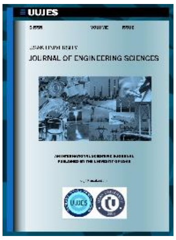

Usak University

Journal of Engineering Sciences

An international e-journal published by the University of Usak

Journal homepage: dergipark.gov.tr/uujes

*Research article*

# EFFECTS OF ZnO AND GRAPHITE PARTICULATES ON MECHANICAL AND WEAR CHARACTERISTICS OF Al-Si ALLOY HYBRID COMPOSITES

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*Received: 13 April 2018 Revised: 17 May 2018 Accepted: 28 May 2018 Online available: 26 June 2018*
*Handling editor: Kemal Mazanoğlu*

## Abstract

Aluminium alloys exhibit some outstanding properties which make them to be widely used in many applications. This study examined the effect of particles of ZnO and graphite on mechanical and wear characteristics of Al-Si alloy hybrid composites developed by stir casting method for automotive application. Zinc oxide and graphite particles were thoroughly mixed in varied weight fractions (11, 14, and 17 wt. %) with Al-Si alloy. The hybrid composite exhibited the highest hardness and tensile strength values of 113.67 VHN and 163.67 MPa respectively at 14 wt. % particles addition. The volume loss during wear increased with speed and load but was marginal in the reinforced samples. The microstructure showed good dispersion of particles of ZnO and graphite in the Al-Si alloy. The mechanical and wear characteristics of the composites were enhanced by the uniform distribution of the ZnO and graphite particles in the Al-Si alloy matrix and the strong adhesion of alloy-particles phases.

***Keywords:*** *Al-Si alloy; hybrid composites; mechanical characteristics; wear characteristics.*



## 1. Introduction

There is increasing demand for materials that are light in weight, strong, and economical especially in automobiles industry. As a result of this, aluminium-silicon cast alloys (Al-Si) and their metal matrix composites (MMCs) are widely used in the production of various automotive engine components such as cylinder blocks and pistons which are often subjected to deformation in service as a result of wear. Their moderate production cost, good castability, appreciable mechanical strength, and recyclability have also been of great advantage. Despite these advantages, their shortcoming is the fact that most Al–Si alloys

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are not very suitable for high temperature applications because their mechanical strengths decrease with increasing temperature. Hence, the addition of reinforcement materials such as zinc oxide and graphite into the Al-Si alloy may improve tensile strength, fatigue strength, and wear properties. This is because graphite is an excellent lubricant at high temperatures.

The density of graphite is low and it is a well-known solid lubricant [1]. In aluminium matrix hybrid composites reinforced by graphite, graphite serves as a solid lubricating layer between the composites and rubbing surface thereby decreasing wear rate without the need for traditional solid and liquid lubrication [2].

There are different methods of producing MMCs on industrial scale such as powder metallurgy (PM) [3], high-energy milling [4] and, severe plastic deformation [5] which are considered as solid state processing. However, the major problems facing these processing methods are contamination resulting from powder preparation and complexity of fabrication steps. Moreover, machining is required to obtain the desired final shape. The other group of the fabrication processes of MMCs is the liquid-state processing, which includes infiltration techniques, stirring techniques, rapid solidification, as well as some in-situ fabrication such as liquid–gas bubbling [6]. These processes offer some advantages compared to the solid-state processing such as energy-efficiency and cost-effectiveness. However, non-homogeneous dispersion or particles agglomeration in the molten matrix during solidification, and pores formation are considered as the problems facing the fabrication of MMCs by liquid-state processes [6]. Hence, one of the most effective and economical method of producing Al-alloy MMCs is the conventional casting methods.

Much research has not been done in developing Al-Si alloy hybrid composites reinforced with zinc oxide and graphite for mechanical and wear properties improvement. Hence, this study aims at developing Al-Si alloy hybrid composite materials by stir casting using graphite and ZnO as reinforcement for automotive application.

## 2. Materials and method

### 2.1. Materials

Zinc oxide (ZnO) and graphite powders were the reinforcing materials while magnesium powder was used as a wetting agent. These materials were purchased from a chemical supplier in Lagos. The materials were manufactured in China while the Al-Si alloy matrix was obtained from piston scrap. Pictures and chemical composition of these materials are presented in Fig. 1 and Table 1.

(a) (b) (c)

**Fig. 1** Photographs of materials (a) ZnO, (b) graphite, and (c) piston scraps.

**Table 1** Chemical composition of the materials.

| Elements/Compounds | Quantity (wt. %) | | |
|---|---|---|---|
| | ZnO | Mg powder | Al-Si alloy piston scrap |
| Al | - | 0.02 | 81.94 |
| Si | - | 0.01 | 13.91 |
| Cu | - | 0.01 | 1.533 |
| Ni | - | 0.01 | 1.099 |
| Mg | - | 99.9 | 0.71 |
| Fe | 0.0003 | 0.01 | 0.504 |
| Zn | - | 0.02 | 0.143 |
| Cr | - | - | 0.023 |
| Pb | 0.02 | - | 0.01 |
| Mn | 0.001 | 0.02 | 0.13 |
| ZnO | 99.5 | - | - |
| Acid-insoluble water | 0.01 | - | - |
| Carbonate ($CO_3$) | 0.05 | - | - |
| Chloride (Cl) | 0.002 | - | - |
| Sulphur Compounds ($SO_4$) | 0.01 | - | - |
| Arsenic (As) | 0.0001 | - | - |
| Cadmium (Cd) | 0.002 | - | - |
| Reducing Substance (O) | 0.0016 | - | - |
| Loss at 600 $^0$C | 0.5 | - | - |

## 2.2. Melting and casting

Each of the samples was prepared and weighed using an electronic weighing balance to give a total of 550 g. The proportion of the materials mixture presented in Table 2 is the weight fraction (wt. %) of 550 g for each of the samples. Measured wt. % of 150 µm graphite and ZnO particles were preheated to 500°C to remove moisture and enhance wettability. Weighed quantity of Al-Si matrix was placed in a crucible pot, charged into a pit furnace as shown in Fig. 2, and heated to temperature of 750°C until molten form was obtained. Appropriate quantities (11, 14, and 17 wt. %) of reinforcing particles were poured into the molten matrix and stirred thoroughly for 10 mins using a long stainless steel rod to avoid clustering and to achieve good dispersion of the particles in the matrix. The slurry was steadily poured into the sand moulds and cured for one hour after which they were removed from the moulds as presented in Fig. 2. Three batches of reinforced samples were produced with varied weight fractions (wt. %) of (a) ZnO particles, (b) graphite particles, and (c) hybrid (equal mixture of ZnO and graphite) particles. Batch A are the Al-Si matrix samples of varied wt. % reinforcement of ZnO particles. Batch B are the Al-Si matrix samples of varied wt. % reinforcement of graphite particles. Batch C are the Al-Si matrix samples of varied wt. % reinforcement of hybrid (equal blend of ZnO and graphite) particles. For 11 wt. % of hybrid (5.5 wt. % ZnO + 5.5 wt. % graphite) particles were blended with 89 wt. % Al-Si matrix. For 17 wt. % of hybrid (8.5 wt. % ZnO + 8.5 wt. % graphite) particles were blended with 83 wt. % Al-Si matrix. The unreinforced (control) samples contain only Al-Si alloy.

## 2.3. Properties characterisations

Microstructural examination was carried out on the developed samples. They were ground and polished to obtain a mirror-like surface. They were then etched using Keller's reagent (95 ml water, 2.5 ml $HNO_3$, 1.5 ml HCl, 1.0 ml HF) by swabbing for 15 secs at room temperature. An ASPEX 3020 model variable pressure scanning electron microscope was then used to examine the microstructure of the samples.

(a) (b)

**Fig. 2** Photographs of (a) mould preparation and (b) pit furnace.

**Table 2** Quantity of materials.

| **Matrix (wt. %)** | **Reinforcement (wt. %)** | | | |
|---|---|---|---|---|
| **Al-Si matrix** | **150 µm ZnO** | **150 µm graphite** | **150 µm hybrid (ZnO + graphite)** | **Total (wt. %)** |
| 100 (control) | - | - | - | 100 |
| | **1st Batch** | | | |
| 89 | 11 | - | - | 100 |
| 86 | 14 | - | - | 100 |
| 83 | 17 | - | - | 100 |
| | **2nd Batch** | | | |
| 89 | - | 11 | - | 100 |
| 86 | - | 14 | - | 100 |
| 83 | - | 17 | - | 100 |
| | **3rd Batch** | | | |
| 89 | - | - | 5.5 ZnO + 5.5 C | 100 |
| 86 | - | - | 7 ZnO + 7 C | 100 |
| 83 | - | - | 8.5 ZnO + 8.5 C | 100 |

C=Graphite particles (wt. %)

An Instron universal testing machine was used to determine the tensile property of the samples at room temperature based on ASTM 8M-91 standard. Circular tensile test piece with one step grip was used with dimension of 6 mm diameter and gauge length of 4 mm. The samples were stressed to fracture while the data generated was used to evaluate the tensile property. The hardness behaviour of the composites was evaluated by using Vickers hardness (VH5) scale (Micro hardness Tester). The samples were prepared by polishing with a silica paper to obtain a flat and smooth surface. A direct load of 5 kg was then applied on each of samples for about 10 secs. The Micro hardness tester was placed on the sample to make indentation at three different positions in the sample and the average reading values were selected.

Dry sliding abrasive wear test was conducted on the samples of dimension 50 mm x 12 mm x 8 mm with the aid of a pin-on-disc wear tester at room temperature. Four normal loads (11.4, 15.3, 19.3, and 23.5 N) were applied using dead weights with disc rotation at 1.31

m/s (low) and 2.62 m/s (high) using a D.C. motor. Sliding occurred between the fixed sample and the rotating disc.

# 3. Results and discussion

## 3.1. Microstructure of samples

The microstructure of the unreinforced Al-Si alloy matrix sample is presented in Fig. 3a while that of the hybrid samples are shown in Figs. 3b and 3c. Generally, the microstructures show fine dendrite grain structure distribution. These dendrite microstructures may be mainly attributed to the high silicon content of the matrix (13.91 wt. %) which is above the eutectic composition (12.6 %) [6]. This is characteristic of unmodified eutectic solidification of an Al-Si system. The SEM micrographs of the hybrid composites show a uniform distribution of graphite and ZnO reinforcement particles within the Al-Si alloy matrix shown in Figs. 3b and 3c with very low agglomeration of particles, and porosity. This indicates that stirring and the method of production adopted are effective.

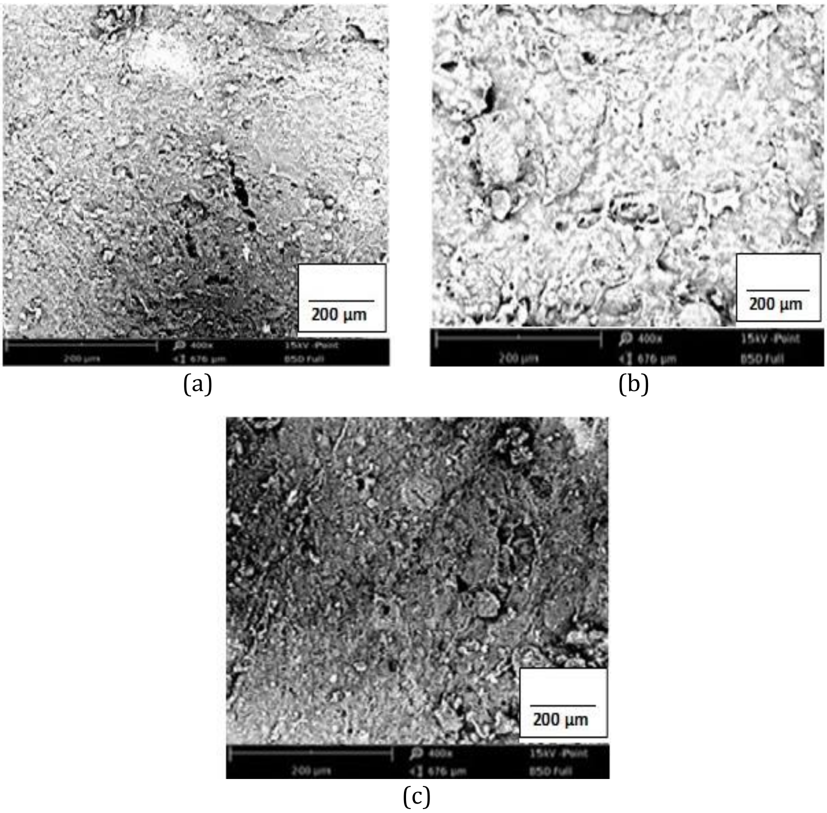



**Fig. 3** Microstructure of the samples (a) unreinforced Al-Si alloy, (b) 14 wt. % hybrid composite, and (c) 17 wt. % hybrid composite.

## 3.2. Hardness

The hybrid composite sample exhibited the highest hardness value of 113.67 VHN at 14 wt. % reinforcement as presented in Fig. 4. The level of hardness exhibited by the reinforced samples is generally higher than the unreinforced Al-Si matrix alloy sample. This shows the ability of the blend of particles of ZnO and graphite in the molten alloy which refined the microstructure. The enhancement of the hardness values is due to the dispersion of particles of ZnO and graphite in the molten alloy and the strong adhesion of the particles-matrix interphase. A decrease in the hardness value is observed at 17 wt. % reinforcement which may be due to the agglomeration of the particles which may result from composites preparation during casting and the higher amount of porosity at higher wt. % reinforcement [6].

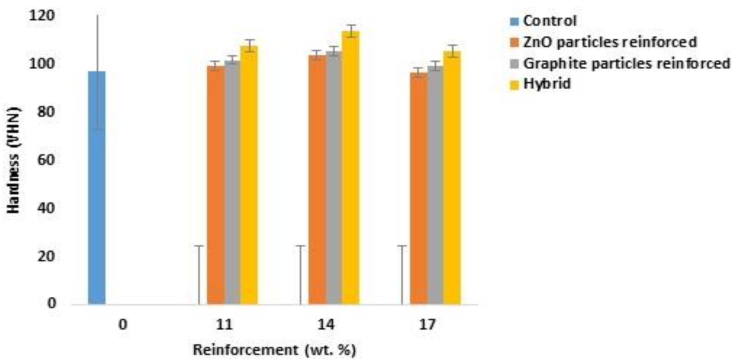



**Fig. 4** Graph of hardness against wt. % reinforcement of the composites.

### 3.3. Ultimate tensile strength

As shown in Fig. 5, the ultimate tensile strength (UTS) of the reinforced samples are greater than the control sample which was not reinforced. At 14 wt. %, the hybrid sample demonstrated the greatest ultimate tensile strength value of 163.67 MPa. This shows the ability of the blend of particles of ZnO and graphite in enhancing the UTS. The good wettability of the particles of graphite and ZnO with the molten piston alloy must have enhanced the adhesion which promoted load distribution [6]. There is a reduction in the UTS of the samples at 17 wt. % reinforcement. This is due to agglomeration of the reinforcing particles which caused weak adhesion between the particles of graphite and ZnO with the molten piston alloy which adversely affected load distribution [7, 8].

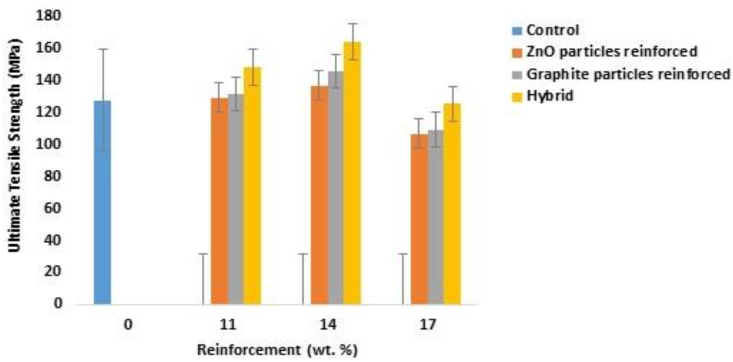
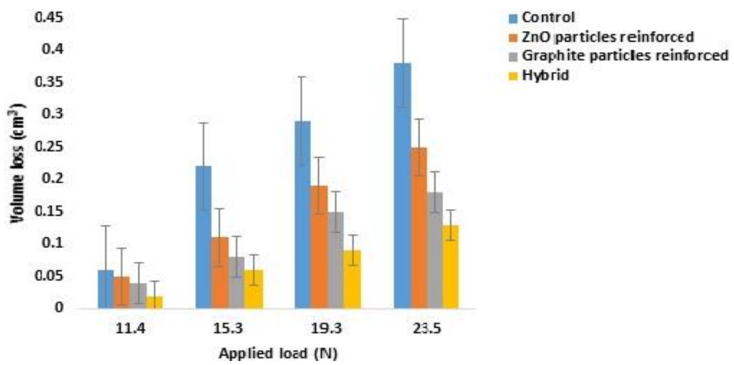


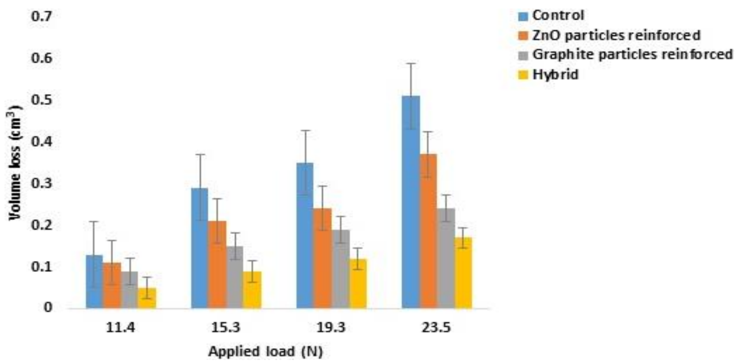

**Fig. 5** Graph of ultimate tensile strength against wt. % reinforcement of the composites.

### 3.4. Wear studies and worn surface analysis

As presented in Figs. 6a and 6b, the volume loss due to wear is higher at high speed (2.62 m/s) than low speed (1.31 m/s) and also increases significantly as the load increases. The unreinforced Al-Si matrix alloy demonstrated greater wear than the reinforced samples. There is always greater wear of materials with increasing load and sliding velocity. Increase in the work done as a result of friction to resist disc rotation during the test must have also caused the increase in wear volume. There is an increase in deformation of the surfaces of the samples due to wear with increasing sliding speed. Increase in surface deformation of the samples increased fractures in contact areas and breaking of asperities. The graphite particles present in the reinforced samples hindered wear due to the fact that graphite has high resistance to wear. High hardness of the reinforced samples must have also contributed to the reduction of wear. Increase in hardness results in improvement of wear and seizure resistance of materials.



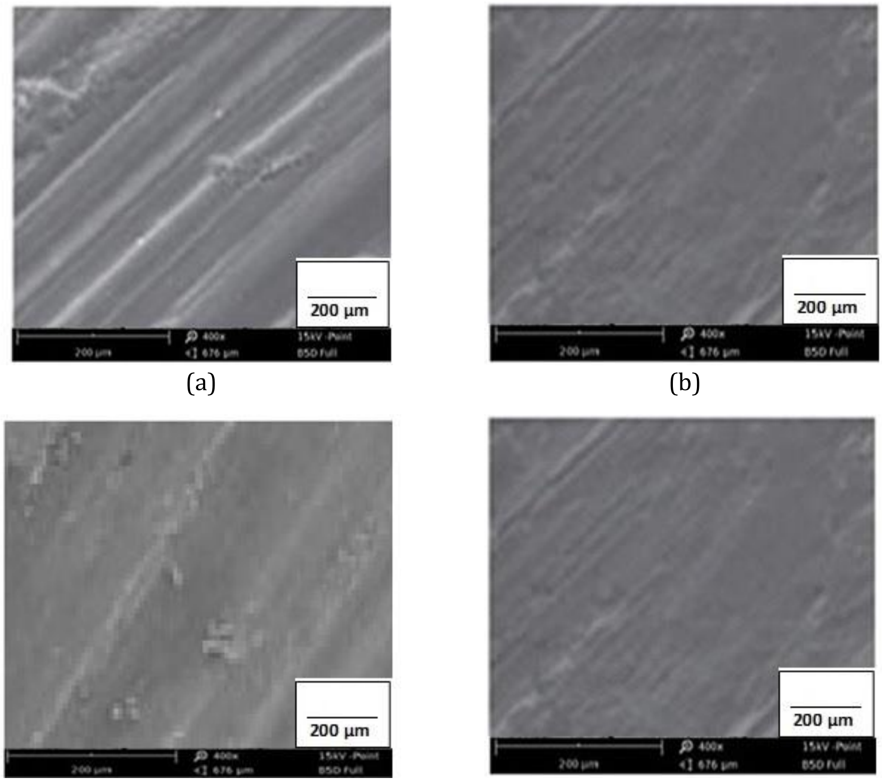

(a)




(b)

**Fig. 6** Wear volumes against load (a) at low speed and (b) at high speed.

It is observed that the microstructure of the surface of the worn unreinforced sample in Fig, 7a shows more severity of deformation than that of the reinforced shown in Figs. 7b, 7c, and 7d. As observed from the SEM micrographs of the reinforced samples of Figs. 7b, 7c, and 7d, there is a reduction in the scratches on the worn surfaces as reinforcement increased. This shows the ability of particles of graphite and ZnO in reducing wear. The wear track is an indication that abrasive wear is the main wear mechanism at lower loads with small amount of de-lamination while adhesion with de-lamination are the major wear mechanisms operating at higher loads and lower speeds. There is much removal of materials at higher loads than at lower loads. The scratches in the micrographs may also be as a result of pulling out of graphite and ZnO particles due to strain hardening of aluminium during sliding with applied load. Weak adhesion of the alloy-particles phases may promote formation of cracks with increasing loads.




(a) (b) (c) (d)

**Fig. 7** Worn surface micrographs of the samples (a) Al-Si alloy piston scrap, (b) 17 wt. % graphite reinforced, (c) 14 wt. % hybrid, and (d) 17 wt. % hybrid.

## 4. Conclusion

In this research, hybrid composite samples reinforced by particles of zinc oxide and graphite have been successfully developed and characterised. The highest hardness value of 113.67 VHN and tensile strength of 163.67 MPa were exhibited by the hybrid samples at 14 wt. % reinforcement. The level of deformation due to wear as a result of increasing speed and load was pronounced in the control sample but was marginal in the reinforced samples. The microstructure showed good dispersion of particles of ZnO and graphite in the Al-Si alloy. The mechanical and wear properties of the composites were enhanced by the uniform distribution of the ZnO and graphite particles in the Al-Si alloy matrix and the strong adhesion of the two phases. Conventional casting method is still an effective method of developing Al-alloy MMCs.

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