Sustainability in Production and Selection of Reinforcement particles in Aluminium Alloy Metal Matrix Composites: A Review

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Abstract.
This paper reviews relevant literature in the area of incorporating sustainable materials into the material selection process of metal matrix composites (MMCs) production. Agricultural and industrial waste materials used as reinforcements in MMCs have been reviewed to highlight the need for establishing a lean production process. The reviewed investigations have recorded improvements in both the microstructure, density and mechanical properties such as hardness, strength, tensile, and impact strength of the resulting MMC. The reviewed literature highlights stir casting as the most used method of producing aluminium and magnesium-based matrix composites due to its relatively low cost, simplicity, and efficiency. Based on the results of various studies, it is highly recommended that the use of these sustainable materials as reinforcements in MMCs possess the necessary properties to be used in engineering industrial applications.

Key Words: MMCs, Sustainable materials, reinforcements

1. Introduction
Metal matrix composites (MMCs) have become an important part of most production component in terms of material selection. Application not limited to the aerospace and automotive industries have the pressing need for weight reduction in their components while promoting properties such as strength, corrosion and wear resistance among others. Aluminium and its alloys have attracted the most attention as base materials in MMCs due to their low density and corrosion resistance [1]. Aluminium and magnesium based MMCs are the most widely studied and used MMC due to the need for lightweight materials in production. Magnesium is, in fact, the lightest structural material [2] but due to its cost, aluminium is preferred for applications where weight is a critical factor in material selection. In terms of material utilization, magnesium is the 3rd most commonly used metal in engineering industrial application behind iron and aluminium [3]. Research carried out in the area of MMCs has attempted to improve mechanical properties, density, microstructure, cost, wear and corrosion resistance of the base metal by reinforcing them with other materials. The resultant materials are what is referred to as composites. The most researched materials used in reinforcing metal matrices include Al₂O₃, TiC, SiC, C, B, BN and B₄C [4]. Among the listed materials used as reinforcement, SiC is the most widely used in aluminium MMC because they have close density
values at both room and elevated temperatures [5]. For MMCs, ceramics are mostly used as reinforcements to obtain better properties.

In the production of aluminium based metal matrix composites with particulate reinforcement, the stir casting route has been favoured with respect to its simplicity and cost efficiency [6] [7] [8]. Stir casting is a liquid production route for metal matrix composites which the conventional metal casting process with certain modifications to avoid defects, uneven dispersion of the reinforcement in the melt while maintain wettability between the matrix and the reinforcement. These modifications include a stirrer which is incorporated into the process to provide uniform distribution of the reinforcement in the matrix, a motor which rotates at a predetermined speed to turn the stirrer. In some cases for safety and functionality, a rack and pinion mechanism is used to move the stirrer up and down [8]. Hashim et al. [9] identified 4 factors that influence the process of stir casting in metal matrix composites. These factors include; the difficulty in obtaining uniform dispersion of the particulate reinforcement material, the wettability between the reinforcement and the metal matrix, porosity, and possibility of chemical reactions between the matrix and the reinforcement material. These identified factors have over time become the governing considerations in engineering metal matrix composites via stir casting route.

Due to environmental concerns, extensive research has gone into sustainability for reinforcements in composite production. Sustainable materials are in the form of agricultural and industrial waste. Some researchers have also in the bid for sustainability utilized some plants in the production of fibre reinforced composites. Based on the most used agricultural and industrial waste reinforcements in literature, egg shells and coconut shell (agricultural), fly ash and red mud (industrial) will be reviewed.

2. Promising waste materials for metal matrix composites

The waste materials highlighted in the section above have been used as both single and hybrid reinforcements. In most reviewed literature, these sustainable materials are being combined with existing synthetic materials to be used as reinforcements for the selected MMC. Considerable research has been done with recorded improvements in the mechanical properties among others and the resulting composites which will be reviewed in the sections below.

2.1 Fly ash

Fly ash is a grey by-product of the combustion of coal used in coal-fired electricity and steam generating plants. There are 3 types of coal, bituminous, sub-bituminous, and anthracite from which fly ash can be generated. Based on these types, there are two major classes of fly ash, class C which is gotten from the combustion of sub-bituminous coal and Class F which is generated from the combustion of bituminous and anthracite coal [10]. The chemical compositions of the two classes of fly ash are summarised in table 1.

| Constituents | Class C (%) | Class F (%) |
|--------------|-------------|-------------|
| SO₃          | 1           | 2           |
| MgO          | 2           | 2           |
| CaO          | 9           | 64          |
| Fe₂O₃        | 7           | 2           |
| Al₂O₃        | 26          | 4           |
| SiO₂         | 55          | 23          |
Constituents such as Al₂O₃ and SiO₂ make fly ash a good candidate for an investigation into its application as reinforcements for MMCs. In India, data generated by [11] indicates that 169.25 million tons of fly ash were generated in 2017 of which its utilization is 63.28 million tons. Current areas of exploitation include cement production, mining, and agriculture. The data provided by [9] suggest that 62.15 million tons of fly ash were unused and typically dumped. Data like this has prompted research to relieve this burden of the underutilization of fly ash. The choice to use fly ash as reinforcement in aluminum matrix metal composites in due to its low density, availability and good proportions of Al₂O₃ and SiO₂ content refer to table 1. Figure 1 depicts a pictorial representation of fly ash.

Several research endeavours in the use of fly ash as reinforcement have produced significant results such as research conducted by Shivandan & Yogananda [12] which aimed at the development and characterization of wear properties of AA 8011 hybrid metal composite. Using glass short fibers and fly ash to reinforce the aluminum alloy via stir casting method showed a reduction in wear rate with increments in the reinforcement weight percentage. As described earlier, most works in the use of sustainable reinforcement materials have attempted to combine a sustainable reinforcement particle to an already existing synthetic reinforcement in order to study its effect on the formed composite. Such studies were conducted by Kulkarni et al [13] in which the effect of fly ash and Al₂O₃ on the mechanical properties and density of aluminum 356 alloy. The studies reported a reduction of density while the mechanical properties increased. Sharm et al [14] performed a similar investigation with [13] of which the effects of fly ash particulates on pure aluminum were studied. The aluminum MMC reinforced with fly ash was produced using stir casting method. The fly ash was added to the base metal in proportions of 2-4-6wt%. Surface analysis was conducted to determine the distribution of the fly ash particles and the presence of porosity on the MMC. The investigation showed a 13.6% reduction in wear rate compared to the monolithic aluminum. Based on the result it was concluded that the increase in the wt% of fly ash showed an increase in the coefficient of friction. The results reported so far clearly indicates that the performance of a produced composite material is greatly influenced by the choice of reinforcements when hybrid reinforcements are being considered. Gireesh et al [15] in an experimental investigation studied the effect of fly ash, SiC, and Al₂O₃ as hybrid reinforcements for Al 6061. The method of production of the composite was stir welding. The weight fraction of the fly ash was kept
constant at 5wt% while that of the SiC and Al₂O₃ was varied at 5-7.5-10wt%. Table 2 summaries the studied mechanical properties.

| Material                        | Density (g/cm³) | Tensile Strength (MPa) | Yield Strength (MPa) | Hardness (Brinell Hardness number) (BHN) |
|---------------------------------|-----------------|------------------------|----------------------|----------------------------------------|
| Al 6061                         | 2.67            | 115                    | 48                   | 30                                     |
| 5% Fly ash + 5% SiC             | 2.48            | 117                    | 79                   | 53                                     |
| Al₂O₃ + 7.5% SiC                | 2.56            | 126                    | 108                  | 64                                     |
| 5% Fly ash + 10% Al₂O₃ + 10% SiC| 2.44            | 129                    | 99                   | 45                                     |

From the results shown in table 2, increasing the wt% of SiC and Al₂O₃ to 7.5wt% led to an increase in tensile strength by 8.2%, the yield strength and hardness value increased by 36.48% and 20% respectively. An increase of the wt% for SiC and Al₂O₃ to 10wt% also showed an increment of the yield strength, tensile strength, and hardness by 25%, 10.4%, and 16%.

Kesavulu et al [16], conducted a study aimed at reinforcing aluminum with fly ash particulate. Weight fractions of 15% and 20% for the reinforcement were selected. It was reported that the tensile strength and hardness value increased with increasing weight fraction of the fly ash reinforcement in the aluminum metal composite. A recommendation based on the improvements reported that the aluminum-based MMC can be applied in aerospace and production of lightweight vehicles.

### 2.2 Eggshells

Eggshells are a major source of food waste ultimately making its disposal a critical environmental factor. Means of egg disposal are limited. Egg shells are being used locally in Nigerian communities as an abrasive for washing aluminum pots and pans. There is approximately 150,000 tons of eggshell waste in the US per annum of which 26% is used as fertilizers, 21.1% as animal feed ingredients [17]. This leaves approximately 78,000 tons disposed of in landfills. This reason along with the fact that egg shells are bio-materials comprised of 94 - 97% [18][17][19] CaCO₃ have lower density when compared to synthetic CaCO₃ has led to its recognition as a good source of reinforcements in MMCs. Various stages of eggshells used in reinforcing metals in MMC production are shown in figure 2.
Researchers in several fields are also looking into incorporating eggshells and its ash into their studies. Such studies include exploitation of eggshells for use as an additive in cement production, utilization as radiation protection for buildings and use for production of biodiesel. [20] [21]. Table 3 summarizes the compositions of eggshells.

| Constituents               | (%)  |
|----------------------------|------|
| CaCO₃                      | 94-97|
| Mg                         | 0.2-1.0 |
| Ca₃(PO₄)₂                  | 0.2-1.0 |
| Na, Fe, Cu, Mn, K          | 0.1  |
| Organic materials          | 2-3.3|

Hassan and Aigbodion [22] studied the effects of eggshell particles on the microstructure and properties of Al-Cu-Mg Metal matrix. This study compared the effects of both carbonized and uncarbonized eggshells. The milled eggshells were placed in a graphite crucible and heated to 1200°C to form eggshell ash (carbonized eggshell). Using stir cast method, the Al-Cu-Mg/ES MMC was produced. Properties such as density, tensile strength, impact energy, and hardness values were measured for the MMC. The result obtained was compared against those obtained for uncarbonized eggshells. The microstructure analysis showed the presence of carbon in the carbonized eggshells. The grain size of the carbonized eggshells was smaller than those of the uncarbonized eggshells. Results also showed that the Al-Cu-Mg/carbonized eggshells produced better results than the uncarbonized eggshell reinforced composites. It was recommended based on the results that the addition of 12wt% carbonized eggshells can be utilized in low-cost production of MMCs for engineering applications. Recently, studies conducted attempted to investigate the production of Al-Si-Mg-Ti matrix reinforced with eggshells [23]. Microstructural analysis revealed that the addition of eggshell particles resulted in grain refinement of the resulting composite. It was also reported that the addition of 1.5wt% eggshell particles increased the yield strength by 8% while the weight was reduced by 7-10%. Agunsoye et al [24] stressed the need for sustainability in all phases of the MMC. The mechanical properties and wear resistance were evaluated for recycled aluminum cans and egg shells for matrix and reinforcements respectively. The elemental analysis of the recycled aluminum cans
showed that aluminum was 98.10% with trace amounts of silicon, iron, copper, manganese, magnesium, and titanium [24]. Using stir casting, the composite was produced. The results of the microstructural analysis showed a homogenous distribution of eggshell particles with the recycled aluminum can matrix. The composite saw increased wear resistance of 65% while the Young's modulus of elasticity, yield strength and hardness increased by 62.98%, 31.28% and 11.85% respectively. At 12wt%. [25] studied the microstructural and mechanical properties of Al 6061 reinforced with eggshell particulates. The weight fraction of the eggshells was varied; 5wt%, 10wt%, and 15wt%. The results showed an increase in the hardness value with an increase in weight fraction (5wt%, 10wt%, 15wt% gave 32.32 BHN, 33.83 BHN and 37.13 BHN) respectively. The sample with 10wt% showed the best value for density which was 2.33g/cm³. The microstructural analysis showed that the eggshell reinforcement was evenly distributed in the matrix phase.

2.3 Coconut shell ash
The coconut is a palm fruit available in most tropical countries worldwide. It is an important agricultural product due to the usefulness of every part. There has been relevant research in coconut shells in areas such as biomass, building ultraviolet rays shielding and more recently composite reinforcement. The results of characterization done of coconut shell ash by [26] indicate hard phases such as SiO₂, Fe₂O₃, Al₂O₃ and MgO as seen in table 4. These properties are clear indications of the viability of coconut shell ash as reinforcements for MMCs. Figure 3 represents coconut shells crushed, milled coconut shells and coconut shell ash.

| Constituents | SiO₂ | MgO | Al₂O₃ | Fe₂O₃ | CaO | K₂O | Na₂O | MnO | ZnO |
|--------------|------|-----|-------|-------|-----|-----|------|-----|-----|
| %            | 45.05 – | 16.2- | 15.6– | 8.98 – | 0.57 – | 0.42 - | 0.41 - | 0.17 - | 0.3 - |
|              | 45.6 | 19.4 | 16.76 | 12.4 | 0.78 | 0.52 | 0.45 | 0.22 | 0.39 |

Figure 3. (a) coconut shells (b) milled coconut shells (c) coconut shell ash

The effect of coconut shell ash on the wear behavior of AL-1100 metal matrix at elevated temperature was investigated by [28]. The AL-1100/coconut shell ash MMC was produced using stir casting route in weight fractions of 5wt%, 10wt% and 15wt% coconut shell ash. The characterization revealed the presence of Fe₂O₃, Al₂O₃, SiO₂, CaO, MgO, and fixed carbon (refer to [21]). The density of coconut shell ash was reported to be 2.04g/cm³. The results obtained for the wear analysis showed that at elevated temperatures, Al-1100/coconut shell ash had better wear resistance at 150°C. The specific strength at 15wt% of reinforcement increased by 70%. Daramola et al [29], using double stir casting produced AA6063/coconut shell ash
MMC. The weight fraction of the coconut shell ash was varied (3wt%, 6wt%, 9wt%, and 12wt%). The studies indicated a decline in the density while the tensile strength and hardness values increased. Sankara et al [30] evaluated the tribological behavior of AA 1100/coconut shell ash + graphite MMC. Three other composites were produced using the same matrix and coconut shell, Al2O3 and Al2O3 + graphite. Each of these reinforcements was used with the base alloy in equal weight fractions for comparative studies. The Al/coconut shell ash showed improved tensile strength and hardness values. It was also evident from the results obtained that the AA 1100/coconut shell-graphite MMC showed the best wear resistance. All the composites produced had improved tribological and mechanical properties in comparison to the AA 1100 base metal. Kumar et al [31] characterized and studied the mechanical properties of AA 6082 reinforced the ZrO2 and coconut shell ash. The production method was reported to be stir casting. The microstructure showed homogeneity in the distribution of ZrO2 and coconut shell ash. It was observed that the presence of the ZrO2 particles resulted in the increase in density while the tensile strength was higher than that of the alloy. The overall impact strength of the hybrid composite increased by 28.6%.

2.4 Red mud
Like fly ash, red mud is an industrial by-product of a process which is considered as waste. Red mud is the residue produced during the production of aluminum oxide by the Bayer process. Aluminum oxide is reduced to aluminum through electrolytic reduction. The disposal of red mud has been identified by [32] as a major environmental issue for the aluminum industry due to the fact that about 95% of virgin aluminum produced is produced using the Bayer’s process. The production of 1 ton of aluminum leads to the generation of between 1 and 2 tons of red mud [33][34]. The interest of researchers in the utilization of red mud as a sustainable material for reinforcement is due to its constituents as shown in table 5.

| Constituents | Fe2O3 | Al2O3 | SiO2 | Na2O | TiO2 | CaO | MnO |
|--------------|-------|-------|------|------|------|-----|-----|
| %            | 48.50 | 14.41 | 11.53| 7.50 | 5.42 | 3.96| 0.17|

Studies of the tribology of red mud reinforced aluminum metal composites were undertaken by S. Rajesh et al [36]. The microstructural analysis showed a uniform distribution of red mud reinforcement in the aluminum matrix. The experimental density obtained using the Archimedes principle was 2.62g/cm³. Vickers hardness values and impact strengths were 55.6 VHN and 8.74kgm/cm³ respectively. Using ANOVA, it was concluded that the specific wear rate depends on the weight fraction of the reinforcement, sliding velocity and applied load. Using stir casting method, [37] studied the mechanical properties of Al2O3 and red mud hybrid particulate reinforce AA 6061 MMC. Weight fractions of 2.5-10wt% for equally mixed Al2O3 and red mud particles were used. The SEM observations showed that the dispersion of larger particle sizes was more uniform than the finer particles. The density, porosity, tensile strength and hardness all increased with increasing weight fraction of reinforcements [37]. Singh and Chauhan [38] studied the fabrication characteristics and tensile strength of Al 2024/SiC/red mud MMC. The selected processing route for the MMC was stir casting. It was observed from the microstructural analysis that there was an even dispersion of the hybrid reinforcement in
the aluminum alloy matrix. It was also observed that the addition of red mud to the composite decreased the density and porosity. The measured strength of the MMC was approximately 34% more than that of the monolithic aluminum alloy.

3. Conclusion
The reviewed works in the use of sustainable materials as reinforcements for aluminum metal matrix composites identifies stir casting as the most cost-effective and efficient method of producing selected MMCs. The choice of the relevant method of MMC processing to a large extent is determined by the type of matrix and reinforcements to be used for the composite [39]. Particulate reinforcement through literature are very compatible with MMCs processed using the stir casting method. The results from the analysis of mechanical and physical properties, microstructural and wear analysis are indications of the wide applications possible for sustainable materials to be used as reinforcements in MMCs. In addition to its possible applications, the issue of the adverse environmental impact of the accumulation of the perceived ‘waste’ materials is also being tackled. More researches are and will be conducted to further utilize more sustainable materials in the production and selection of metal matrix composites.

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