MATERIALS ENGINEERING | RESEARCH ARTICLE

Improved mechanical and wear characteristics of hypereutectic aluminium-Silicon alloy matrix composites and empirical modelling of the wear response

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Abstract: For the first time, Silicon Carbide-Zinc Oxide-Graphite reinforced hypereutectic Aluminium–Silicon composites were fabricated by two-step stir casting. The mechanical properties and abrasive wear performance of the composites were experimentally tested. A multilevel factorial design of experiment was conducted to develop a numerical model for predicting the wear rate of composites and optimization of their wear performance as a function of reinforcement characteristics. The results indicated that high content of silicon carbide in the composites superlatively enhanced hardness, tensile strength and fracture toughness by 69.04%, 163.22% and 77.42%, respectively. Correspondingly, high content of graphite indicated superlative wear resistance of 95.87% reduction in wear index while high zinc oxide

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PUBLIC INTEREST STATEMENT

In recent times, aluminium–silicon alloy matrix composites have been considered principally as an alternative and sustainable material for the production of automobile engine block due to its excellent wear resistance it offers over monolithic aluminium alloys. Aluminium alloys were introduced to replace traditional cast iron due to its strength to weight ratio with overall goal of reducing fuel consumption; thereby, cutting down carbon emission to the environment. In the early state of application of this promising material for the production of automobile engine block, the predominant problem reported among many automotive giants was found to be associated with the short life span of the engine block as a result of low wear resistance of the bore, and one of the choices of overcoming this problem is reinforcement of the matrix-based aluminium alloy with high wear resistance particulate materials. In this research, mechanical and wear properties of aluminium–silicon alloy matrix composites were investigated and found suitable for the production of engine block.
content revealed enhanced fracture toughness highly comparable with that observed for high silicon carbide content. Nevertheless, in comparison with the monolithic alloy, the trade-offs in the strains-to-fracture of the composites were more pronounced with high silicon carbide content. The developed 2-factor-interaction effects model strongly agrees with the experimental results after passing various model validity tests available in Design Expert Software. It revealed that the composition of reinforcing constituents influenced the model more than the volume fraction, and the interaction between the composition of reinforcement constituents and volume fraction.

**Subjects:** Mechanical Engineering; Plant Engineering & Maintenance; Manufacturing Engineering; Materials Science

**Keywords:** metal matrix composites; inorganic fillers; design of experiment; wear resistance; mechanical properties

1. Introduction

Recent advances in materials design and their processing technologies have opened myriad channels for researchers to develop lightweight materials with high-performance capability and cost-effectiveness (Daramola et al., 2020; Mallick, 2010). Consequently, the applications of these materials have become pervasive in the built-environment, automotive, aerospace and aeronautical industries (Campbell, 2012; Daramola et al., 2015). One of these materials that have made considerable inroads into the core of the transport industry and of great interest to the present study is Aluminium/Aluminium Alloy-Based Composites (ABCs) (Mavhungu et al., 2017). ABCs are a class of lightweight and high performance advanced materials that offer numerous advantages as structural materials. Some of their attractive properties include high strength-to-weight ratio, anti-corrosion resistance, excellent working temperature range and superior tribological properties (Daramola et al., 2015; Mavhungu et al., 2017). Consolidated superlative properties of each material that constitute the multiphase composites impart attractive combination of properties to ABCs (Mavhungu et al., 2017). Various components in the automotive and aerospace industries that require low density to bring about efficient engine performance and fuel economy are now mostly made of ABCs (Bodunrin et al., 2015; Das et al., 2014; Mavhungu et al., 2017; Singh & Chauhan, 2016). As obtainable in the literature, the latter end of the twentieth century marked the notable advent of the upsurge in the applications of ABCs as structural materials in lieu of ferrous materials (Bodunrin et al., 2015; Das et al., 2014; Daramola et al., 2019; Mavhungu et al., 2017; Singh & Chauhan, 2016). Light metallic alloys and their composites and fibre/filler-reinforced polymer composites are swiftly replacing ferrous materials wherever possible (Bodunrin et al., 2015; Das et al., 2014; Daramola et al., 2019; Mavhungu et al., 2017; Singh & Chauhan, 2016). However, despite the increasing demand for ABCs, there are still some fragmentary challenges that need tremendous research effort in terms of desirable material properties with respect to specific applications (Bodunrin et al., 2015; Das et al., 2014; Daramola et al., 2019; Mavhungu et al., 2017; Singh & Chauhan, 2016). Thorough investigations in this context are ongoing with the exploitation of various reinforcements; most especially agro-industrial ashes, metal oxides/carbides/nitrides and organic/inorganic particles/particulates for selected properties’ improvement in ABCs (Adediran et al., 2018; Bodunrin et al., 2015; Das et al., 2014; Daramola et al., 2019; Mavhungu et al., 2017; Singh & Chauhan, 2016). The prominent downside of this development is the trade-offs in some of the properties of the resultant composites at the expense of other improved ones (Adediran et al., 2018; Bodunrin et al., 2015; Das et al., 2014; Daramola et al., 2019; Mavhungu et al., 2017; Singh & Chauhan, 2016). Although, there are several metallurgical processing routes (Veličković et al., 2017) to eliminate this pitfall, it would be imprudent of material scientists to ignore the adverse effects, the processes incur on the economic viability of developing ABCs. Thus, it is very crucial for researchers to settle for optimization in the course of designing and
developing these materials. One effective way to establish the optimum combination of material properties at the design stage is to adopt a Design of Experiment (DOE) approach. Substantial research findings (Edoziuno et al., 2020; Sharma et al., 2015; Stojanović et al., 2016; Veličković et al., 2017) have shown the capabilities and efficiency of DOE in minimizing experimental time and cost and in developing empirical models for material properties prediction and performance optimization. The prevalent three types of DOE methodologies that have proven impressively reliable in this regard are Taguchi Designs, Factorial Designs (FDs) and Response Surface Models (RSMs) (Edoziuno et al., 2020; Sharma et al., 2015; Stojanović et al., 2016; Veličković et al., 2017). This study considered FD most appropriate for the present investigation. Primarily, this research focused on using Zinc Oxide (ZnO) particles as additional reinforcement for supplementary enhancement of fracture toughness and ductility of as-cast hypereutectic Aluminium (Al)-Silicon (Si) Alloy filled with Graphite (Gr) and Silicon Carbide (SiC) particles. This is the first time ZnO would be introduced alongside SiC and Gr for the development of ABCs. According to previous studies, ZnO particles have demonstrated the ability to improve both strength and ductility of some materials simultaneously, which is attributed to their moderate stiffness (30–250 GPa) relative to that of the selected matrix materials (Tun et al., 2012). However, they are more susceptible to abrasive/dry sliding wear in comparison with SiC and Gr (Selvam et al., 2014). Therefore, it is of paramount importance to establish a satisfactory range of optimum combination of these reinforcements for the best performance of the resultant composites.

In this study, the suitability and reinforcing efficiency of using varied reinforcement compositions and volume fractions of ZnO, SiC and Gr in hypereutectic Al–Si matrix for mechanical and abrasive wear performance enhancement were investigated. In addition, a DOE study with Design Expert Software (Version 11) was conducted on the wear behaviour of the composites to develop a mathematical model for the prediction of wear index of composites and optimization of their wear performance as a function of reinforcement characteristics. The findings of this research are considered satisfactory for researchers to have a comprehensive understanding of the mechanical properties and abrasive wear behaviour of hypereutectic Al–Si alloy reinforced with SiC-ZnO-Gr inclusions. Correspondingly, the findings are expected to serve as pertinent reference material for constitutive model development and validation with respect to abrasive wear performance of ABCs.

2. Experimental

2.1. Materials

The materials used for this work, their properties and the suppliers are shown in Table 1

| Table 1. Properties and Suppliers of the Experimental Materials |
|---------------------|----------------|-------------------|---------------------|-----------------|
| Material            | Elastic         | As-Supplied       | Average             | Supplier          |
|                     | Modulus (GPa)  | Density (g/cm³)   | Particle Size (µm)  |                  |
| Matrix Material     |                |                  |                     |                  |
| Al–Si Alloy (Piston | 68–150          | 2.68              | 30 ± 2              | Local Vendor, Mechanical Village, Ajaokuta, Kogi State |
| Scraps)             |                |                  |                     |                  |
| Reinforcements      |                |                  |                     |                  |
| ZnO (99.5 % Purity) | 30–250          | 5.61              | 30 ± 2              | Pascal Scientific Ltd, Akure, Ondo State |
| SiC (99.99 % Purity)| 419             | 3.16              | 30 ± 2              | Pascal Scientific Ltd, Akure, Ondo State |
| Gr (99.99 % Purity) | 4.7–41          | 2.09              |                     | Online Vendor     |
| Wetting Agent       |                |                  |                     |                  |
| Mg Powder (99.99 %  |                |                  | < 30                | Pascal Scientific Ltd, Akure, Ondo State |
| Purity)             |                |                  |                     |                  |
2.2. Methods

2.2.1. Composites development
Prior to the composites development, low-cost 2-in-1 casting moulds (Figure 1(a)) for mechanical and abrasive test pieces were developed. The need to improve the economic viability of developing the moulds inspired the design. Impressively, the design proved effective by reducing casting duration and quantity of materials needed for the test coupons. Similarly, to improve mixture homogeneity of the constituent materials, the research featured a low-cost and user-friendly automatic stirrer designed with Solid works Software and fabricated by Shielded Metal Arc Welding as shown in Figure 1(b)

To facilitate quick melting of the as-procured Al–Si alloys (piston scraps), they were charged into a clean crucible furnace preheated to 300°C. This approach reduces the oxidation level of the process, which in turn enhances the wettability between Al–Si alloys and the reinforcing constituents (Daramola et al., 2018; Kumar, 2017). The step one of the stir casting process proceeded with heating of the charged Al–Si alloys to 750 ± 30°C. A drop in temperature of the melt to 650°C ensued for convenient removal of impurities from the melt and introduction of second phase particles (already preheated to 500°C). The impurities were removed to achieve effective wettability of the ABCs’ constituents and near porosity-free cast products. Still at 650°C, predetermined reinforcement compositions and weight percent (wt. %) of the SiC, Gr and ZnO (Table 2) with lean addition of Mg powder (wetting agent) and inert CO$_{2}(g)$ (oxidation level minimizer) were added to the melt. Clustering of the particles during dispersion into the melt was avoided with the aid of a particle distributor slightly placed above the crucible. Then, step 2 of the stir casting commenced with manual stirring of the melt for 4 min and heating the melt to 800 ± 30°C above the liquidus of the composite slurry. Automatic stirring of the slurry began at this temperature. Figure 2 shows the progression of the automatic stirring as a function of speed and time. The resultant composite slurry was poured at 750 ± 30°C into the mould after the preferred stirring of the mixture. Figure 2 shows the experimental flowchart of the casting process.

2.2.2. Density and porosity measurements
Density measurement is an important parameter for determining the efficiency of the production techniques used in composite development. In this research, the percentage porosity
of the composite was determined through density measurement. This was carried out by comparing the experimental and theoretical density of each weight ratio of the composite developed. Experimental density of each grade of the composite produced was determined by dividing the measured weight of a test sample by its volume; also, the theoretical density of the composite was determined by using a composite rule of mixture. Equations (1)-(3) show the mathematical framework adopted for the evaluation of the theoretical density, experimental density and percent porosity of the composites, where Equation (2) is the Rule of Mixture (Sharma, 2003).

\[ \rho_{Ec} = \frac{W_c}{V_c} \]  

\[ \rho_{Th} = (\rho_{m}W_m) + (\rho_{m} - \rho_{m})(\rho_{m}W_m) + \ldots (\rho_{m}W_m) \]  

Table 2. Sample designation and mixing ratio of reinforcements in the ABCs

| Sample Designation | Reinforcement Composition (wt. %) | Reinforcement Weight % (wt. %) |
|--------------------|----------------------------------|-------------------------------|
| ABC Grade 1 (G1)   | 100 ZnO—0 SiC—0 Gr              | 7, 9, 11 (R7,R9,R11)         |
| ABC Grade 2 (G2)   | 100 SiC—0 ZnO—0 Gr              | 7, 9, 11 (R7,R9,R11)         |
| ABC Grade 3 (G3)   | 100 Gr—0 ZnO—0 SiC              | 7, 9, 11 (R7,R9,R11)         |
| ABC Grade 4 (G4)   | 33.33 ZnO—33.33 SiC—33.33 Gr    | 7, 9, 11 (R7,R9,R11)         |
| ABC Grade 5 (G5)   | 50 ZnO—33.33 SiC—16.37 Gr       | 7, 9, 11 (R7,R9,R11)         |
| ABC Grade 6 (G6)   | 50 SiC—33.33 Gr—16.37 ZnO       | 7, 9, 11 (R7,R9,R11)         |
| ABC Grade 7 (G7)   | 50 Gr—33.33 ZnO—16.37 SiC       | 7, 9, 11 (R7,R9,R11)         |

Figure 2. 3D schematic flow-chart of the improved two-step casting technique adopted for composites production.
\[ \text{% Porosity} = \frac{\rho E_c - \rho E_m}{\rho E_c} \]  

where \( \rho E_c \) is the experimental density of composite, \( \rho E_m \) is the theoretical density of composite, \( W_c \) is the actual weight of composite in (g) (measured with a digital weighing balance of \( \pm 0.0001 \) precision), \( V_c \) is the actual volume of composite in (cm\(^3\)), \( \rho_m \) is the density of the matrix, \( W_m \) is the weight fraction of the matrix, \( \rho_n \) is the density of nth reinforcement and \( W_n \) is the weight fraction of nth reinforcement.

2.2.3. Microstructural examination

Microstructural characterisation and chemical composition are important factors used in this research to determine the efficiency of the stirrer machine designed for the experiment. Through composite characterisation, the reinforcement distribution within the matrix was examined. Scanning electron microscope (SEM) equipped with an energy dispersive spectroscopy (EDS) was used for detailed morphology and elemental compositions of the composites produced.

2.2.4. Mechanical tests

2.2.4.1. Tensile test. Tensile test was performed according to ASTM E8 M-16a test standard (American Society for Testing and Materials). The test samples were cylindrical rods of 6 mm diameter and 4 mm gauge length with a one-step grip. The equipment used for this test was Instron universal testing machine operated at a strain rate of \( 10^{-3}/s \) and a temperature of 25 \( \pm \) 2°C. Following the evaluation of tensile properties, the ultimate tensile strength, elastic modulus and the strain to fracture results of the composites were obtained.

2.2.4.2. Hardness test. Hardness test was performed according to ASTM E92-17 test standard (American Society for Testing and Materials). The hardness behaviour of each grade of composite produced was evaluated by using the Vickers hardness scale on a hardness testing machine (LECO AT 700 Micro Hardness Tester). Before testing, each specimen was prepared by polishing the surface to obtain a flat and smooth surface finishing. A direct load of 50 gf (0.4903 N) was then applied on each grade of specimens for 10 seconds. Seven hardness indentations were made on each sample and readings within the margin of \( \pm 2\% \) were taken for the computation of the average hardness values of each grade of the composite.

2.2.4.3. Fracture toughness. The fracture toughness \( (K_{ic}) \) of the composites was evaluated in accordance with a method available in (Suresh, 2013). The circumferential notch tensile (CNT) samples have a machine configuration of 5 mm sample diameter (D) and 4 mm notched diameter (d). To evaluate the fracture toughness, the CNT samples were subjected to tensile loading to fracture using an Intron Universal Testing Machine. After the test, the fracture load obtained from the CNT sample load–extension plot was used to calculate the fracture toughness of the composite using empirical relations in Equation (4) and the results are validated with Equation (5).

\[ K_{ic} = \frac{P_f}{\sqrt{d}} \left[ 1.7 \left( \frac{D}{d} \right) - 1.27 \right] \]  

(4)

\[ D \geq \left( \frac{K_{ic}}{\sigma_f} \right)^2 \]  

(5)
where \( D \) is the diameter of the specimen, \( d \) is the diameter of the notched section, \( \rho_f \) is the fracture load and \( \sigma_y \) is the yield strength.

2.2.5. Wear test
The wear test was performed according to ASTMD4060-16 Test Standard (American Society for Testing and Materials). In this test, the rubbing action occurs between the test sample's surface and abrasive wheel during the rotating action of the machine which results in the generation of loose debris from the test sample's surface. The specimens have disc-like shapes with a diameter of 100 mm and a thickness of 4 mm. The Wear Index of the composite was evaluated as a function of weight loss due to abrasion and time as shown in Equation (6).

\[
W_{In} = \frac{W_o - W_i}{T} \times 1000
\]

where \( W_{In} \) is Wear Index, \( W_o \) is initial weight of test sample before abrasion in (mg), \( W_i \) is final weight of test sample after abrasion in (mg) and \( T \) is time of test cycles in (minutes).

2.2.6. Multilevel categoric factorial DOE
In this research, due to the dissimilarity between the levels of each factor considered for numerical study of composites' wear performance and reinforcements' optimization, a multilevel/general factorial (two-factor) DOE was considered suitable. The simplest types of designs involve only two factors or sets of treatments as in the case of this study. There are \( a^* \) levels of factor A (Reinforcement content—\( \text{Rcont} \)) and \( b^* \) levels of factor B (Reinforcement Composition—\( \text{Rcomp} \)) and these were arranged in a factorial design; that is, each replicate of the experiment contains all \( a^*b^* \) treatment combinations. In general, there are \( n \) replicates. The order in which \( abn \) observations were taken was selected at random so that the design was a completely randomized design (Montgomery, 2013).

To study the main effect of the factors and their interaction on the wear response, experimental data sets from the result of the Taber test were used as building blocks for the development of a 2-factor interaction (2FI) full factorial DOE model. Factor A was set to three levels while B was set

| Table 3. DOE design parameters and design matrix with factors’ level |
|---------------------------------------------------------------|
| **Design Parameters’ Designation**                          |
| Factor | Name    | Units | Type          | Minimum | Maximum | Level |
|--------|---------|-------|---------------|---------|---------|-------|
| A      | Rcont   | wt. % | Categoric     | R7      | R11     | 3     |
| B      | Rcomp   | wt. % | Categoric     | G1      | G7      | 7     |

| Design Matrix in Coded Factors |
|-------------------------------|
| Factor A                      |
| A(1) | A(2) |
| R7   | 1    | 0    |
| R9   | 0    | 1    |
| R11  | -1   | -1   |
| Factor B                      |
| B[1] | B[2] |
| B[3] | B[4] |
| B[5] | B[6] |
| G1   | 1    | 0    |
| G2   | 0    | 1    |
| G3   | 0    | 0    |
| G4   | 0    | 1    |
| G5   | 0    | 0    |
| G6   | 0    | 0    |
| G7   | -1   | -1   |

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to seven levels for perfect modeling and simulation of the experimental runs in Design Expert software (Version 11). Table 3 shows the DOE table, and the flowchart showing the details of the selected approach is shown in Figure 3.

In a factorial experiment, an effects model can describe the observations. The effects model is

\[ x_{ijk} = \alpha + \beta_i + (\alpha \beta)_{ij} + \epsilon_{ijk} \quad (i, j, k = 1, 2, \ldots, a, b, n) \]  

where \( x_{ijk} \) is the observed response when Factor A is at the \( i \)th level and Factor B is at the \( j \)th level for \( k \)th replicate. \( \alpha \) is the overall mean effect, \( \beta_i \) is the effect of the \( i \)th level of the row factor A, \( (\alpha \beta)_{ij} \) is the effect of the interaction between \( \alpha_i \) and \( \beta_j \), and \( \epsilon_{ijk} \) is the random error component. Both factors are assumed to be fixed, and the treatment effects are defined as deviations from the overall mean, so that \( \sum_{i=1}^{a} \alpha_i = 0 \) and \( \sum_{j=1}^{b} \beta_j = 0 \). Similarly, the interaction effects are defined such that \( \sum_{i=1}^{a} (\alpha \beta)_{ij} = \sum_{j=1}^{b} (\alpha \beta)_{ij} \). Because there are \( n \) replicates of the experiment, there are \( abn \) total observations (Montgomery, 2013).
3. Results and discussion

3.1. Spectroscopic observations for the ABCs’ constituents
Table 4 and Figures 4 and 5 show the spectroscopic analysis results of the composites’ constituents and the distribution of second phase particles within the Al-Si matrix, respectively.

3.2. Density measurement and percent porosity
Figures 6 and 7 present the density and percent porosity values for the MLA and the ABCs. It was observed that there is no significant difference (0.20–0.34) between the theoretical and experimental density values of the ABCs. In comparison with the MLA, the maximum deviation was observed for the G1-R11 ABC with an increment of 8.76%. The density of ZnO (5.16 g cm⁻³) greater than that of MLA (2.68 g cm⁻³) explains this occurrence. Nevertheless, the observed deviation shows that the addition of the selected reinforcing constituents to ABC did not result in unsatisfactory weight increment. Most importantly, ABCs with high GR contents showed a reduction in weight as expected. The lightweight of ABCs is one of the attractive properties that make them suitable for several applications where lightweight and high performances are of primary concerns (Bodunrin et al., 2015; Das et al., 2014; Daramola et al., 2019; Mavhungu et al., 2017; Singh & Chauhan, 2016).

The maximum porosity level of 3.7% observed for the ABCs did not exceed 4%, which is the maximum permissible porosity level in cast metal matrix composites (Selvam et al., 2014). This is a clear indication that the improved two-step stir casting shown in Figure 2 proved effective in minimizing the porosities level in the as-cast ABCs.

| Constituent (wt. %) | Spark Spectroscopy Result | X-Ray Fluorescence Spectroscopy Result |
|---------------------|---------------------------|----------------------------------------|
|                     | Al-Si Alloys              | ZnO Powder                             | Mg Powder |
| ZnO                 |                           | 99.5                                   |           |
| CO₂                 |                           | 0.25                                   |           |
| SO₄                 |                           | 0.01                                   |           |
| HCl                 |                           | 0.02                                   |           |
| Al                  | 81.95                     |                                        |           |
| Si                  | 14.02                     |                                        |           |
| Cu                  | 0.79                      | 0.0002                                 |           |
| Zn                  | 0.12                      |                                        | 0.1       |
| Ti                  | 0.21                      |                                        |           |
| Fe                  | 0.61                      | 0.05                                   |           |
| Mg                  | 0.54                      |                                        | 99.9      |
| Ni                  | 1.60                      |                                        |           |
| Sn                  | 0.21                      |                                        |           |
| Pb                  | 0.01                      |                                        | 0.01      |
| As                  |                           | 0.0001                                 |           |
| Cl                  |                           | 0.001                                  |           |
| N                   |                           | 0.0005                                 |           |
| Cd                  |                           | 0.002                                  |           |
| Ca                  |                           | 0.002                                  |           |
| Mn                  |                           | 0.0005                                 |           |
| Na                  |                           | 0.001                                  |           |
| O                   |                           | 0.0016                                 |           |
3.3. Mechanical Behaviour

3.3.1. Tensile properties
3.3.1.1. Ultimate tensile strength. In Figure 8, the result indicated the performance of the ABCs improved under tensile loading irrespective of variations in the reinforcement composition (Rcomp) and reinforcement constituent (Rcont). Contrary to observations under hardness result, the Rcomp has almost the same influence on the UTS of the ABCs as the Rcont, that is, both the hybrid and dual-phase ABCs exhibited little variations in improved tensile behaviour. The G6-R11 showed the superlative enhancement of 162.33% in comparison with that of the MLA. Observations from the result revealed a linear relationship between increment in UTS of the ABCs and corresponding increase in Rcont for all the ABCs with high contents of ZnO and SiC particles. In contrast, a linear reduction (however greater than that of the MLA) in UTS of the ABCs was observed for the ABCs with high contents of GR particles. This is discredited to the brittle nature of graphite due to its sheer planes (carbon atoms are arranged in sheets instead of 3D crystalline pattern) which facilitates the cracking of matrix-particle interface (Bodunrin et al., 2015). However, improvement in UTS of particulate-filled metal matrix composites is preeminently reliant on the strength of interfacial adhesion between the reinforcing particles and the metal matrix (Bodunrin et al., 2015). This result revealed that the addition of Mg powder as a wetting agent during the casting process proved effective in enhancing particle-filler adhesion. In addition, the strengthening mechanism in play here according to Bodunrin et al., (2015) is a function of increased load sustaining capacity of the composite with an increase in weight ratio of hard particulates, and the resistance to dislocation movement by the particles. Upon rapid solidification of the melt during production, the dislocation population is increased due to thermally induced residual stresses arising from the mismatch in the coefficient of thermal expansion values of the Al-Si alloy matrix and the ceramic
reinforcements (Bodunrin et al., 2015; Das et al., 2014). The interaction of dislocations with the hard and insurmountable particles increases the composite's strength.

3.3.1.2. Elastic modulus. In Figure 9, the result showed that the stiffness of hypereutectic Al-Si alloy significantly improved by the addition of both singular and multiple inclusions of ZnO, SiC and Gr. For most of the ABCs, low Rcont (R7) favoured this improvement. Actually, sharp drops in elastic moduli were observed for ABCs with high contents of ZnO and Gr as Rcont increased by 2%. This is due to the highly brittle nature of both particles even though their elastic moduli are lower than that of SiC as shown in Table 1. In contrast, ABCs with high SiC ((G2 and G6)) contents showed very slight drops in elastic moduli with 2% increment in Rcont for singular inclusion (G2). This is because SiC particles are not as brittle as ZnO and Gr particles despite the elastic modulus being higher, which is due to their higher crystallinity indices (Bodunrin et al., 2015; Mavhungu et al., 2017; Singh & Chauhan, 2016). Thus, ABCs reinforced with high content of SiC took longer to reach Critical Reinforcement Content (CRC). It was found that only the G5 ABCs exhibited progressive improvement in elastic modulus with an increase in Rcont which is attributed to the properties of ZnO (Tun et al., 2012). The superlative enhancement in elastic modulus was observed for the G7-R7 ABC with 74.78 % enhancement in comparison with that of the MLA. Overall, all the ABCs possess elastic moduli that supersede that of the MLA. The primary mechanism of strengthening in play here is the introduction of more rigid fillers (excluding Gr) into the Al-Si matrix (Bodunrin et al., 2015; Mavhungu et al., 2017; Singh & Chauhan, 2016).
3.3.1.3. Strain to fracture. Figure 10 presents the result of strain-to-fracture (percent elongation) for the MLA and the ABCs. The result indicated that the addition of both singular and multiple inclusions of ZnO, SiC and Gr did not improve the ductility of the ABCs. The superlative ductility amid the ABCs was exhibited by the G5-R7 composite, which is also the only composite that showed inverse variation between ductility and Rcont. This justifies the selection of ZnO for ductility improvement in this research. The ductility of the G5-R7 ABC is highly comparable with that of the MLA (< 6% variation). Similarly, high content of singular inclusion of Gr in the Al–Si matrix (G3 ABC) and its combination with ZnO and SiC in the hybrid composite (G7 ABC) also showed satisfactory ductility range (< 14% variation) in comparison with that of the MLA. This behaviour is expected at the micro-scale for most as-cast ABCs as improvement in strength invariably results in a trade-off in ductility of the material (Bodunrin et al., 2015; Das et al., 2014). In this study, all the ABCs with improved UTS (Figure 8) and hardness (Figure 11) have their percentage elongation values reduced. The best way to override this drawback is by subjecting the materials to appropriate metallurgical processing routes such as heat treatment operations or grain refinement processing technologies (Das et al., 2014).

3.3.2. Hardness

Figure 11 shows the Vicker Hardness Numbers (VHNs) for the MLA and the ABCs. The result indicated that the improvement in hardness is more dependent on Rcomp (>120 VHN variation) than on Rcont (<50 VHN variation). Nevertheless, there is a similar trend in response to indentation for both the hybrid and the dual-phase ABCs. In comparison with the MLA, the superlative improvement in hardness was observed for the G6-R11 ABC with an improvement of 69.04%. In conformity with the findings of previous research (Campbell, 2012; Daramola et al., 2015; Mavhungu et al., 2017; Singh & Chouhan, 2016), the influence of both the individual and combined effects of ZnO and SiC on the hardness of the ABCs is more pronounced than that of Gr. As for the
3.3.3. Fracture toughness

From Figure 12, it was shown that the multiple inclusions (G5-G7 ABCs) in Al–Si matrix improved the fracture toughness ($K_{IC}$) of ABCs more than singular inclusion of each particles (G1–G3). For the ABCs with high contents of ZnO and SiC inclusions, the $K_{IC}$ increased with an increase in the content of the reinforcing phases and for the Gr inclusion, the opposite was observed (the reason being the inability of brittle Gr particles to impede dislocation motion effectively, thus, the particles and particle–matrix interfaces crack easily under the application of applied force; Bodunrin et al., 2015). The CRC of Gr in the ABCs was observed at R7 for both ABCs with singular and hybrid inclusions. However, all the ABCs exhibited superior $K_{IC}$ in comparison with that of the MLA. Similar to the observations in Figure 11 (Hardness Result) and Figure 8 (UTS Result), the G6-R11 exhibited the superlative $K_{IC}$ with an enhancement of 77.42% in comparison with that of the MLA. Researchers have explained this improvement in $K_{IC}$ of particle-reinforced metal matrix composites to be reliant on the roles of second phase particles. Second phase particles act as a barrier to dislocation motion by pinning down and blocking advanced crack tips in the ABCs, thereby slowing down crack propagation and eventual failure (Bodunrin et al., 2015; Das et al., 2014; Mavhungu et al., 2017; Singh & Chauhan, 2016; Suresh, 2013). In addition, mixture homogeneity (achieved by

Figure 7. Percent porosity values of the ABCs.
the adopted casting processing in this research confirmed by the EDS result) in the ABCs must have resulted in the favourable interparticle distance that prevents the matrix ligament to lie in plane strain state, thus, post-yield deformation of the matrix is easily possible (Bodunrin et al., 2015; Kumar, 2017; Singh & Chauhan, 2016). The ability of a material to undergo post-yield deformation (absorbing energy by localized shear yield deformation) under applied load translates to an impressive plastic deformation prior to failure (Bodunrin et al., 2015).

3.4. Wear performance

3.4.1. Wear index
The result of resistance to abrasion for the MLA and the ABCs is presented in Figure 13. Observations showed that an increase in Rcont varies directly with an increase in resistance to abrasive wear for all the ABCs, irrespective of Rcomp. However, the best improvements were observed for the hybrid composites (G4-G7 ABCs). The G7-R11 ABC exhibited the superlative resistance to abrasive wear with a reduction of 95.87% in wear index in comparison with that of the MLA. The combined effects of Gr self-lubricating property and the hardness, of ZnO and SiC particles, are the major factors responsible for this improvement (Bodunrin et al., 2015; Sharma et al., 2015). On one hand, Gr particles act as lubricating film on worn surfaces during the dry sliding action of the abrasive wheel against the ABC surface. The lubricant film decreases the overall friction coefficient during this action by separating the surfaces thus lowering wear rate as a function of less abrasive contact (Sharma et al., 2015). On the other hand, introduction of hard, stiff and ZnO and SiC particles into the matrix of Al–Si alloy may not negatively affect the degree of asperity on the surface topography of the ABCs, which in turn would reduce wear indices of the ABCs (Bodunrin et al., 2015). In addition, the ZnO and SiC particles are more thermally stable than the Al–Si matrix, thus the heat generated during the abrasive action would be ineffective in facilitating particle-matrix cracking and dislodgment from the matrix (Das et al., 2014).
3.4.2. Numerical optimization of wear performance

Figure 14 presents the 2FI effects model generated from the DOE of 63 runs. The result showed that all the factors in the models are outstanding. However, the Rcomp has more effect on the model than the Rcont and the interaction between Rcomp and Rcont. This is supported by the wear index result of the ABCs where the hybrid composites exhibited superior resistance to abrasion in comparison with the ABCs with singular inclusions. In addition, 16.67% variation was observed between Rcont and improvement conferred to the ABC with singular inclusions and 92% variation for the hybrid composites. Table 5 shows the statistical and mathematical significance of the model. The results presented in Table 5 showed that the developed model is significant and valid; hence, the equation in terms of coded factors can be used to make predictions about the response for given levels of each factor. The Model F-Value of 2013.93 implies that the model is significant. There is only a 0.01% chance that an F-Value this large could occur due to noise. P-value less than 0.0500 indicates that the model is significant. In this case, A, B and AB are significant model terms. Values greater than 0.100 indicate the model terms are not significant. The predicted $R^2$ of 0.9977 is in reasonable agreement with the Adjusted $R^2$ of 0.9985; i.e. the difference is less than 0.2. Adq Precision measures the signal-to-noise ratio. A ratio greater than 4 is desirable. The ratio of 216.228 shows an adequate signal. Hence, the model can be used to navigate the design space. Similar observations are available in the work of Stojanović et al. wherein they studied the tribological behaviour of ABCs by factorial techniques (Stojanović et al., 2016).

3.4.2.1. Model equation.
Figure 10. Strain-to-fracture result of the MLA and the ABCs.

Figure 11. VHN values of the MLA and the ABCs.
Figure 12. Fracture toughness result of the MLA and the ABCs.

Figure 13. Wear index result of the MLA and the ABCs.
Table 6 shows the design matrix with the experimental wear responses for the MLA and the ABCs. The predicted wear responses from Equation (8) for both the MLA and ABCs were fitted against that of the experimental outcome and presented in Figure 14(b). From the results presented in Figure 14(b), the experimental wear result shows good agreement with the predictions of the DOE model. With reference to Figure 13, the G7-R9 and G7-R11 ABCs exhibited the lowest wear rates in comparison with the MLA and other ABCs. On the other
| Source      | Sum of Squares | Degree of Freedom | Mean Square | F-Value | P-Value | Significance |
|------------|----------------|-------------------|-------------|---------|---------|--------------|
| Model      | 5.70           | 20                | 0.2848      | 2013.93 | <0.0001 | Significant  |
| Rcont[A]   | 0.7909         | 2                 | 0.3954      | 2796.39 | <0.0001 | Significant  |
| Rcomp[B]   | 3.00           | 6                 | 0.5006      | 3540.00 | <0.0001 | Significant  |
| [A][B]     | 1.90           | 12                | 0.1585      | 1120.49 | <0.0001 | Significant  |
| Pure Error | 0.0059         | 42                | 0.0001      |         |         |              |
| Cor. Total | 5.70           | 62                |             |         |         |              |

Fits Statistics

| Source    | Value       | 
|-----------|-------------|
| Std. Dev. | 0.0119      |
| Mean      | 3.55        |
| CV. %     | 0.3345      |

R²          | 0.9990

Adjusted R²  | 0.9985

Predicted R² | 0.9977

Adq. Precision | 216.2275

Model Comparison Statistics

| Statistic  | Value  |
|------------|--------|
| PRESS      | 0.0134 |
| −2 Log Likelihood | −405.18 |
| BIC        | −318.17 |
| AICc       | −340.64 |
| Std | Run | A: Rwgt | B: Rcomp | Wear Index | Std | Run | A: Rwgt | B: Rcomp | Wear Index |
|-----|-----|---------|----------|------------|-----|-----|---------|----------|------------|
| 22  | 1   | R7      | G1       | 6000       | 61  | 33  | R7      | G7       | 3110       |
| 27  | 2   | R11     | G2       | 4800       | 21  | 34  | R11     | G7       | 200        |
| 3   | 3   | R11     | G1       | 5000       | 5   | 35  | R9      | G2       | 5000       |
| 16  | 4   | R7      | G6       | 3500       | 2   | 36  | R9      | G1       | 5150       |
| 28  | 5   | R7      | G3       | 5200       | 13  | 37  | R7      | G5       | 4600       |
| 33  | 6   | R11     | G4       | 3800       | 40  | 38  | R7      | G7       | 3000       |
| 9   | 7   | R11     | G3       | 3800       | 54  | 39  | R11     | G4       | 3800       |
| 60  | 8   | R11     | G6       | 3000       | 10  | 40  | R7      | G4       | 5000       |
| 53  | 9   | R9      | G4       | 4200       | 17  | 41  | R9      | G6       | 3700       |
| 26  | 10  | R9      | G2       | 4900       | 47  | 42  | R9      | G2       | 5950       |
| 20  | 11  | R9      | G7       | 2200       | 15  | 43  | R11     | G5       | 2900       |
| 12  | 12  | R11     | G4       | 3850       | 23  | 44  | R9      | G1       | 5000       |
| 37  | 13  | R7      | G6       | 3610       | 63  | 45  | R11     | G7       | 190        |
| 39  | 14  | R11     | G6       | 3000       | 30  | 46  | R11     | G3       | 3800       |
| 59  | 15  | R9      | G6       | 3700       | 8   | 47  | R9      | G3       | 4900       |
| 56  | 16  | R9      | G5       | 4000       | 50  | 48  | R9      | G3       | 4900       |
| 25  | 17  | R7      | G2       | 5200       | 45  | 49  | R11     | G1       | 5100       |
| 18  | 18  | R11     | G6       | 3100       | 11  | 50  | R9      | G4       | 4200       |
| 43  | 19  | R7      | G1       | 6000       | 57  | 51  | R11     | G5       | 2900       |
| 55  | 20  | R7      | G5       | 4600       | 29  | 52  | R9      | G3       | 4900       |
| 62  | 21  | R9      | G7       | 2200       | 48  | 53  | R11     | G2       | 4800       |
| 44  | 22  | R9      | G1       | 5000       | 4   | 54  | R7      | G2       | 5200       |
| 38  | 23  | R9      | G6       | 3750       | 1   | 55  | R7      | G1       | 6000       |
| Std  | Run | Factor 1 | Response 1 | Std  | Run | Factor 1 | Response 1 | Wear Index |
|------|-----|----------|------------|------|-----|----------|------------|------------|
| 49   | 24  | R7       | G3         | 24   | 56  | R7       | G3         | 5100       |
| 36   | 25  | R11      | G5         | 3000 | 57  | R11      | G5         | 5000       |
| 31   | 26  | R9       | G4         | 4250 | 58  | R9       | G4         | 4000       |
| 41   | 27  | R9       | G7         | 2200 | 59  | R11      | G2         | 4900       |
| 4     | 28  | R7       | G3         | 5100 | 60  | R7       | G3         | 5000       |
| 34   | 29  | R7       | G5         | 4620 | 61  | R11      | G3         | 3900       |
| 31   | 30  | R7       | G4         | 4900 | 62  | R7       | G2         | 5150       |
| 56   | 31  | R7       | G6         | 3600 | 63  | R9       | G5         | 4000       |
| 19   | 32  | R7       | G7         | 3200 |     |          |            |            |

*(Continued)*
hand, numerical optimization showed that the G7-R11 ABC possesses the greatest desirability (Figure 14(c)) if the wear rate is to be minimized.

3.5. Suggested automotive application (Cylinder Liner) for the G6-R11 and G7-R11 ABCs

In automobile industries, aluminium alloys and composites have been used for the fabrication of almost 100% of pistons, about 75% of cylinder heads, 85% of intake manifolds and transmission (Bodunrin et al., 2015; Hirsch, 2014; Mavhungu et al., 2017; Singh & Chauhan, 2016). The suppliers of engine blocks are constantly endeavouring to manufacture better and lighter blocks in order to improve and enhance the efficiency of automobile internal combustion engines. The engine blocks are the largest and most intricate single piece of metal used in internal combustion (IC) engines on which other important engine parts are mounted. The engine block alone accounts for 3–4% of the total weight of the average vehicle (Hirsch, 2014). Aluminium casting alloys as a substitute or replacement for the traditional cast iron can mean a reduction in engine block weight of between 40% and 50%. In addition, the aluminium alloys and composites for a cylinder liner must have high wear resistance, anti-galling resistance and corrosion resistance among others (Mehta et al., 2004). The possession of these properties would make such material satisfy the functional requirements of a cylinder liner, thus serving as an alternative to the traditional cast-iron liners.

The G6-R11 (with optimum combination of improved mechanical and wear properties) and the G7-R11 (with superlative wear properties) ABCs are proposed as suitable materials for cylinder liners of automobile engines. Both composites show mechanical and wear properties in the same range with typical gray cast iron cylinder liners (Wopelka et al., 2018), however, with about 70% reduction in density.

4. Conclusions

The findings of this research indicated that the mechanical properties and wear performance of hypereutectic Al–Si alloy improved with both singular and multiple inclusions of SiC, ZnO and Gr, though a satisfactory trade-off in ductility was observed for all the composites (G1–G7) developed as the strength increases. The optimum combination of both mechanical and wear properties was observed for the composites designated as G6-R11 ABC (50 wt. % SiC- 33.33 wt. % Gr −16.37 wt. % ZnO) which is 11 wt. % in the Al–Si matrix. The Vicker hardness, ultimate tensile strength, elastic modulus, fracture toughness and wear index of this composite supersede that of the as-received monolithic alloy by 69.04%, 162.3%, 69.91%, 77.42% and 65.69% (reduction), respectively. However, with a 33.33% reduction in ductility. Result also indicated that a varied proportion of the individual particles in the Al–Si matrix show better results than their equal distributions in the Al–Si matrix. This is also an indication that the improved casting technique adopted in this research for mixture homogeneity of composite slurry is effective. The 2FI normal effects model plot shows good agreement with the experimental results and can be used for further predictions of wear performance of the developed composites and reference for constitutive model development and validation. It also showed that reinforcement composition has the greatest influence on the model, which is evidenced by the superior properties exhibited by the hybrid composites. Further research to investigate the thermal properties of the developed composites should be carried out.

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