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Production of Silicon Carbide Particulate Reinforced Aluminium Composite Using Indigenous Stir Casting Technology

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Authors' contributions

This work was carried out in collaboration among all authors. Author EAI designed the study, wrote the protocol and managed the analyses of the study. Author EAM performed the statistical analysis. Author JMY wrote the first draft of the manuscript. Author TJH managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Aims: In this research work the viability of producing silicon carbide reinforced aluminium composite using indigenous casting technology has been investigated.
Place and Duration of Study: AfDB Lab, African University of Science and Technology, Abuja between August 2018 and September 2019.
Methodology: The materials used are aluminum alloy 6063 of the following composition: Al - 98.5%, Mg -0.51%, Si-0.46%, silicon carbide of particle size 30 μm, and sodium tetra borate (borax) as a wetting agent. In order to produce the composite, the following steps were taken: 6%, 9%, 12%, and 15% volume fractions of Silicon carbide of 1 kg, 1.2kg, 1.5 kg, and 1.6 kg

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respectively of aluminium alloy 6063 ingots were weighed and preheated to 450°C with simultaneous dehydration of the borax at 250°C. The alloy 6063 was charged into the diesel fire furnace, heated above the liquidus at 750±50°C and then the temperature was allowed to drop to the semi-solid state at about 600°C. The preheated Silicon carbide and dehydrated borax mixture was charge in the ratio 2:1 into the semi-solid alloy and was manually stirred using a preheated stirrer. The composite temperature was raised back to above the liquidus at 750±50°C and automatic stirring was done for 10 minutes using an electric motor with a speed of 300rpm. The molten composite at about 700°C was poured into a green sand mold with graphite coated cavities and the composites solidified into a trapezoidal cross-sectional bar.

Results: It was observed that in terms of weight there is practically little or no difference between the indigenously produced composite and the ones produced by standard technology. The hardness properties of the composite increases with increase in the volume percent of silicon carbide.

Conclusion: Diesel fired crucible furnace can be used to produce quality aluminium silicon carbide composite from locally sourced materials and equipment.

Keywords: Stir casting technology; aluminium composite; the molten composite; silicon carbide particulate.

1. INTRODUCTION

Why does the plastic tea-spoon buckle as you stir your tea? Why does a fleet of aircraft get grounded far earlier than its expected life span? It is because the engineers who designed them used the wrong materials or did not understand the properties of those he did use to make adequate provision for inherent or likely service induced cracks which in most cases prompts such failures. So, it is vital that professional engineer should know how to select materials which best fit the demands of his design-economy and aesthetic demands of his materials, and their limitations [1]. Since civilization began materials along with energy have been used by people to improve their standard of living. The production and processing of materials into finished goods constitute a large part of our present economy.

Research and development engineers work to create new materials or to modify the properties of existing ones. Design engineers used existing, modified, or new materials to design and create new products and systems. Materials are evolving today faster than any time in history. Industrial nations regard the development of new and improved materials as an "underpinning technology" one which can stimulate innovation in all branches of engineering, making possible new designs for structures, appliances, engines, electrical and electronics devices, processing and energy conservation equipment, and much more. Many of these nations (particularly the US, Japan and West Germany) have promoted government backed initiatives to promote the development and exploitation of new materials: their list generally includes: "high performance" composites, new engineering ceramics, high-strength polymers, glassy metals, and new high-temperature alloys for gas turbines. These initiatives and new being felt throughout engineering and have already stimulated design of a new and innovative range of consumer products [2].

Many of modern technology require materials with unusually combinations of properties that cannot be met by the conventional metal alloys, ceramics, and polymeric materials. This is especially true for materials that are needed for aerospace, underwater, and transportation applications. Therefore, the search for new materials for improved performance goes on continuously, which may be specified by various criteria including less weight, more strength and lower costs, currently-used materials frequently reach the limit of their usefulness. Thus materials scientist, engineers and scientist are always striving to produce either improved traditional materials or completely new materials. Composites are example of the latter category.

The term "composite" broadly refers to a material system which is composed of a discrete constituent (the reinforcement) distributed in a continuous phase (the matrix), and which derives its distinguishing characteristics from the properties of its constituents, from the geometry and architecture of the constituents, and from the properties of the boundaries (interfaces) between different constituents [3]. Composite materials are usually classified on the basis of the physical or chemical nature of the matrix phase, e.g., polymer matrix, metal-matrix and ceramic composites. Metal-matrix composites are unique materials for use in the military and space applications. The factors that control the properties of metal- matrix composites are processing route, matrix alloy, reinforcement level, size and distribution of the reinforcement [4]. In addition, there are some reports to indicate the emergence of Intermetallic-matrix and carbon-matrix composites. This project is concerned with metal matrix composites and more specifically on the Aluminium Matrix Composites (AMCs) reinforced with Silicon Carbide (SiC). Aluminium Matrix Composites (AMCs) refer to the class of light weight high performance aluminium centric material systems. Aluminium metal matrix composites (AMCs) are a class of materials that have proven successful in meeting most of the rigorous specifications in applications where light-weight, high stiffness and moderate strength are the requisite properties [5]. In AMCs one of the constituents is aluminium/aluminium alloy, which forms percolating network and is termed as matrix phase. The other constituent is embedded in this aluminium/aluminium alloy matrix and serves as reinforcement, which is usually non-metallic and commonly ceramic such as Silicon carbide. Properties of AMCs can be tailored by varying the nature of constituents and their volume fraction.

The major advantages of AMCs compared to unreinforced materials are as follows:

- Greater strength
- Improved stiffness
- Reduced density(weight)
- Improved high temperature properties
- Controlled thermal expansion coefficient
- Thermal/heat management
- Enhanced and tailored electrical performance
- Improved abrasion and wear resistance
- Control of mass (especially in reciprocating applications)
- Improved damping capabilities

AMC material systems offer superior combination of properties (profile of properties) in such a manner that today no existing monolithic material can rival. Over the years, AMCs have been tried and used in numerous structural, non-structural and functional applications in different engineering sectors. Driving force for the utilization of AMCs in these sectors include performance, economic and environmental benefits. The key benefits of AMCs in transportation sector are lower fuel consumption, less noise and lower airborne emissions. With increasing stringent environmental regulations and emphasis on improved fuel economy, Use of AMCs in transport sector will be inevitable and desirable in the coming years. AMCs are intended to substitute monolithic materials including aluminium alloys, ferrous alloys, titanium alloys and polymer-based composites in several applications. It is now recognized that in order AMCs substitution for monolithic materials in engineering system to be wide spread, there is a compelling need to redesign the whole system to gain additional weight and volume savings. In-fact according to the UK Advisory Council on Science and Technology, AMCs can be viewed either as a replacement for existing materials, but with superior properties, or as a means of enabling radical changes in system or product design.

Moreover, by utilizing near-net shape forming and selective-reinforcement techniques AMCs can offer economically viable solutions for wide variety of commercial applications. Recent success in commercial and military applications of AMCs are based partly on such innovative changes made in the component design. Lack of knowledge and information about utilization possibilities, service properties and material producers have hindered the wider usage of AMCs. Recognizing these peripheral and extraneous difficulties, AMCs community in USA and Europe are pursuing consortium and networking approaches to implement the applications of AMCs in everyday societal use [3]. When the Wright brothers flew their 'heavier-than-air' machine the aerospace industry have grown to the point that airplane are much faster and bigger, the need to improve the quality of materials for the aviation industry has not subsided [6]. Therefore, this study aims at investigating the cast-ability of silicon carbide particulate reinforced aluminum alloy composites by indigenous stir casting techniques to evaluate the influence of different weight fractions of silicon carbide on the mechanical properties of the aluminium matrix composite and to assess the technical superiority and limitations of the silicon carbide reinforced aluminium over that of the pure Aluminium alloy.

2. MATERIALS AND METHODS

2.1 Equipment

The equipment used in this research work are; power hack saw, electrical power motor mixer (stirrer), hardness testing machine, optical microscope, thermocouple, diesel fire furnace, electronic weighing balance, green sand mold, steel crucible, tongs, timer temperature controller ceramics crucible for preheating, polishing and grinding machine.

2.2 Materials

The base material for this research work is aluminium alloy (6063) obtained from Nigalex PLC, Oshodi Lagos. The chemical composition of the unreinforced aluminium alloy is as shown in Table 1. Additionally, Silicon carbide of particle size 30μm is used as particulate reinforcement for the composite and borax-$(Na_2B_4)_7.10H_2O$

2.3 Methods

The method employed in this project work is two step casting technique. The preheating of the SiC was done to oxidized the surface to improve wettability and prevent the formation of Al_4C_3 at Al/SiC interface which could be detrimental to the mechanical properties of the composites The first stage stirring was done at semi solid state manually for proper mixing and wettability because at the SiC/Borax mixture when charged coagulates although the borax also enhanced good wetting; while the final stirring with an electric motor stirrer helps in homogenization of the mixtures.

2.3.1 Stir casting

The composite was prepared using aluminium alloy 6063, SiC particulates of size 30μm and borax-sodium tetraborate by two-step stir casting technique. In order to produce the composite, the following steps were taken; 6%, 9%, 12%, and 15% volume fractions of SiC of 1kg, 1.2 kg, 1.5 kg, and 1.6 kg respectively of aluminium alloy 6063 ingots were weighed and preheated to 450°C with simultaneous dehydration of the borax at 250°C. The alloy 6063 was charged into the diesel fire furnace, heated above the liquidus at 750±50°C and then the temperature was allowed to drop to the semi-solid state at about 600°c. The preheated SiC and dehydrated borax mixture was charge in ratio 2:1 into the semi-solid alloy and was manually stirred using a preheated stirrer. The composite temperature was raised back to above the liquidus at 750±50°C and automatic stirring was done for 10 minutes using an electric motor with a speed of 300rpm. The molten composite at about 700°C was poured into a green sand mold with graphite coated cavities and the composites solidified into a trapezoidal cross-sectional bar.

2.3.2 Density measurement

2.3.2.1 Rule of mixtures

Rule of Mixtures is a method of approach to approximate estimation of composite material properties, based on an assumption that a composite property is the volume weighed average of the phases (matrix and dispersed phase) properties. According to Rule of Mixtures properties of composite materials are estimated as follows [7].

Density

$$dc = dm*Vm + df*Vf$$

Where,

dc,dm,df – densities of the composite, matrix and dispersed phase respectively;
Vm,Vf – volume fraction of the matrix and dispersed phase respectively.

2.3.3 Hardness test

The hardness test is the property of the composites by virtue of which it is able to resist wear, scratching, indentation (or penetration), deformation and machinability. It also means the ability of a material to cut another material. Bulk hardness measurements are carried out on the base metal and composite samples by using the standard Vickers, Brinel hardness test, ultimate tensile strength and yield strength. All the hardness measurements are carried out in orderto investigate the influence of SiC particulate weight fractionson the matrix hardness.

Table 1. Chemical composition of unreinforced aluminum alloy 6063 composites from nigalex

SI	FE	CU	MN	MG	ZN	CR	TI	AL	OTHERS
0.46	0.23	0.02	0.03	0.51	0.02	0.03	0.03	98.5	0.03

Hardness values obtained at various sections are given in Table 2 and Figs. 3, 4, 5 and 6 shows increase in hardness with increasing SiC content. The hardness test used Indentech microhardness testing machine and the processes involved are cutting, grinding and polishing of samples.

2.3.4 Microstructural examination

This helps to study the internal structure of the composites, in relation to its physical and mechanical properties under an optical microscope. The microstructure is revealed by etching the polished surface. The action of etching reagents is based on their ability to colour and dissolve various constituents in different manner and to widen microcavities, cracks and similar defects [8].

i) Cutting of Samples: Test samples from the 6% and 9% volume fraction, respectively, of the composite were cut using hack saw and a bench vice.
ii) Grinding and Polishing of Samples' surfaces: after grinding, empty papers of grades 200, 600, 1200 grits were respectively used to polish the samples to a mirror-like state to make them ready for microstructural examination.
iii) Etching of Samples: the etchant used for this work is Keller's. It has the following compositions: distilled water 190mL, nitric acid 6mL, hydrochloric acid 4mL.
iv) Microstructural Examination: Optical microscope was used to observe the microstructures of the various samples. Micro hardness of the samples was also carried out using Indentech micro hardness machine.

3. RESULTS AND DISCUSSION

The results obtained are shown in figures, table and chart below.

3.1 Stir Casting

The production of the composite was sound despite the use of non-convention equipment such as green sand mold, steel crucible locally fabricated stirrer, diesel fired furnace. This fact is established by observation of Fig. 1 which show the photographs of the visually examined castings. From Fig. 1, it is observed that the casting had little or no defects on its surface. It is equally observed that the riser was properly formed indicating that sufficient melt was utilized for the casting. The sectioned parts of the casting, as shown in Fig. 1, confirms to a reasonable extent that there was absence of internal casting defects, which implies that the unorthodox casting technique utilized effectively yielded sound castings.

The evaluations were further performed to compare properties of the indigenously produced castings with that of aluminum-silicon carbide composites produced using standardized techniques.

3.2 Density

Density measurements of the prepared composites were carried out under ASTM B962-15 standard test method. The density obtained was 2.95 g/cm^3 with very little variation of less than 0.1% between 6% and 9% volume fractions which is very much consistent with the densities of aluminum-silicon carbide composites produced by standard technology. Tarek and Tamer [9] reported that the density of aluminum-silicon carbide is within the range of 2.95 – 3.0 g/cm^3. Thus, in terms of weight there is practically little or no difference between the indigenous product and the ones produced following standard procedures. Chandio et al., [10] reported increased in density with the additions of hard reinforcement particles such as Silicon carbide (SiC) as the maximum density of 2.4 g/cm3 was observed with addition of 20wt% of Silicon carbide (SiC).

Scientifically established density of aluminium composite reinforced SiC is 2.95-3.0 g/cm^3

Actual density

Area of composite = ½(l+b) h
= ½(12.4)1.8
= 21.7cm^2

Volume of composite = area * length
= 21.71*4.2 = 91.47cm^3

Mass of composite = 0.275kg = 275g, density = mass/volume = 275/91.476 =2.95 g/cm^3

Actual density = 2.95g/cm^3.

The table below shows the Vicker's hardness of samples X and Y with volume fractions 6% and 9% SiC. The vicker's hardness of silicon carbide reinforced aluminium (6063) composite is: 25HV (Aalco datasheet).

Fig. 1. Showing sound casting

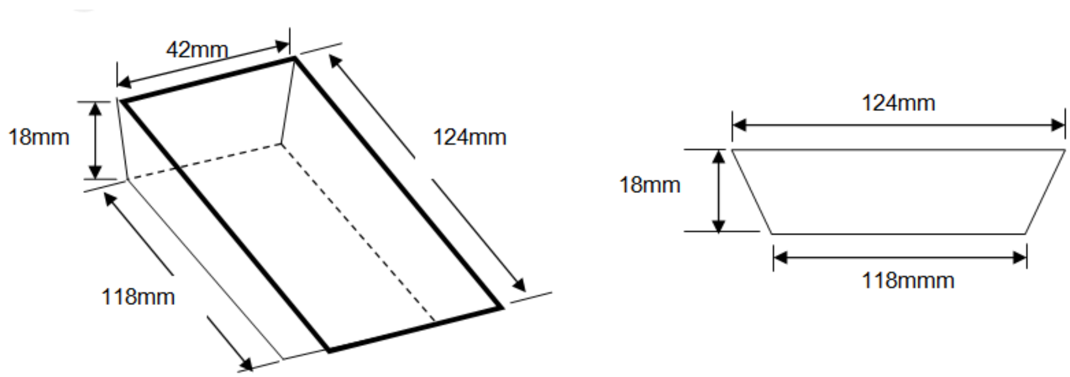

Fig. 2. Shape and dimension of casting

3.3 Hardness

The hardness properties as presented in Table 2 and Figs. 3&4 shows that the hardness of the composite with increasing wt% of SiC particles, it is due to the presence of well bonded SiC particles in Aluminium matrix that are hard in nature which causes the movement of dislocations to hinder resulting in increased hardness of composite [10]. This is expected as silicon carbide is a hard-ceramic material having hardness values of 2800kg/mm^2. Thus, from the rule of mixture relationship we would naturally expect the 9% volume to have higher hardness value. The hardness values in comparison with that of aluminum-silicon carbide composites produced using standard techniques are very much in agreement. Tarek and Tamer [9] also reported that the hardness of aluminum-silicon carbide composite with 10 percent volume fraction of silicon carbide that was worked with had a hardness value of 44HV which is very consistent with the one obtained from the indigenous process.

Fig. 5 shows the variation of UTS with respect to weight percent of silicon carbide particulates. The UTS of 9% reinforced composites is higher than the 6% reinforced composites. The tensile strength increases with increase in SiC content in Aluminium alloy matrix. Any significant increase in UTS leads to an increased in yield strength as shown in Fig. 6 due to the fact that Sic particulate are well bonded with the Aluminium matrix and hinders the movement of dislocation resulting in less interface failure between the SiC and the aluminium alloy matrix. Hence, we can conclude that an increased in UTS leads to an increase in increase in yield strength. The strong interfacial bonding between the matrix and SiC reinforcement also improves the tensile strength of the composites. The strengthening mechanism of the composites is a result of high movement of dislocations within the materials due to difference in thermal expansion coefficient introduced when the particulates of SiC were charged into the melt of Aluminuim alloy matrix as report by [11,12]. The dislocations interaction, constrain of plastic flow by the particles, dislocation density and grain size are the probable reasons for strengthening of composite as reported by Dhanasekaran et al., [13].

Table 2. Vickers's hardness samples of x and y

SAMPLES	A	B	C	AVERAGE
X	38.0	37.0	36.1	37.03
Y	46.9	39.7	43.2	43.27

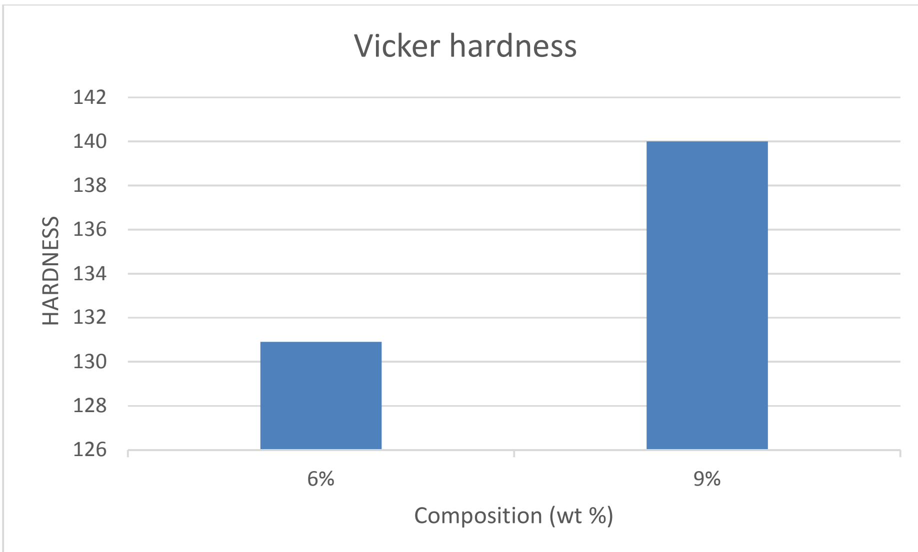

Fig. 3. Vickers hardness versus SiC wt%

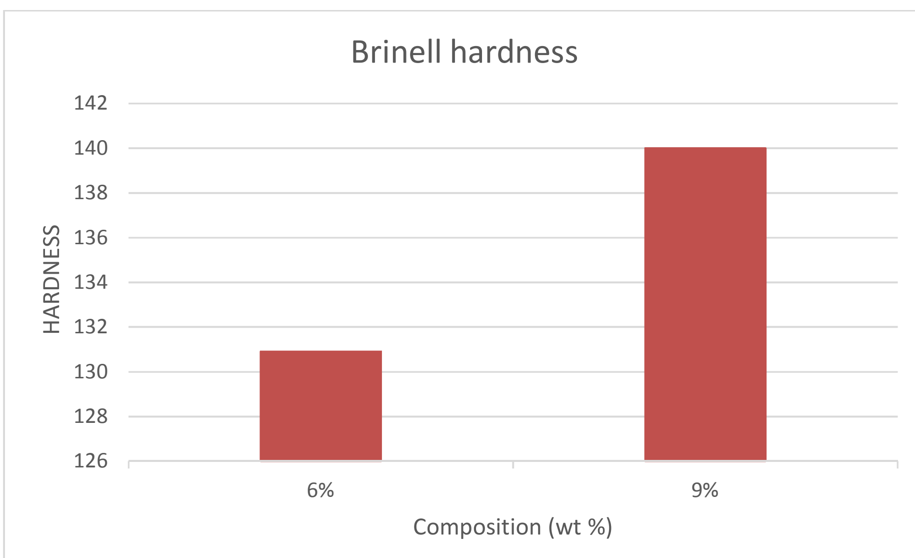

Fig. 4. Brinell hardness versus SiC wt%

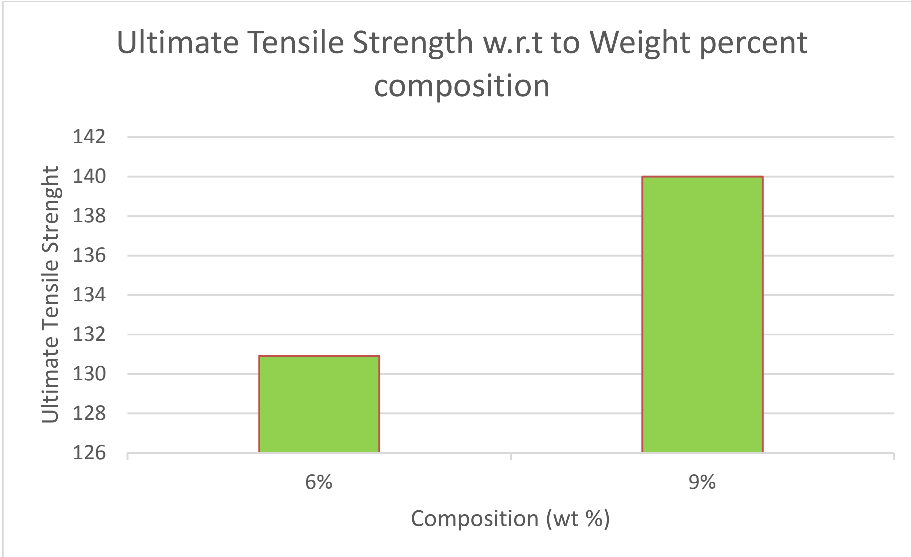

Fig. 5. Ultimate tensile strength versus Wt.%

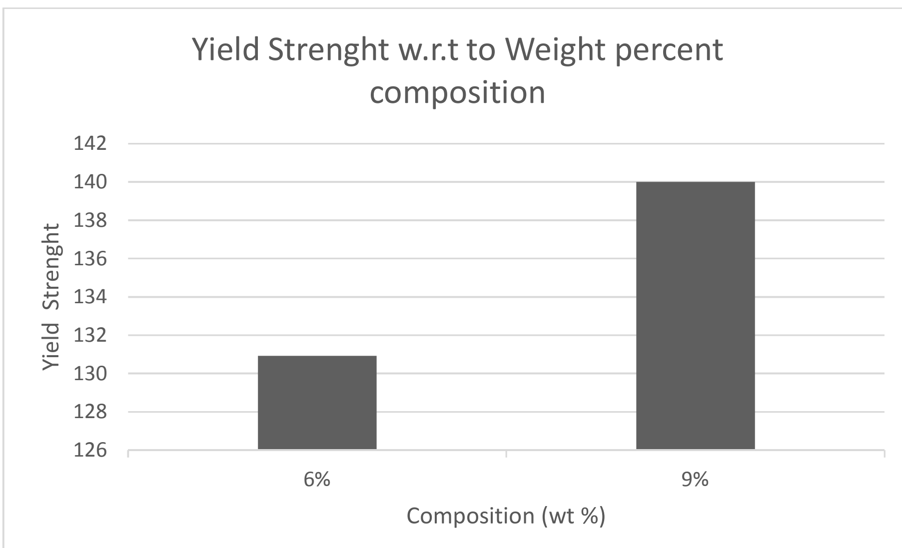

Fig. 6. Yield strength versus Wt%

3.4 Microstructural

Reinforcements distribution inside the matrix are essential to the final properties of composites prepared through powder metallurgy, to investigate distribution of reinforcements on composites SEM analysis was performed and it showed that the particles were dispersed fairly uniformly. The SEM images were taken using CarL Zeiss EVO LS 10.

The micrograph shows that as the silicon carbide reinforcement increases its exposes the porosity of the composites. Hence increase in reinforcement increases the porosity of the samples. The 9% Silicon carbide reinforcement is more porous than the 6% Silicon carbide reinforcement because during the casting process the silicon carbide particles trap air which causes void formation during the solidification process. A higher volume fraction of the particulate leads to a higher amount of air trapped, thereby creating more pores which agrees with [14].

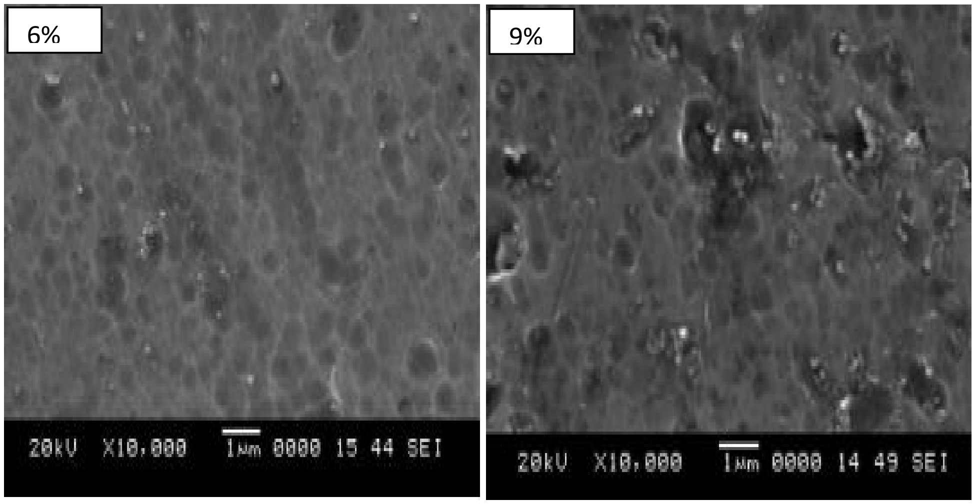

Fig. 7. Micrograph of composite with 6% and 9% volume fraction respectively

4. CONCLUSION

The following are the concluding remarks based on present experimental conditions.

i) The SiC particles were fairly distributed with the aluminum alloy matrix and increased in SiC particles leads to increase in porosity of the composites.
ii) It was observed that an increased in SiC particles also leads to significant increase in the Tensile strength and yield strength of the composites.
iii) Increased in the mechanical properties is as a result of increased in the reinforcement of the particulate as can been see from the hardness values of 6% and 9% values respectively
iv) Locally sourced materials and equipment can be used to produce quality aluminium silicon carbide composite using diesel fired crucible furnace.
v) Density: There is practically little or no difference between the indigenous composite and the ones produced following standard procedures.
vi) The hardness values in comparison with that of Al/SiC composites produced using standard technique are very much in agreement. It was also observed that the hardness of the composite increases with increasing percentage volume fraction of silicon carbide.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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