Original Article

Development of aluminium-based composites reinforced with steel and graphite particles: structural, mechanical and wear characterization

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\begin{abstract}
Apparent limitations in toughness and ductility of ceramic reinforced aluminium matrix composites have prompted considerations of metallic reinforcements. In the present study, the structural characteristics, mechanical and wear behaviour of stir cast Al-Mg-Si alloy-based composites reinforced with different weight percent of steel-, steel-graphite hybrid mix-, and SiC-particles were investigated. The results show that the hardness of the composites increased approximately by 11\% with increase in steel particles from 4 to 8 wt.\%. For the same range of steel concentration, the ultimate tensile strength also increased with increase in steel wt.\%. These strength values were all higher than that of 8 wt.\% reinforced SiC by a margin of 3.2–24\%. The specific strength and fracture toughness equally followed the same trend with respect to steel concentration with strain to fracture, the exception where slight decrease (less than 4\%) is observed. For these properties, the values were superior to the SiC reinforced composite and ascribed to improved grain refinement and interface bonding, and the inherent ductility of the steel particles. For the 8 wt.\% hybrid reinforced composite compositions containing steel and graphite, all the mechanical properties decreased slightly with increase in graphite content and trailed the composite reinforced with 8 wt.\% steel. However, the wear rates were lowest for the hybrid reinforcement mix of steel and graphite, followed by those containing only steel; while that reinforced with SiC had the highest wear susceptibility. Nonetheless, abrasive wear was the dominant wear mechanism observed in all the composites.

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\end{abstract}
1. **Introduction**

Aluminium-based composites (AMCs) have been successfully utilized in many technological sectors including, automobile, aerospace, microelectronics, marine, recreational and military for the design of a wide range of components and devices [1]. AMCs are highly recommended because of the versatile property combinations, which they can be tailored to possess, properties such as: high specific strength and stiffness, good corrosion and oxidation resistance, tribological properties, low coefficient of thermal expansion, among others [2,3]. Being mostly reinforced with the use of ceramic materials, the major short comings reported on AMCs, are their low ductility and toughness in comparison to the unreinforced Al and alloys [4]. The low ductility and toughness can arise from a combination of factors such as inherent brittle nature of ceramic reinforcements [5]; and the generally poor wettability between ceramics and metallic melts, which results in poor interface strength [6]. The latter factor is often responsible for load transfer inefficiencies from the matrix to the reinforcements [7]. As a result, several strategies have been adopted in order to ameliorate these problems, albeit the successes and failures reported. Some of the approaches involve: modification of the processing technique [8], pre-heat treatment of reinforcing particles [9], coating of the particles with wetting agents [10], hybrid particle reinforcement [11], use of nano and sub-micron particles [12,13], friction stir and deformation processing [14,15].

The use of metallic materials as reinforcement in AMCs, is lately among the strategies deployed to enhance the low ductility and toughness observed in ceramic reinforced AMCs. The selection of metallic materials is based on the good wettability between metals compared with metal and ceramic systems [16], which enhances interface strength and consequently, load transfer from the matrix to the reinforcement. This is in addition to the inherent ductile nature of the metal reinforcement, which makes them less susceptible to brittle fracture compared to ceramics. In this regard, a number of studies have been carried out to demonstrate the viability of this design strategy, with Ni and Fe being the most reported metallic reinforcement studied [17,18].

The use of Ni as the sole reinforcement or in combination with ceramic particles as hybrid reinforcement, has been reported to offer the possibility of combining high strength with improved toughness and ductility, compared with the use of sole ceramic reinforcements [7,17,19]. Fe on the other hand, is an unusual element to be considered as reinforcement in Al because the low solid solubility of Fe in Al, often results in the formation of a number of iron rich intermetallic phases, reported to be responsible for reduced ductility observed in Al-based alloys [20,21]. But a few studies have actually pointed to the viability of using Fe and its alloys as reinforcing material, and as potential substitute for ceramic reinforcement in Al-based composites. Viala et al. [22] reported that a continuous metallurgical bond at the insert/alloy interface is achieved in cast iron insert reinforced Al-Si alloy, consequently giving rise to good thermal conductivity and mechanical properties. Wang et al. [23] reported that reinforcing Al with steel chips resulted in improved compressive strength but reduced ductility. Fathy et al. [24] studied the effect of iron addition on powder metallurgy processed Al-matrix composites. It was reported that iron improved the compressive strength and hardness of the composites but little was reported on its effect on the ductility or toughness. The strengthening mechanism was linked to the grain refinement of the Al matrix, the uniform distribution of the Fe particles, as well as the formation of $\text{Al}_{13}\text{Fe}_4$ intermetallic compound. The investigation by Emara [18] focused on the mechanical properties and wear behaviour of aluminium matrix reinforced with steel machining chips processed by powder metallurgy. The investigation showed that the addition of steel machining chips, resulted in significantly low porosity levels in the aluminium matrix composites, compared with the use of SiC as reinforcement. The mechanical properties as well as the wear resistance, were also improved with the use of the steel machining chips as reinforcement. From available literature, insight on the mechanism of strengthening, toughening, and wear in steel reinforced AMCs, is still tentative. Also, the analysis of the mechanical and wear performance of Al-based composites reinforced with steel and graphite particles are yet to receive accessible coverage in literature.

This research intends to investigate the structural features, mechanical and wear behaviour of stir cast aluminium-based composites reinforced with steel and graphite particles. The steel particles will be processed through milling of steel chips, which can be cheaply sourced from industrial machining shops. The choice of steel machining chips as starting material is informed by its high strength compared to bulk steel material, arising from the ultra-fine/nano grain structure it is reported to possess [5]. The ultra-fine/nano scale grain structure that develops is a characteristic resulting from the high deformation strains steels sustain during the process of chip formation [6].

2. **Materials and methods**

2.1. **Materials**

The Al-Mg-Si alloy with chemical composition presented in Table 1, served as the metal matrix for the Al-based composite development. Steel particulates, graphite and silicon carbide were selected as reinforcements for the composite production. The steel particulates were processed from Steel machining chips obtained from boring operation on medium carbon steel, graphite and silicon carbide. The steel chips, which were initially of average particle size of 600μm, were ball milled to 100μm passing, before being used as reinforcement particles. The graphite and silicon carbide, were both of analytical pure grades with an average particle size of 30μm. Both the graphite and silicon carbide were purchased from a

| Table 1 – Chemical composition of aluminium-based alloy. |
|-------------------------------|---|---|---|---|---|---|
| Element | Al | Si | Fe | Mn | Mg | Zn | Cr | Ti |
| Composition (wt.%) | 98.7 | 0.45 | 0.10 | 0.02 | 0.48 | 0.02 | 0.01 | 0.01 |
Table 2 – Sample designation and composite compositions.

<table>
<thead>
<tr>
<th>Sample designation</th>
<th>Composite composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA</td>
<td>Al-Mg-Si alloy</td>
</tr>
<tr>
<td>AA/4Sp</td>
<td>Al-Mg-Si alloy + 4 wt.% steel particles</td>
</tr>
<tr>
<td>AA/6Sp</td>
<td>Al-Mg-Si alloy + 6 wt.% steel particles</td>
</tr>
<tr>
<td>AA/8Sp</td>
<td>Al-Mg-Si alloy + 8 wt.% steel particles</td>
</tr>
<tr>
<td>AA/7Sp + 1Cg</td>
<td>Al-Mg-Si alloy + 7 wt.% steel + 1 wt.% graphite particles</td>
</tr>
<tr>
<td>AA/6Sp + 2Cg</td>
<td>Al-Mg-Si alloy + 6 wt.% steel + 2 wt.% graphite particles</td>
</tr>
<tr>
<td>AA/8SiC</td>
<td>Al-Mg-Si alloy + 8 wt.% SiC</td>
</tr>
</tbody>
</table>

licensed local vendor of industrial materials and chemicals in Lagos State, Nigeria.

2.2. Composite production

The composites developed in this study were produced using double stir casting process performed in accordance with Alaneme and Aluko [25]. Steel particles required for the production of 4, 6, and 8 wt.% reinforcement in the Al-based alloy, were determined using charge calculations. The charge materials for three other compositions having 8 wt.% reinforcement, were constituted: two compositions by varying the amount of steel and graphite, with compositions 7 wt.% steel and 1 wt.% graphite, 6 wt.% steel and 2 wt.% graphite, and the third prepared with 8 wt.% SiC. The unreinforced Al alloy was also prepared as control composition. The composite compositions produced with corresponding designations, are presented in Table 2. The production process was undertaken by first, preheating the reinforcements to a temperature of 250 °C to eliminate dampness, reduce the temperature gradient arising from addition of cold materials into the melt, and improve wettability with the molten alloy. A gas fired crucible furnace was used to melt the alloy completely at a temperature of 750 ± 30 °C (above the liquidus temperature of the alloy). The liquid alloy was allowed to cool to a semi solid state at a temperature of about 600 °C. The preheated steel, steel-graphite hybrid, and SiC particulates depending on the composition, were added at this temperature, and stirred manually in the semi-solid melt, for 5–10 min. The composite slurry was then superheated to 780 ± 30 °C, and a second stirring performed using a mechanical stirrer. The stirring operation was performed at a speed of 400 rpm for 10 min to help improve the dispersion of the particulates in the molten Al-Mg-Si alloy. The molten composite was then cast into metallic molds to facilitate fast cooling rates, which engenders refinement of the grain structure.

2.3. Composite density and percentage porosity

The experimental density of each grade of composite produced was determined by dividing the measured weight of a test sample by its measured volume using a digital weighing balance with tolerance of ±0.0001 g. Three repeat tests were performed using different samples of same composition to ensure the measured values are consistent and reliable. The theoretical densities of the composites were evaluated using the relations given in Eqs. 2.1–2.3.

\[ \rho_{\text{Al-Mg-Si/Sp}} = \frac{W_{\text{f}} \rho_{\text{Al-Mg-Si}} + W_{\text{f}} \rho_{\text{Sp}}}{\rho_{\text{f}}} \]  

(2.1)

\[ \rho_{\text{Al-Mg-Si/Sp/Cg}} = \frac{W_{\text{f}} \rho_{\text{Al-Mg-Si}} + W_{\text{f}} \rho_{\text{Sp}} + \rho_{\text{Cg}}}{\rho_{\text{f}}} \]  

(2.2)

\[ \rho_{\text{Al-Mg-Si/SiC}} = \frac{W_{\text{f}} \rho_{\text{Al-Mg-Si}} + W_{\text{f}} \rho_{\text{SiC}}}{\rho_{\text{f}}} \]  

(2.3)

where \( \rho_{\text{f}} \) is the theoretical density (g/cm³), and \( \rho_{\text{fX}} \) is experimental density (g/cm³).

2.4. Composition and structural characterization

2.4.1. XRD analysis

A Bruker D2 phaser machine with X-ray source of cobalt Kα radiation (\( \lambda = 1.7890 \AA \)) was used to determine the crystalline phases and compositions in the AMCs produced. The samples were prepared for XRD analysis following standard procedures in accordance with Alan and Ansari [27]. The tests were carried out by scanning the samples for possible diffraction directions through a range of 2θ angles from 10° to 90° (which was adequate in establishing all viable peaks), utilizing a scan size (2θTb) of 0.0260 and scan step time of 37 s. The metal or intermetallic phases present in the AMCs produced, were identified by comparing the d-spacing obtained from the analysis with that of standard references patterns. A PANalytical software was used for the matching of peaks, plotting of the XRD profiles, and analyzing the diffraction phase parameters of the samples.

2.4.2. Scanning electron microscopy (SEM)

A Carl Zeiss Sigma field emission scanning electron microscope (FE-SEM) equipped with an energy dispersive X-ray spectrometer (EDS) was used for detailed characterization of microstructural features of the composites. Back scattered electron (BSE) and secondary electron (SE) imaging modes, alongside energy dispersive spectroscopy (EDS) were used for microstructural and qualitative composition analysis of the composites. The samples for the examination were ground polished to 1 μm finish using alumina as the lubricant for the final stage. The samples were then etched in Keller’s reagent, swabbing for 10–20 s, after which microstructural examination and analysis was performed. Furthermore, the wear track
morphology and fractographic features of the wear and fracture surfaces were also examined using the FE-SEM.

2.5. Mechanical behaviour

2.5.1. Hardness measurement

The hardness values of the composites were evaluated on a hardness testing machine using Brinell Hardness Scale. The sample preparation and testing procedures were in accordance ASTM E10-17 [28] standard. The samples for the test were prepared to have smooth, plane parallel surfaces; and the indentation was performed, using a direct load of 125 kgf for a dwelling time of 10 s. Six hardness indents were made on each sample, and readings within the margin of ±2%, were used for the computation of the average hardness values for each respective composite composition.

2.5.2. Tensile testing

A universal testing machine was used to perform tensile tests and evaluate the tensile properties of the composites produced. The composites were machined to round tensile test specimen configuration with dimensions of 30 mm gauge length and 5 mm diameter. The samples were clamped on the testing platform and pulled in tension at a strain rate of 10^{-4} \text{s}^{-1} until fracture. The sample preparation, testing procedures, and analysis of results were performed in accordance with ASTM E8/E8M-16a standard [29]. Multiple tests (three repeat tests) were performed for each composite composition to guarantee reproducibility and repeatability of the test results. The tensile properties evaluated from the test are the ultimate tensile strength, specific strength and % elongation.

2.5.3. Fracture toughness

The fracture toughness values of the composites were evaluated from tensile tests performed on circumferential notch (CNT) tensile samples, following the procedures reported in details by Alaneme [30]. The composite samples for the test were machined to gauge length of 30 mm, gauge diameter of 5 mm (D), notch diameter of 4.2 mm (d), and notch angle of 60°. The notched samples were pulled in tension mode at a strain rate of 10^{-3} \text{s}^{-1} to fracture, using a universal tensile testing machine. The fracture loads (Pf) obtained from the load-extension plots of the CNT samples, were used to evaluate the fracture toughness using the empirical relation by Dieter [31]:

\[
K_{IC} = \frac{P_f d^2}{D} \left[ 1.72 \left( \frac{D}{d} \right) - 1.27 \right] \tag{2.5}
\]

where D and d, are the un-notched and notched diameters of the CNT samples, respectively. Plane strain condition, which is required for valid fracture toughness determination, was established using the relation in Eq. 2.6, which is in accordance with Nath and Das [32]:

\[
D \geq \left( \frac{K_{IC}}{\sigma_Y} \right)^2 \tag{2.6}
\]

Three repeat tests were performed for each composite composition to ensure repeatability and reliability of the results generated.

2.6. Wear behaviour

Wear test was performed on the composites produced using a Rotopol-v type wear testing machine following general wear test procedures outlined in ASTM G99 standard [33]. The samples for the test were machined to 30 mm length and 20 mm diameter, and were weighed prior to testing using an electronic weighing machine. The wear test was performed at a speed of 80 rpm for 240 s, after which the samples are re-weighted to determine the final weight, from which the weight loss was determined. The wear rate of the composites was evaluated using the relation adapted from Archard’s equation [34], given in Eq. 2.7:

\[
\text{Wear rate} \quad (\text{cm}^2) = \frac{\Delta m}{\rho 2\pi R t} \tag{2.7}
\]

where \(\Delta m\) is weight loss (in grams), \(\rho\) is the density of the tested material (g/cm^3), \(r\) is the specimen radius (cm), \(R\) is revolutions per minute, and \(t\) is time in minutes.

3. Results and discussion

3.1. Composite densities and percent porosities

The composite densities and percent porosities are presented in Table 3. It is observed that the composite densities increased with increase in wt.% of steel particles. The Al-based composite composition containing 8 wt.% steel particles had a density of 3.11 g/cm^3, which is 13.50% higher than the composite containing 8 wt.% SiC (2.74 g/cm^3). This is basically, due to the difference in densities between steel (7.8 g/cm^3) and SiC (3.2 g/cm^3). The 8 wt.% hybrid reinforcement mix containing steel and graphite particles, both had slightly lower densities compared to composite containing 8 wt.% steel particles. The lower densities reported for the hybrid mix compositions are due to the lower density of graphite (2.23 g/cm^3). The percentage porosities of all the composites produced are less than 1.5%, and noted to be less than 4%, which is reported to be the maximum permissable in cast metal matrix composites [26]. This point to the reliability and efficiency of the double stir casting process, which is reported to break the surface tension between the Al alloy melt and the particulates, and allows

<table>
<thead>
<tr>
<th>Table 3 – Composite densities and percent porosities.</th>
<th>Samples designation</th>
<th>Theoretical density (g/cm^3)</th>
<th>Experimental density (g/cm^3)</th>
<th>Porosity (%)</th>
</tr>
</thead>
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<td>2.7</td>
<td>2.66</td>
<td>1.48</td>
<td></td>
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<tr>
<td>AA/4Sp</td>
<td>2.91</td>
<td>2.87</td>
<td>1.37</td>
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<tr>
<td>AA/6Sp</td>
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<td>2.97</td>
<td>1.32</td>
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<tr>
<td>AA/8Sp</td>
<td>3.11</td>
<td>3.07</td>
<td>1.28</td>
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<tr>
<td>AA/7Sp + 1CG</td>
<td>3.06</td>
<td>3.02</td>
<td>1.31</td>
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<tr>
<td>AA/6Sp + 2CG</td>
<td>2.99</td>
<td>2.96</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>AA/8SiC</td>
<td>2.74</td>
<td>2.70</td>
<td>1.46</td>
<td></td>
</tr>
</tbody>
</table>
3.2. Compositional and structural characterization

Fig. 1 shows representative micrographs of the reinforced AMCs produced. It is observed that the reinforcing particles are visible, clearly delineated, and well dispersed in the Al alloy matrix. The EDS profiles of the AMCs presented in Fig. 2, show peaks of aluminium (Al), iron (Fe), silicon (Si), and magnesium (Mg), which is consistent with the elemental constituents of the primary charge materials of the composites produced, that is, Al-Mg-Si alloy and steel particles.

The X-ray diffractograms for the composites produced are presented in Fig. 3. From Fig. 3(a), it is observed that apart from Al and Fe peaks, which are the metallic phases present in the alloy, iron silicon (FeSi) and Al2FeSi are the intermetallic compound phases identified in the unreinforced Al-Mg-Si alloy. However, the Fe and the Fe-rich intermetallic compound phases are observed as minor peaks which reflects the minute quantities of the intermetallic phases. Compared with the Al-Mg-Si alloy, the composites composition containing 8 wt.% steel particulates has an additional phase: Al2Fe3Si4. Ji et al. [21] reported that Fe content in Al-Mg-Si-based metallic systems can influence the type, volume fraction and morphology of Fe-rich intermetallic compounds formed in cast Al-Mg-Si alloys. For the composite containing 7 wt.% Fe and 1 wt.% graphite, it is observed that the phase composition is similar to that of the composite containing 8 wt.% steel particulates. The only distinction is the presence of FeCO3, which is attributed to the presence of graphite (C) in the reinforcement. The C in the composite was not identified by the XRD scan because the concentration of C (initially 1 wt.%), left after some have reacted to form FeCO3, is below the XRD detection limit. The compounds observed in the Al-Mg-Si alloy reinforced with 8 wt.% SiC, included SiC, MnSi (Fe3Mn)3 Al2(SiO4)3, and SiO2. The formation of the compounds can be attributed to reactions between SiC and the Al-Mg-Si melt.

In summary, it is noted that difference in the compounds detected and the intensities of phases observed in the composites are influenced by the composition of the reinforcement.

3.3. Mechanical properties

The macrohardness values of the composites produced are presented in Fig. 4. It is observed that compared to the unreinforced alloy, the hardness values of the composites reinforced with steel particles, increased with increase in wt.% steel particles. This amounts to approximately 10% increase in hardness when 8 wt.% steel particles are added to the Al-Mg-Si alloy. The observed increase in hardness may be due to higher volume fraction of steel particles and intermetallic phases formed with steel particle addition. The contribution of intermetallics is supported by the investigation by Darvish et al. [20], where it was reported that the correlation between hardness and iron content in the Al-based alloy investigated, was due to increase in the size and volume fraction of iron-rich intermetallics. Compared with the composites containing 8 wt.% SiC, the hardness value of the 8 wt.% steel particles reinforced composite was slightly lower, although less than
Fig. 2 – Secondary electron image and EDS profile of the Al-Mg-Si alloy reinforced with 8 wt.% steel particles.

Fig. 3 – Representative X-ray diffraction patterns of the (a) unreinforced Al-Mg-Si alloy, and the Al-Mg-Si based composites reinforced with (b) 8 wt.% steel particles, (c) 7 wt.% steel and 1 wt.% graphite particles, and (d) 8 wt.% SiC particles.
2%. The hardness values for the hybrid composites containing steel and graphite particles are observed to be also slightly lower than that of the composite composition containing 8 wt.% steel particles, decreasing with increase in the graphite content. The corollary from the analysed results is that, there is no major loss in the capacity to resist indentation in the composites when SiC is replaced with steel particles of equal wt.% within the range (8 wt.% and below) utilized in this investigation.

Representative stress–strain curves of the composites from which the ultimate tensile strength, specific strength and strain to fracture were evaluated, are presented in Fig. 5. From the ultimate tensile strength values of the composites presented in Fig. 6, it is observed that all the steel containing composites, have UTS values higher than that of the composite composition containing 8 wt.% SiC. The difference in UTS between the 8 wt.% SiC containing composites and that containing only steel particles, is within the range 3.2–24% for the 4–8 wt.% steel particles reinforced composites. The improved UTS with the use of the steel particles may be attributed to grain refinement arising from greater undercooling from the steel particles [21]. The interface between the steel particles and the Al-Mg-Si alloy matrix is less likely to create severe stress gradients, since the steel particles are ductile and hence plastically deformable. In contrast, the interface between the SiC and Al alloy matrix, may serve as sites for stress concentration, because of the difference in plastic deformation characteristics between Al, which is ductile, and SiC, which is hard and brittle. This will result in lower nominal applied stresses to induce failure in the material, that is, a relatively lower applied stress is sufficient to attain the maximum stress bearing capacity of the material on account of the stress concentration sites [35]. There is also the likelihood of improved interface bonding between the steel particles and the Al alloy, which Emara [18] reported to be achievable with the use of steel reinforcement materials (steel chips in this case), compared with the use of ceramics. The improved interface bonding allows for the effective transfer and distribution of load from the Al alloy (the matrix), to the stronger steel particles [6,36]. Another potential factor for stress concentration are the porosity sites [7], but since the porosity levels reported for all the composites are very low and at the same level, it is reasonable to assume that the effect is constant for all the composite systems. Hence, it should not be factored in the relative difference in UTS of the composites.

Furthermore, the UTS variations for the composite compositions containing only steel particles and steel and graphite particles were similar in trend to that observed for hardness (Fig. 4). That is, the UTS increased with increase in wt.% steel particles (from 0 to 8 wt.%); and for the 8 wt.% compositions, decreased with increase in graphite content (8.4% for up to 2 wt.% graphite in the hybrid mix of steel and graphite particles).

The specific strength values of the composites are presented in Fig. 7. It is observed that the specific strength of the composites, increases with an increase in the wt.% of steel particles. This is despite the increase in the density of the Al-Mg-Si alloy-based composites with increase in the steel content added as reinforcement (Table 3). It is observed that with the exception of the composite composition containing 4 wt.% of steel particles, the other composite compositions containing only steel or steel and graphite particles, had specific strength higher than that of the composite containing 8 wt.% SiC. Compared with the 8 wt.% steel particle reinforced composite, there is approximately 9% increase in specific strength. The high specific strength values for the steel particles containing composites suggest the possibility of utilizing thinner gauges of the material for service applications to compensate for the slightly higher densities.

The strain to fracture (in percent) of the composites produced is presented in Fig. 8. It is observed that the percent elongation of the composites containing only steel particles decreased marginally (less than 4%) with an increase in steel particles, but were all higher than that containing 8 wt.% SiC. This suggests that increase in the wt.% of steel particles within the range reported in this paper, did not result in corresponding decrease in the ductility of the composites. The improved ductility in the steel containing composites compared to that reinforced with SiC, is due to the ductility of the steel particles compared to SiC which is brittle, and also
Fig. 5 – Representative stress – strain plots of the unreinforced Al-Mg-Si alloy and Al-Mg-Si alloy based composites.

Fig. 6 – Ultimate tensile strength values of the unreinforced Al-Mg-Si alloy and Al-Mg-Si alloy based composites.

the reported good Al-Mg-Si alloy matrix/Steel reinforcement interface bonding [18]. It is noted that the hybrid composite compositions containing steel particles and graphite had lower percent elongation (particularly the grade containing 6 wt.% steel and 2 wt.% graphite particles) compared to the SiC reinforced composite. This is similar to the observation in Zn-27Al-based composites reinforced with steel chips and graphite [37] and Al reinforced with Ni and graphite [10]. In both studies, the tendency for metal/graphite particle contact which does not bond with the matrix may be responsible.

The fracture toughness values of the composites produced are presented in Fig. 9. It is observed that the fracture toughness of the composites containing steel particles only and those containing steel and graphite particles, have values higher than that of the composite composition containing 8 wt.% SiC. The improved fracture toughness, is attributed to the presence of the steel particles which is equally a ductile material as Al but stronger. Ductile materials are known to generally show a better resistance to crack propagation because of the tendency to redistribute applied stresses and strains by plastic deformation (due to yielding), which can also facilitate crack tip blunting-deflating the effect of stress concentration [38]. Hence, the inherent ductility of the steel particles, contributes to the intrinsic toughening of the Al-Mg-Si base composite. Unlike ceramics, where the inherent brittleness, particle cracking and pull out, interface cracking or particle decohesion, can create stress states which facilitate rapid crack propagation and brittle fracture [11]. These conditions (which facilitate rapid crack propagation) are reported to be prevalent in metal matrix composites reinforced with hard and brittle materials [39]. It is also observed
that for the composites reinforced with only steel particles, the fracture toughness increases with an increase in steel particle content. This can with caution, be linked to the higher fracture toughness of steel (~50 MPa m\(^{1/2}\)) compared with Al (18–24 MPa m\(^{1/2}\)) [38]. The fracture toughness decreased slightly when the steel particles are replaced with 1 and 2 wt.% graphite, which can be understood as a graphite is a soft relatively brittle substance. Fig. 10a shows that the composites reinforced with steel particles fail by dominantly ductile fracture mode as reflected in the massive presence of dimples which usually characterize the fibrous micro-mechanism of ductile fracture [31]. The SiC reinforced Al composite (Fig. 10b) is observed to show features indicative of mixed (ductile-brittle) mode fracture which is largely the effect of the SiC particles.

3.4. Wear behaviour

Fig. 11 shows the wear rate computed for the composites produced. It is observed that all the composite compositions containing steel particles, had wear rates lower than the composite containing 8 wt.% SiC. It is also noted that the composite compositions containing steel and graphite particles, had the lowest wear rates of all the composites produced. This is mainly due to the presence of graphite which acts as a solid lubricant. The results suggest that the use of steel particles or steel and graphite particles as reinforcement will offer better wear resistance compared with the use of SiC. Fig. 12 presents the SEM images of the worn surfaces of wear tested samples. Examination of the worn wear surfaces of the composites, help in establishing the wear mechanism,
Fig. 9 – Fracture toughness values of the unreinforced Al-Mg-Si alloy and Al-Mg-Si alloy based composites.

Fig. 10 – Representative SEM fractographs of the Al-Mg-Si alloy based composites reinforced with (a) 8 wt.% steel particles, and (b) 8 wt.% SiC particles.

Fig. 11 – Wear rate values of the unreinforced Al-Mg-Si alloy and Al-Mg-Si alloy based composites.
and providing logical scientific explanations of the wear rates recorded in the composites. From Fig. 12, it is observed that abrasive wear is the dominant wear mechanism observed for the unreinforced alloy and the representative composite compositions presented. It is noted that abrasive wear normally occurs when hard asperities or particles rub under load against a relatively softer surface. The ploughing action of the hard contact surface, usually results in the formation of wear grooves on the substrate [40]. Fig. 12a show that abrasive wear characterized by wear grooves formation, with signs of adhered sheared materials from the alloy were the dominant features observed on the worn track of the unreinforced Al-Mg-Si alloy. The worn surface of the 4 and 8 wt.% steel particles reinforced composites (Fig. 12b and c), are observed to exhibit abrasive wear as evidenced by the presence of wear grooves; there are also signs of adhering wear debris which is largely due to the ductile nature of the steel particles. The worn surface of the composite composition containing steel and graphite particles (Fig. 12d), is observed to exhibit finer and shallow grooves and a relatively smooth surface compared to that observed in other composite compositions, which can be attributed to the presence of graphite as part of the reinforcement mix. The graphite as a solid lubricant, helps to serve as a lubricant between the composite substrate and the wear
disc - reducing the ploughing action of the wear disc, thereby improving its wear resistance. Abrasive wear is also the wear mechanism noticed in the 8 wt.% SiC reinforced composite composition (Fig. 12e). However, it is observed that the wear grooves present in the 8 wt.% SiC reinforced Al-Mg-Si alloy are deeper and more prominent than that for the 7 wt.% steel and 1 wt.% graphite particles reinforced Al-Mg-Si alloy-based composite. This supports the relatively higher wear rate observed for the SiC reinforced composite compared to that observed in the other composite compositions.

4. Summary and conclusions

The structural features, mechanical properties, fracture and wear behaviour of Al-Mg-Si alloy-based composites reinforced with steel and graphite particles, were investigated in this research. From the results, the use of steel particle as replacement of conventional reinforcements such as SiC in AMCs, has great promise for applications where high specific strength, toughness and wear resistance are desired in service. Specifically, the following observations are made from the investigation: Steel particles and a number of reinforcement composition dependent Fe-rich intermetallics and compounds were present in the composites. The steel particles are well dispersed in the composites and have porosities less than 1.5%. The hardness of the composites increased approximately by 10% with increase in steel particles from 4 to 8 wt.%; also, for the same range of steel concentration, the ultimate tensile strength increased with increase in steel wt.% and were all higher than that of 8 wt.% reinforced SiC by a margin of 3.2–24%. The specific strength and fracture toughness equally followed the same trend with respect to steel concentration, and comparison with SiC reinforced composite composition. The strain to fracture difference among the steel reinforced composites was less than 4%, even when it apparently decreased slightly with increase in steel particle concentration. The strengthening mechanism was attributed to the improved grain refinement and interface bonding, and increase in steel particle volume fraction and intermetallics, while the improved toughness was linked to the intrinsic toughening induced by the steel particles which are ductile, stronger than Al, and show a less likelihood to create severe stress gradients. For the 8 wt.% hybrid reinforced composite compositions containing steel and graphite particles, all the mechanical properties decreased slightly with increase in graphite content and trailed the composite reinforced with 8 wt.% steel particles. The wear rates were lowest for the hybrid reinforcement mix of steel and graphite particles, followed by that reinforced with only steel particles; while that reinforced with SiC had the highest wear susceptibility. In all cases, abrasive wear characterized by wear groove formation by ploughing action, was established as the dominant wear mechanism.

Conflicts of interest

The authors declare no conflicts of interest.

REFERENCES


[38] Courtney TW. Mechanical behaviour of materials. 2nd ed. India: Overseas Press; 2006.
