Fe_2O_3	5.68
CaO	10.34
MgO	2.70
Na_2O	0.85
K_2O	1.70
SO_3	2.78
MnO	2.58
P_2O_5	0.44
CuO	0.07
ZnO	0.95
Ag_2O	0.39
BaO	0.19

Methods

In this study, stir casting was used for the preparation of the developed composites. **Figure 1** is a schematic illustration of the stir casting apparatus. This method involves melting the Al6063 alloy in a furnace at a temperature higher than its liquidus temperature (more than 750 degrees Celsius). Before the introduction of the OCA particles into the molten matrix alloy, a pre-treatment of the OCA particulates was done at 250ºC. This pre-treatment is paramount for the removal of impurities, inherent moisture, and for wettability enhancement of the particulates with the matrix alloy. The molten matrix obtained was then permitted to cool down to a semi-solid state in the furnace before charging the preheated reinforcement materials into it. The mixture was properly stirred for 10 mins at a stirring speed of 500 rpm. The slurry was later poured into an already prepared mould and allowed to solidify. The solidified products are displayed in **Figure 2**.

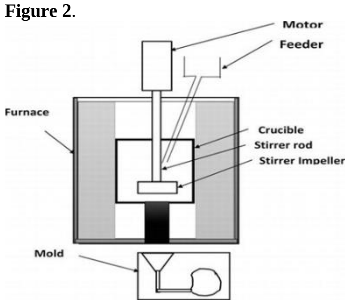

Fig. 1 Stir casting set-up

Fig. 2 AMCs produced at various weight percentages (0, 2, 4, and 6 wt.%) of OCA

Tribological Characterization

The wear resistance of the composite produced was done with the utilization of Taber type Abrasion tester (Model No: TSE-A016) (**Figure 3**) based on ASTM D4060-16 standard. The as-cast MMCs were machined to 100 mm diameter and 4 mm thickness. The samples were fixed on the abrasion machine's turntable platform and were gripped at constant pressure by two abrasive wheels lowered onto the surface of the sample. At a rotating speed of 1000 rpm, two different loads (500 and 750 g) were applied to each sample. During the machine operation, there was the generation of loose composite debris based on the frictional interaction between the sample and the abrasive wheels. The duration of the abrasion testing was 16 mins; thereafter, the weight (mass (g)) loss was determined

Equation (1), while the volume loss (cm3) was evaluated using Equation (2). Equation 3 was employed to evaluate the Taber wear index.

$$Mass\ loss = m_i - m_f \quad (1.)$$

$$Volume\ loss = \frac{mass\ loss}{\rho} \quad (2.)$$

$$I = \frac{m_i - m_f}{T} \times 1000 \quad (3.)$$

where: m_i and m_f are initial and final mass, respectively, ρ is density of each composite composition, T [min] is time of test cycles, I is Taber wear index.

Microstructural Characterization of the Composites

To obtain the surface morphology of the composite, samples are coated with platinum coating of electrically conducting material by low-vacuum sputter coating deposition. Scanning electron microscopy (SEM) (Vega 3 Tescan model) was utilized in obtaining the morphological structure of the developed samples. Samples were cut from the machined rods obtained after production of the composites. To obtain a shining surface preferred for morphological examination, as displayed in grinding and polishing the surface of the samples was done with the aid of different grits of emery paper and polishing clothes. The SEM equipment was, thereafter, loaded with the samples for the examination.

RESULTS AND DISCUSSION

Tribological Analysis

The results of the mass loss, volume loss, and wear index when loads of 500 g and 750 g were applied at a constant speed of 1000 rpm, are presented in **Tables 3** and **4**, respectively. From Tables 3 and 4, the unreinforced alloy showed the highest mass loss, volume loss and wear index compared to the reinforced composites. The lower value is attributed to the improvement in wear resistance obtained from the OCA particles introduced into the matrix alloy. It can be observed that the increase in load leads to the generation of more debris from the metal surface. More so, the increase in the amount of OCA contents as reinforcement in the matrix alloy improved the wear index, which is linked to wear resistance.

Table 3 Test result for 500 g at 1000 rpm

wt.%	Load (g)	Speed (rpm)	Initial mass (g)	Final mass (g)	Mass loss (g)	Volume loss (cm^3)	Wear index (g/min)
0%	500	1000	124.833	124.694	0.139	0.052	8.688
2%	500	1000	114.520	114.426	0.094	0.035	5.878
4%	500	1000	126.697	126.631	0.066	0.025	4.125
6%	500	1000	122.976	122.976	0.093	0.034	5.813

Table 4 Test result for 750 g at 1000 rpm

wt.%	Load (g)	Speed (rpm)	Initial mass (g)	Final mass (g)	Mass loss (g)	Volume loss (cm^3)	Wear index (g/min)
0%	750	1000	124.694	124.545	0.149	0.055	9.313
2%	750	1000	114.420	114.306	0.124	0.046	7.75
4%	750	1000	126.631	126.517	0.114	0.043	7.125
6%	750	1000	122.883	122.783	0.100	0.037	6.25

In **Figures 4** and **5**, the optimum index value can be obtained when the reinforcement percentage was 4 wt.%, at an applied load of 500 g and a speed of 1000 rpm. Hence, the lower the wear index, the better the abrasion resistance. According to the Table 3, where 4 wt.% OCA at 500 g applied load and 1000 rpm has the lowest wear index and has up to 52.53% reduction in wear rate compared to the base Al6063. While 2 wt.%, and 6 wt.% has a reduction of 31.941% and 33.092%, respectively at 500 g load. At 750 g load, the wear rate reduces compared to 500 g, where the highest reduction occurs at 4 wt.% which is 23.49% compared to 52.53% at 500 g load while 2wt.%, and 6 wt.% has a reduction of 25.96% and 32.89%, respectively This indicates that the greater the load, the higher the wear index and the lower the abrasion resistance. This implies that the influence of load is a great factor when reinforcing MMCs. Also, the study by Ikubanni et al. [17], where Taguchi and Grey's relational analysis was used to optimize the tribological properties of the produced MMCs showed that the influence of speed as a factor of performance was higher than load, which in turn was a better-influencing factor than wt. % of reinforcements in the composite.

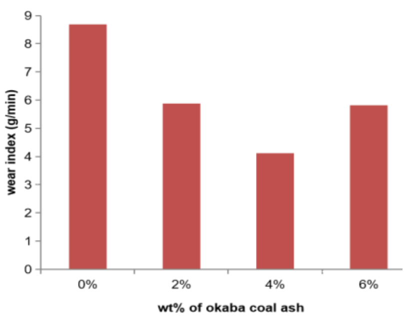

Fig. 4 Effect of OCA wt.% on the wear index for 500 g at 1000 rpm

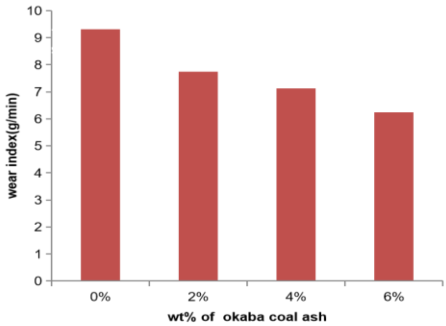

Fig. 5 Effect of OCA wt.% on the wear index for 750 g at 1000 rpm

Microstructural Analysis
The microstructures of the unreinforced alloy and metal matrix composites produced are shown in Figure 6. The micrograph, in Figure 6a, revealed no representation of reinforcement since the sample has no reinforcement addition to the matrix alloy. There is a uniform distribution of the reinforcement particles in the matrix irrespective of the weight percentage (Figure 6b-d). The reinforced MMCs with OCA particles have large and coarse grain sizes which also predict an increase in ductility. Engineering materials with fine and small grain sizes are quite brittle than materials with large and coarse grain sizes which are ductile in nature (Hall-patch relations). This suggests that the composite produced is more ductile than the base aluminum (Al6061) with a fine grain which means it is brittle and also has high strength with low ductility. This result can be attributed to the proper mixing between the reinforcement phase and the base metal using the stir casting method. The addition of Okaba coal ash helps to improve the wettability of the reinforcements and the matrix; thereby increasing the strength of the MMCs. Although, the strengthening mechanism of MMCs is not based on one mechanism on several mechanisms acting simultaneously. It is established that the introduction of hard reinforcement particles into a matrix alloy has the tendency to improve the composites' strength owing to the direct and indirect strengthening mechanisms alliance. The occurrence of direct strengthening has been linked to the load transfer between the matrix alloy and reinforcement particulates, which has the tendency to cause plastic

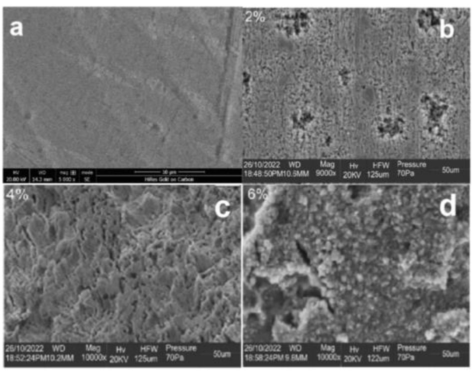

Fig. 6 Scanning electron micrograph of: (a) base aluminum alloy (b) + 2wt% of Okaba coal ash (c) + 4wt% of Okaba coal ash (d) +6wt% of Okaba coal ash

deformation due to increased obstacles; hence, the composites receive superior work hardening ability. However, the indirect strengthening mechanism is attributed to the high thermal discrepancy or mismatch occurrence due to asymmetrical cooling between the matrix (high thermal coefficient of expansion) and reinforcing particle (low thermal coefficient of expansion) [2, 19, 47, 50-54]. These mechanisms are pointers to good microstructural observations in the reinforced matrix alloy.

CONCLUSIONS

The study utilized Okaba coal ash (OCA) as reinforcements in the development of aluminium matrix composite at different weight percentages using the stir casting method. The microstructural examination showed uniformly distributed reinforcement in the matrix, which is capable of improving the strength and wear resistance. The tribological parameters investigated showed that load is an important parameter that influences the volume loss and wear index of the MMCs produced. The introduction of the OCA reinforcement into the matrix has the tendency to improve the wear resistance as the quantity of the reinforcement increases in the matrix alloy. Hence, OCA is viable to be used in the production of metal matrix composites for engineering applications. Further studies should be carried out where OCA would be used as complementary reinforcement along with some synthetic ceramic reinforcements such as SiC, B_4C, Al_2O_3, and so on.

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