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Development of Hybrid Particle Reinforced Aluminium Alloy Metal Matrix Composite for the Production of Brake Disc

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ABSTRACT: *In this research, a standard Honda Accord 2000 model brake disc has been produced from hybrid metal matrix composite. The brake disc was produced from aluminium alloy 6061 as the matrix and combination of silicon carbide and coconut shell ash as reinforcements. The composite samples were produced by using liquid state fabrication techniques through the method of stir casting. The percentage composition of silicon carbide and coconut shell ash were varied while the percentage composition of magnesium and graphite were kept constant. Magnesium was added to increase wettability by reducing the surface tension of the molten aluminium and graphite was added to improve the tribological properties of the cast composites. The stir casting machine was designed and fabricated specifically for this research work by the authors. The test samples were produced and machined into standard specimens for microstructure analysis, density test, mechanical tests (hardness, tensile and impact), thermal test and wear test. Six samples were produced, four of which are composite samples (S2, S3, S4 and S5). The other two are aluminium alloy sample (S1) and as-cast nodular cast iron sample (S6). From the results obtained, composite sample 'S5' produced a uniform microstructure with the optimal composition having Density of 3.15g/cm^3, Hardness of 68 VHN, Tensile Strength of 196N/mm^2, Impact Energy of 8.05J, Wear Rate of 0.0002328g/m and Thermal Conductivity of 72.57W/mk while the as-cast nodular cast iron (S6) has Density of 5.81g/cm^3, Hardness of 88VHN, Tensile Strength of 221.16N/mm^2, Impact Energy of 6.00J, Wear Rate of 0.0001208g/m and Thermal Conductivity of 64.79W/mk. Based on the results obtained for composite sample 'S5', it is obvious that composite sample 'S5' gives lower values for density and impact energy than the As-cast nodular cast iron sample (S6). Hence, the problems of heavy weight and breakage due to heavy impact associated with cast iron brake disc have been addressed using the developed composite.*

KEYWORDS: *Aluminium Alloy, Silicon Carbide, Coconut Shell, Brake Disc, Metal Matrix Composites.*

ABBREVIATIONS Al6061: Aluminium Alloy 6061; Al4C3: Aluminum Carbide; AMCs: Aluminium Matrix Composites; ASTM: American Standard of Testing and Measurement; CSA: Coconut Shell Ash; CSAp: Coconut Shell Ash Particles; MMCs: Metal Matrix Composites; SiC: Silicon Carbide; SiCp: Silicon Carbide Particles.

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I. INTRODUCTION

Composite material is a combination of two or more materials having compositional variations and depicting properties distinctively different from those of the individual materials of the composite. The base material surrounding other materials is normally present in higher percentage and is called the matrix. Other materials which reinforce the properties of the base material are called reinforcements [1]. Among the various types of MMCs, particulate reinforced composites are the most versatile and economical [2].

Metal Matrix Composite materials can be produced by many techniques. The selection of suitable production process is dependent on the type, quantities and distribution of reinforcement components, the matrix alloy or metal matrix and the applications [3]. In recent times, the use of coconut shell ash reinforcements has increased due to their low cost, density and availability as agricultural waste.

Coconut shells have suitable particulate reinforcement properties. The realization of coconut shell ash particles through continuous research is pertinent in achieving a low cost metal matrix composite with uncompromised strength for various engineering application [4].Coconut shell ash particle could be used in the production of light MMC with good thermal and wear resistance [5]. Al-Si alloy is well known casting alloy with high wear resistance, low thermal expansion coefficient, good corrosion resistance and improved mechanical properties at wide range of temperature [6].

Mechanical properties of silicon carbide (SiC) reinforced Aluminium Matrix Composites (AMCs) have been studied extensively, the studies found that with increase in reinforcement ratio, the tensile strength, hardness and density of AMC material increased but the impact toughness decreases [7]. SiC is an abundant non-oxide ceramic which has diverse industrial applications that is suitable for abrasion and cutting application due to its high hardness, strength, chemical and thermal stability, high melting point, oxidization resistance etc [8].

Aluminium is the most abundant metal and the third most abundant chemical element in the earth's crust, comprising over 8% of its weight. The melting point of aluminium is 660^0C, density is one-third of steel or copper alloy [1]. Aluminium alloys are broadly used as main matrix element in composite material.

Brake system converts kinetic energy of moving vehicle into thermal energy. Brake disc and brake drum are the two types of braking systems used in automobiles. Brake discs are designed and produced for front and rear wheel of vehicles while brake drums are designed and produced for use only on the rear wheel of vehicles. The brake disc is usually made from cast iron and it is fix between the wheel rim and the wheel hub [9-10].

This paper is a research work on the development of hybrid particle reinforced aluminium alloy metal matrix composite for the production of brake disc. It is aimed at comparing the mechanical, tribological and thermal properties of the developed MMC with that of the nodular cast iron used for the production of the conventional brake disc. The details of experimentation and results are discussed in subsequent sections below.

II. REVIEW OF RELATED WORKS

Poornesh M. [11] investigated the effect of coconut shell ash and silicon carbide particles on mechanical properties of aluminium based composites. He concluded that the composite was successfully cast using stir casting techniques under teeming temperature of 750^o and a stirring speed of 600rpm. He further concluded that inclusion of reinforcing particles helps in increasing the hardness of the composite.

David R. S. et al. [12] characterized Al6061-fly ash-SiCp composites. It was observed that the wettability of fly ash particles and SiC in the matrix was improved by adding magnesium into the melt. The microstructure study revealed a homogeneous dispersion of both fly ash particles and SiC in the molten Al matrix. The addition of fly ash particles prevents the dissolution of SiCp and the formation of Al_4C_3. Hardness and tensile strength were improved with the increase in weight percentage of SiCp with constant weight percentage of fly ash into the Al matrix.

Veeresh K.G.B. et al. [13] conducted dry-sliding wear test using a computer aided pin-on-disc wear-testing machine at constant sliding velocity (V = 2.62 m/s) and the load on the pin was varied from 10 to 60 N while the sliding distance of 3500m was maintained and tests were conducted at room temperature in accordance with ASTM – G99 standard (diameter of the pin was 10 mm and 25 mm in length). It was found that the volumetric wear loss of the composites decreases with increased contents of SiC reinforcement in the aluminium alloy matrix.

Himansu M. [14] studied the mechanical and machinability properties of aluminium coconut shell ash composite by Taguchi approach and concluded that the mechanical properties (Hardness and Tensile strength) increases with increasing coconut shell ash.

Manoj S. et al. [15] conducted a study on Wear Properties of Al-SiC Composites. Al–SiC composites containing four different weight percentages (5%, 10%, 20% and 25%) of SiC fabricated by liquid metallurgy method. Dry sliding wear test was carried out using pin-on-disc with normal loads of 5, 7, 9 and 11 N and at constant sliding velocity of 1.0m/s. It was found that the wear rate decreases linearly with increasing weight fraction of silicon carbide and the average coefficient of friction decreases linearly with increasing normal load and weight fraction of SiC. The best results was obtained at 20% weight fraction of 320 grit size SiC particles for minimum wear.

Parth S. J. et al. [3] used silicon carbide in the manufacturing of Brake disc Rotor Alumnium Metal Matrix Composite (AMMC). It was observed that the addition of silicon carbide as reinforcement reinforces the overall properties of AMMC. It improves the mechanical properties of the AMMC; it increases the strength and hardness of the composite. And also it improves the thermal conductivity and thermal shock resistance of the material. It was concluded that; gravity stir casting is most economical process used for casting of AMMC, pre heating of mould reduces porosity and enhances mechanical properties, pre heating of reinforcement results in uniform distribution and better mechanical properties and addition of magnesium is important to increase wettability.

II. MATERIALS, EQUIPMENT AND METHODS

2.1 Materials

Aluminium alloy (Al6061) was used as the matrix, coconut shell, silicon carbide and graphite were used as the reinforcements, Sodium hydroxide was used as the degassing agent and magnesium powder serves as the wetting agent.

Plate I: Aluminum Alloy **Plate II: Silicon Carbide** **Plate III: Coconut Shell**

2.2 Equipment

The equipment used in this research are; Crucible furnace, Universal thermocouple, Graphite crucible, Mechanical stirrer, Avery Hardness Testing Machine, W-type Monsanto Tensometer, Avery Denison Impact Testing Machine, Pin-on-Disc Machine, Optical Microscope (OM), X-ray Fluorescent (XRF), Searle's Apparatus, Grinding and Polishing Machine, Mould, Table Lathe Machine, Centre Lathe Machine.

2.3 Methods

2.3.1 Processing of Coconut Shell Ash

Coconut shells were ground to obtain coconut shell powder. The powder was packed in a graphite crucible and preheated for about 45minutes to produce coconut shell ash particle (CSAp). The coconut shell ash particles were sieved to obtain fine and uniform particle size as shown in Plate IV below. The chemical analysis of the coconut shell ash was carried out using X-ray Fluorescent (XRF) equipment.

Plate IV: Coconut Shell Ash

2.3.2 Preparation of Samples

The Stir casting method as shown in Plate VI which is a type of liquid state method of composite fabrication was used. In this study, aluminium alloy scraps were cleaned and preheated to a temperature below the melting temperature of aluminium for 30 minutes to remove any moisture before being charged into the furnace. Silicon carbide and magnesium powder were also preheated for 45minutes to remove moisture and gases from the surfaces of the particles. The coconut shell ash particles (CSAp) were preheated for about 45minutes to eliminate impurities and moisture content. The coconut shell ash was sieved to give uniform particle size. The preheated aluminium was charged into the furnace and heated to a temperature of 750^0C to form molten aluminium before the addition of sodium hydroxide to degas the melt. The melt was stirred with a steel shaft stirrer having 3 blades at the bottom made at an angle of 120^0 from each other. The stirring was done at a speed of 200 rpm and 700^0C. Coconut shell ash, graphite and silicon carbide particles were added to the molten metal while the stirring was on-going. The speed was thereafter reduced and maintained to 80 rpm due to increase in viscosity of the mixture. At the maintained speed of 80 rpm, magnesium powder was added to reduce the surface tension of the mixture so as to enhance wettability between the particles (reinforcements) and the molten aluminium. The stirring was maintained for another 15 minutes for homogeneous mixing before pouring the mixture into moulds to form cast composite rods (Plate V) which were used as samples. The process was repeatedly done by varying the percentage by weight of coconut shell ash and silicon carbide while graphite and magnesium remain the same for all samples as shown in Table 1 below.

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Plate V: Cast Composite Rod Samples

Plate VI: Stir Casting Set-Up

(i) (ii) (iii)

Plate VII: Specimens before Hardness, Tensile and Wear Tests from the Samples

(i) (ii) (iii)

Plate VIII: Specimens after Tensile, Hardness, and Impact Tests

Table 1: Weight Composition of the Samples

Samples	Aluminium alloy (g)	Silicon carbide (g)	Coconut shell ash (g)	Graphite (g)	Magnesium powder (g)	Total (g)
S1 (Aluminium alloy)	875	0	0	0	0	875
S2 (Composite)	600	50	200	10	15	875
S3 (Composite)	600	100	150	10	15	875
S4 (Composite)	600	150	100	10	15	875
S5 (Composite)	600	200	50	10	15	875

2.4 Experimentation

The following tests and examinations were conducted on the specimens using various international standard procedures; Density Test (ASTM D792), Hardness Test (ASTM E10), Impact Test (ASTM E23), Tensile Test (ASTM E8), Wear Test (ASTM G99), Thermal Test(ASTM C518), Microstructure Examination (ASTM E3)

2.5 Production of Prototype Composite Brake Disc

The steps used in the production of the composite brake disc (PLATE IX) are itemized below;

(i) A wooden pattern was produced using the standard dimension of the conventional cast iron brake disc as shown in Table 2 below and divided into two halves along the parting line, one for the drag and the other for the cope. The pattern was used to form the mould cavity. The pattern was made oversize to account for shrinkage in cooling and solidification, and to provide enough metal for subsequence machining operation.

(ii) Core was made from foundry sand with the addition of resin for strength by means of core boxes and was used to produce internal surface in the casting.

(iii) The sand for the mould was prepared and was used to make the mould with the help of the pattern and the core. A sprue was made to pour the melt into the mould cavity and a riser was also made to feed the casting as it shrinks and solidifies.

(iv) The optimized formulation of the composite in molten form was poured into the prepared mould through the sprue which then solidifies after some time to form the composite brake disc.

(v) The mould was removed and the brake disc was cleaned and then inspected.

(vi) Surface finishing such as polishing was done on the brake disc for better appearance.

Table 2: Pattern Design Parameter

Parameter	Size (mm)
Outer (Rotor) diameter	256
Center(hub) hole diameter	64.2
Bolt size	12.6
Bolt circle	4 x 114.3
Height	47

Plate IX: Prototype of Composite Brake Disc Produced

III. RESULTS AND DISCUSSION

3.1 Results of Experiments

The various results obtained during the experimental work are shown in the below;

Table 3: Chemical Composition of Analysis of Al6061

Element	Mg	Si	Cu	Cr	Al
Weight percentage	0.01	0.60	0.28	0.20	98.91

Table 4: Chemical Composition of Nodular Cast Iron

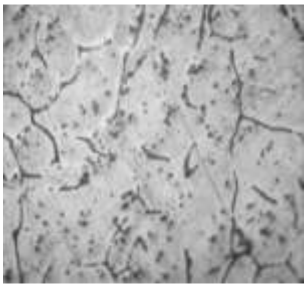
Constituents	Carbon	Silicon	Manganese	Phosphorus	Sulphur	Iron
Weight Percentage	3.4	2.6	0.8	0.15	0.1	92.95

Table 5: Chemical Composition of Coconut Shell Ash

Constituents	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	N_2O	SiO_2	ZnO	MnO	Loss of Ignition
Weight percentage	15.4	0.59	12.3	0.62	16.2	0.45	45.01	0.33	0.26	8.84

3.2 Microstructure Examination Results

The micrographs for the samples using optical microscope with a magnification of 100 are shown in plates 4.1 to 4.6 below:



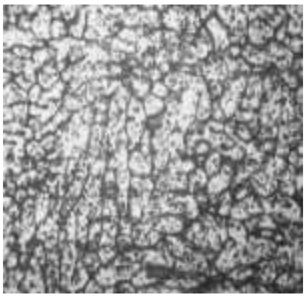


Fig. 10: Micrograph of S1 Fig. 11: Micrograph of S2 Fig 12: Micrograph of S3

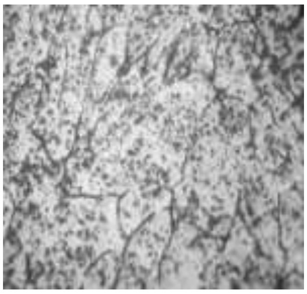
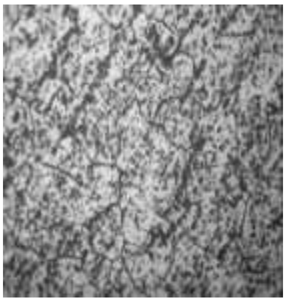
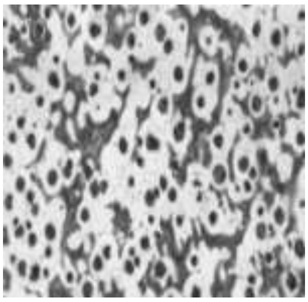




Fig. 13: Micrograph of S4 Fig. 14: Micrograph of S5 Fig 15: Micrograph S6

From the micrographs above, it can be seen that the microstructures of the composites i.e. S2, S3, S4, S5 show small discontinuities and a reasonable uniform distribution of the reinforcement particles. The dark phase is the reinforcement phase, the white phase is the aluminium alloy phase and the thin black lines are the interface. The presence of considerable amount of CSA, SiC and graphite particles in the matrix aluminium alloy ensured the formation of the required bonds between the components of the composites and the matrix examined. Interfaces between the particles and the matrix are free from intermediary phases. In the composites examined no effects of unfavourable phenomena such as sedimentation or flowing out of the reinforcing phase, as well as the formation of particle agglomerate or gas blisters were observed which are mostly seen in cast composite structure. This goes to show that there is a good interfacial bonding between the CSA, SiC, graphite particles and the aluminium alloy matrix.

The microstructure of sample S6 (nodular cast iron) shows the presence of graphite which is in the form of tiny black balls or nodules. The nodules are responsible for the strength and ductile nature of the nodular cast iron.

3.3 Discussion of Results of Experiments

3.3.1 Density Test

From the density test, it can be seen in Figure 1 below that the density of the composites increases with increase in the volume fraction of silicon carbide particles with a maximum value of 3.15g/cm^3 for composite 'S5'. The density of composites automatically increases when the aluminium alloy matrix is reinforced with silicon carbide particles having density higher than that of the aluminium alloy and the coconut shell ash. The density of the as-cast nodular cast iron (S6) is 5.81 g/cm^3, which is higher than the density of composite 'S5'.

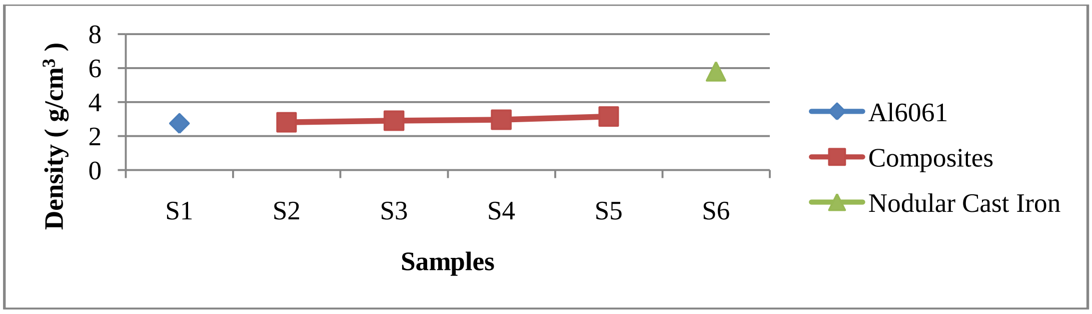


Fig. 1: Variation Density with Samples

3.3.2 Hardness Test

Figure 2 reviews the hardness values of various samples using vicker's hardness scale. The maximum hardness of the composites is obtained in 'S5' with value of 68 VHN while that of the as-cast nodular cast iron (S6) is 88VHN. The increase in hardness of the composites is because of the larger volume fraction of hard and brittle phase of SiC coupled with the presence of hardening metallic oxide such as SiO_2, Al_2O_3, Fe_2O_3 etc of CSA particles in the aluminium alloy matrix. The hardness of the composites can be attributed to uniform distribution of the SiC and the CSA particles in the aluminium alloy matrix coupled with the strong interfacial bond that exist between the SiCp, CSAp and the aluminium alloy matrix.

Also the increase in the hardness of the composite could be as result of dispersion strengthening due to the introduction of finely divided SiC and CSA hard particles in the soft aluminium alloy matrix which retards the movement of dislocation.

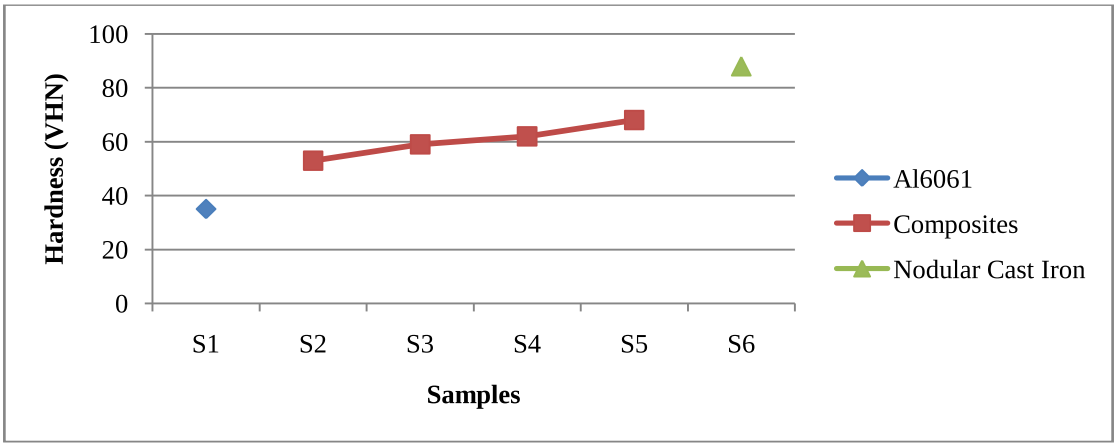


Fig. 2: Variation of Hardness with Samples

3.3.3 Tensile Test

The tensile strength of the composites is maximum for 'S5' with value of 196.12 N/mm^2 while that of the as-cast nodular cast iron (S6) is 221.16N/mm^2 as shown in Figure 3 below. The increase in tensile strength can also be explained on the basis of difference in thermal expansion coefficient of aluminium alloy and the SiC and CSA particlses. Due to this difference, strains are created during solidification. As the strain increases, the dislocations occur and during this process the SiC and CSA particles offer resistance to crack propagation during tensile loading.

Therefore, it can be said that incorporation of hard and brittle SiC and CSA reinforcement particles in the soft and ductile aluminium alloy matrix increases the tensile strength of the composites.

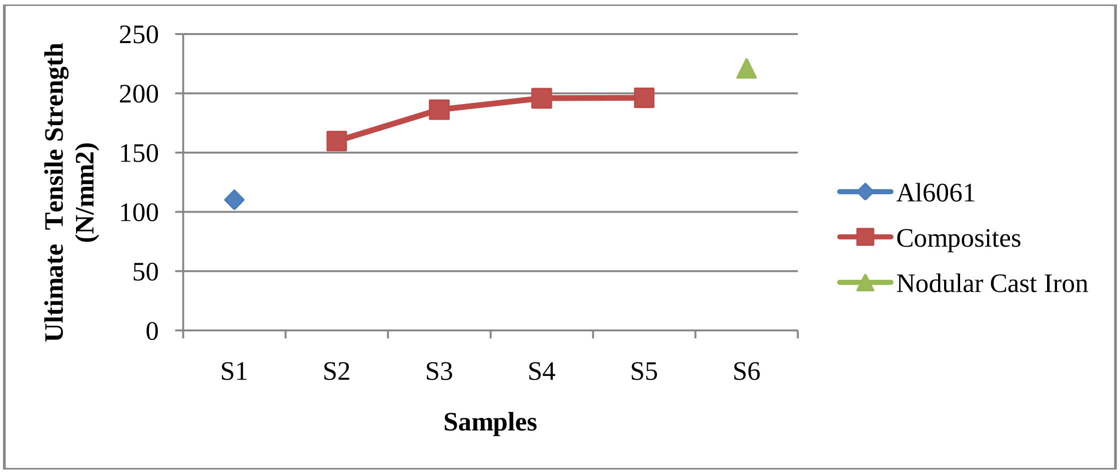


Fig. 3: Variation of Ultimate Tensile Strength with Samples

3.3.4 Impact Energy Test

The impact energy of the composites decreases with SiC and CSA particles addition as seen in Figure 4 below. The impact energy of the composites is minimum for 'S5' with a value of 8.05J while that of the as-cast nodular cast iron (S6) is 6.00J. The increase in hardness of the composites due to SiC and CSA particles addition causes decrease in the impact energy, this is because the ductile nature of the aluminium alloy matrix has been distorted and degraded by the brittle SiC and CSA particles. The ceramic metallic oxides present in CSA particle further enhance the brittleness of the composite.

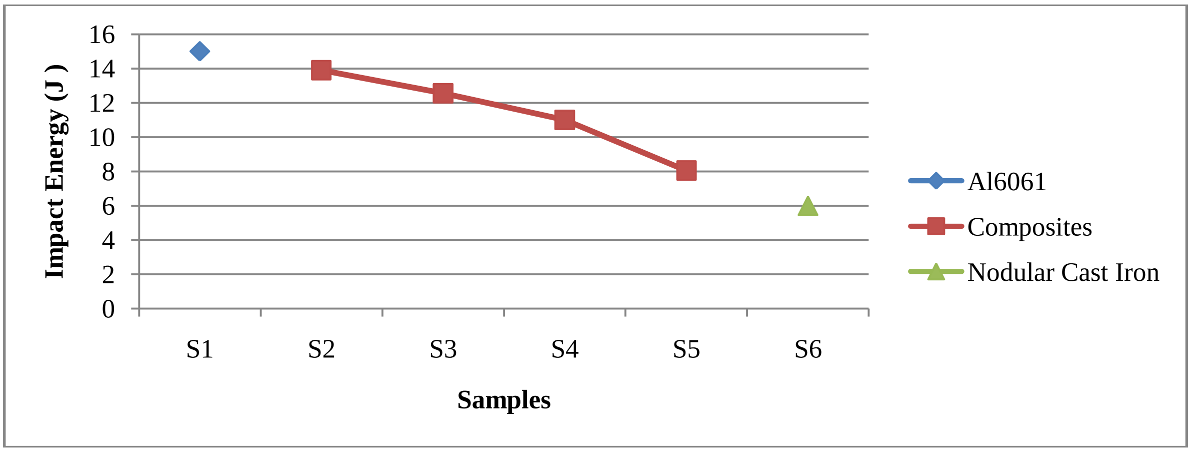


Fig.4: Variation of Impact Energy with Samples

3.3.5 Wear Test

In Figure 5, the wear rate decreases with increasing amount of SiC and CSA particle into the aluminium alloy. The wear rate of the composite is minimum for composite 'S5' with a value of 0.0002328g/m while that of the as-cast nodular cast iron (S6) is 0.0001208g/m. The combination of abrasive properties of SiC, the inherent abrasive oxides in CSA and the addition of graphite increase the hardness of the ductile aluminium alloy matrix thereby making it more resistant to wear by so doing reducing he wear rate of the composites and increasing the coefficient of friction.

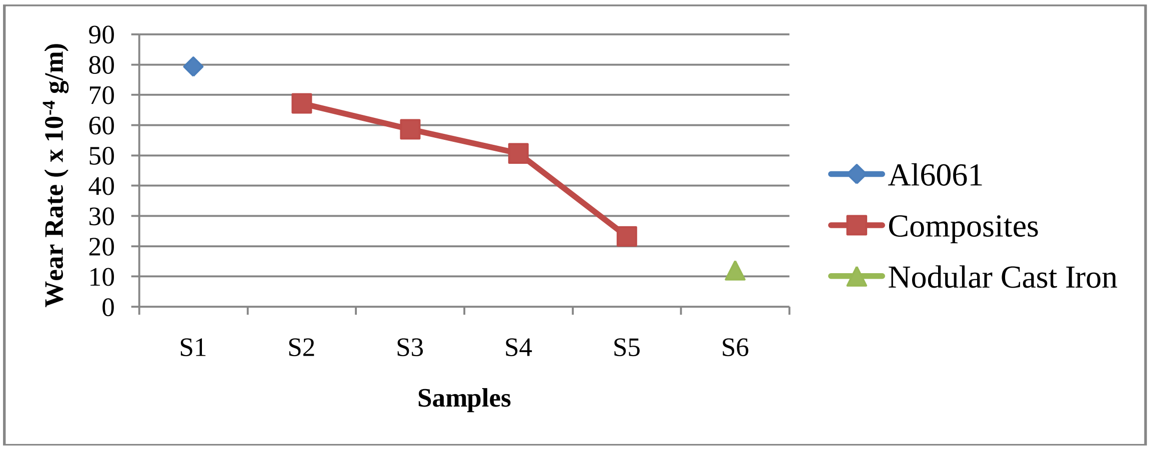


Fig. 5: Variation of Wear rate with Samples

3.3.6 Thermal Test.

From the test result in Figure 6 below, the thermal conductivity of the composites samples is seen to have decreased with a minimum value of 72.57W/mk for 'S5' compared to the thermal conductivity of the aluminium alloy (S1). The reason for the decrease is because thermal conductivity of metals is generally higher than that of ceramic material and as such the addition of SiC particles and the metallic oxides in CSA particles are responsible for the decrease.

The introduction of the reinforcement into the aluminium alloy altered or scattered the orderly arrangement of free electrons in the alloy which are responsible for the transfer of heat in the alloy.

The thermal conductivity of composite 'S5' can also be seen to be higher than that of the as-cast nodular cast iron (S6).

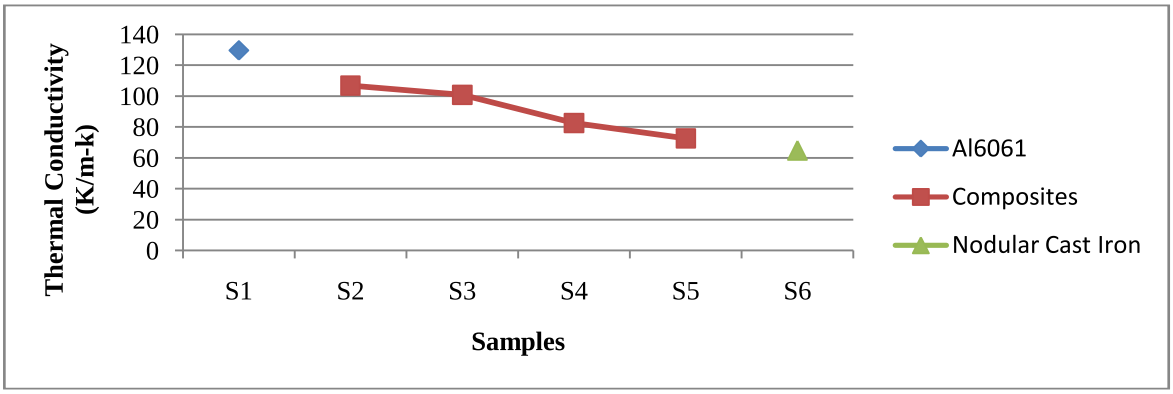


Fig. 6: Variation of Thermal Conductivity with Samples

3.4 Optimization of Results

From the above results, it can be seen that the developed composites 'S5' has the lowest value of density, wear rate, impact energy and thermal conductivity. It can also be seen that 'S5' has the highest value of hardness and tensile strength. S5 also gives a relatively better microstructure than the other cast composites (S2, S3 and S4).

From the results obtained, it is therefore evident that composite sample 'S5' gives the best result, hence it was used in the production of the brake disc.

IV. CONCLUSION

The properties and microstructures of the samples were characterized and the following conclusions were drawn:

(i) The microstructure analysis of the composites revealed a uniform distribution of the reinforcement particles in the matrix. This resulted in excellent bonding properties.
(ii) Addition of magnesium increases the wettability of the reinforcement particles with the aluminium alloy thereby enhancing bonding between them.
(iii) The density of the developed composites increases with increasing amount of silicon carbide with the maximum value of 3.15g/cm^3 for composite sample 'S5' which is lower than the value (5.81g/cm^3) obtained for the as-cast nodular cast iron brake disc. This is obviously expected.
(iv) The incorporation of the silicon carbide and coconut shell ash particles into the aluminium alloy matrix increased the hardness and tensile strength values of the composites with maximum values of 68VHN and 196.12 N/mm^2 respectively for composite sample 'S5' which compared favourably with as-cast nodular cast iron brake disc with Hardness-88VHN and Tensile strength-221.16N/mm^2.
(v) The addition of graphite in the matrix increases the Hardness, Tensile Strength but decreases the Impact Energy of the composite.
(vi) The impact energy of the composites decreases with the minimum value of 8.05J for composite sample 'S5' which is higher than the value (6.00J) obtained for the as-cast nodular cast iron.
(vii) The wear rate of the composites under dry sliding reduced with increased amount of silicon carbide and coconut shell ash particle with the minimum value of 0.0002328g/m for composite sample 'S5' which is slightly higher than that obtained for as-cast nodular cast iron with a wear rate of 0.0001208g/m.
(viii) The thermal conductivity of the composites decreases with increase in the amount of silicon carbide and coconut shell ash particles with the minimum value of 72.57W/mk for composite sample 'S5' which is higher than the corresponding value (64.7W/mk) obtained for as-cast nodular cast iron .
(ix) From the results obtained, it can be said that since the developed composite sample 'S5' gives lower values for density and impact energy than the as-cast nodular cast iron brake disc, the problems of heavy weight and breakage due to heavy impact associated with cast iron brake disc has been addressed using the developed composite. Hence, it was used to produce the Honda accord 2000 model composite brake disc.

V. RECOMMENDATIONS

The following recommendations are made for further studies;
(i) Mechanical properties such as creep and fatigue should be carried out on developed composites.
(ii) The reinforcing properties of coconut shell and silicon carbide should be further investigated with other metal matrices.
(iii) The National Automotive Council of Nigeria should commercialise the production of brake disc using the newly developed composite.

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