Original Article

Corrosion and wear behaviour of Al–Mg–Si alloy matrix hybrid composites reinforced with rice husk ash and silicon carbide

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A R T I C L E   I N F O

Article history:
Received 3 September 2013
Accepted 10 October 2013
Available online 23 November 2013

Keywords:
Al–Mg–Si alloy based hybrid composites
Rice husk ash
Silicon carbide
Corrosion
Stir casting
Wear

A B S T R A C T

The corrosion and wear behaviour of Al–Mg–Si alloy matrix hybrid composites developed with the use of rice husk ash (RHA) and silicon carbide (SiC) particulates as reinforcements were investigated. RHA and SiC mixed in weight ratios 0:1, 1:3, 1:1, 3:1, and 1:0 were utilized to prepare 5, 7.5 and 10 wt% of the reinforcing phase with Al Mg Si alloy as matrix using double stir casting process. Open circuit corrosion potential (OCP) and potentiodynamic polarization measurements were used to study the corrosion behaviour while coefficient of friction was used to assess the wear behaviour of the composites. The corrosion and wear mechanisms were established with the aid of scanning electron microscopy. The results show that the effect of RHA/SiC weight ratio on the corrosion behaviour of the composites in 3.5% NaCl solution was not consistent for the different weight percent of reinforcement (5, 7.5, and 10 wt%) used in developing the Al–Mg–Si based composites. It was evident that for most cases the use of hybrid reinforcement of RHA and SiC resulted in improved corrosion resistance of the composites in 3.5% NaCl solution. Preferential dissolution of the more anodic Al–Mg–Si alloy matrix around the Al–Mg–Si matrix/RHA/SiC particle interfaces was identified as the primary corrosion mechanism. The coefficient of friction and consequently the wear resistance of the hybrid composites were comparable to that of the Al–Mg–Si alloy matrix reinforced with only SiC.

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1. Introduction

The development of Aluminium based composites using agro-based wastes as sole or complementary reinforcement to the more conventional reinforcing materials such as alumina and silicon carbide is attracting much attention from researchers [1,2]. Aluminium based metal matrix composites (MMCs) are highly acclaimed for the attractive property combinations which they possess, making them very popular and top choice candidate material for a wide range of engineering applications [3]. The properties of aluminium matrix composites...
(AMCs) which have been explored for varied technical uses are: high specific strength and stiffness, good wear and corrosion resistance, low thermal coefficient of expansion, good high temperature mechanical properties, and excellent thermal management potentials among others [4–6]. Aluminium based matrices are also noted to be the cheapest among other common metallic matrix materials (copper, titanium, magnesium) for metal matrix composites (MMCs) production [7]. They can also be processed easily using similar techniques adopted for the production of metals and alloys [8]. Currently, AMCs are being reinforced using waste products derived from industrial processes (red mud, fly ash) and agro based materials (rice husk ash, bamboo leaf ash, ground nut shell ash, bagasse, among others) [9,10]. All the enumerated advantages have made AMCs become very popular and among top choice materials for a wide range of engineering applications by virtue of its excellent combination of material properties, ease processing, reduced cost, and accommodation of waste materials as reinforcement resource materials.

The development of reliable material property database for AMCs newly developed with the use of agro wastes as hybrid reinforcing materials (to either alumina or silicon carbide) is highly imperative. This is of vital importance in the area of materials selection to determine the most suitable areas and limits of application of these AMCs reinforced with agro based wastes. To this end, there have been efforts to generate material properties data for a number of AMCs developed with the use of agro waste based reinforcements [11–13]. From the results generated, a fairly consistent trend in mechanical behaviour has been observed for the different agro wastes used as hybrid reinforcements in AMCs [10,14]. But in the case of corrosion and wear properties, the results have not been as consistent as the observations recorded for mechanical properties [15].

Corrosion behaviour of AMCs in particular has been acknowledged to be difficult to comprehensively predict as shown by the wide variation and not too infrequent contradicting results reported by researchers for different AMC systems [16–18]. A measured forecast of the corrosion behaviour of AMCs in different environments is very helpful as part of assessments required in establishing its performance and suitability in a number of service environments. This is of paramount importance in AMCs developed with the use of agro wastes as hybrid reinforcements, since little corrosion data are currently available to understand its mechanisms of corrosion. Wear assessments are also very crucial where AMCs developed with the use of hybrid reinforcements are to be considered as replacement for the conventional AMCs (reinforced with Silicon carbide or alumina solely) for tribological applications [19].

There is currently no work available which has studied the corrosion and wear behaviour of Al–Mg–Si alloy matrix composites reinforced with rice husk ash and silicon carbide. The interest in studying the corrosion and wear behaviour is motivated by the promising mechanical properties of these Al–Mg–Si alloy based hybrid composites which have shown comparable strength characteristics and improved fracture toughness over the single reinforced Al–Mg–Si alloy/SiC composites [20]. The output from this research will be helpful in understanding the corrosion and wear behaviour of these peculiar AMCs. It would also serve as resource information in building a database of material properties for Al–Mg–Si alloy/RHA–SiC hybrid composites.

| Table 1 – Elemental composition of Al–Mg–Si alloy. |
|-----------------|---------|---------|-------|-------|---------|-------|-------|-------|-------|
| Element         | Si      | Fe      | Cu    | Mn    | Mg     | Cr    | Zn    | Ti    |
| wt%             | 0.4002  | 0.2201  | 0.008 | 0.0109| 0.3961 | 0.0302| 0.0202| 0.0125|

<table>
<thead>
<tr>
<th>Element</th>
<th>Ni</th>
<th>Sn</th>
<th>Pb</th>
<th>Ca</th>
<th>Cd</th>
<th>Li</th>
<th>Na</th>
<th>V</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt%</td>
<td>0.0101</td>
<td>0.0021</td>
<td>0.0011</td>
<td>0.0015</td>
<td>0.0003</td>
<td>0.0000</td>
<td>0.0009</td>
<td>0.0027</td>
<td>98.88</td>
</tr>
</tbody>
</table>

| Table 2 – Chemical Composition of the Rice Husk Ash. |
| Compound/element (constituent) | Weight percent |
| Silica (SiO₂)                  | 91.56          |
| Carbon                        | 4.8            |
| Calcium oxide CaO             | 1.58           |
| Magnesium oxide, MgO          | 0.53           |
| Potassium oxide, K₂O          | 0.39           |
| Haematite, Fe₂O₃              | 0.21           |
| Others                        | 0.93           |

2. Materials and methods

2.1. Materials

Al–Mg–Si alloy was selected as aluminium alloy matrix for the investigation. The alloy was obtained in form of billets and its chemical composition determined using spark spectrometric analysis (Table 1). Silicon carbide (SiC) and rice husk ash (RHA) were selected for use as hybrid reinforcement for the composites to be developed. For this purpose high purity silicon carbide with average particle size of 28 μm was procured. The rice husk ash (with mesh size under 50 μm and chemical composition as presented in Table 2) was prepared from complete burning of the rice husks, thermal processing, and sieving following procedures in accordance with Alaneme [10]. Magnesium was selected as wetting agent to improve wettability between the Al–Mg–Si alloy and the reinforcements.

2.2. Composites production

The Al–Mg–Si alloy matrix composites reinforced with RHA and SiC were produced using double stir casting process [21]. The quantitative amounts of rice husk ash (RHA) and silicon carbide (SiC) required to produce 5, 7.5, and 10 wt% reinforcement consisting of RHA and SiC in weight ratios 0:1, 1:3, 1:1,
3:1, and 1:0, respectively, were initially determined. In order to eliminate dampness in the reinforcements and improve wettability with the molten Al–Mg–Si alloy, the rice husk ash and silicon carbide particles were preheated in an oven at a temperature of 250 °C. A gas-fired crucible (fitted with a temperature probe) was used to melt the Al–Mg–Si alloy billets completely by firing to a temperature of 750 ± 30 °C (above the liquidus temperature of the alloy). The molten liquid alloy was then allowed to cool to a semi solid state at a temperature of about 600 °C before charging in the preheated rice husk ash and SiC particles (along with 0.1 wt% magnesium). Manual stirring of the slurry was performed at this temperature (600 °C) for 5–10 min. The composite slurry was afterwards superheated to 800 ± 50 °C and a second stirring performed using a mechanical stirrer. The stirring was performed at a speed of 400 rpm for 10 min before casting into prepared sand moulds inserted with metallic chills. Table 3 presents the designations used to represent each grade of the composites produced.

2.3. Corrosion test

The corrosion behaviour of the composites produced was investigated in 3.5% NaCl solution at room temperature (25 °C) using potentiodynamic polarization electrochemical methods. A Princeton applied research Potentiostat (VersaSTAT 400) with versaSTUDIO electrochemical software was utilized for the corrosion studies. The experiments were performed using a three-electrode corrosion cell set-up comprising the sample as the working electrode, saturated silver/silver chloride as reference electrode, and platinum as counter electrode. Working electrodes were prepared by attaching an insulated copper wire to one face of the sample using an aluminium conducting tape, and cold mounting it in resin. Prior to testing, the surfaces of the samples were wet ground with silicon carbide papers from 220 down to 600 grade in accordance with ASTM [22] standard. Afterwards, the samples were washed with distilled water, degreased with acetone and dried in air. Open-circuit corrosion potential (OCP) measurements were carried out in a separate cell for 120 min while Potentiodynamic polarization measurements were performed using a scan rate of 1.6 mV/s at a potential initiated at −200 mV to +1500 mV. After each experiment, the electrolyte was replaced, while the test samples were polished, rinsed in water and washed with acetone to remove the products that might have formed on the surface which could affect the measurement. Three repeat tests were performed for each grade of composite produced to guarantee reproducibility and repeatability of test results that were actually observed to be good as there were no significant differences between results from triplicates.

2.4. Wear test

The wear behaviour of the composites produced was tested using a CETR UMT-2 Tribometer. A load of 25 N was used for 1000s at a frequency of 5 Hz; and the coefficient of friction with time for each grade of composite recorded.

2.5. Scanning electron microscopy (SEM)

The corrosion and wear mechanisms of the composites were established by scan electron microscopic (SEM) analysis of the surface morphology of the test samples. A JSM 7600F Jeol ultra-high resolution field emission gun scanning electron microscope (FEG-SEM) was utilized for the microscopy studies.

3. Results and discussion

3.1. Electrochemical behaviour

The variation in the open circuit potentials of the produced composites exposed to 3.5% NaCl solution is presented in

<table>
<thead>
<tr>
<th>Sample designation</th>
<th>Composition weight ratio of RHA:SiC</th>
<th>E_{corr} (V)</th>
<th>I_{corr} (µA/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
<td>0 wt%</td>
<td>−807.772</td>
<td>0.819</td>
</tr>
<tr>
<td></td>
<td>5 wt%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>0.1</td>
<td>−794.939</td>
<td>1.754</td>
</tr>
<tr>
<td>B2</td>
<td>1:3</td>
<td>−808.280</td>
<td>0.542</td>
</tr>
<tr>
<td>B3</td>
<td>1:1</td>
<td>−801.970</td>
<td>0.945</td>
</tr>
<tr>
<td>B4</td>
<td>3:1</td>
<td>−710.055</td>
<td>0.415</td>
</tr>
<tr>
<td>B5</td>
<td>1:0</td>
<td>−765.650</td>
<td>3.812</td>
</tr>
<tr>
<td></td>
<td>7.5 wt%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>0.1</td>
<td>−758.550</td>
<td>4.261</td>
</tr>
<tr>
<td>C2</td>
<td>1:3</td>
<td>−754.751</td>
<td>7.103</td>
</tr>
<tr>
<td>C3</td>
<td>1:1</td>
<td>−808.853</td>
<td>7.837</td>
</tr>
<tr>
<td>C4</td>
<td>3:1</td>
<td>−822.612</td>
<td>2.706</td>
</tr>
<tr>
<td>C5</td>
<td>1:0</td>
<td>−780.424</td>
<td>0.940</td>
</tr>
<tr>
<td></td>
<td>10 wt%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>0.1</td>
<td>−773.265</td>
<td>0.901</td>
</tr>
<tr>
<td>D2</td>
<td>1:3</td>
<td>−805.241</td>
<td>4.329</td>
</tr>
<tr>
<td>D3</td>
<td>1:1</td>
<td>−814.855</td>
<td>2.345</td>
</tr>
<tr>
<td>D4</td>
<td>3:1</td>
<td>−821.102</td>
<td>5.978</td>
</tr>
<tr>
<td>D5</td>
<td>1:0</td>
<td>−760.232</td>
<td>2.076</td>
</tr>
</tbody>
</table>
3:1) had the highest open circuit potential in comparison with the other composite grades. This suggests that B4 will have the least thermodynamic tendency to corrode in the 3.5 wt% NaCl solution. It also appears that the OCP profiles of the composites containing higher weight ratios of RHA (B3, B4, and B5) are shifted to higher values in comparison with those containing more of SiC (B1, and B2) and the unreinforced Al–Mg–Si alloy (A0). This indicates that the RHA–SiC reinforcing phase, there was no clear advantage of higher OCP values for the composite grades with higher RHA content as observed in the case of the 5 wt% reinforcement. By contrast, it is noted that the hybrid composites C2 and C3 (containing RHA and SiC in weight ratios of 1:3 and 1:1, respectively) had higher OCP values in comparison with the single reinforced composites (C1 and C5), and the unreinforced Al–Mg–Si alloy (A0). This again shows that some of the hybrid composite grades in this series have a lower thermodynamic tendency to corrode in the NaCl solution in comparison with the single reinforced composites. However, for the composites containing 10 wt% RHA–SiC reinforcement, it is observed that it is the composite grades containing higher weight ratios of SiC (D1 and D2 – which are respectively the single reinforced and the hybrid composite containing RHA and SiC in weight ratio 1:3) that had higher values of OCP in comparison with the other composite grades in this series.

The potentiodynamic polarization curves for the composites in 3.5% NaCl solution (Fig. 2) helped in analysing more thoroughly the corrosion behaviour of the composites. Fig. 2 shows that the composites generally displayed similar polarization curves and passivity characteristics. But the corrosion potentials (Ecorr) of the composites were clearly distinct for and defined in the ranges of −0.83 to −0.71 V. Table 3 presents the corrosion potential (Ecorr) and corrosion current density (Icorr) data of all the composites produced was obtained from Fig. 2. It is seen clear that the corrosion potentials (Ecorr) and corrosion current density (Icorr) of the composites did not follow a consistent trend with variation in the weight percent of reinforcement phase and RHA/SiC weight ratios of the composites produced as was the case with the OCP curves (Fig. 1). The scatter in the corrosion current density (Icorr) of the composites is better appreciated from Fig. 3. In this figure, it is observed that the corrosion current densities of the composites with 5 wt% reinforcement (B series) were averagely lower than that of the 7.5 wt% and 10 wt% RHA–SiC reinforced composites. This indicates that the 5 wt% RHA–SiC reinforced Al–Mg–Si based composites have lower corrosion susceptibility in 3.5% NaCl solution in comparison with the higher reinforcement grades. For the 5 wt% RHA–SiC reinforced composite series, it is further noted that specimen B4 (the hybrid Al–Mg–Si composite containing RHA and SiC in weight ratio 3:1) had the least corrosion current density indicating that it has the overall best corrosion resistance. This observation is consistent with the results from the OCP values (Fig. 1a) discussed earlier. It is also observed that the other hybrid composite grades B2 and B3 (containing RHA and SiC in weight ratios of 1:3 and 1:1, respectively) also had lower corrosion current densities in comparison with

![Fig. 1](image_url) - Variation of the open circuit potential with time for the Al–Mg–Si based composites containing (a) 5 wt% RHA–SiC reinforcement, (b) 7.5 wt% RHA–SiC reinforcements, and (c) 10 wt% RHA–SiC reinforcement; in 3.5% NaCl solution.
the single reinforced grades B1 and B5 which had higher corrosion current densities. In the case of the composites with 7.5 wt% reinforcement, the corrosion current density increases with increase in the RHA weight ratio attaining peak corrosion current density for specimen C3 (which has RHA:SiC weight ratio of 1:1). Further increase in the RHA weight ratio resulted in decrease in the corrosion current density. For the composites containing 10 wt% RHA–SiC reinforcement, there was no coherent trend in the corrosion behaviour (corrosion current density variation) with respect to changes in the RHA/SiC weight ratio. However the corrosion current density values were averagely lower than that of the composites having 7.5 wt% RHA–SiC reinforcement. Although the effect of RHA/SiC weight ratio was not consistent for the different weight percent of reinforcement (5, 7.5, and 10 wt%) used in developing the Al–Mg–Si based composites, it was very clear that for most cases the use of hybrid reinforcement of SiC and a cheap complement RHA does not degrade the corrosion properties of the composites in 3.5% NaCl solution.

Secondary electron imaging of all the composites after the corrosion test indicates that the corrosion mechanism for all the composites was preferential dissolution of the more anodic Al–Mg–Si alloy matrix which occurs around the Al–Mg–Si matrix/RHA/SiC particle interfaces. Representative SEM images of some of the composites are presented in Fig. 4 confirming the afore-mentioned corrosion mechanism. The presence of physical or chemical heterogeneities such as reinforcement/matrix interface, defect, intermetallic, mechanically damaged region, grain boundary, inclusion, or dislocation is responsible for the localized corrosion commonly observed in MMCs [23,24]. This is due to the difference in electrochemical potentials between these heterogeneities and the matrix which is often more anodic [18].

3.2. Wear behaviour

The variations of coefficient of friction with time for the composites produced are presented in Fig. 5. For the composite grades containing 5 wt% RHA–SiC reinforcement (Fig. 5a), it is observed that the hybrid composite B2 (which has RHA and SiC weight ratio of 1:3) had the least coefficient of friction in comparison with the other composites in this series. The other hybrid composite compositions B3 and B4 (which have RHA and SiC weight ratios of 1:1 and 3:1, respectively) had coefficient of friction comparable to that of the single reinforced composites B1 (single reinforced Al–Mg–Si matrix composite containing SiC) and B5 (single reinforced Al–Mg–Si matrix composite containing RHA). This is a clear indication that the addition of low cost agro waste product, RHA, as complementary reinforcement to SiC in Al–Mg–Si alloy based composites does not degrade the wear resistance characteristics of the composites. The unreinforced Al–Mg–Si alloy, as expected, had the highest coefficient of friction. For the Al–Mg–Si alloy based
composites containing 7.5 wt% RHA–SiC reinforcement, it is observed that the hybrid composites C2, C3, and C4 (which contain RHA and SiC in weight ratios 1:3, 1:1 and 3:1, respectively) had comparable coefficient of friction with the single reinforced Al–Mg–Si/SiC composite (C1). For the 10 wt% reinforcement, it is observed that D4 (hybrid composite containing RHA and SiC in weight ratio of 3:1) and D5 (single reinforced Al–Mg–Si/RHA composite) which are both characterized by higher RHA content have lower coefficient of friction in comparison with the other hybrid composite grades (D2 and D3) and the single reinforced grade D1. This is an added indication that the addition of RHA can improve the wear resistance of Al–Mg–Si based composites.

The wear results reported in Fig. 5 are supported by the SEM micrographs mechanisms proposed above and confirmed by the secondary electron images of the worn surfaces of all the composite grades. These images show similar wear surface topographies characterized mostly by abrasive wear features which occasional worn debris welded to the surface of the samples. The samples C5 and A0 were the few exceptions that showed a more predominant adhesive wear mechanism due to the large accumulation of debris visible on the surfaces (Fig. 6c and d). Adhesion of worn out debris to the surface of these composites is largely responsible for the higher friction coefficients observed [25,26].

Fig. 4 – Some representative SEM photomicrograph of the corroded surfaces of the Al–Mg–Si based composites after the electrochemical test in 3.5% NaCl solution (a) Al–Mg–Si/5 wt% SiC (B1), (b) Al–Mg–Si/5 wt% RHA–5 wt% SiC (C3), and (c) Al–Mg–Si/7.5 wt% RHA.

Fig. 5 – Variation of coefficient of friction with time for the Al–Mg–Si based composites containing (a) 5 wt% RHA–SiC reinforcement, (b) 7.5 wt% RHA–SiC reinforcements, and (c) 10 wt% RHA–SiC reinforcement.
consistent for the different weight percent of reinforcement (5, 7.5, and 10 wt%) used in developing the Al–Mg–Si based composites.

- It was evident that for most cases the use of hybrid reinforcement of RHA and SiC resulted in improved corrosion resistance of the composites in 3.5% NaCl solution.
- Preferential dissolution of the more anodic Al–Mg–Si alloy matrix around the Al–Mg–Si matrix/RHA/SiC particle interfaces was identified as the primary corrosion mechanism.
- The coefficient of friction and consequently the wear resistance of the hybrid composites were comparable to that of the Al–Mg–Si alloy matrix reinforced with only SiC.
- The production of low cost Al–Mg–Si alloy matrix hybrid composites using rice husk ash as a complementing reinforcement to silicon carbide has great promise for high corrosion and wear resistance applications judging from the corrosion and wear properties exhibited by most of the hybrid composites.

**Conflicts of Interest**

The authors declare no conflicts of interest.

**REFERENCES**


