ISSN 2320-9186

Global Scientific JOURNALS

GSJ: Volume 6, Issue 8, August 2018, Online: ISSN 2320-9186
www.globalscientificjournal.com

Development and Characterization of Aluminum Matrix Composites Reinforced with Carbonized Coconut Shell and Silicon Carbide Particle for Automobile Piston Application

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KeyWords

Al6061 Alloy, Carbonized Coconut Shell particle, Mechanical Properties, Metal Matrix Composite, Powder metallurgy, SiC particles, Sintering

ABSTRACT

In the present work, an effort has been made to develop a hybrid aluminium matrix composite for automobile piston application using locally available material: Al 6061 alloy was selected as the matrix material while carbonized coconut shell particles ($CCNS_p$) and SiC_p as reinforcement. Composite were prepared using powder metallurgy technique with 0, 2, 4, 6, 8, and 10 wt % of reinforcement. The requisite mixtures were obtained using high energy mixer and loaded into a steel mould and compressed using a Compac hydraulic press of 500kN capacity to obtain the green compacts. The green compacts were carefully ejected and sintered in a muffle furnace at 527^{o}C for 1hour. Mechanical and thermal properties were investigated. For green compacts, a range of 66.17-107Hv, was obtained for hardness, while for sintered compacts the values obtained are 72.57-105.47Hv, 172.25-207.61MN/m^2 and 2.2136-2.5804x10^{-5}K^{-1} for hardness, tensile strength and coefficient of thermal expansion respectively. Microstructural examination of developed composites materials reveals that the reinforcement's particles were uniformly distributed in the base matrix and that bonding took place between the base matrix and reinforcements after sintering.

ISSN 2320-9186

I. INTRODUCTION

Composite is the combination of two phases of material, usually with strong interface between the base metal and reinforcement. When at least three materials are present, it is called a hybrid composite. They usually consist of a continuous phase called the matrix and a discontinuous phase in the form of fibres, whiskers, or particles called the reinforcement (Dinesh et al.., 2013). Usually the reinforcing component is distributed in the matrix component. When the matrix is a metal, the composite is termed a metal matrix composite (MMC). Due to its high strength, low density, high temperature stability, high electrical and thermal conductivity, adjustable CTE, corrosion resistance, improved wear resistance etc. metal matrix composite are increasingly becoming attractive materials for automobile, aircraft, defence, sports and appliance industries. Ceramic fibres, such as Al_2O_3 and SiC are advantageous in very high temperature applications, and also where environment attack is an issue (Poornesh et al.., 2017b). There has been an increasing interest in composites containing low density and low cost reinforcements (Poornesh et al.., 2017a). Fly ash, red mud, rice husk ash, groundnut shell ash, and coconut shell ash are some of the various discontinuous reinforcement used today as a result of its low cost and density and being available in large quantity as solid waste by product.

Due to its outstanding natural structure and low ash content, coconut shells are appropriate for preparation of carbon black (Lancaster et al.., 2013). MMC are usually fabricated with numerous method among include powder metallurgy. Powder Metallurgy is a production technique in which components with desired properties and shape are fabricated through the utilization of metal and non- metal powder. Manufacture by powder metallurgy involves basically blending, compacting, sintering, finishing and sizing. The low strength and linear thermal expansion coefficient of aluminium and its alloys is still a big problem in their use in internal combustion engines. Hence, this present research work intends to exploit the powder metallurgy route towards the development and characterization of a hybrid metal matrix composite suitable for automobile piston application.

II. MATERIALS AND METHOD

2.1 Materials

Aluminium alloy 6061 is used as base material; silicon carbide and carbonized coconut shell are used as the reinforcements. Table 1 shows the chemical composition of Al6061 Alloy.

Table 1: Chemical Composition of Al 6061 Alloy (Bharath et al., 2014)

Elements	Si	Fe	Cu	Mn	Ni	Pb	Zn	Ti	Sn	Mg	Cr	Al
Percentage	0.6	0.17	0.24	0.139	0.05	0.24	0.25	0.15	0.001	0.802	0.25	Balance

2.2 Methods

2.2.1 Production of carbonized coconut shell particle ($CCNS_p$)

The collected coconut shell was washed with water to remove impurities and dried in an oven at 110^OC to reduce its moisture content. It was then crushed and grinded to form coconut shell powder. The powder was packed in a graphite crucible and fired in an electric furnace in the absence of air to a temperature of 400^OC and held for 10 hrs to form carbonized coconut shell ash. In order to further reduce the particle size, the carbonized coconut shell ash was ball milled for 16hrs in accordance with (Bello et al., 2016). After-ball milling the carbonized coconut shells ash was sized using a set of sieves.

2.2.2 Characterization of carbonized coconut shell particle

The carbonized coconut shell ash was characterized based on particle size and it constituents. The particle size analysis of carbonized coconut shell particle was carried out in accordance with Rajan et al., (2007). About 100g of the carbonized coconut shell particle was placed unto a set of sieves and shaken for 15 minutes to achieve classification in accordance with Madakson et al. (2012). A mini pal compact energy dispersive X-ray spectrometer (XRF) was used for the elemental analysis of the carbonized coconut shell particle. The system is monitored by a PC running the dedicated Mini Pal analytical software.

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2.2.3 Experimental Plan for Formulation of Composite Materials

Table 2: Experimental Plan for Formulation of Composite materials

%compositionof Reinforcement	% composition of Reinforcing component (Label)	25% $CCNS_p$	50% $CCNS_p$	75% $CCNS_p$
		75% SiC_P	50% SiC_P	25% SiC_p
0	A			
2	B	B1	B2	B3
4	C	C1	C2	C3
6	D	D1	D2	D3
8	E	E1	E2	E3
10	F	F1	F2	F3

2.2.4 Experimental Plan for Formulation of Composite Materials

In formulating the composite materials, capital English alphabets were used to denote type of composite based on variation in percentage reinforcement while Arabic numerals represented the variation in relative weight within the reinforcing components. Thus letters A,B,C,D,E and F respectively represented 0,2,4,6,8 and 10%wt composition of the hybrid reinforcement. 1, 2 and 3 represent composites with 25, 50, and 75%wt content of SiC_p relative to $CCNS_p$ content in the respective composites. Table 2 shows the experimental plan.

2.2.5 Mould Specification

The specification of mould used for compaction as shown in Fig 1 is a cylindrical die of internal diameter of 25mm, thickness of 10mm and heights of 70mm and 120mm respectively, made of steel with hardness 65HRC.

Figure 1: Photo of mould Assembly

2.2.6 Mixing of Powders

After the various powders were measured according to the various compositions, the mixing of the powder was performed using a high energy mixer. To ensure a proper homogenous mixture of the powers, the mixing process was carried out for 30minutes for each sample.

2.2.7 Powder Compaction

The conventional compaction method is pressing, in which opposing punches squeeze the powders contained in a die in accordance to Baskaran et al., (2015). Green compacts of the powder blend were prepared using a 500kN capacity compact hydraulic press with punch and die assembly. Here the measured powder mixture was carefully poured into the die with one end temporarily closed. A manually operated pressure of 450kN was applied for powder compaction as shown in Fig 2. After compaction the sample is brought out through one end of the die by applying pressure on the punch to allow it pass through the die therefore ejecting the green compact. Fig 3 shows the compact after compressing and ejection.

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Figure 2: Powder compaction

Figure 3: Green compact specimen

2.2.8 Sintering

After compaction, some of the specimens were sintered in a muffle furnace to improve its bonding as well as its mechanical properties. During sintering the power particles are bonded together by diffusion and other atomic transport mechanisms, and the resulting porous body acquires a certain mechanical strength. In order to protect the green compact from oxidation and reduce residual surface oxides during sintering, sintering was carried out in argon atmosphere in a muffle furnace with sintering temperature starting form room temperature 27^{o}C to 527^{o}C (90% of the base matrix melting temperature, 585^{o}C). The sintered sample was then held for 1hour at 527^{o}C after which it was allowed to slowly cool down in the furnace. Fig 4 is a picture of samples after sintering.

Figure 4: Sintered specimen

2.2.9 Machining of Specimen

Specimens are brought out and carefully machined according to ASTM E228 standard for coefficient of thermal expansion (CTE).

2.3.10 Tests

The various test conducted on the composite include indirect tensile strength, micro hardness, and co-efficient of thermal expansion

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III. RESULTS AND DISCUSSION

3.1 Chemical Composition of Carbonized Coconut Shell Ash.

The results obtained from the XRF chemical composition result of the carbonized coconut shell particle ($CCNS_p$) is shown in Table 3. The Analysis of the result reveals that SiO_2, MgO, Al_2O_3 and Fe_2O_3 were the major constituents of the ash. SiO_2, Fe_2O_3 and Al_2O_3 are known to be the hardest substances. Other oxides found to be present in traces include CaO, K_2O, Na_2O, MnO and ZnO. The presence of hard substances like SiO_2, Al_2O_3 and Fe_2O_3 suggest that the carbonized coconut shell particle can be used as particulate reinforcement in various metal matrix composites (Madakson *et al.,* 2012). After ball milling for about 16hrs, the particles sizes was found to be in the range of 90-120nm.

Table 3: Chemical Composition of carbonized coconut shell particle

Element	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	Na_2O	SiO_2	MnO	ZnO
%	16.6	0.57	14.5	0.50	16.4	0.45	46.5	0.22	0.3

3.2 Hardness

The variation of Micro-hardness test conducted on base alloy (Al6061) and the various composite containing different weight percentages of SiC and CCNS particle shows that the base alloy has a Vickers hardness value of 75.93 and 79.67HV for the green and sintered specimen respectively indicating an increase in micro- hardness of approximately 5% on sintering. As observed from Figure 5, the highest micro hardness value was observed to be 107.67HV and 114.87HV for the green and sintered specimen indicating an increase of 6.7% in hardness after sintering. Comparing the optimum hardness value obtained to that of the master alloy for both green and sintered specimen, it shows that there was an increase of 41.8% and 44.1% respectively. The general effect of sintering resulted in the improvement of hardness across all specimens since particle to particle bonding is enhanced on sintering. Higher hardness value is an indication that the addition of SiC and CCNS particles impact brittleness on Al6061, therefore enhancing its hardness and offering more resistance to plastic deformation. The clustering of $CCNS_p$ with each other as a result of non- uniform mixture could be the reason behind as much as five samples having its micro hardness value below the base alloy.

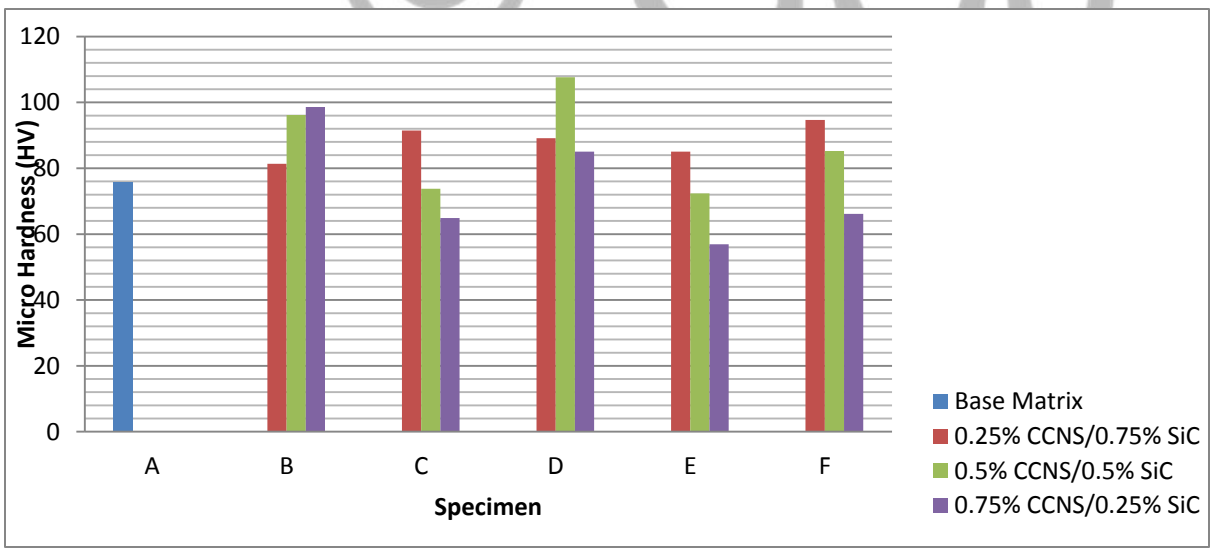


Figure 5(a) Variation of Vickers Hardness for green compacts

ISSN 2320-9186

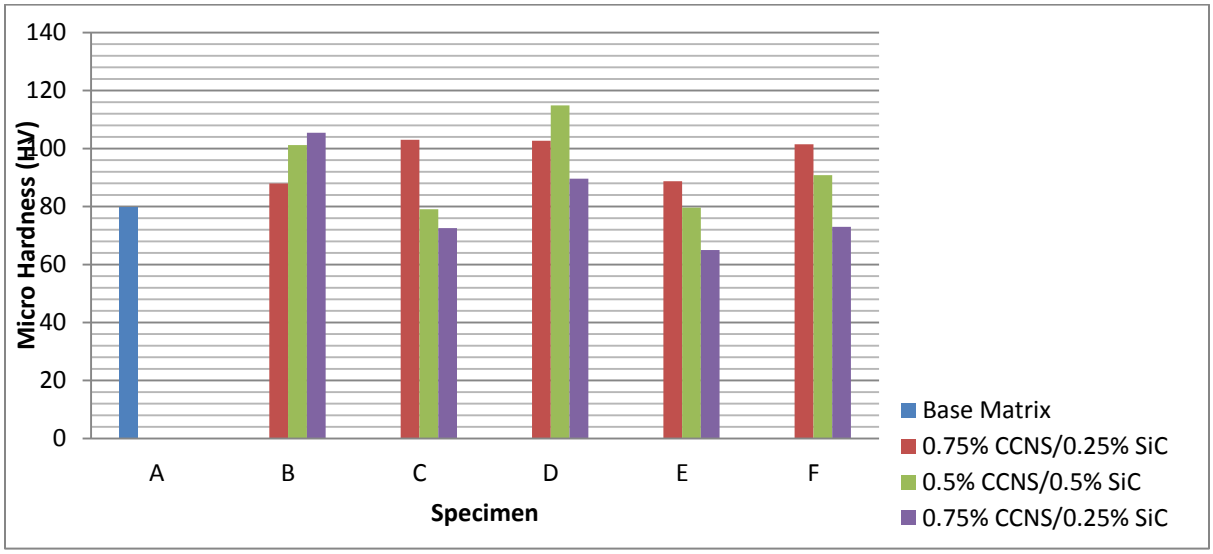


Fig. 5(b) Variation of Vickers Hardness for sintered compacts

Figure 5 Variation of Vickers Hardness with specimen compositions

3.3 Indirect Tensile Strength

The variation of indirect tensile strength for specimens is shown in Fig 6. It is observed that there is a significant increase in tensile strength for all specimens compared to base alloy as base alloy is observed to have a tensile strength of 167.54MN/m^2 which is lower than the tensile strength for all composites specimen. A maximum tensile strength of 207.61MN/m^2 was obtained indicating an increase of 24% when compared to the base matrix. Although the incorporation of SiC_p and $CCNS_p$ as reinforcement into the base alloy showed improvement in tensile strength for composites but this values was observed to decrease for each specimen as percentage weight of $CCNS_p$ increases with decrease in SiC_p. The presence of particles like SiO, MgO, MnO, Al_2O_3 in the ash which are clearly ceramic based and the facts that SiC particles are ceramics in nature, blends and binds with the matrix material. Hence when the tensile test is conducted, the load applied on the specimen is transferred from the matrix and hence will be taken upon by the reinforcing particles. These reinforcing particles aid the matrix material to resist any sort of deformation up to the yield point as the particles obstructs the motion of dislocations in the period of plastic deformation (Poornesh *et al.,* 2017). The tensile strength is though seen to decrease down each group and this can be attributed to the fact that the ash contains ceramic or oxide based particles while SiC_p being a ceramic material in nature is a load bearing and load taking element as a result decrease in weight percentage of SiC_p and corresponding increases in $CCNS_p$ result to decrease in tensile strength of composites down each group.

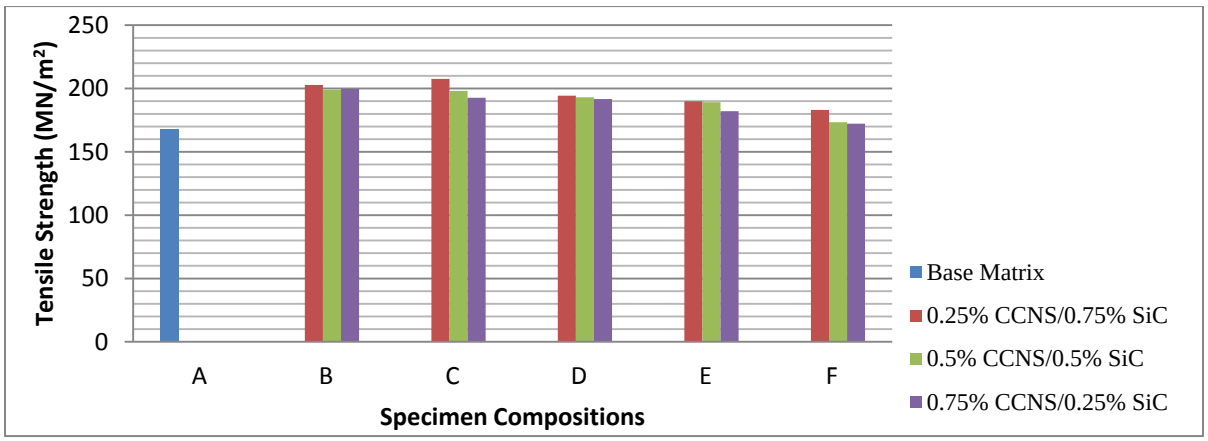


Figure 6 Variations of Indirect tensile strength with specimen compositions

3.4 Coefficient of thermal expansion (CTE)

The variation of CTE is shown in Figure 7. It is observed that the base matrix has a CTE value of $2.5930x10^{-5}K^{-1}$. This value is higher than the average CTE of each composite. The CTE was observed to decreases significantly as weight percentage of reinforcement is increases up to 4% but a further increase in reinforcement leads to gradual increases in CTE of composites for specimen. The minimum CTE was observed to be $2.2136x10^{-5}$ k^{-1}, indicating a decrease of 14.6%. Metal matrix composites are characterized by a large difference in the thermal expansion coefficient of the matrix and reinforcement such that a small change in temperature generates thermal stresses in the aluminium matrix (Dora et al., 2014). The presence of CCNS and SiC particles in the alloy decreases the dislocation movement at the particles-matrix interfaces. This is as a result of difference in CTE between the hard and brittle reinforcement and the soft and ductile metal matrix which results to elastic and plastic incompatibility between the matrix and the reinforcement (Aku et al., 2013). A careful observation of these groups reveals that composite having more weight percentage of SiC_p have lower CTE than the rest. This is due to the hardness and lower CTE SiC_p possess compare to that of the $CCNS_p$ which further lowers the dislocation movement of the particles when subjected to heat.

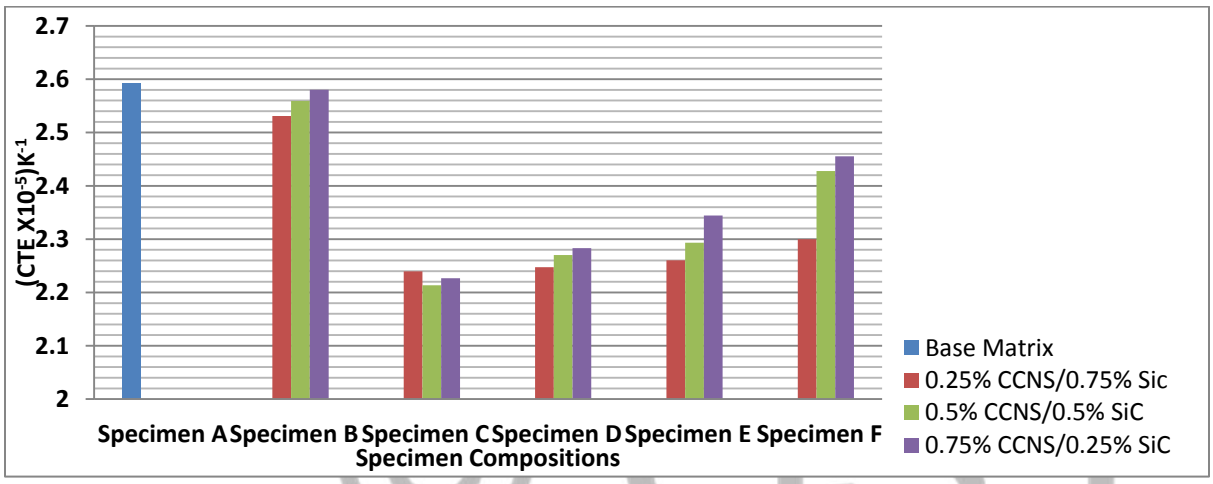
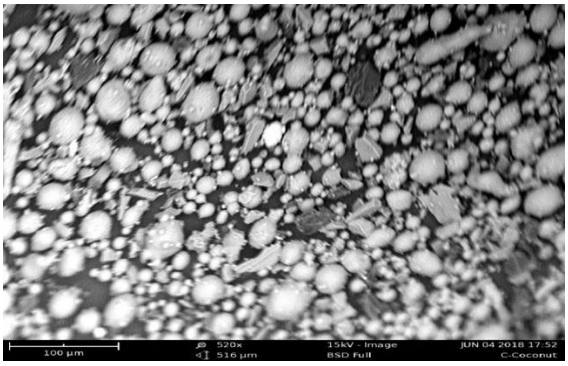
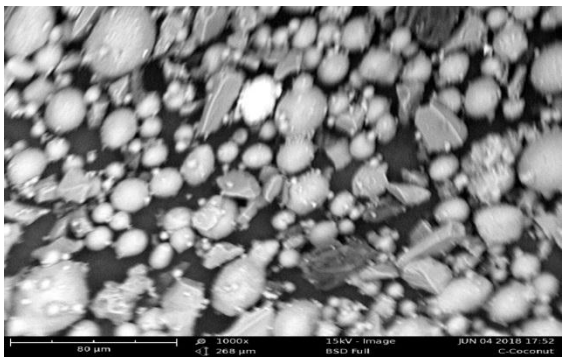


Figure 7 Variation of CTE with specimen compositions

3.6 Microstructural Analysis

Figure 8 shows the scanning electron micrograph of sintered 6061Al-$CCNS_p$-SiC_p composite specimen with 4 weight % of SiC_p and $CCNS_p$. The micrograph shows that $CCNS_p$ and SiC_p were uniformly distributed in the base matrix and also showed that bonding has taken place between the base matrix Al6061, SiC_p, and $CCNS_p$ after sintering. Some amount of porosity was also visible as shown in the micrographs.





ISSN 2320-9186

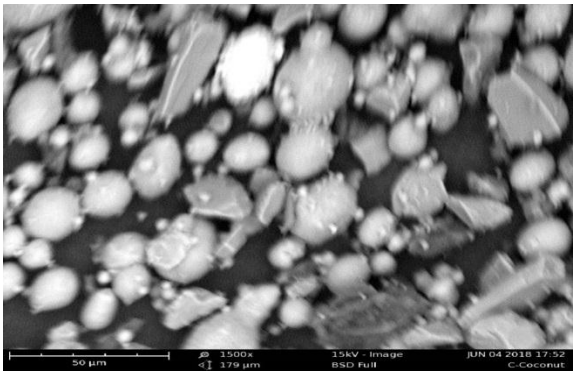


Fig 8 Scanning electron micrographs of sintered 6061Al-CCNS$_p$-SiC$_p$ with 4 weight % of reinforcement particles

3.7 **Comparison of obtained results with generic properties of materials used for piston production**

Materials used in the fabrication of piston must possess high strength and hardness, good wear resistance and thermal conductivity, low CTE and light weight properties.

Sheikh et al.,(2015), studied the mechanical properties and wear strength of piston alloy reinforced with alumina. The desired composite where produced using stir casting technique for 5, 10, and 15 wt % of alumina particles with scrap piston alloy as the master alloy. Their result reveals significant improvement as tensile strength and hardness varies from 160.61-176.9 MPa and 81.76-85.02 HRB respectively.

Lokesh et al.,(2015), designed, fabricated and tested the mechanical properties of piston from aluminium metal matrix composites. The piston was designed by using uni-graphics modelling software. Specimens were fabricated with aluminium 6061 alloy reinforced with silicon carbide and graphene nano particles. The various specimens were prepared for 10 wt % of silicon carbide and 0, 3, 5, and 7 wt % of graphene. Their results shows that the tensile, flexural and hardness strength varies approximately from 158-190 MPa, 170-260 MPa and 50-56 HV respectively. Manikandan et al., (2017), analyse the hardness and tensile properties of aluminium 6061 alloy reinforced with silicon carbide, aluminium oxide and zirconium oxides in order to improve the strength of piston material. Composite was prepared using stir casting technique. Their results reveal a significant improvement as tensile strength and hardness varied from 306-398 MPa and 101-140 Hv respectively.

Table 4 shows the obtained and generic piston material properties. The obtained tensile strength, hardness, and coefficient of thermal experimental for the base alloy are 167.54 MN/m^2, 79.67HV, and 2.59x10^{-6}K^{-1}, respectively while the corresponding properties of prepared composite varies from 172.25-207 MN/m^2, 64.97-114.87Hv, and 22.1-25.5x10^{-6}K^{-1}, respectively. Comparing the obtained properties of prepared composite material with that of the generic material for piston application shows that the obtained values is within the generic properties of a piston materials for tensile strength, and hardness except for the coefficient of thermal expansion which is slightly higher than the generic value as shown in Table 4.

Table 4: Comparison of obtained and generic piston material properties

	Tensile Strength (MN/m^2)	**Hardness (HV)**	**CTE (X10^{-6}) K^{-1}**
Generic Value	180 – 230	95 - 135	20.5–21.5
Base Alloy	167.54	79.67	25.9
Obtained Value	172.25 – 207	64.97- 114.87	22.1-25.5

IV. Conclusions

The primary aim of this research was to evaluate the possibilities of developing aluminum alloy based composites material for automobile piston application from carbonized coconut shell particle and silicon carbide particles using powder metallurgy method. The following conclusion can be drawn from the study:

1. Preparation of Al6061-$CCNS_p$-SiC_p composites by powder metallurgy techniques is successful during the research work. Composite are produced by varying the composition of the various constituents. The composition of prepared composites are: 98%Al6061+2%reinforcement, 96%Al6061+4%reinforcement, 94%Al6061+6%reinforcement, 92%Al6061+8%reinforcement, and 90%Al6061+10%reinforcement.

2. Compaction of powder was successfully done at 450 kN using a 500 kN Capacity Compact hydraulic press.

3. Sintering of specimen was successfully done in a Muffle Furnace at $527^{O}C$ for 1 hour.

4. On sintering hardness showed significant improvement.

5. A maximum tensile strength of 207.61 MN/m^2 was obtained, indicating an increase of 24% compared to the base alloy.

6. The coefficient of thermal expansion measured over the temperature range (27-$200^{O}C$) turned out to decrease with increase in reinforcement particles in all composites specimen produced. A maximum decrease of 14.6% was observed compared to the base alloy.

7. The Microstructural Examination of developed composite materials using Scanning Electron Microscope (SEM) reveals uniform distribution of reinforcements within the alloy.

8. Finally it can be concluded that the develop composites showed a significant improvement in mechanical and thermal properties

Acknowledgment

The authors wish to acknowledge the authorities of Skills Acquisition Centre Yola, Ahmadu Bello University, Zaria and Modibbo Adama University of Technology, Yola for giving them access to their equipment during the course of carrying out this work.

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