Synthesis and properties analysis of char-reinforced Al–13.5Si–2.5Mg alloy composites

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The re-evaluation of previous and existing methods in materials processing is becoming ever more critical because of processing and starting materials cost factors. A study on the synthesis and properties investigation of hypereutectic Al–13.5Si–2.5Mg alloy reinforced with carbon chars using coconut shell as the organic precursor has been carried out. The low-cost, double compaction solid-state technique was used. Reinforcing the hypereutectic alloy with coconut shell char particles (size: <140 μm) at 2 vol % and consolidating by reaction sintering at 600 °C in vacuum for 15 min, followed by near net-shape compaction at 250 MPa, increased the hardness of the alloy 6% while reducing its strength (UTS) by only 3%. The use of palm kernel shell char as the dispersed phase was found to yield identical results. At 2 vol % char, the mechanical properties, sintered density and dimensional changes were optimally found to be suitable for lightweight anti-friction electromechanical applications. Attempts to reinforce the alloy with 2 vol % coconut shell chars activated in CO₂ reduced its strength in the range of 19 to 26% at different burn-off percentages. This is attributed to the higher amount of oxide products formed during the activation process. At 600 °C, formation of the brittle Al₄C₃ phase in the different sintered composites containing activated and unactivated chars was identified by X-ray studies.

1. Introduction
As starting materials and processing costs are increasingly becoming a critical factor in materials development, previous and existing synthesis methods of composite materials are being re-evaluated by scientists for optimum applications at a reduced cost without impairing the product properties [1–4, 7, 19, 25]. The solid-state fabrication route in metal–matrix composites (MMC) synthesis is known to have several advantages over liquid metallurgy technique, and these can be exploited to fabricate cost-effective parts. One of these benefits include the use of lower temperatures resulting in less interaction between the matrix and reinforcement [1]. This yields composites with excellent interfacial properties because of greater latitude to control the matrix–reinforcement interaction. More composites such as a composite of SiC and Ti alloy, which otherwise, is impossible as SiC dissolves in the molten alloy [2], can also be produced. Elemental consolidation aids can also be homogeneously blended into the matrix particles which leads to improved compositional and microstructural control [3]. Although the production of specialty products requires the use of costly equipment, less time at processing the fabrication of sound final parts and the lower energy requirement go a long way to offset this factor [4]. Also, further attempts to control porosity and boundary precipitates have been based upon controlled compositional changes and careful application of the consolidation techniques. Smith and Froes [6] agree with other investigators [7] that particulate and discontinuous filament composites are easier and much less expensive to fabricate through powder metallurgy (PM) than continuous filament composites because good interfacial properties added to microstructural and compositional homogeneity are achievable. With these, PM methods alone can be used to develop particulate composite materials possessing the combination of properties required for any specific working conditions of the friction and autoparts assemblies. From the point of view of the various levels of porosities which they can produce, higher technology applications in military, aerospace, and special automobiles require parts (both heavy-duty, and of intricate nature) made from the high-cost hydrostatic
and explosive compaction methods while the relatively low-cost methods of single compaction, double compaction, and mechanical deformation following hot pressing are used to produce parts for electromechanics, automobiles, and low-duty machinery [8].

Aluminium alloys are widely applied in transportation, construction and leisure fields because of their excellent combination of properties such as low density, high strength–weight ratio, good corrosion resistance, high thermal conductivity and good fabricability. Different cast Al alloys reinforced with particulates of mica [9–11], coconut shell char [12], graphite [13], SiC [14–16] and zircon sand [17, 18] have been studied and proposed for various automotive uses. Among the investigators, few [12, 14] have used the well-known cast-alloy, Al–Si. Besides, little work has been done on the introduction of these particulates to the alloy through conventional PM for cost-effective, similar applications [19, 20]. Recent advances on the Al–Si alloy PM particulate composites [21–23] employed only the use of relatively costly consolidation techniques to satisfy the various needs of aerospace, defence, and special automobile industries. Silicon imparts strength and low shrinkage to Al and this lends aluminium–silicon alloys to near netshape processing, as is readily achieved in solid-state processes. Also, the use of an Al–Si alloy instead of pure Al as the matrix is also known to decrease the coefficient of thermal expansion of a composite with minimal reduction in thermal conductivity [24], which is a critical property in contact and electromechanical applications. These properties are also exploited for pistons, and the high hardness of the Si particle for wear resistance. The alloy becomes abrasion resistant at eutectic and hypereutectic (13–25 wt %) compositions with the additions of Ni, Cu, Mg, Mn, Co and Cr [25] because the presence of intermetallic phases cause good wear properties, high abrasion resistance and good heat resistance.

Coconut and palm-kernel shell chars are specially light and porous forms of carbon, currently being underutilized in Asia, India, and Africa. They are renewable and their resources in the world are expected to be more than 3 million tonnes. This work has therefore investigated the potential of these chars in hypereutectic Al–Si alloy through a low-cost, cold pressing powder technique for lightweight, contact applications. The process variables and the volume fractions were optimized and the applicable physical and mechanical properties determined.

2. Experimental procedure

2.1. Materials

In this synthesis, cold-pressed, double compaction PM processing was used. The major stages are elemental blending and mixing of the matrix powders and the reinforcements, pressing into green compacts, delubrication (or presintering), and sintering of the compacts. A flowsheet of these stages are schematically shown in Fig. 1. The matrix alloy powders, Al and Si, were supplied by the Aluminium Powder Co. Ltd (ALPOCO), West Midlands, UK, and by Goodfellow, Cambridge, UK respectively. They were analysed for elemental compositions using atomic absorption spectroscopy (AAS) and the results are as shown in Table I. The Al powder was produced by air-atomization, and Si, by comminution and milling.

The organic precursors used in this work were coconut shells (aged < 1 year) and palm kernel shells (aged between 4 and 5 years), supplied from Uke Grains Ltd, Nigeria. Samples of the shells were milled and analysed for organic constituents. The results are shown in Table II. The shell fragments (approx: 4.5 kg) were primarily carbonized (charring) in a closed thick mild steel pot (without the use of a suitable gasket) for 3.5 h. A slit at the top end was provided for the insertion of the platinum–rhodium thermocouple used for reading the temperature. The maximum temperature of charring was 655 °C. Volatile gases, such as those of carbon and hydrogen, were recirculated in the pot and were condensed to solids. The carbonization process

![Figure 1](image-url)