# DEVELOPMENT AND FABRICATION OF FUNCTIONALLY GRADED ALUMINIUM METAL MATRIX COMPOSITE FOR AUTOMOBILE COMPONENT APPLICATIONS

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**December 2021**

**Supervisor's Declaration**

As the candidate's supervisors, **I agree** / ~~do not agree~~ to the submission of this thesis.

Signed [redacted]     Date: 24th Dec 2021

**Name**: Prof. Freddie L. Inambao

Signed [redacted]     Date: 24th Dec 2021

**Name**: Dr William S. Ebhota

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# Declaration 2 – Publications

This section presents the articles that form part and/or include the research presented in this thesis. The following papers have been published:

**Publication 1**

**A. O. Owoputi,** F. L. Inambao, and W. S. Ebhota, "A review of functionally graded materials: Fabrication processes and applications," International Journal of Applied Engineering Research, vol. 13, no. 23, pp. 16141-16151, 2018.
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**Publication 2**

**A. O. Owoputi,** F. L. Inambao, and W. S. Ebhota, "Influence of $SiC_p$ reinforcement on the mechanical properties of functionally graded aluminium metal matrix composites fabricated by centrifugal casting technique," International Journal of Mechanical Engineering and Technology, vol. 10, no. 8, pp. 306-316, 2019.
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**Publication 3**

**A. O. Owoputi,** F. L. Inambao, and W. S. Ebhota, "Effect of percentage weight and particle size of $SiC_p$ reinforcement on the mechanical behavior of functionally graded aluminium metal matrix," International Journal of Engineering Research and Technology, vol. 13, no. 3, pp. 444-453, 2020.
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*****The candidate is the main and corresponding author for all the publications and conference presentations while Prof. Freddie L. Inambao is the supervisor and Dr William S. Ebhota is the co-supervisor.

# Dedication

This work is dedicated to God Almighty, the giver and sustainer of life.

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# Abstract

In recent times, interest in aluminium matrix composites (AMCs) have garnered traction over conventional aluminium alloys as the material of choice in the manufacturing of components for various engineering applications. Engineering components developed from single-element material are increasingly less favored over materials engineered from two or more elements. The rise in the demand for a multifunctional engineering material to exhibit opposing yet complementary engineering properties at different spatial positions within the material due to functionality requirements, has birthed several innovative fabrication processes.

This study focuses on the development and fabrication of functionally graded aluminium metal matrix composite (FGAMMC) through the liquid metallurgy route for proposed automobile component production. Industrially produced A356 aluminium alloy and silicon carbide powders (Al-SiC) was adopted as the base matrix and reinforcement materials for the fabrication of the metal matrix composites. Centrifugal casting technique was used to fabricate seven samples of Al-SiC functionally graded aluminium metal matrix composites with varied reinforcements particle size and weight percent addition. Samples A, B, and C contained 1 wt.%, 3 wt.%, and 5 wt.% of SiC of size 7 µm reinforcement, respectively, while samples E, F, and G had 1 wt.%, 3 wt.%, and 5 wt.% of SiC of size 15 µm reinforcement respectively. Sample D with no reinforcement additions served as the control sample for the experiment.

Microstructural characterization showing the elemental composition and reinforcement distribution of silicon carbide particles within the matrix of the cast composite was carried out using optical microscopy (OM), optical emission spectroscopy (OES), energy dispersion x-ray (EDX), and scanning electron microscopy (SEM). The influence of $SiC_p$ on the mechanical, wear behavior and thermal properties of the cast aluminium composites were determined by subjecting the cast samples to mechanical, tribological, and thermal tests. Sample C with 5 wt.% and 7 µm of SiC particle reinforcement recorded improved hardness, compressive strength, Young's modulus, shear strength, and shear modulus of 112.7 $HV_{0.1}$, 3107 MPa, 6.39 GPa, 14.4 GPa, and 9.29 GPa, respectively. Tribological analysis show an increase in the cast composites' wear resistance and frictional coefficient proportional to the frequency of contact between the counterface ball of the tribometer and the dispersed SiC reinforcements in the composites' matrices. Thermogravimetric analysis showed the weight loss and heat flow rates exhibited by the cast samples as the temperature was increased from 25 °C to 1000 °C in an Argon environment. Although negligible weight loss was recorded for all the cast composites within the experimental temperature boundary, sample C with 7 $\mu$m

and 5 wt.% of the $SiC_p$ reinforcements showed the least weight loss of 0.37 %. Differential scanning calorimetry (DSC) analysis showed a similar heat flow behavior for all the cast FGM samples at temperatures below 655 °C. Beyond 655 °C, the heat flow through the FGM samples was observed to increase rapidly to maximum experimental temperature. The lowest heat flow of 0.004 w/g at 1000 °C was recorded by sample G with 15 $\mu$m and 5 wt.% of the $SiC_p$ reinforcements.

The results generated highlight the potential for replacement of conventional aluminium alloy with FGAMM using SiC reinforcement as the material of choice in automobile engine components such as piston heads, cylinder walls, and gears. These high-impact components require structural stability when acted upon by external forces over an extended service period which these fabricated Al-SiC composites provide. From the microstructural, mechanical, tribological and thermal analysis conducted on all the cast FGM composites in this study, sample C with 7 $\mu$m and 5 wt.% of $SiC_p$ reinforcement showed the most improved properties, thereby making it suitable as a candidate material for high impact and thermal automobile applications.

# Table of Contents

# Acronyms and Abbreviations

| | |
|---|---|
| FGM | Functionally graded material |
| SiC | Silicon carbide |
| KMM | Knowledge-based multifunctional materials |
| AMC | Aluminium matrix composite |
| TGA | Thermogravimetric analysis |
| OM | Optical microscopy |
| SEM | Scanning electron microscopy |
| MMC | Metal matrix composite |
| EDX | Energy dispersive x-ray |
| OES | Optical emission spectroscopy |
| FGDI | Functionally graded ductile iron |
| PM | Powder metallurgy |
| AMC | Aluminium matrix composites |
| DSC | Differential scanning calorimetry |
| ALD | Atomic layer deposition |
| CVD | Chemical vapor deposition |
| IBAD | Ion beam assisted deposition |
| CSPM | Centrifugal solid particle method |
| CISM | Centrifugal *in situ* method |
| FGAMMC | Functionally graded aluminium metal matrix composite |
| CCT | Centrifugal casting technique |
| Al-SiC | Aluminium silicon carbide |

# CHAPTER 1: INTRODUCTION

## 1.1 Introduction

Knowledge-based multifunctional materials (KMMs) are advanced materials which, other than their obvious mechanical or chemical characteristics, are designed specifically for predetermined purposes, albeit in a controlled way. Specifically, the materials investigated in relation to KMM are designed for enhanced performance in highly demanding loading and environmental conditions such as thermo-mechanical and impact loading, high strain rates and temperature regimes, aggressive chemical environments, and combinations thereof. The aforementioned material behavioral characteristics are typical of applications in aerospace and automotive transport, turbo-machinery industry, chemical industry, electronic devices, biological implants, microsensors, and household appliances, among others. KMMs include intermetallic, metal-ceramic composites, functionally graded materials (FGMs), and thin layers.

The rise in the applications of FGMs since they first emerged in the 1980s in the course of building the frame of a space rocket, has been tremendous. The ability to influence and vary the properties of fabricated materials to a high degree across the material length has caught the interest of researchers over the years, resulting in manufacturing of engineering materials with the ability to exhibit extreme and opposing properties at opposite ends of the same material during service conditions.

The abundance and processing ease of aluminium has made it one of the leading derivative metal composites of interest in various engineering applications such as automobile, structural, aviation and military [1]. Furthermore, properties such as good tensile strength, toughness and wear resistance also lend it credence. Particles of oxides, nitrides and carbides are a few of the type of reinforcements that have been exploited and utilized in the manufacturing of aluminium-based composites [2-4]. The size and percentage content as well as the nature of these reinforcements in aluminium matrix have been demonstrated by researchers to influence the properties of aluminium composites [5, 6]. Aluminium matrix composites are among the most adopted metal matrix composites for automobile, structural, and other engineering applications due to the wide array of desirable properties they possess. The ability to closely control and vary the concentration of reinforcement in the aluminium matrix has given rise to the unique material referred to as functionally graded aluminium matrix composites (FGAMC).

The choice of fabrication techniques of FGMs are largely dependent on the type of FGM to be manufactured, which in turn depends on the application it is to be used for [7, 8]. Finding the most suitable manufacturing process that will produce a near net-shape FGM at the most cost-effective price with the greatest of operational ease has been a major focus of researcher in recent past. Metal deposition, powder metallurgy, and metal casting techniques are the most commonly used fabrication routes for manufacturing FGM [9]. Metal casting techniques such as stir casting and centrifugal casting are the most favored techniques used in fabrication of FGM for automobile applications such as pistons, flywheels, and brake rotor disks [10-12].

## 1.2 Background of Functionally Graded Materials

Pure metals have limited application in engineering due to the demand for contradictory property conditions. Consequently, two or more different metals are combined to produce alloys. Alloys provide enhanced properties which are unique from those which are present in parent materials. However, constraints to conventional alloys such as thermodynamic equilibrium limitations and thermal dissimilarities between alloying materials has presented challenges in this alloying process [8, 13]. Other methods of material combinations such as powder metallurgy also present challenges such as difficulties encountered during the fabrication of parts with intricate configuration, and delamination. These challenges, among others, have led to the development of unique types of materials known as functionally graded materials (FGM).

FGMs are specialized types of advanced materials, possessing unique volume fraction distribution of the alloying elements which vary seamlessly across the dimensions of the part being produced [14]. They are developed such that the properties, composition and features of the constituent elements of the material vary with respect to the location and dimensions of the material [15]. The need for FGMs arise from the desire to have a material which possesses the ability to retain its structural integrity during service when exposed to opposing conditions simultaneously from different ends. Interest in FGMs have increased over the years due to the advantages of FGMs over single component materials or alloys in various engineering applications. An example of this is the elimination of the sharp interface which serves as a stress concentrator region in traditional composite or alloy materials which can trigger failure, substituting it with a gradient type of interface [16]. Furthermore, FGMs are unique in that they can be designed specifically for predefined applications [15].

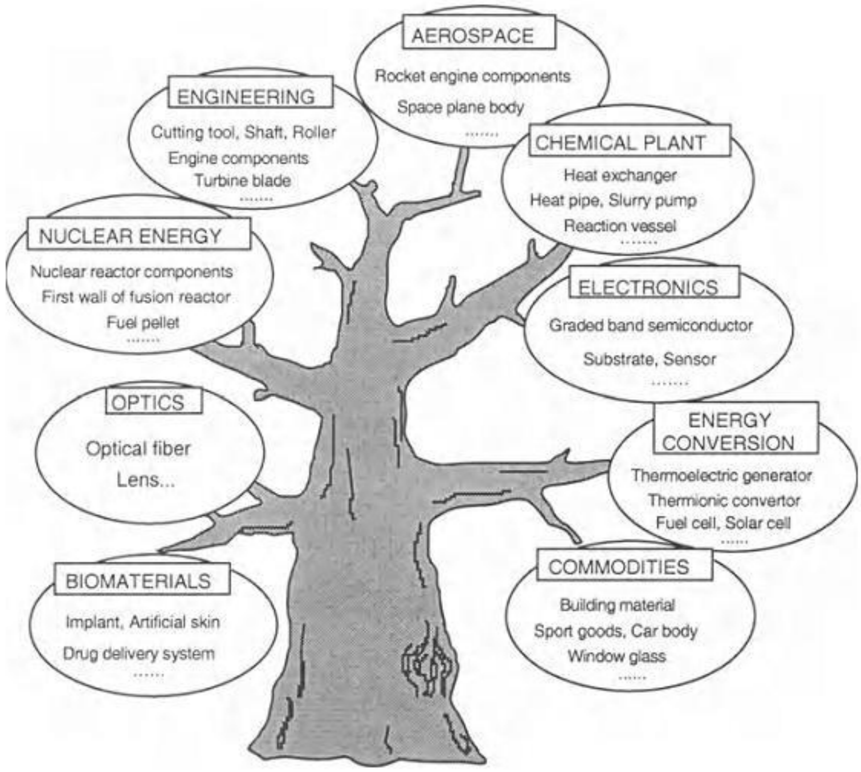


**Figure 1 Areas of application of functionally graded material [17]**

The two broad categories of FGMs are bulk FGMs and thin FGMs for surface coating. The fabrication process of FGMs are therefore determined by the volume size of the FGM to be produced. Examples of the fabrication techniques for FGMs are powder metallurgy (PM), melting (casting) process, solid freeform fabrication, compo-casting, vapor deposition among others, as documented in the literature [15, 18, 19]. This research is focused on the development and characterization of bulk functionally graded aluminium matrix composite using the centrifugal casting technique.

### 1.2.1 Current Trends in Functionally Graded Materials

FGMs are a new generation of engineering materials whereby the microstructural details of the materials vary spatially throughout the materials' geometry as a result of uneven distribution of the reinforcement phase(s). Engineers accomplish this by using reinforcements with different properties, sizes, and shapes, as well as by interchanging the roles of the reinforcement and matrix phases in a continuous manner. The outcome is a microstructure that produces continuously or discretely changing thermal and mechanical characteristics at the macroscopic or continuum scale. In this new concept of engineering, the material's microstructure marks the beginning of a revolution both in materials science and mechanics of materials as it allows one, for the first time, to fully integrate the material and structural considerations into the final design of structural components. FGMs offer great options in applications or operating conditions which are extreme. For example, wear-resistant linings for handling large heavy abrasive ore particles, rocket heat shields, heat exchanger tubes, thermoelectric generators, heat-engine components, plasma facings for fusion reactors, and electrically insulating metal / ceramic joints. They are also ideal for minimizing thermomechanical mismatch in metal-ceramic bonding [20].

Modern day FGMs were birthed as a solution to the challenge faced by Japanese engineers in the mid-80s where the materials for the frame of a space plane project was required to possess the ability to withstand two temperature extremes on both sides of the material. The inner and outer working temperatures of the materials were 1000 K and 2000 K respectively, while the material thickness was less than 0.1 cm [8, 15, 21]. The successful implementation of this gave rise to the production of FGM through various techniques and for a wide range of applications such as automobile, health, defence among others.

The merits of FGM in the component parts of automobile engine parts cannot be over emphasized. Consequently, this research sought to develop FGMs with enhanced mechanical properties in service conditions with locally sourced aluminium ingots using the advanced centrifugal casting technique for auto engine components. This method was employed to develop functionally graded hypereutectic Al-SiC composite materials suitable for engineering applications.

### 1.2.2 Fabrication Processes of Functionally Graded Materials

Various fabrication processes such as sintering, laser deposition and casting have been adopted over the years in the manufacturing of FGM composites. The centrifugal method of metal casting is one of the most efficient methods for processing FGMs, using aluminium matrix composites (AMCs). This is so because centrifugal forces propel heavier material like ceramics particles in the liquid metal such that they are displaced towards the outer surface of the casting [22]. Furthermore, the centrifugal casting process has the desired effect of good mold filling while it also allows for control of the microstructure of the material. As a result, the overall mechanical properties of the material are improved [23]. Furthermore, the centrifugal method of casting is cost effective as the overall production costs of FGM through this process are much lower than when conventional processes are employed, as these would need to incorporate additional production steps with surface modification and coating methods which are performed independently [24].

Owing to the above stated considerations, this research sought to develop FGAMMs for production of auto engine components by means of centrifugal casting using aluminium alloys with selected reinforcement. Examination of the microstructure of the centrifugally cast material was carried out to determine the influence of reinforcement on the properties of the cast composites.

## 1.3 Problem Statement

Catastrophic failures of engineering materials during service are a serious challenge. The automobile and aviation sector have recorded quite a number of fatal casualties caused as a result of material failure due to inherent stress, corrosion, micro-cracks and fatigue. The need for engineering materials, produced from aluminium matrix, capable of retaining their structural integrity by withstanding extreme service conditions, cannot be overemphasized. In recent times, research interests have been tilted towards the development of various aluminium matrix composites using different types of reinforcement. In the same vein, the manufacturing techniques that are employed in producing components which are tailormade for specific applications are of utmost importance. The right choice of suitable reinforcement(s) and appropriate manufacturing procedures in the fabrication of aluminium-based metal matrix composites used in automobile and aerospace applications can contribute to a decline in the frequency of catastrophic material failures in service conditions.

However, the selection of suitable reinforcement from numerous reinforcing particles has remained a drawback in the fabrication of aluminium based composites. It is essential to note that the reinforcement choice determines the material's behavior which include but are not limited to the mechanical, microstructural, tribological and thermal characteristics. Reinforcements exhibit different properties, owing to the difference in their chemical composition.

Thermal dissimilarities between aluminium base material and $SiC_P$ reinforcement has also been identified as a major drawback in the fabrication of Al-SiC composite. this leads to sputtering, that is, the violent ejection of reinforcement particles when introduced into the molten base material.

## 1.4 Research Questions

The present study was guided and centered around the questions stated below:

- How does the particulate reinforcement of silicon carbide influence the mechanical, tribological and thermal properties of fabricated Al-SiC composite?

- What combination of percentage weight and particle size of the reinforcement produces the optimal material characteristics of the aluminium matrix composite desired?
- How does the choice of production technique affect the microstructural properties of the aluminium matrix composite?
- What will be the effect of varying reinforcement particle size on the thermogravimetric properties of fabricated composites?
- How will reinforcement granularity and proportion impact on the mechanical properties such as hardness, tensile, compressive, shear strength, and tribological behavior of the fabricated FGM composites?

## 1.5 Aim

The aim of this research was to develop a functionally graded aluminium matrix material (FGAMM) for automobile piston component.

## 1.6 Objectives

i. Review bulk fabrication technologies for functionally graded materials (FGMs).
ii. Develop a high strength functionally graded aluminium matrix composite using SiC reinforcement for automotive applications by the centrifugal casting method.
iii. Characterization of samples using OM, OES, EDX, and SEM.
iv. Investigate the impact of particle size and varying weight percentages of the reinforcement particles on the mechanical behavior of hardness, compression, tension, and shear strength of the fabricated FGM.
v. Determine the tribological properties of wear rate and frictional coefficient of the fabricated composites as influenced by varied reinforcement addition.
vi. Determine the thermal decomposition properties and heat flow rate of the fabricated composites at the elevated temperature region.

## 1.7 Research Justification

In an effort to mitigate in-service material failure and to develop engineering materials capable of responding adequately to extreme service conditions, material research development has been at the forefront in engineering research. This effort has generated several researches into the dynamics of particulate reinforced metal matrix composites. This study sought to proffer insights into the impact of reinforcement weight-percent and granularity on the behavior of fabricated metal matrix composites with potential application in high temperature and wear-susceptible environments in automobiles. The failure of automobile pistons resulting from low strength, low abrasion resistance, fatigue, and other thermomechanical causes creates a knowledge gap in the efficient / optimal applications of these components during service. This gap raises research interest in understanding the probable causes and mitigation of such failure through the development of special types of materials referred to as functionally graded composite materials.

Functionally graded aluminum metal matrix composites are increasingly becoming the material of choice in applications where varied, and sometimes contrasting, properties are desired across the geometry of an engineering material in service. This, therefore formed the core of this research in developing aluminium composite materials able to withstand harsh service conditions during application in the automobile engine, and by extension, other engineering machine parts.

## 1.8 Scope of the Work

This study is divided into four sections

i. To establish baseline knowledge of the existing FGM fabrication techniques.
ii. Fabrication of Al-SiC composites through the liquid metal processing technique.
iii. Determination of process parameters to obtain gradient dispersion of reinforcement in fabricated composites.
iv. Characterization of fabricated functionally graded Al-SiC composites for automobile piston application.
v. Analysis of experimental data.
vi. Conclusion and recommendations.

## 1.9 Structure of Thesis

This thesis is a compilation of published journal articles addressing the various objectives outlined in this research.

**Chapter 1** presents background to the research, problem statement, research questions, aim, objectives, research justification, research scope and thesis structure.

**Chapter 2** provides a wholistic review of the literature on functionally graded material, metal-reinforcement interaction, various fabrication techniques available, the pros and cons of the various techniques, and process parameters adopted by researchers.

**Chapter 3** presents the process of fabrication and parameters adopted for this research. The results of the mechanical characterization performed and the resultant effects of reinforcement particle granularity and weight proportion on the fabricated FGM samples were established. These results were published in a peer review journal and compiled in this chapter.

**Chapter 4** discusses the tribological behavior of frictional coefficient and wear rate of the fabricated Al-SiC composites. The effect of configuration of the added reinforcement to the composites' matrices is reported.

**Chapter 5** reports the thermal characteristics of the fabricated Al-SiC composites at elevated temperature. The thermal degradation and the heat flow attributes of each composite with varying amounts of reinforcement additions were analyzed and compared with each other.

**Chapter 6** discusses the results obtained from the various analyses undertaken in this research. The rationale of the analyses conducted and a flow process of the research is also presented.

**Chapter 7** presents a conclusion to the thesis, the contribution to knowledge, and recommendations for further study.

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# CHAPTER 2: LITERATURE REVIEW

## 2.1 Chapter Synopsis

The use of aluminium and aluminium-based composites are ever increasing in today's technologically advanced world. Aluminium's abundance in nature coupled with its desirable properties of light weight, corrosion resistance, high strength-to-weight ratio, among others, makes it a sought-after material for many engineering applications. The increase in the demand for aluminium-based composite materials possessing varied material properties across its bulk has brought FGMs to the fore. Various manufacturing procedures have been researched and developed for different applications. The choice of reinforcements and processing parameters are influenced by the intended use of the FGM.

This chapter presents a critical review of the various types of functionally graded material and the different fabrication processes that have been adopted by several researchers in the recent past. The areas of application and outlook for functionally graded materials are also discussed. This chapter has been published as a review article in the *International Journal of Applied Engineering Research*.

**A. O. Owoputi**, F. L. Inambao, and W. S. Ebhota, "A review of functionally graded materials: fabrication processes and applications," International Journal of Applied Engineering Research, vol. 13, no. 23, pp. 16141-16151, 2018. http://ripublication.com/ijaer18/ijaerv13n23_01.pdf

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## 2.2 Chapter 2 Article 1: A Review of Functionally Graded Materials: Fabrication Processes and Applications

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# A Review of Functionally Graded Materials: Fabrication Processes and Applications

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**Abstract**

Functionally graded materials (FGMs) are materials that possess variance in properties across the geometry of the material. They are a class of materials developed from the existing knowledge of material alloying. This paper discusses the evolution and the background study of FGMs. The different FGMs processing techniques and their comparative advantages were discussed. Furthermore, the paper classified FGMs based on the principle of their manufacturing method. Various application areas of FGMs were discussed.

**Keywords**: Functionally graded materials, metal casting, alloying materials

## 1. INTRODUCTION

Pure metals have limited applications in engineering due to the demand for contradictory properties due to functionality requirements [1]. In engineering applications there is a need for materials with different properties which will enable them to perform optimally under service conditions. Such properties are non-existent or difficult to obtain in a pure metallic material. Therefore, two or more different metals, each of which possess one of the required properties for optimum performance, are combined to produce what is known as alloys. The importance of metals in day-to-day life and particularly in engineering cannot be overemphasised. These range from domestic to industrial applications, such as manufacturing and construction. The working condition of the metal during service as well as expected performance informs the choice of the metal to be selected for any particular engineering application. Owing to the less desirable properties of pure metals, metal alloys, such as aluminium alloys are generally preferred for engineering applications.

Aluminium in its raw form is abundant in nature, comprising about 8% of the earth's crust. Pure aluminium is of low strength and easily deforms under load. In engineering applications such as automobile components and aerospace designs, the use of aluminium alloys are employed due to their light weight and lower density compared to steel. Good thermal and electrical conductivity are also desirable properties of aluminium for electrical cable production and kitchenware. Alloying elements such as magnesium, manganese, copper, zinc, tin and silicon, when added to aluminium, enhance its properties thereby making it suitable for use in industrial as well as domestic applications. One of the most essential alloying elements for aluminium is silicon as it improves the cast-ability of aluminium metal. Alloys provide enhanced properties that are unique compared to those which are present in parent materials on their own. However, conventional alloys face constraints such as thermodynamic equilibrium limitations and thermal dissimilarities between alloying materials [1, 2]. These challenges, among others, have led to the development of unique materials known as functionally graded materials (FGMs).

Functionally graded materials are specialized types of advanced materials developed to withstand severe service conditions while performing at optimum during service. They are developed such that the properties, composition and features of the constituent elements of the material varies with respect to the location and dimension along the material [3, 4] as shown in Fig. 1. The composition, microstructure or the porosity gradient of the FGM can vary either continuously or discontinuously and can be specifically designed to provide specific functionality during service [5].

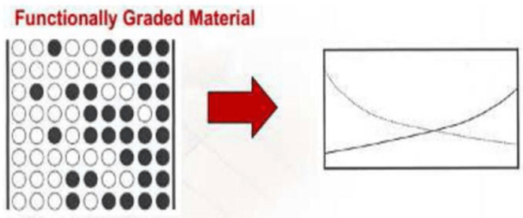


**Fig. 1.** Profile of FGM

Similar to conventional composite materials, the properties and characteristics of FGMs are different from those of the individual elemental materials which form the FGM. The property(ies) of the FGM are graduated across the volume of the material because of the dependability of the chemical composition, microstructure or atomic order of atoms, and of their position within the material [4, 6].

The need for FGMs arises from the desire to have materials which possesses the ability to retain their structural integrity during service when exposed to opposing conditions simultaneously from different ends. Interest in FGMs has increased over the years due to the advantages of FGMs over single component materials or alloys. One example of an advantage is the elimination of sharp boundaries which serve as stress concentrator regions that trigger failure in conventional composite materials, and substituting it with the gradient type boundaries, while also eliminating the thermodynamic limitations encountered in alloy applications [1, 7]. Furthermore, FGMs are unique in that they can be designed specifically for predefined applications [3, 4]. The ability to influence and manipulate the properties of composite materials for a specific engineering application makes the research into FGMs of immense importance.

## 2. BACKGROUND OF FGMs

Material development in the past focused on producing materials with homogenous properties which exhibit little or no property variance when finished and which are capable of producing optimum performance during service. However, arising from the limitations encountered in the application of conventional homogenous materials such as polymers, ceramics and metal alloys, the need for FGMs arose. The use of FGMs over the past few decades has witnessed tremendous growth both in the area of development and in the area of application, particularly in the aerospace, automobile and health sectors. Various manufacturing methods to produce FGMs have been developed over time, particularly in Japan between 1987 and 1991. The earliest form of fabrication methods in the thin group of FGMs were mostly in form of layer processing, examples of which included spraying, vapor deposition and self-propagating high-temperature synthesis (SHS). Powder metallurgy (PM) was employed in processing of bulk FGMs [1]. The use of conventional composites has not been successful in spacecraft and aviation applications. Continuous texture control was developed and adopted in 1985 to improve the binding strength and decrease the stress due to the rise in temperature in the ceramics coating of rocket engines [1].

Modern day FGMs were developed as a result of the challenges encountered by Japanese engineers in the mid-80s when building the frame of a space rocket because the material needed to be able to withstand opposing temperature extremes on opposite sides of the material. The inner and outer working temperatures of the materials were 1000 K and 2000 K respectively, while the material thickness was less than 0.1 cm [3, 8]. The success of that project kick-started evolution of modern day use of FGMs. This led to the first national symposium on FGMs which took place in 1990 in Japan [9]. At the turn of the new century, production processes of FGMs were already widespread, with FGMs finding their way into Europe, leading to the establishment of a trans-regional research centre in Germany in 2006. The centre was tasked with the exploitation of manufactured graded mono materials like steel and aluminium, joined thermally and mechanically [1].

## 3. GROUPS OF FGM

Depending on the geometry and the cross-sectional area of the material to be produced, FGMs can be categorized into two major groups, the thin and bulk FGMs.

### *3.1. Thin FGMs*

These are usually in form of surface coating and have thin cross sections. The choice of surface deposition method employed in the manufacturing of thin FGM is dictated by the service requirements of the material. Various deposition techniques for thin FGMs include vapor deposition, plasma spraying, atomic layer deposition (ALD), electrodeposition, SHS, among others [1, 8, 10]. Thin FGMs are usually not suitable for applications with extreme service conditions.

### *3.2. Bulk FGMs*

Bulk FGMs are those with thickness greater than 1 mm and whose functional properties vary with respect to the gradient profile of the material. Bulk FGMs are produced through different techniques such as the solid freeform (SFF), PM, metal casting (MC) among others

## 4. FGM CHARACTERIZATION

The characterization of FGM is often based on the variation of the structure and composition of the constituent materials which make up the graded material. These variations in turn influence the overall properties exhibited by the material during service. The literature generally groups FGM manufacturing processes into four major categories [1, 4, 11, 12], namely, bulk, layer, preform and melt processes as shown in Fig. 2.

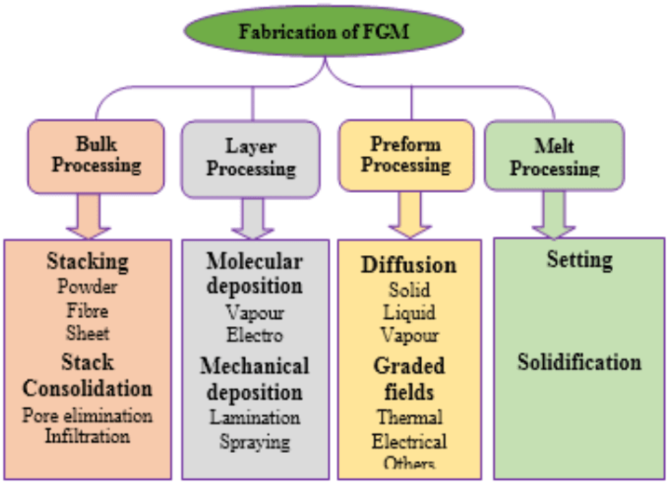


**Fig. 2.** FGM processing techniques [1]

## 5. FABRICATION PROCESSES OF FGMs

As discussed earlier, the choice of FGM fabrication technique is mainly influenced by both the desired service properties and the FGM group of the material to be produced.

### *5.1. Thin Group FGM Manufacturing Process*

Thin FGM is usually produced through various deposition processes such as vapor deposition, atomic layer deposition, spray deposition, electrodeposition and laser deposition. The choice of deposition is dependent on the service required of the material.

#### *5.1.1. Vapor Deposition Process*

Vapor deposition techniques are used in producing thin FGMs. There are various types of vapor deposition techniques, which include but are not limited to, chemical vapor deposition, physical vapor deposition and sputter deposition. Vapor deposition techniques are excellent in deposition of a graded surface coating producing desirable microstructure. However, they are only efficient in producing thin FGMs, as they are relatively tedious and labor intensive. Furthermore, cost of production is comparatively high and toxic gases are given off as a by-product [13]. Other processing techniques for thin FGMs include SHS, plasma spraying, and ion beam assisted deposition (IBAD) [14].

#### *5.1.2. Atomic Layer Deposition (ALD)*

ALD involves a process of deposition of thin film metal and metal oxide deposition in Ångstrom scale (i.e. $10^{-10}$) to produce an FGM. This is advantageous compared to other deposition techniques such as thermal spray and chemical vapor deposition [15]. The quest to develop semiconductors and capacitors with improved cycle performance has driven research interest in ALD. The ability to have control over the film thickness during deposition adds to the advantages of this process. Sun et al. [16] developed a $Ti_2O$-graphene functionally graded material for a super-capacitor using the ALD process. $Ti_2O$ was deposited on the graphene material in nanoscale. When used as a super capacitor, Sun et al. [16] reported that the $Ti_2O$-G composites showed exceptional charge transfer conductivity and good ion diffusion with negligible deterioration in electrochemical performance compared to when pure graphene was used.

#### *5.1.3. Spray Deposition*

The spray deposition process of producing FGMs is a relatively recent technique that involves the use of inert gas to atomize liquid melt into fine droplets and then deposit the droplets on a metallic substrate. The process has been successfully applied to preparing ceramic particle reinforcement of metal matrix composites [17]. The spray deposition process eliminates challenges such as liquid aluminum particle rejection encountered during liquid state processing of composite matrix. Su et al. [18] developed a SiC particle Al-20Si-3Cu FGM using the spray deposition process coupled with a programmable control system. It was established that an increase in the SiC particle weight fraction in the as-deposited preform brought about an increase in the porosity and micro hardness of the material. Furthermore, as seen in Fig. 3, a homogenous distribution of the SiC particles in the as-deposited preform is observed across the material bulk in the longitudinal direction. Due to its advantages over other liquid state processing methods, spray deposition processing of FGM appears to be the preferred processing method for a wide range of FGMs.

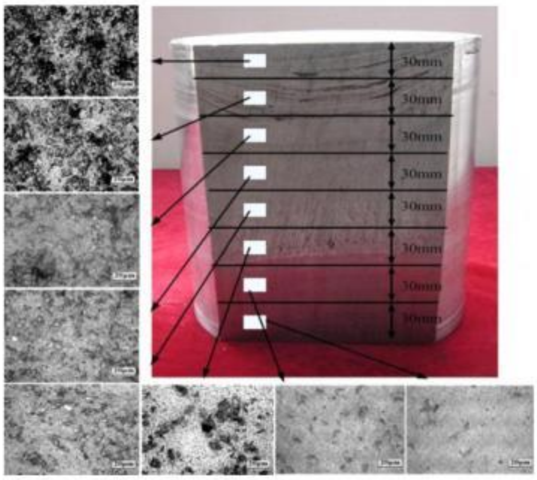

**Fig. 3.** Microstructure of the distribution of SiC particles in the FGM perform [18]

#### *5.1.4. Electrodeposition*

Electrochemicals as a form of surface coating have been considered as viable options in the manufacturing of FGMs [19], due to advantages such as uniform dispersal of allotting elements, continuous processing and reduced waste when compared to methods like the chemical vapour deposition (CVD) and physical vapour deposition (PVD) [20]. Some common factors that influence electrodeposited graded coatings are density of current, and particle loading in bath electrolyte [19, 20]. Torabinejad et al. [19] fabricated a functionally graded coating of $Ni$-$Fe$-$Mn/Al_2O_3$ 70 μm thick on mild steel via the electrodeposition method. Two types of coatings were produced: one was synthesized by steadily reducing the duty cycle and keeping the frequency unchanged while the other was electrodeposited by steadily increasing the frequency while keeping the duty cycle unchanged. The effect of pulse parameters like frequency and duty cycles on corrosion and wear behaviour as well as the composition, microstructure and micro-hardness of the functionally graded nanocomposite coatings were examined. Torabinejad et al. [19] found that with the increase in frequency, chemical composition of the matrix in nanocomposite coatings remained unchanged across the cross-section. Additionally, the micro-hardness and wear resistance of the coating was enhanced due to refinement of the grains when frequency increased. Conversely, a decrease in the duty cycle resulted in a change in chemical composition across the coating cross-section. Other research work conducted using electrodeposition process can be found in the literature [21-23].

### 5.1.5. *Laser Deposition (LD)*

Laser deposition (or laser metal deposition) is a relatively new additive manufacturing process that can be adapted to making FGMs from three-dimensional computer-aided designs. Process parameters for laser deposition require optimization for the desired application. Mahamood and Akinlabi [24] produced a functionally graded titanium alloy composite. They obtained the optimized process parameters for all material combinations from an earlier study [25]. The FGM with optimized processing parameters for all the material combinations showed improved properties, whereas those without optimized parameters for all material blends did not [24].

### 5.2. *Bulk Group FGM Manufacturing Process*

Processing of bulk FGMs are usually energy intensive and slow and cannot be produced using deposition techniques such as vapor deposition [3]. The process of manufacturing bulk FGM is generally grouped into two: the gradation process and the consolidation process. The gradation process comprises the constitutive, homogenizing and the segregation processes. The constitutive process is based on a layered build-up of the FGM from its powdered form. This process has over time become viable economically and technologically owing to the innovation recorded in the automation industry. The homogenizing process eliminates the sharp interface which exists in the bulk FGMs by converting it into a gradient form through material transport. The segregation process uses external gravitation or electric fields to convert a material from a homogenous to a graded form [6, 8]. The bulk FGMs consolidation process follows the gradation process. This process involves the sintering and solidification of the powder material. Processing conditions for the material are chosen such that their gradient structure is not altered while unequal shrinkage is also mitigated [8]. Bulk manufacturing processes include PM, MC and SFF [3].

### 5.2.1. *Powder Metallurgy (PM)*

PM is a bulk manufacturing process which produces finished or semi-finished metal components from powder whose particle sizes are less than 0.1 cm. There are two main types of PM: stepwise compositional control (SCC) and continuous compositional control (CCC). In SCC, the microstructural properties of the material are observed to be in layered form across the cross-section of the material, whereas the CCC exhibits a position dependent composition and microstructure across material.

Generally, there are four main stages in PM processes: production, weighing and mixing of metal powder, stacking, compaction of the powdered metal and sintering [1, 8, 26] as shown in Fig. 4. The main process parameters in PM are powder mixture composition, shape, compacting pressure, particle size, and sintering temperature [6].

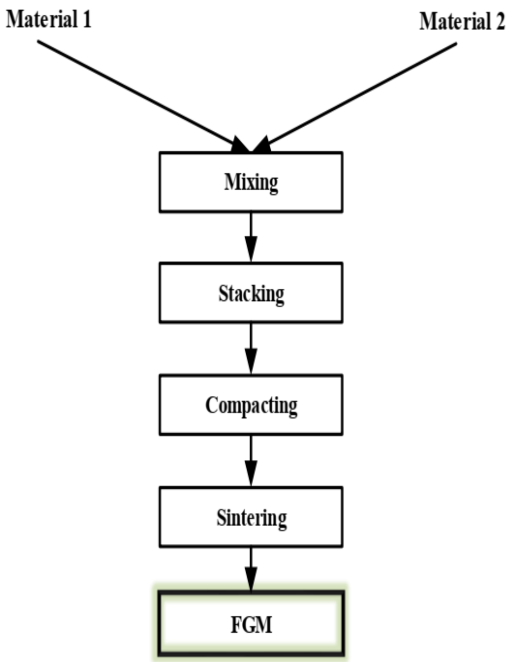


**Fig. 4.** Processes involved in powder metallurgy

### 5.2.2. *Metal Casting (MC)*

Examples of casting techniques applicable in the production of FGMs are slip casting, centrifugal casting, stir casting and the squeeze casting. Other casting techniques are sedimentation casting, sequential casting, controlled mold filling, infiltration, and directional solidification [6]. All of these are well documented in the literature although there is room for further research.

#### 5.2.2.1. *Slip Casting*

A slurry solution made up of material particles, dispersing agents and water is poured into a spongy plaster mold as depicted in Fig. 5. As solidification occurs, the solid particles are drawn to the wall of the mold. An outlet valve attached to the base of the mold is released and the slurry is drained from the cast. The cast material is allowed to solidify and dry and the mold is then removed. The desired gradient of the material can be obtained by varying the composition and particle size of the material suspension during the casting process [27]. The slip casting process is similar to the slurry dipping process of fabricating FGM [6].

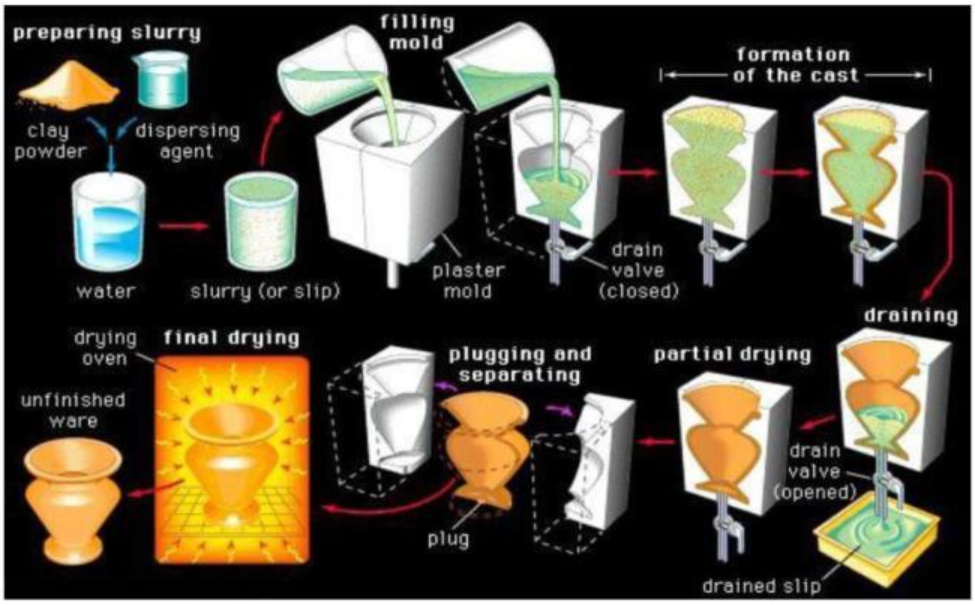


Fig. 5. Slip casting steps [28]

Katayama et al. [29] produced an $Al_2O_3$-W FGM with one of the materials containing oxidized powder of W while the other contained "as-received" W (not oxidized). The result showed that the $Al_2O_3$-W FGM, which contained as received W showed a distinct interface between the $Al_2O_3$ and the W particle, as shown in Fig. 6, whereas the $Al_2O_3$-W FGM with oxidized W showed a compositional gradient in its microstructure as seen in Fig. 7.

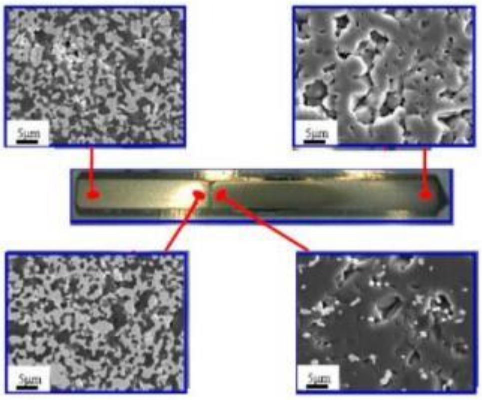

**Fig. 6.** Optical micrograph and SEM images of FGM of $Al_2O_3$-W with as-received W powder [29]

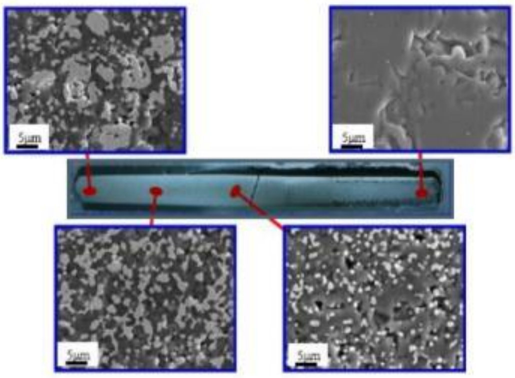

**Fig. 7.** Optical micrograph and SEM images of FGM of $Al_2O_3$-W with oxidized W powder [29]

The distinction observed in Fig. 6 is attributed to the difference in the densities of the powders. It is worth noting that the slip casting process is followed by a consolidation step to allow for a sintered material.

*5.2.2.2. Centrifugal Casting*

The centrifugal method of casting FGM uses a spinning mold in casting of the materials rather than using gravity force. The mold is mounted on a rotational shaft while the melt is poured into it [30] and allowed to solidify while the mold is still rotating [31, 32]. A typical centrifugal casting setup is shown in Fig. 8.

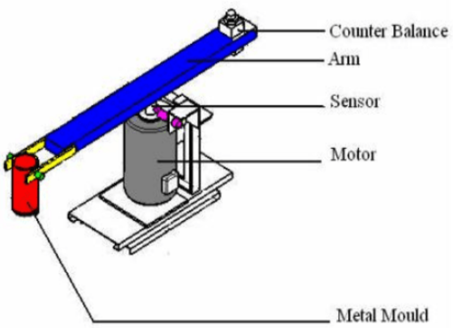


**Fig. 8.** Vertical setup of centrifugal casting [27]

Gradients formed through this method are largely dependent on the variance of the densities of the materials that make up the melt as well as the speed of rotation of the mold [3]. Gradient material produced through the centrifugal method is formed from a metallic melt which contains solid particles of secondary material(s) in varying concentration across the material. The melting temperature of the secondary particle (in solid phase) may be higher or lower than the temperature of the melt during casting. This phenomenon informs the two classifications of the centrifugal method namely, centrifugal solid particle method (CSPM) and the centrifugal *in situ* method (CISM). The former occurs due to the melt having a lower temperature compared to the melting temperature of the secondary particle, hence, the secondary particle remains in its solid state during solidification. The latter occurs when the melt has a higher temperature than the melting temperature of the secondary particle. As a result, the particle melts in the mix as the material solidifies under centrifugal action [27]. The centrifugal process offers continuous compositional graduation of the material and in the CSPM method, high wear resistance and material toughness is observed as seen in Fig. 9. The CISM method possesses advantages such as homogenous dispersion of reinforcing particles, good thermodynamic stability and good wettability compared to the CSPM method [33].

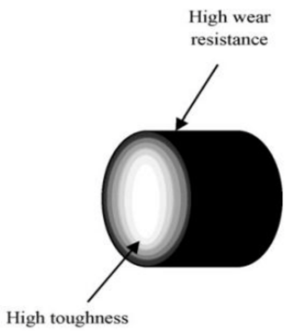


**Fig. 9.** Showing areas of high toughness and wear resistance for a CSPM processed material [27]

The geometry of the FGMs produced centrifugal method (CM) is limited to cylindrical shapes [3] and the types of gradients formed are limited due to the parameters involved in the formation of those gradients, namely, material densities and applied centrifugal force [6, 26]. Furthermore, the denser particle reinforcement tends to move towards the outer wall of the cast during the rotation of the mold [1]. This phenomenon is governed by Stokes law, which is expressed as:

$$v = \frac{d^2(\rho_p - \rho_l)g}{18\mu} \quad (1)$$

Where $v$ is the particle velocity, $d$ is particle diameter, $\mu$ is viscosity of liquid metal, $\rho_l$ is density of liquid metal and $\rho_p$ is density of particle.

The basic expression of the centrifugal casting process of producing FGM is given as follows:

$$\omega = \frac{v}{r} = \frac{2\pi N}{60} \quad (2)$$

Where $\omega$ is the angular force an $N$ is speed in rev/min.

The centrifugal force that acts on particle is given as:

$$F_c = m\omega^2 r = m_p \frac{4\pi^2 N^2}{3600} \quad (3)$$

Where $F_c$ is Centrifugal Force, $m_p$ is mass of particle an $r$ is distance.

The difference in the densities of the melt and the reinforcing particle(s) results in a particle concentration gradient which is observed in the solidified FGM processed from CM [6] and a distinct gradient in composition is observed for FGMs produced through the CSPM method as opposed to those produced through the CISM method [27]

*5.2.2.3. Stir Casting (SC)*

The stir casting process of manufacturing FGMs involves the use of an automated stirrer to facilitate the desired dispersion of reinforcing particles in the melt before solidification takes place (Fig. 10). This can be applied to a mixture of two slurries or a slurry-particle combination. In addition to proper dispersion of the reinforcing particles within the mix [34], stirring also helps to keep the particles suspended in the slurry. Introducing the reinforcing particle into the melt is a vital stage in the SC process. There are various methods of introduction amongst which the vortex method yields the best output. This method involves the vigorous stirring of the melt until a vortex is formed in the melt and the reinforcing substances are introduced into the slurry through the vortex. Other stir casting methods are injection gun particle insertion, particle spraying into slurry, particle addition during pouring [1].

There are various factors which affect the quality of the FGMs produced through the stir casting process, including: stirring time and speed of rotation of stirrer in the melt. Brabazon et al. [35] observed that a homogenous particle suspension is obtainable in the melt when rotation speeds of 200 rpm are employed during the stir casting process. Other determining factors which influence quality are pouring rate, pouring temperature and angle of the stirring blade within the melt [1].

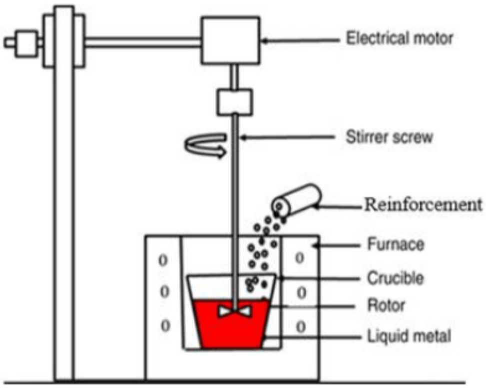


**Fig 10** A schematic stir casting set up [1]

*5.2.2.4. Squeeze Casting*

The squeeze casting process of producing FGMs involves the melting and pouring of the material into a mold followed by addition of reinforcing particles and stirring to obtain uniform distribution and squeezing of the soft material through a die to obtain the finished material. This process usually requires minimal post-manufacture finishing as the material obtained is in near-finished form. Vital operations such as degassing, mold preheating, pouring and squeezing are performed to obtain quality casting for aluminium based FGM. Additional operations such as preheating of reinforcing substance, its addition to the melt and further stirring of the melt before squeezing are performed for a metal-ceramic FGM [1].

Reihani, [36] using the squeeze casting method, studied the influence of SiC reinforcing particles on the mechanical properties, ageing behaviour and wear properties of aluminium based material. It was concluded that a near pore-free cast with uniform dispersal of the SiC particles is obtainable through this processing technique. Furthermore, the material wear resistance and strength appear to increase while the ductility appears to decrease.

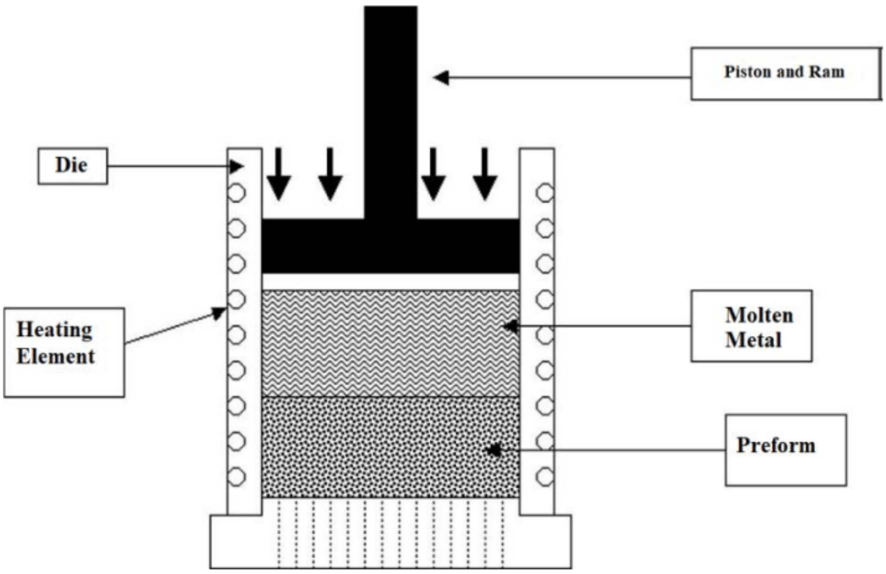


**Fig. 11.** Schematic diagram of the squeeze casting apparatus [36]

*5.2.3. Other Fabrication Processes for FGMs*

In addition to the above-mentioned fabrication processes, other types of fabrication processes that have been researched and are available in literature are listed in Table 1.

**TABLE 1**

OTHER FABRICATION PROCESSES FOR FGMS

| Processing Techniques | Procedure | References |
|---|---|---|
| **Sequential Casting** | The sequential casting process or controlled mold filling, as used by [37] in the designing and processing of bimetallic aluminum alloys, involves pouring of different melted alloys which have similar solidification temperature ranges in succession into a mold to form a single FGM. The melt from the second material is poured into the mold containing the first melt whose solidification process is in progress. Formation of gradient structure across the material profile occurs as a result of forced thermal convection between the individual materials [6]. | [6, 37] |
| **Infiltration Technique** | The infiltration process involves pouring of a melt into a porosity gradient refractory preform whose temperature is greater than that of the melt. The preform is produced from sintering of powdered materials [6]. | [6] |
| **Solid Freeform** | Solid freeform processing, also referred to as material prototyping, is a software-based method with great research interest in the production of FGMs. The process involves five stages as described by [1, 3, 6], and offers advantages such as less energy consumption, manufacture of intricate profiles, direct manufacture from CAD STL data file as well as material optimization. Research is intensifying on how to improve on the surface finishing and dimensional accuracy of the FGM obtained through solid freeform processing. | [1, 3, 6] |
| **Frictional Stir Casting** | Frictional stir casting involves the plastic deformation of a bulk material by inserting a rotating tool on it and moving it along a desired path on the material [38]. Results obtained from this processing technique have been found to produce aluminum alloys with improved properties and microstructure [39, 40]. | [38-40] |
| **Electrophoretic Deposition** | This is a low-cost deposition process capable of producing FGMs with intricate shapes. This technique is useful in producing multi-layered composite materials from simple equipment [41]. The process was used by Askari et al. [42] in producing a $Al_2O_3/SiC/ZrO_2$ FGM to be used for artificial bio implants. | [41, 42] |

## 6. TRENDS IN FGM AND AREAS OF APPLICATION

Since the introduction of continuous texture control application of FGM in 1985, FGMs have found relevance in various engineering and non-engineering applications due to excellent in-service performance in extreme conditions. Applications in FGM have been able to blend properties which were, in the past, considered incompatible. Table 2 shows the various applications in which FGMs have been deployed.

**TABLE 2**

AREAS OF APPLICATION OF FGMS

| Area of Applications | Uses |
|---|---|
| **Aerospace** | Due to the ability to withstand severe thermal differences during service, FGMs have been employed suitably for building of rocket engine parts as well as body parts for space plane [3]. Growth in aviation technologies have prompted demanded the service of materials with good thermal qualities and service durability. In the past, these qualities were sort for from artificial metal, ceramics or organic fiber composites[43]. |
| **Medical** | Due to its similarities in microstructural arrangements in bio tissues like teeth and bones, FGM have been found as applications in the orthopedic and dental practice for production of biomaterials. |
| **Manufacturing and Energy** | Owing to high thermo-mechanical, properties FGM are used in the production of thermal barrier coatings and heat exchanger tubes for power plant. FGM also provide protective coating for turbine blades in turbine engines. |
| **Automobile** | FGMs have been used for automobile parts such as pistons, gears and exhaust valves |
| **Defense** | The ability to impede the spread of cracks within a material is a core property of FGM, as such, it has been found suitable in the production of armored plates for bulletproof vest and military helmets. |
| **Electronics and optoelectronics** | FGMs are used for optical fibers for wave high-speed transmission. Computer circuit boards (PCB) for cell phones. |
| **Cutting tools** | Tungsten carbide/cobalt and aluminum/stainless steel have found commercial success in being used as cutting tools [1]. |

## 7. OUTLOOKS OF FGMs

Over the years FGM has received huge research interest owing to its numerous advantages. However, the production and fabrication costs, especially with PM and techniques dependent on it, are relatively high. Furthermore, the production of semi-finished FGMs which still need further machining to obtain the desired geometry, pose a challenge. SFF offers a viable solution to the above challenges; however, more research works are needed on its performance to generate an all-inclusive database through characterization of FGM. Furthermore, with the rising interest in additive manufacturing techniques such as 3-D printing, the production of aluminum based FGM using 3-D printing can be exploited as a viable fabrication route for FGM.

## 8. CONCLUSION

This paper presents a general review of FGM, its evolution, manufacturing techniques and applications. The choice of manufacturing process is dependent on both the type of FGM and the required service properties of the material to be manufactured. Thin FGMs are usually fabricated through vapor and spray depositions. Bulk FGMs are mainly manufactured via the PM and MC processes. Despite the increase in research of FGMs, challenges of large scale production as well as trade-offs of certain material properties during production still exist and this hampers its deployment in manufacturing. Regardless of these challenges, FGM application areas will continue to increase in engineering material development.

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# CHAPTER 3: MECHANICAL EVALUATION OF SIC REINFORCED FUNCTIONALLY GRADED ALUMINIUM MATRIX COMPOSITE

## 3.1 Chapter Synopsis

The mechanical properties of aluminium matrix composite materials are indicators of the materials' behavior when encountered by mechanical forces during their application. Parameters such as percentage volume fraction, particle size, density, particle orientation, wettability have been documented as impacting properties of engineering composite materials. This chapter contains three published articles on the effect of SiC particulate reinforcement on the mechanical properties of Al-356 aluminium matrix composite.

Article 1 discusses the influence of the varied weight percent of silicon carbide particulate on the properties of strength and hardness of the fabricated composite. Adopting an average particle size of 7 µm, the volume of reinforcement introduced to the aluminium matrix was varied by 1 %, 3 %, and 5 %. Observation on strength and hardness of the material as well as the distribution of the reinforcement within the matrix were documented and published in the *International Journal of Mechanical Engineering and Technology (IJMET)*.

> **A. O. Owoputi**, F. L. Inambao, and W. S. Ebhota, "Influence of $SiC_p$ reinforcement on the mechanical properties of functionally graded aluminium metal matrix composites fabricated by centrifugal casting technique," International Journal of Mechanical Engineering and Technology, vol. 10, no. 8, pp. 306-316, 2019. [Online]. Available: https://iaeme.com/MasterAdmin/Journal_uploads/IJMET/VOLUME_10_ISSUE_8/IJMET_10_08_024.pdf
>
> **Article status:** Published

Article 2 reports on the effect of the percentage weight variation of the reinforcement particles on the properties of the fabricated aluminium matrix composite. A reinforcement of particle size of 15 µm varied at 1 %, 3 %, and 5 % of the weight was adopted for the study. The result of the investigation was subsequently published in the *International Journal of Engineering Research and Technology*.

> **A. O. Owoputi**, F. L. Inambao, and W. S. Ebhota, "Effect of percentage weight and particle size of $SiC_p$ reinforcement on the mechanical behavior of functionally graded

aluminium metal matrix composite," International Journal of Engineering Research and Technology, vol. 13, no. 3, pp. 444-453, 2020.

Available Online: http://www.irphouse.com/ijert20/ijertv13n3_10.pdf.

**Article status:** Published.

Article 3 presents the compression test results obtained for each particle when the reinforcement composition was varied by weight and size.

**A. O. Owoputi**, F. L. Inambao, and W. S. Ebhota, "Analyzing the impact of reinforcement addition on the mechanical properties of aluminium A356 alloy" International Journal of Mechanical and Production Engineering Research and Development (IJMPERD), vol. 11, Issue 4, pp. 047-056.

**Available Online:** http://www.tjprc.org/publishpapers/2-67-1624421857-4IJMPERDAUG20214.pdf

**Article status:** Published.

## 3.2 Chapter 3 Article 1: Influence of $SiC_p$ Reinforcement on The Mechanical Properties of Functionally Graded Aluminium Metal Matrix Composites Fabricated by Centrifugal Casting Technique

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# INFLUENCE OF SiC$_P$ REINFORCEMENT ON THE MECHANICAL PROPERTIES OF FUNCTIONALLY GRADED ALUMINUM METAL MATRIX COMPOSITES FABRICATED BY CENTRIFUGAL CASTING TECHNIQUE

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**ABSTRACT**

*The influence of the addition of silicon carbide (SiC) reinforcement on the microstructural and mechanical properties of functionally graded aluminum metal matrix composites fabricated through the centrifugal casting technique was investigated. Hardness and tensile strength testing were carried out on reinforced and non-reinforced cast materials. The overall hardness of the cast samples were found to be 102 HV100, 106.8 HV100, 111HV100 and 112.7 HV100 for 0 wt.%, 1 wt.%, 3 wt.%, and 5 wt.% of SiC reinforcement respectively while the tensile strength of was observed to be 339.0 MPa, 355.0 MPa, 369.0 MPa and 374.5 MPa respectively. Owing to the movement of the reinforcements to both ends of the samples due to centrifugal force, the mechanical properties of the fabricated functionally graded materials was observed to be improved at both ends of the samples compared to their centers.*

**Key words:** Silicon carbide, reinforcement, matrix, composite, tensile strength, centrifugal casting

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http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=10&IType=8

## 1. INTRODUCTION

In recent years, functionally graded materials (FGMs) have been the preferred over other monolithic alloys for automobile and engineering purposes. This is due to the numerous advantages which functionally graded materials offer compared to monolithic alloys. The concept of FGM arose from the desire to have a material which possesses microstructural and / or mechanical properties with variation along its axes. Functionally graded materials focus on the measured distribution of reinforcements in varying concentration within the matrix along a defined direction while conventional alloys focus on the even distribution of reinforcement within the matrix material [1]. There is increasing interest in the use of FGMs in various engineering applications due to the advantages possessed by this class of special materials [2, 3]. This has led to the development of several FGM manufacturing techniques [4-10]. These manufacturing methods (solid phase, liquid phase or vapor phase) are generally categorized based on the material to be fabricated [11]. Among the various manufacturing techniques that have been employed in the fabrication of FGMs over the years is the centrifugal casting technique (CCT).

The CCT has often been the favored technique to producing FGMs consisting of metal-metal compositions or metal-ceramics composition due to advantages of processing flexibility, ease of operation, and cost effective material fabrication technique among others [12-17]. During centrifugal casting, the size and mass of the particles, density of particles, density of molten metal among other factors, influence the dispersion of the reinforcement within the melt. The significant difference in the densities of $SiC_p$ (3170 kg/m$^3$) and molten aluminum (2400 kg/m$^3$ to 2700 kg/m$^3$) ensures that the SiC particles are forced to the ends of the material during casting. According to Watanabe et al. [18], particles in molten metal under centrifugal action experience two types of forces acting on them. These are the radial centrifugal forces pushing them towards the mold wall and an opposing drag due to the viscosity of the melt. Equation 1 shows the relationship between these forces.

$$m_p \frac{d^2x}{d^2t} = [p_p - p_m]\frac{4}{3}\pi\left(\frac{D_p}{2}\right)^3 Gg - 3\pi\eta D_p \frac{dx}{dt} \quad (1)$$

Where the mass and acceleration of the particle is given by $m_p$and $\frac{d^2x}{d^2t}$ respectively; $p_p$ and $p_m$ are the densities of the particle and the melt; $D_p$ is the particle diameter; $\eta$ is the viscosity; and $g$ is the acceleration due to gravity. The ratio of the centrifugal force to force due to gravity is expressed in equation 2 as:

$$G = 2D_0N^2 \quad (2)$$

With $D_0$ as the cast ring diameter in meters and $N$ is the velocity of the rotating mold.

The equation suggests that reinforcing particles would migrate away from the center of the melt under centrifugal action if their density were higher than the density of the melt. The converse is also true. Primary silicon and air entrapment with lower density ($\rho Si$ = 2330 kg/m$^3$) compared to the melt migrate to the center of the melt where the centrifugal force is least experienced.

The effects of the various processing parameters involved in the manufacture of FGM through CCT have been well documented in literature. In a study conducted by [19], hollow cylindrical functionally graded aluminum matrix materials having 12% mass fractions of reinforcing materials were fabricated through centrifugal casting. A base aluminum alloy matrix, Al-12Si-Cu, was used owing to its range of usage for automobile applications, while $B_4C$, SiC, $Al_2O_3$ and $TiB_2$ were selected as reinforcing materials. The mechanical properties of the FGMs produced using the various reinforcements were studied and it was observed that the outer zone of all the FGMs produced displayed considerable hardness compared to the middle and inner zones of the materials for all the reinforcement used. El-Galy et al. [20] carried out an investigation analyzing the effects of varying reinforcement particle sizes and weight fractions on the microstructural orientation of functionally graded aluminum matrix composites and how these structural morphologies in turn influence the mechanical behavior of the material such as hardness, tensile and tribological properties. Pure aluminum was used as the base matrix while SiC particles are the reinforcement of choice using the horizontal centrifugal casting technique. The effect of varying the particle reinforcement sizes (500 µm, 23 µm and 16 µm), mold rotation and pouring mechanism on particle distribution was studied. Following this, the effect of reinforcement particle distribution on the mechanical properties of wear resistance, hardness, tensile strength and ductility were investigated. El-Galy et al. [20] reported that the smaller the particle sizes for the reinforcement, the higher the hardness value of the material. Furthermore, the authors found that the increased weight to 10 wt.% of SiC reinforcement in the matrix resulted in a proportionate increase in the hardness of the material beyond which point a slight decrease in the hardness was observed, with reinforcement with a weight percent range of 7.5 wt.% to 10 wt.% of $SiC_p$ yielding the finest wear resistant property.

This paper seeks to add to existing knowledge on the effects of silicon carbide particulate reinforcement on the mechanical properties of a functionally graded aluminum metal matrix composite fabricated using the centrifugal casting technique while adopting some processing parameters obtainable in the literature. The choice of silicon carbide powder as reinforcement for the aluminum alloy for this study was due to its desirable effects on the mechanical properties of aluminum-based alloys and the application of the alloys as engineering material [21, 22].

## 2. MATERIALS AND METHODS

### 2.1. Materials

Aluminum A356 alloy received in form of ingots was used for the purpose for this research. Silicon carbide particles were supplied by Capital Lab Supplies Pty with an average particle size of 7 µm was used as reinforcement material. The chemical compositions of the aluminum alloy and the silicon reinforcement are shown in Table 1.

**Table 1.** Elemental compositions of the aluminum alloy and the silicon reinforcement

| | Al | C | O | Fe | Si | Total |
|---|---|---|---|---|---|---|
| Aluminum Alloy | 92.3 wt.% | 5.83 wt.% | 1.52 wt.% | 0.36 wt.% | - | 100% |
| Reinforcement | - | 42.63 wt.% | 3.01 wt.% | - | 54.36 wt.% | 100% |

### 2.2. Methods

The base material was measured and divided, by weight, into four equal parts. The material was melted in a furnace at 750 °C to produce a slurry. A 1 wt.% silicon carbide particle which was preheated in a muffle furnace for 2 h at a temperature of 300 °C was introduced into the melt. A mechanical stirrer was utilized to facilitate an even distribution of the reinforcement within the matrix of aluminum melt. The molten composite was poured into the rotating mold of a vertical centrifugal casting machine. The solidified composite was removed from the cavity of the mold and the process was repeated for 3 % wt.% and 5 % wt.% respectively. The process was repeated to produce a cast control sample with no reinforcement addition (0 wt.%). The centrifugal casting machine, shown in Figure 1, comprised a mold affixed on a rotating wheel. The wheel was connected to an electric motor via a pulley belt which causes it to rotate.

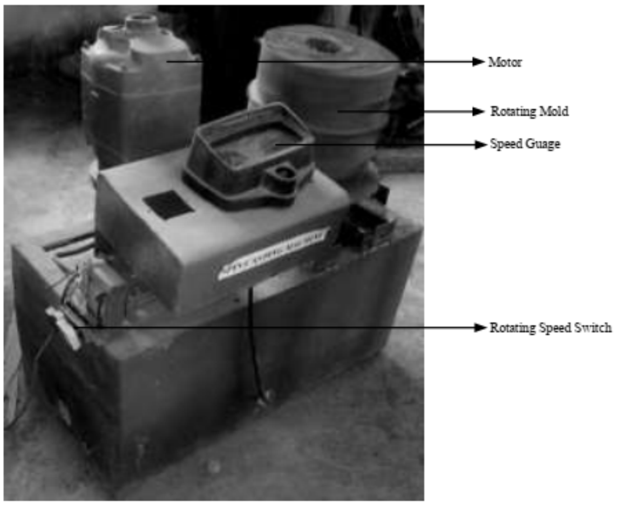



**Figure 1.** Centrifugal Casting Machine

The rotating speed of the mold was set at 800 rpm, allowing the melt to solidify under centrifugal action. Table 2 shows the processing parameters adopted for the process.

**Table 2.** Processing Parameter of Al-SiC Alloy

| Sample | %Wt. of $SiC_p$ | Mold Rotating Speed | Melt Temperature |
|---|---|---|---|
| Control | 0 | 800 rpm | 750 °C |
| A | 1 | 800 rpm | 750 °C |
| B | 3 | 800 rpm | 750 °C |
| C | 5 | 800 rpm | 750 °C |

Four cast samples of aluminum alloy with 0 wt.%, 1 wt.%, 3 wt.% and 5 wt.% of $SiC_p$ were fabricated using the CCT method. Hardness test as well as microstructural examination were performed on cast samples to determine their properties.

## 2.3. Characterization of Cast FGM Samples

### *2.3.1. Hardness and Tensile Tests*

Round FGM samples with length of 100 mm and 20 mm diameter were produced and prepared for characterization, from centrifugal casting. The Vickers hardness test was carried out using the LECO® M-400-H1 hardness testing machine with an applied load of 100 g and dwell time of 15 sec. Hardness value was obtained from the average of five indentations which were taken across the cut surfaces of the test as revealed by the microscope attached to the hardness tester.

### *2.3.2. Microstructural Examination*

The cast specimens were prepared for microstructural examination using standard metallographic procedures. A two-step grinding operation (plane grinding and fine grinding) of the surfaces was done to obtain a flat surface, in accordance with Struer Metalog Guide using the Struer grinding and polishing machine. Prior to grinding, sectioned samples were hot mounted in Bakelite resin using the Struer hot mounting machine. For the plane grinding, MD-Primo 220 disc with silicon carbide abrasive was used. The grinding wheel was set to rotate at 300 rpm with a force of 120 N and grinding time was 3 min. This was followed by a fine grinding procedure on the material to remove surface scratches using the MD-Largo grinding disc with a 9 μm grit size diamond polishing (DP) suspension as the abrasive. The grinding wheel was set to rotate at 150 rpm with a force of 180 N applied on the specimen for 8 min. The polishing procedure was carried out using the same equipment with the configuration set for the polishing process. An MD-Nap polishing disc surface fixed on a grinding wheel rotating at 150 rpm was used with a DP-Suspension abrasive of 1 μm size. Polishing time was set for 5 min with an applied force of 150 N applied to the specimen, after which the specimens were etched in Kellers reagent to obtain clear microstructural details. Figure 2 shows a prepared sample for metallographic examination. The Zeiss Ultra Plus scanning electron microscope was used to examine $SiC_p$ powder particles used for reinforcement and its distribution within the matrix of the cast FGM containing varying percentage weight composition.

**Figure 2.** Prepared Sample Surface for Metallographic Examination

## 3. RESULTS AND DISCUSSION

Optical micrographs and SEM images were taken from the prepared surfaces of the fabricated FGM samples. The SEM image of the as-received reinforcement particle is shown in Figure 3 while Figure 4 shows the distribution of the reinforcement particles within the matrix of the FGM. The SiC particles were coated with gold dust in a Quorum Q150A ES sputtering machine to enhance their conductibility during SEM analysis.

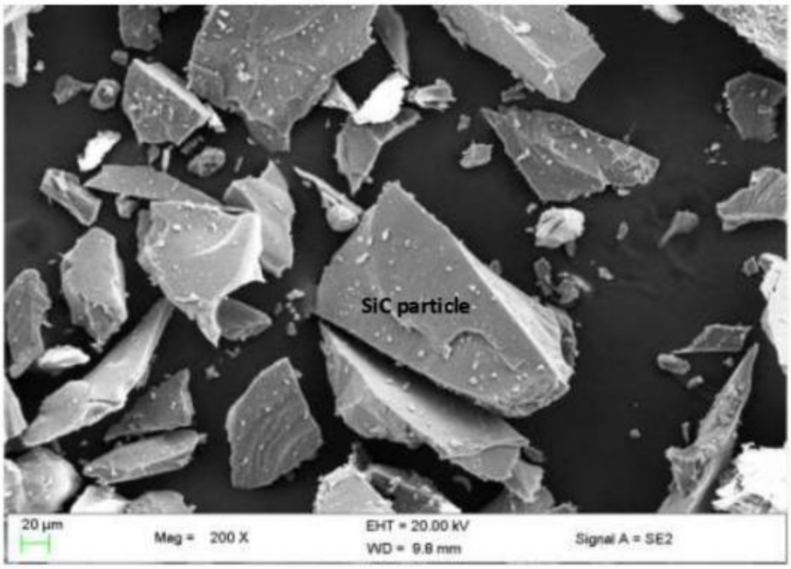



**Figure 3.** SEM images of as-received $SiC_p$ reinforcements coated in gold dust on a carbon tape background.

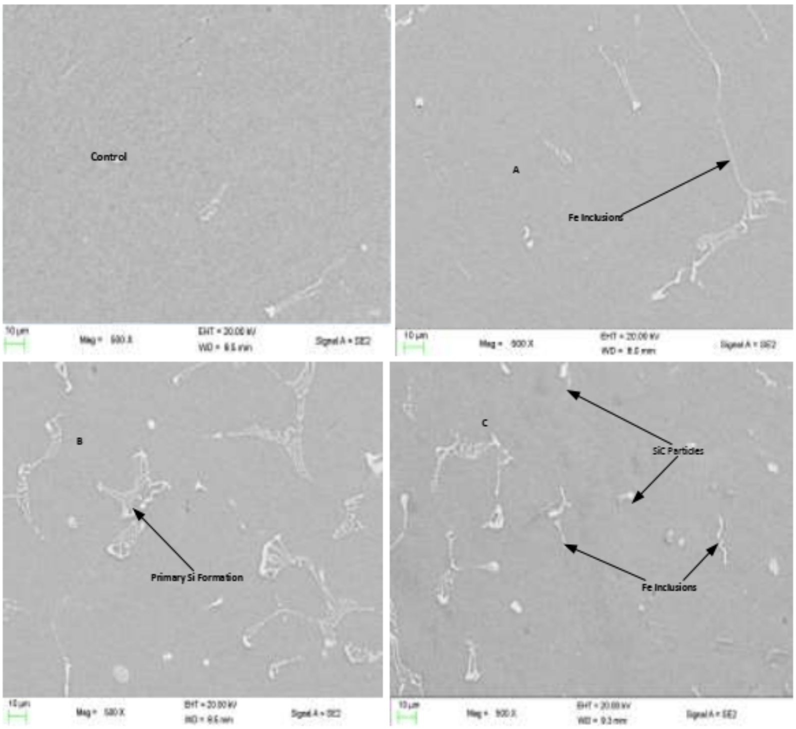
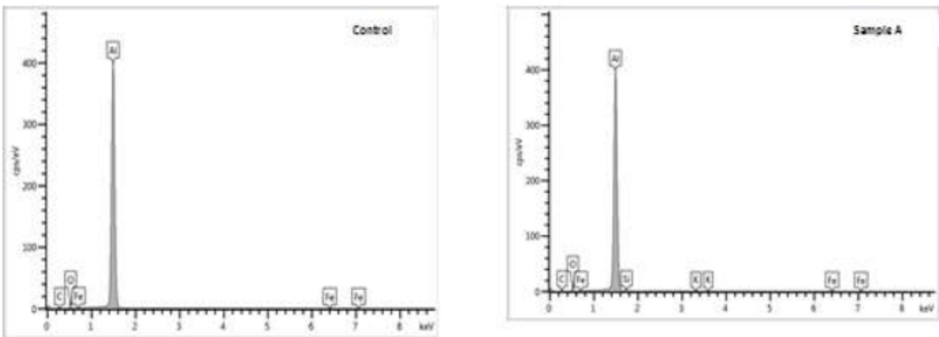


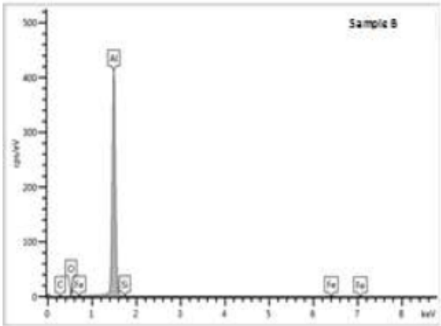

**Figure 4.** SEM micrographs for composite with (A) 1wt.% SiC (B) 3 wt.% SiC (C) 5 wt.% SiC and control sample with 0 wt.% SiC.

The elemental composition of the samples are shown in Table 2 while Figure 5 shows the Energy Dispersion X-ray (EDX) images showing the peaks of the elemental composition of the fabricated FGM samples with different SiC weight percent. Aluminum, which made the bulk of the alloy matrix, was observed to have the highest peak.

**Table 2.** Elemental composition of the samples from EDX analysis

| | Al (%) | Si (%) | C (%) | O (%) | Fe (%) | K (%) |
|---|---|---|---|---|---|---|
| **Control Sample** | 92.30 | - | 5.83 | 1.52 | 0.36 | - |
| **Sample A** | 91.11 | 0.85 | 5.81 | 1.28 | 0.95 | - |
| **Sample B** | 89.42 | 0.93 | 7.04 | 1.80 | 0.81 | - |
| **Sample C** | 77.81 | 1.37 | 16.98 | 3.12 | 0.62 | 0.10 |





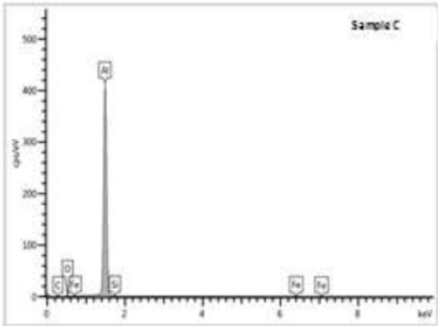




**Figure 5.** EDX images obtained from SEM analysis

### 3.1. Hardness Tests

Material hardness is the ability of the material to withstand deformation plastically through abrasion or impact. The knowledge of an engineering material's hardness informs its service application. The Vicker's hardness test was carried out on the material and the effect of the reinforcement weight percentages was determined. When measured from end-to-end, the materials showed an increasing value of hardness from their centers toward their ends as shown in Figure 6. Under centrifugal force, more $SiC_p$ reinforcements are forced towards the end of the bar, which results in an increase in the hardness value towards the sample ends.

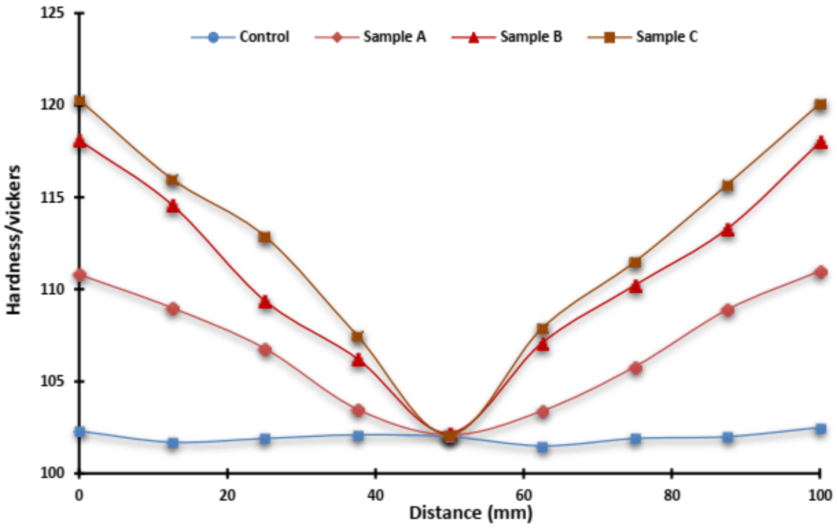



**Figure 6.** Hardness value variation along the samples' length

The material sample A, which contained 1 wt.% of $SiC_p$ reinforcement gave a hardness value of 102.1 HV100 at the mid-length of the sample and 110.8 HV100 at one end of the sample with 111.0 HV100 at the other end of the sample. In a similar trend, it was observed that for material samples B and C, which contained 3 wt.% and 5 wt.% of $SiC_p$ respectively, the hardness value increased from the mid-length of the sample toward both ends. The control sample without reinforcement (0 wt.%) gave a hardness value of 102.0 HV100 at the mid-length of the sample and 102.3 HV100 and 102.5 HV100 at both ends of the sample. The plot for overall hardness values obtained for all samples with respect to the percentage weight of the silicon carbide reinforcement is shown in Figure 7. Increase in the percentage weight of the $SiC_p$ within the aluminum matrix leads to a corresponding increase in the hardness of the material.

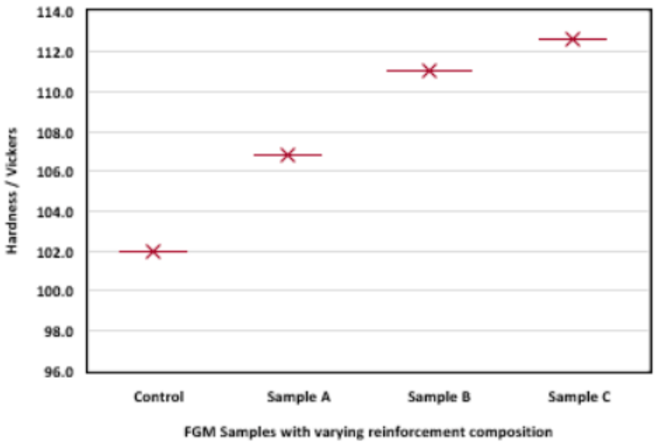



**Figure 7.** Overall hardness of the FGM samples with varying composition of reinforcement

## 3.2 Tensile Property Estimation

The tensile property of the samples were estimated with the aid of engineering database developed by Wu et al. [23] and the values were verified against the hardness-tensile strength conversion using ASTM A370 / ASME SA-370 standard. The tensile property was observed to increase from the mid sections of the samples towards the ends of the samples as shown in Figure 8. This displays consistency with the concentration of the reinforcement along the FGM matrix. Furthermore, it was observed that the tensile strength of the samples increased with increase in the weight percent of the reinforcement within the matrix increases. The control sample (0 wt.% SiC) and sample C (5 %.wt. SiC) recorded an average tensile value of 339.0 MPa and 374.5 MPa respectively.

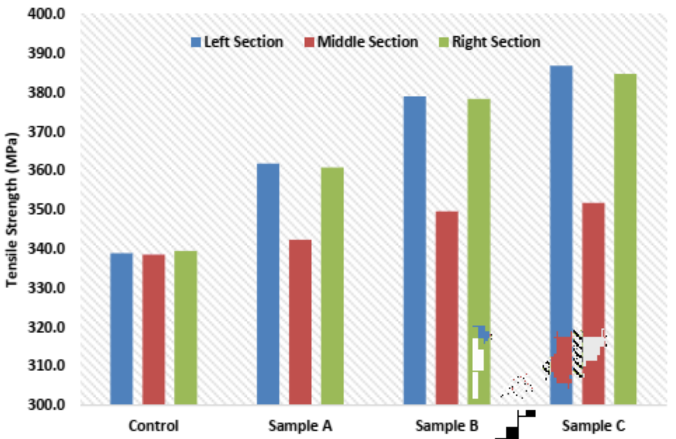



**Figure 8.** Comparative tensile strength of FGM samples with varying amount of SiC reinforcement

## 4. CONCLUSION

In this study, the influence of percentage weight variation of SiC reinforcement in aluminum based composite fabricated through centrifugal casting technique was investigated and the following conclusions were drawn:

1. Owing to the movement of particles within the melt and their significant density difference, a gradient of particles was observed along the line of the centrifugal force, which ensured a variation of properties across the material fabricated.
2. The presence of $SiC_p$ reinforcements enhanced the mechanical properties of hardness and the tensile strength of the aluminum matrix composite.
3. The hardness value and tensile property of the fabricated composite increased with the increase in the weight percent of the reinforcement within the aluminum alloy matrix.
4. The improvements in microstructural and mechanical properties observed in the fabricated aluminium matrix composites largely depended on the amount and distribution of the reinforcement contained within the matrix.
5. Using the parameters of production in this work, structural, automobile and engineering aluminum based FGM can be fabricated successfully through a centrifugal casting method.

## ACKNOWLEDGEMENT

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## 3.3 Chapter 3 Article 2: Effect of Percentage Weight and Particle Size of $SiC_p$ Reinforcement on The Mechanical Behavior of Functionally Graded Aluminium Metal Matrix Composite

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# Effect of Percentage Weight and Particle Size of $SiC_p$ Reinforcement on the Mechanical Behaviour of Functionally Graded Aluminum Metal Matrix Composite

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**Abstract:**

The fabrication of functionally graded aluminum metal matrix composite with varying properties using a centrifugal casting technique was carried out using silicon carbide particles ($SiC_p$) of an average particle size of 15 μm as reinforcement. The effect of the $SiC_p$ reinforcements at different weight-percent on the hardness and tensile properties of A356 aluminum alloy was studied. The effect of particle size of the SiC reinforcement on the properties of the aluminum alloy was also investigated. It was observed that the hardness of the fabricated composite gradually increased from the center of the fabricated materials to their ends while the overall hardness of the samples increased as the weight-percent of the reinforcement addition increased. This observation also held true for the tensile properties of the materials. The property variations observed are attributed to the dispersion of the reinforcement within the aluminum matrix before solidification under centrifugal force action.

**Keywords:** A356 alloy, functionally graded material, hardness, reinforcement, silicon carbide, tensile strength.

## I. INTRODUCTION

In recent years, the development of a metal-based class of material known as functionally graded materials (FGMs) has gained tremendous interest due to properties such as superior strength, wear and creep resistance as well as enhanced mechanical performance. This class of engineering materials is able to exhibit characteristic property variations along the cross-section of an individual unit. The desire for this characteristic has led to the shift from monolithic materials to composites materials for engineering and automobile application.

The fabrication of these functionally graded composite materials through various manufacturing techniques has attracted growing interest. Various researchers have manufactured FGM through techniques such as vapor deposition [1, 2], atomic layer deposition [3, 4], electrodeposition [5, 6], laser deposition [7, 8]. Other manufacturing techniques which have been explored and documented in existing literature are powder metallurgy [9, 10], slip casting [11, 12], stir casting [13] and centrifugal casting [14-16]. The latter technique is regarded as the most suitable casting technique for manufacturing FGMs in commercial quantities due to advantages of processing flexibility, ease of operation, and cost-effective material fabrication [17-20].

Particle dispersion within the matrix during the solidification process under centrifugal action causes a variation in the properties of the material along the path of dispersion. The rate of particle dispersion is dependent on the difference in densities between the matrix and the reinforcement, rotating speed of the mold, and the effect of centrifugal force acting on the individual reinforcement particles [15, 21]. With constant acceleration, the velocity ($v$) of individual reinforcement particles within the matrix under centrifugal action can be evaluated using Stoke's law as seen in equation (1):

$$v = \frac{2{R_r}^2(\rho_r - \rho_m)\gamma}{9\eta} \quad \text{.....................} (1)$$

where $\eta$ is the viscosity of the base matrix, $R_r$ is the reinforcement particle size, $\rho_r$ and $\rho_m$ are the densities of the reinforcement particles and base matrix respectively. Other factors such as drag and viscosity of the molten metal have also been found to influence the dispersion of particles in molten metal. This relationship can be seen in equation (2):

$$m_p \frac{d^2x}{d^2t} = [p_p - p_m]\frac{4}{3}\pi\left(\frac{D_p}{2}\right)^3 Gg - 3\pi\eta D_p \frac{dx}{dt} \quad \text{.........} (2)$$

where the mass and acceleration of the particle is given by $m_p$and $\frac{d^2x}{d^2t}$ respectively; $p_p$ and $p_m$ are the densities of the particle and the melt; $D_p$ is the particle diameter; $\eta$ is the viscosity; and $g$ is the acceleration due to gravity.

Properties such as ductility, corrosion resistivity, thermal, electrical resistivity and light weight make aluminum one of the most important engineering metal there is [22]. However, in its unalloyed form, the metal serves very limited engineering purpose. Alloying of aluminum with other materials in a bid to improve its properties, thereby making it suitable for automobile, electrical and aviation applications amongst others, has been in the forefront of material research in recent years.

The use of aluminum alloys as base material in the development of FGMs for various engineering applications using several reinforcing materials have been examined by researchers. Xiaoyu, et al. [23] conducted an experiment to investigate the effects of operating parameters on the structure and morphology of pistons manufactured by means of centrifugal casting technique (CCT) using AlSi18CuMgNi alloy and silicon carbide particles of varying sizes. Findings were that the greatest concentration of SiC particle was noticed at the piston head while the piston skirt had little or no trace of the reinforcement. This was responsible for the improved properties of wear and hardness observed at the piston head. Contatori, et al. [24] were able to produce functionally graded cylindrical components of Al-19Si alloy using 5 % copper and magnesium reinforcements through CCT. The dispersion of reinforcements and the formation of phases within the alloy matrix was investigated. It was found that there was formation of $Al_5Cu_2Mg_8Si_{16}$ and $Mg_2Si$ phases within the matrix which in turn impeded the formation of primary β phase particles. The gradient dispersion of the reinforcements influenced the property of the Al-19%Si alloy produced.

Using Al-20-45Zn-3Cu as the base material, Shin, et al. [25] were able to investigate the effects of high zinc content on the mechanical and microstructural properties of the alloy produced using the gravity cast technique. The authors noted that an increase in the Zn content of the alloy led to a corresponding decrease in its impact strength while the ductility of the fractured surface decreased with an increase in Zn content. In another study conducted by Rajan, et al. [26], aluminum matrix composites Al-7Si-0.35Mg with SiC (*ex-situ*) reinforcement and Al-17Si-4Cu-Mg with Si (*in-situ*) as reinforcement were fabricated using CCT. They noted that the fabricated part possessed enhanced mechanical properties at cast sections furthermost from the center where the effect of centrifugal force is least experienced during mold rotation and solidification.

This study seeks to show the effects of SiC reinforcement with varying weight-percent on a functionally graded aluminum metal matrix composite produced through CCT. Furthermore, the effects of SiC reinforcement with average particle sizes of 7 µm and 15 µm on hardness and tensile properties of the fabricated functionally graded aluminum metal matrix composite (FGAMMC) would also be discussed.

## II. MATERIALS AND METHODS

### II.I Materials

The base material used was aluminum A356 ingots while the reinforcement material was SiC particles with an average particle size of 15 µm. The aluminum ingots were melted in an induction furnace while the casting process of the melt was done in the rotating mold of a centrifugal casting machine. Table I shows the elemental composition of the aluminum alloy and the silicon carbide reinforcement.

### II.II Methods

A measured weight of aluminum A356 was charged and melted in an induction furnace at a temperature of 750 °C. Silicon carbide particles with 1 % weight-fraction of melted aluminum alloy was preheated in a muffle furnace at a temperature of 300 °C for two hours. The preheated $SiC_p$ was introduced into the molten aluminum and a mechanical stirrer was used to homogeneously disperse the reinforcement within the melt. The speed of rotation of a vertical centrifugal machine was set at 800 rpm and the homogenous molten composite was poured into the cavity of the rotating mold. The mold was allowed to rotate for 6 minutes after pouring to allow the reinforcing particles to disperse within the melt under centrifugal action before solidification. After solidification, the rotation was stopped and the composite material was removed from the mold cavity. The process was repeated to produce aluminum composites containing 3 wt.% and 5 wt.% silicon carbide particles. A control aluminum sample with 0 % $SiC_p$ reinforcement was also produced through the same process bringing the number of cast samples to four. Fig. 1 shows the centrifugal casting setup. The fabricated samples are hereafter referred to as control sample, sample E, sample F and sample G which correspond to 0 wt.%, 1 wt.%, 3 wt.%, and 5 wt.% addition of the SiC reinforcement respectively.

**Table I.** Elemental composition of Aluminum alloy and SiC reinforcement

| | Al | C | O | Fe | Si | Total |
|---|---|---|---|---|---|---|
| Aluminum Alloy (wt.%) | 92.3 | 5.83 | 1.52 | 0.36 | - | 100 |
| Reinforcement (wt.%) | - | 42.63 | 3.01 | - | 54.36 | 100 |


Figure 1 Centrifugal casting setup

II.III Microstructural and Mechanical Analysis of Fabricated Materials

Functionally graded round aluminum alloy samples 10 cm long and 2 cm in diameter were fabricated using centrifugal casting machine. Microstructural analysis, as well as mechanical hardness test, was performed on the samples containing varying percentages of the $SiC_p$ reinforcement to determine their suitability for automobile application.

II.IV Microstructural Analysis

The cast FGM samples were prepared for metallographic analysis. The samples were hot mounted with Bakelite resin. A two-stage grinding operation (fine and plane grinding) was carried out on surfaces of the hot mounted samples. This was followed by a polishing operation of the sample surfaces. The grinding and polishing operations were performed using the Struers grinding and polishing machine. The operating parameters adopted for the hot mounting are shown in Table II while Table III shows the operating parameters for the grinding and polishing procedure for the FGM samples.

**Table II.** Operating parameters for hot-mounting FGM samples.

| Operation | Force | Temperature | Mounting Time | Cooling Time |
|---|---|---|---|---|
| Hot-Mounting | 25 kN | 180 °C | 12 Mins | 3 Mins |

**Table III.** Operating parameters for grinding and polishing of FGM samples.

| Operation | Fine Grinding | Plane Grinding | Polishing |
|---|---|---|---|
| Surface | MD-Primo 220 | MD-Largo | MD-Nap |
| Abrasive Used | SiC | Diamond Polishing Suspension | Diamond Polishing Suspension |
| Grit Size | - | 9 µm | 1 µm |
| Lubricant | Water | Green/Blue | Red |
| Wheel Speed | 300 rpm | 150 rpm | 150 rpm |
| Force | 120 N | 180 N | 150 N |
| Time | 3 Mins | 8 Mins | 5 Mins |

**Figure 2.** Mounted FGM samples prepared for metallographic analysis

A mirror-like surface was obtained for the FGM samples after the polishing operation. Keller's reagent was used to etch the polished surface to enhance the FGM structure when viewed under the scanning electron microscope.

II.V Mechanical Analysis: Hardness and Tensile Properties of the FGM Samples

A Vickers's hardness test was carried out on the fabricated FGM machine to determine its response to the gradient distribution of the $SiC_p$ reinforcement under centrifugal action during solidification. The LECO® M-400-H1 hardness testing machine was utilized for this procedure using a load of 100 g and a dwell time of 15 sec. Hardness values along the length of the cast material were measured at an equal distance apart. The tensile strength values of each sample containing different weight-percent of $SiC_p$ was also derived from the hardness values obtained with the aid of an engineering database developed by Wu, et al. [27].

## III. RESULTS AND DISCUSSIONS

The $SiC_p$ reinforcement and the metallographically prepared surfaces of the cast FGM samples were subjected to microstructural examination using a Zeiss Ultra Plus scanning electron microscope. The $SiC_p$ was first coated with gold dust in a Quorum Q150A ES sputtering machine to enhance their conductibility during SEM analysis. The SEM image for the reinforcement particles is shown in Fig. 3 while Fig. 4 shows the microstructure of the FGM samples containing the different weight-percents of the reinforcement.

The EDX images of the control material and FGMs containing the varied amount of $SiC_p$ reinforcements are shown in Figure 5, while the elemental compositions of all four fabricated materials are presented in Table 4.

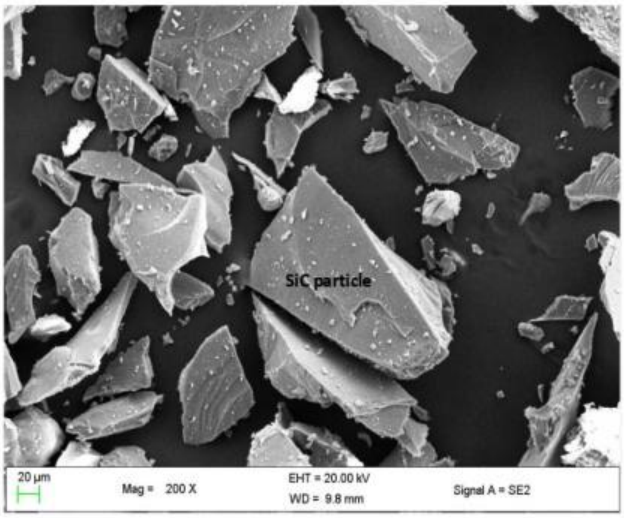


**Figure 3.** SEM images for the reinforcement particles

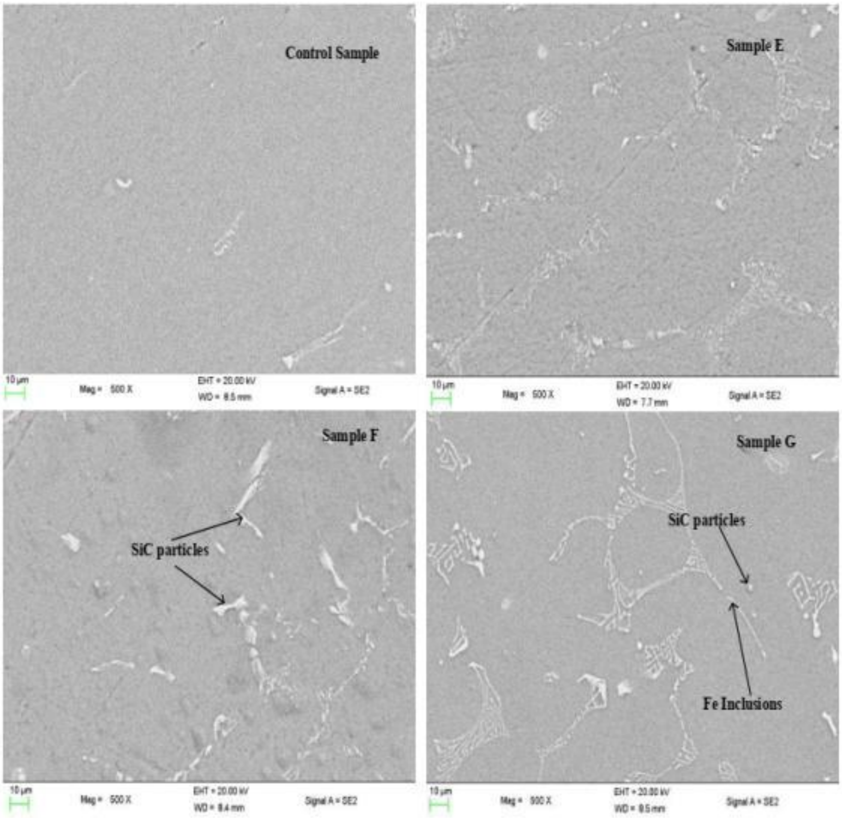


**Figure 4.** SEM micrograph of FGM with different weight-percent of SiC reinforcement

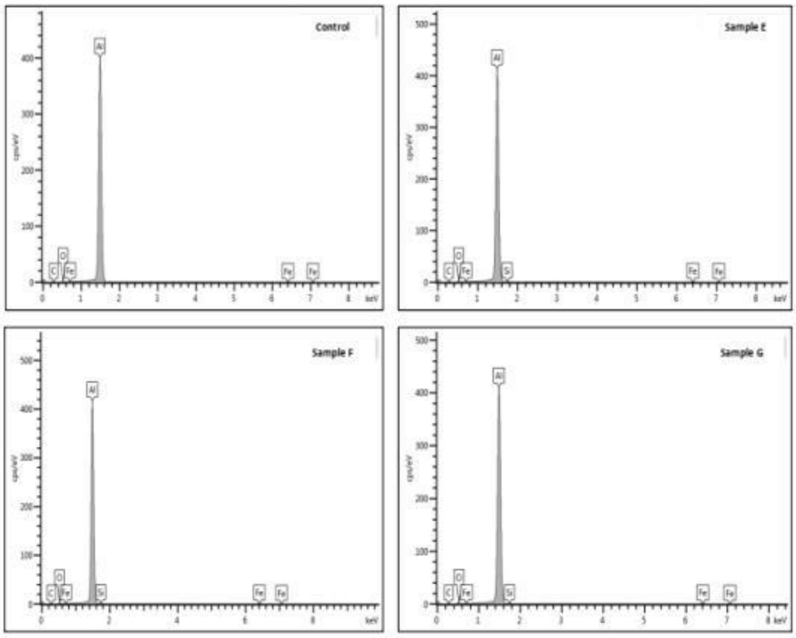


**Figure 5.** EDX images obtained from SEM analysis

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**Table IV.** Elemental composition of FGM samples after EDX analysis.

| | Si (%) | C (%) | O (%) | Fe (%) | Al (%) |
|---|---|---|---|---|---|
| Control Sample | - | 5.83 | 1.52 | 0.36 | Balance |
| Sample E | 0.80 | 5.84 | 1.30 | 0.87 | Balance |
| Sample F | 0.87 | 7.08 | 1.85 | 0.69 | Balance |
| Sample G | 1.29 | 16.85 | 3.24 | 0.48 | Balance |

III.I Hardness Tests

The ability of engineering materials to resist deformation due to external forces is known as the material's hardness. It is a mechanical property that helps in determining the strength of an engineering material as well as its suitability for its intended application. The hardness values obtained along the length of the cast FGMs suggest a steady increase from the middle point of the material to both ends of the material. This is as a result of the migration of the $SiC_p$ from the middle point to the ends of the FGMs under centrifugal action as solidification occurred. The hardness values of the cast materials were observed to be higher at both ends of each sample while the middle portion of the samples had lower hardness values.

The FGM sample E containing 1 wt.% of the $SiC_p$ reinforcements gave a hardness value of 106.3 HV100 and 106.7 HV100 at both ends while the middle portion gave a hardness value of 102.2 HV100. The hardness values obtained from both ends of the FGM samples F and G with reinforcement addition of 3 wt.% and 5 wt.% were 108.9 HV100, 109.1 HV100 and 113 HV100, 112.8 HV100 respectively. The midsection of the cast FGM exhibited reduced hardness properties for all weight-percents of $SiC_p$ addition. The plot of the hardness values is shown in Fig. 6. The hardness values of the individual cast FGM samples was obtained by averaging the hardness values obtained across the length of each material. This is shown in Fig. 7.

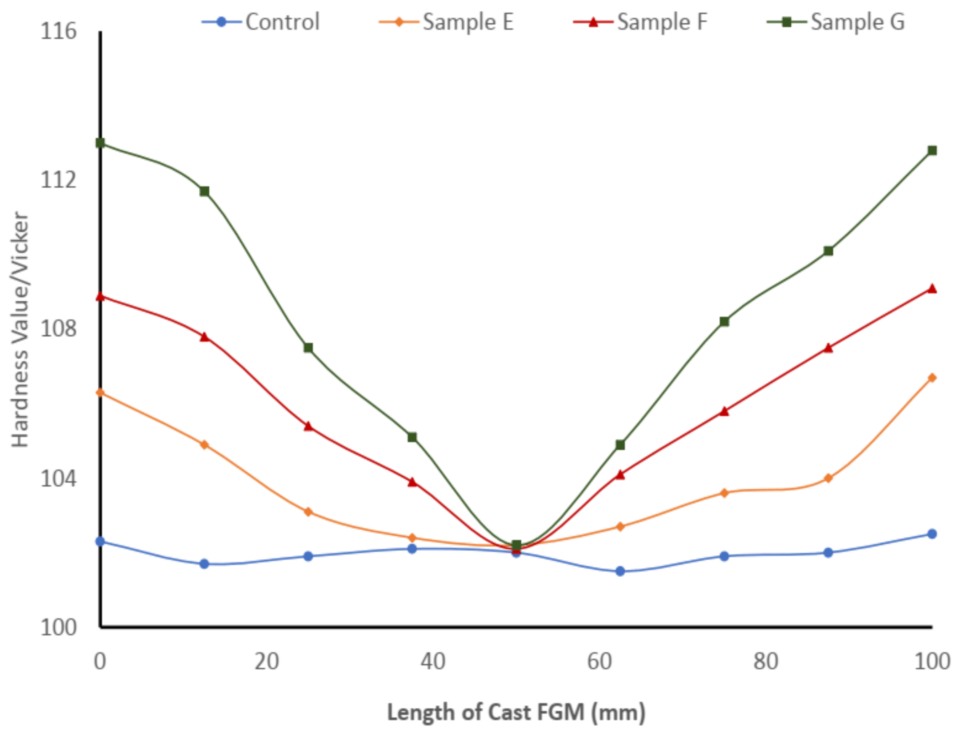


**Figure 6.** Hardness values measured along the length of cast FGM samples

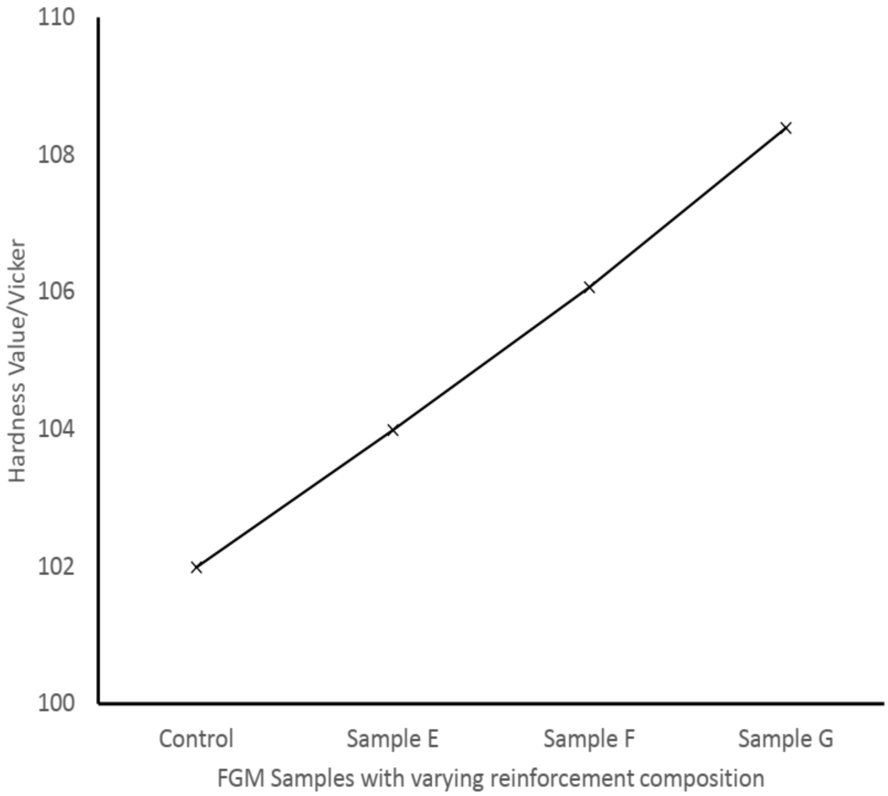


**Figure 7.** Hardness values of cast FGM samples

III.II Guesstimate tensile property of cast FGM samples

The cast samples with 0 wt.%. 1 wt.%, 3 wt.% and 5 wt.% of $SiC_p$ reinforcement produced hardness values of 102 HV100, 104 HV100, 106.1 HV100 and 108.4 HV100 respectively. Corresponding tensile strength guesstimates were obtained from the material hardness with the aid of the engineering database software developed by Wu et al. [28]. The tensile values obtained were compared to those obtained from the ASTM A370 / ASME SA-370 standard manual and a strong correlation was established. The graph in Fig. 8 shows the tensile strength property of the cast materials.

III.III Effect of reinforcement particle size on the properties of cast FGAMMC

Researchers have established that various factors such as percentage-weight, fabrication techniques, operating parameters, and reinforcement particle sizes can influence the mechanical behavior of FGAMMC. Owing to the small sizes of the reinforcement particles compared to those of the base matrix, the reinforcement particles tend to occupy the spaces within the lattice structure of the base material during the solidification process to produce the composite material. This inhibits the mechanical deformation of the material when subjected to external forces which in turn enhances the mechanical properties of the composite [28]. In the previous study conducted by the authors [29], the effect of $SiC_p$ reinforcement with average reinforcement size of 7 μm on the properties of FGAMMC fabricated through CCT was investigated.

The Table 5 shows the summary of the results obtained in the previous work.

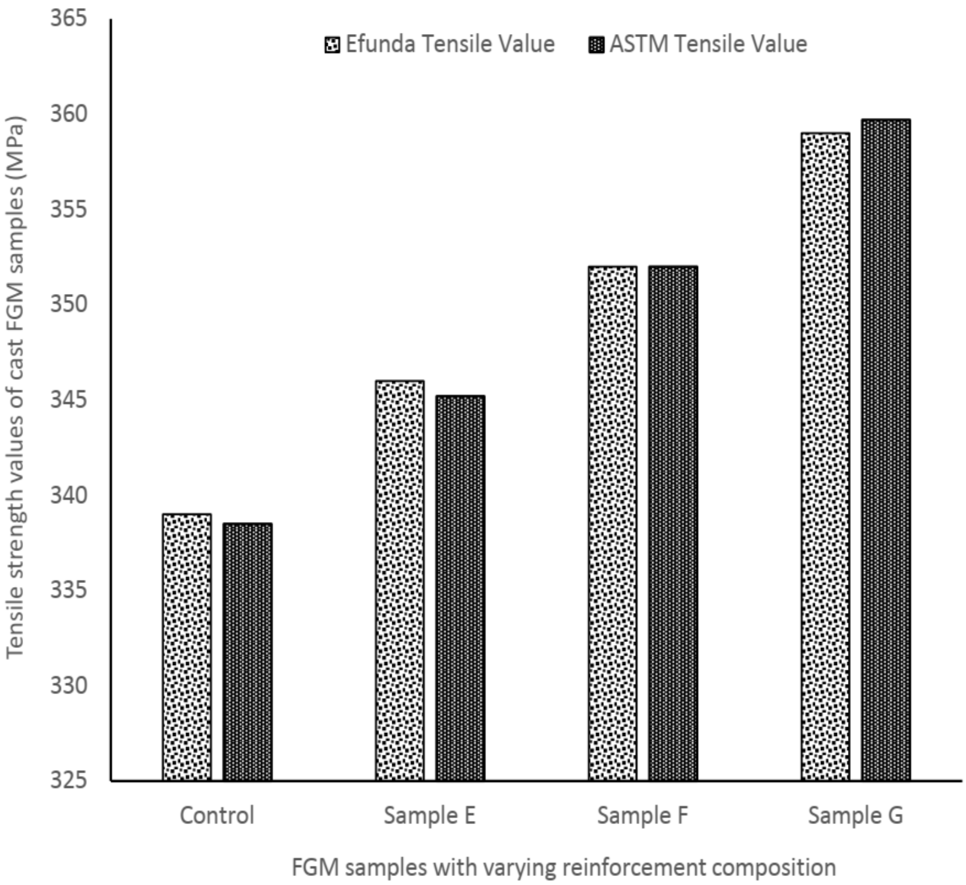


**Figure 8.** Comparative tensile strength property of the cast materials.

**Table V.** Summarized result from previous work by author [27].

| | **SiC particle size 7 µm** | | | |
|---|---|---|---|---|
| | Control Sample | Sample A | Sample B | Sample C |
| Weight-Percent (wt.%) | 0 | 1 | 3 | 5 |
| Hardness Value (Vickers) | 102Hv100 | 106.8Hv100 | 111Hv100 | 112.7Hv100 |
| Tensile Strength (Mpa) | 339 | 355 | 369 | 374.5 |

In the current study, the effects of an increment in the average particle size of $SiC_p$ reinforcement from 7 µm to 15 µm on the mechanical properties of FGMMAC was investigated, while adopting the same parameters as the previous study. On comparing the results from this study to the results obtained from the previous study, it was observed that the hardness and tensile properties of the fabricated material using larger reinforcement particle size (15 µm) decreases under similar fabrication conditions and method. This is graphically analyzed in Fig. 9. This result is in line with the study conducted by El-Galy, et al. [30] where it was reported that the mechanical properties of fabricated FGM decrease with an increase in the particle size of the reinforcement.

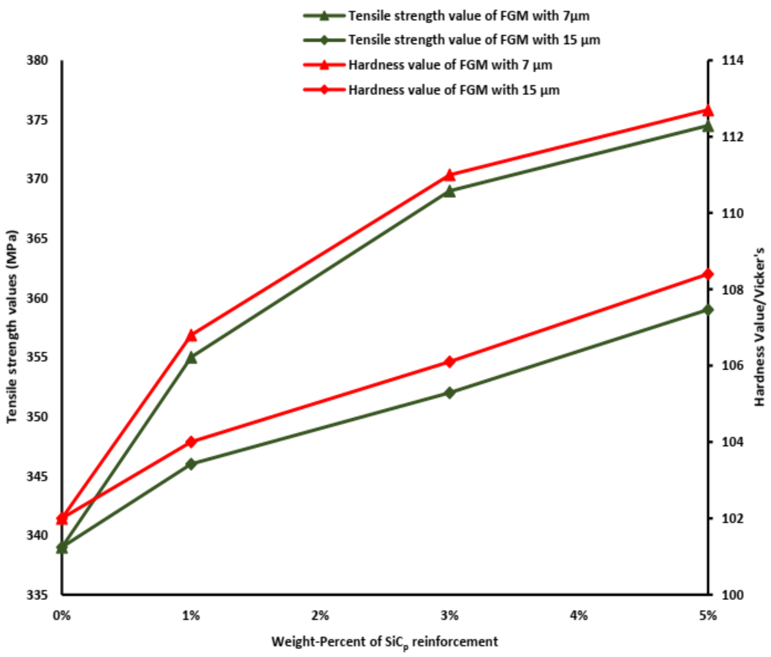


**Figure 9.** Effect of particle size of reinforcements on hardness property of cast FGM

## IV. CONCLUSION

In this study it was determined that:

1. Functionally graded aluminum metal matrix composite (FGAMMC) reinforced with $SiC_p$ of varied weight-percent (0 wt.%, 1 wt.%, 3 wt.%, 5 wt.%) and average particle size of 15 µm was fabricated successfully through CCT.
2. Addition of $SiC_p$ reinforcement improved the hardness and tensile strength properties of fabricated FGAMMC.
3. The movement of reinforcement particles within the melt before solidification is dependent on the size of reinforcement particles as well as the density difference between the particles and the molten aluminum.
4. Increase in the weight-percent of $SiC_p$ within the melt brings about improved mechanical properties of the fabricated FGAMMC.
5. The Al-SiC composite produced with an average reinforcement size of 7 µm exhibited better mechanical properties when compared to Al-SiC composite produced with reinforcement of average particle size of 15 µm using the same fabrication technique and parameters.

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## 3.4 Chapter 3 Article 3: Analyzing the Impact of Reinforcement Addition on the Mechanical Properties of Aluminium A356 Alloy

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# ANALYZING THE IMPACT OF REINFORCEMENT ADDITION ON THE MECHANICAL PROPERTIES OF ALUMINUM A356 ALLOY

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***ABSTRACT***

***The need to have materials which can respond satisfactorily to dynamic changes encountered in service conditions have driven engineering and scientific researchers into fabrication of a unique class of engineering materials known as functionally graded materials (FGM). Consisting of a combination of metal and ceramic reinforcement, FGM exhibit properties which are not achievable with monolithic materials. In this study, the author studied the impact of the variation in size and weight-percent of silicon carbide (SiC) reinforcement particles on the properties of fabricated Al-SiC FGM composites. Two sets containing three FGM samples were fabricated. The SiC configuration by weight-percent and size were (1 wt.%, 3 wt.%, 5 wt.%) 7 µm and (1 wt.%, 3 wt.%, 5 wt.%) 15 µm. A seventh sample containing 0% SiC was used as a control. The experimental results indicate that the introduction of SiC reinforcement into the matrix impacts on the compressive and shear behavior of aluminum A356 alloy. The sample with the combination of the finest granularity (7 µm) and highest percentage-weight (5 wt.%) displayed the highest compressive strength and Young's modulus values of 3.11 GPa and 6.39 GPa respectively, with a shear strength and shear modulus of 14.4 GPa and 9.29 GPa respectively.***

***KEYWORDS: Metal Matrix Composites, Compressive Strength, Young's Modulus, Silicon Carbide & Aluminum A356 Alloy***

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Original Article

## 1. INTRODUCTION

Metal matrix composites (MMCs) are materials with wide range of engineering applications and potentials [1]. During service, MMCs are subjected to varied load capacities, which oftentimes are at elevated temperatures. In automobile manufacture, parts such as the pistons and the shock absorbers are required to retain their structural integrity under compressive forces, hence, the compressive properties of the engineering material adopted for the production of these parts are of great importance. Properties such as yield strength and modulus are also critical engineering properties in relation to automobile applications.

Modern engineering applications have highlighted the need for materials with dynamic property combinations such as, strength, toughness, thermal and wear resistivity, among others. Achieving these property combinations was a huge challenge in times past, more so with monolithic materials. Traditionally, the choice of monolithic material in an engineering application aims to tackle a specific engineering challenge [2]. Herein lies the limitation of these type of materials. This limitation has driven research into the development of advanced engineering materials capable of exhibiting contradictory properties in extreme service conditions without compromise to their structural integrity.

In a bid to manufacture tailor-made materials for specific engineering applications, the concepts of materials alloying and composites manufacture has come to the fore. The applications of alloys and composites date as far back as 2000 BC in the making of various tools and weapons. Alloys are a combination of two or more different materials, usually in liquid phase, to obtain a unique material with properties different from the parent materials after solidification. Composite materials are special engineering materials developed from the combination of two or more materials, usually in different phases. The individual materials that make up an alloy are indistinguishable from each other after solidification, but the material constituents of composites can be distinguished under microscopic examination. Furthermore, regarding composite formation, the position of reinforcing materials within the base matrix of the composite material can be influenced so as to obtain or improve on the desired property(ies) required of the material. As technology advances, the importance of alloys and composite materials for various automobile, spacecraft, military, electronic and medical applications cannot be overemphasized. Research into various types of composite materials such as polymer matrix [3, 4], carbon matrix, ceramics matrix [5] and metal matrix composites [6, 7] have been on the increase in recent years as researchers are constantly seeking ingenious ways to develop materials to meet the ever-dynamic engineering demands of modern times.

Metal matrix composites are engineering materials made up of two or more materials with one of the materials (the matrix) being metal and the other material(s) (the reinforcement) being a ceramic or organic material [8]. The reinforcement materials, introduced to the matrix material to improve on their properties, can be in the form of particulates or a continuous or discontinuous fiber. Particulate reinforcement has often been favored over fiber reinforcement due to the ability to control the resulting composites' properties by varying the granularity and volume ratio of the reinforcement [9, 10]. Aluminum has found use in various engineering applications owing to its properties of formability, good ductility, lightweight as well as its abundance in nature [11]. When reinforced with particles of ceramics such as SiC in adequate proportion and particle size, the mechanical properties of aluminum alloy can be improved upon. Numerous research studies on the effects of reinforcements on the behavior of aluminum metal during service have been conducted.

In a study conducted by Xiaoyu, et al. [12], the effect of melting temperature, mold temperature and rotating speed on the microstructure and the mechanical behavior of fabricated Al-SiC piston was investigated. The gradient distribution of the reinforcing particles was attributed to the centrifugal force which acted on the particles in the aluminum matrix during the casting process, thereby forcing a larger concentration of the particles towards the head of the piston. The good wear and hardness properties subsequently observed at the piston head was attributed to the presence of the SiC reinforcement. In a similar research conducted by Pawar and Utpat [13], a composite material using SiC reinforcement in aluminum matrix was fabricated through centrifugal casting technique. The authors sought to determine the suitability of this type of material composite in the production of power transmission elements such as gears. The hardness and the toughness of the fabricated composite was reported to have increased with an increase in the SiC content of the material. Using modelling and finite element analysis, the suitability of the material as a power transmission material was further established by the authors. The suitability of aluminum composites in the production of electrical and electronic parts due to good coefficient of thermal expansion has been established in literature [8, 14, 15].

Radhika and Raghu [16] conducted a study on the effect of different types of reinforcing particles, $B_4C$, SiC, $Al2O_3$ and $TiB_2$, on the mechanical behavior of Al-12Si-Cu-based composite fabricated through a centrifugal technique. It was reported that the outer zone of the fabricated hollow cylindrical composite exhibited a higher hardness value when compared to the middle and the inner zone of the composite. This was attributed to the presence of a concentrated amount of the reinforcement particles observed at the outer zone and none at the core where the effect of centrifugal force is least. From the four composites fabricated, Al/$TiB_2$ composite was found to exhibit the lowest wear rate due to the high density of the $TiB_2$ reinforcement [16]. Furthermore, a change in the concentration of reinforcement in the matrix of fabricated FGM composites have been reported in literature [17, 18].

Functionally graded materials (FGM) are a unique type of engineering materials with compositional and property variances along the material's geometry. The concept of FGM arose from the need to manufacture an engineering material whose behavior can be influenced in a gradient pattern across its length or cross-section in a controlled process, to suit a predetermined application. In other words, the properties of the FGM such as mechanical, thermal, tribological, and electrical are influenced across the material bulk by closely varying the concentration of the reinforcement material within the matrix. The interest in FGMs and their potential applications in industries such as aviation, medical, automobile, and military have driven engineers into in-depth research on the various fabrication and optimal processing techniques in the manufacture of FGMs. Fabrication techniques such as deposition [19, 20], powder metallurgy [21], and casting techniques [22, 23] have been conducted and well documented in literature.

In this study, the author aimed to fabricate a functionally graded Al-$SiC_p$ composites by means of a liquid metallurgy process. The impact of increase in size and weight-percent of SiC particle addition, on the compressive and shear strength behavior of fabricated composite was studied and reported on accordingly. The composite materials were fabricated using centrifugal casting techniques. This technique has been identified in literature as the most suitable casting process due to its cost-effectiveness for mass production, relative ease of operation, and flexibility of process [24, 25].

## 2. MATERIALS AND METHODOLOGY

Commercially pure aluminum ingots and silicon carbide particles were adopted as the base matrix and reinforcement for the cast composites fabricated through centrifugal technique. Varied weight-percent of the SiC particles with average sizes 7 µm and 15 µm were introduced into the matrix to produce Al-SiC composites.

Each composite material was prepared by determining the weight of the aluminum ingots and then charging it into the furnace with the temperature set to 750 °C. With the aid of a mechanical stirrer, the molten aluminum was stirred to create a vortex into which a measured weight-percent (1, 3, and 5) of the SiC particle reinforcement, preheated at 300 °C, was introduced. The stirring continued until the reinforcement particles were homogeneously dispersed in the aluminum matrix. The molten composite was poured into the vertical rotating mold cavity of a centrifugal machine. The distance travelled by individual reinforcement particle along the cross-section of cast samples has been found to be influenced by the density differential between the matrix and the reinforcements, the size and shape of the particles and the centrifugal force exerted on the individual particles [26]. The parameters adopted for the casting process are shown in Table 1.

**Table 1: Casting Parameters**

| | |
|---|---|
| Melting temperature | 750 °C |
| Melting Time | 10 Min |
| Reinforcement preheated temp | 300 °C |
| Rotating speed of mold | 800 rpm |

Six composite samples were fabricated from different combinations of the SiC reinforcement weight-percent and sizes. The seventh sample had 0 % reinforcement addition and served as a control sample. The samples were prepared for the compression test in accordance to ASTM E9 standard. The SiC specification contained in the individual cast samples are shown in Table 2.

**Table 2: Matrix-Reinforcement Specification of Fabricated Composites**

| Sample Label | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| $SiC_p$ wt.% | 1 | 3 | 5 | - | 1 | 3 | 5 |
| Average $SiC_p$ size (µm) | 7 | 7 | 7 | - | 15 | 15 | 15 |

Energy dispersive X-ray analysis (EDX) performed on the cast FGM composites shows the elemental constituents of each sample as illustrated in Table 3. The SiC reinforcement particle was determined to contain 54.36% Si, 42.63% C, and 3.01% O.

**Table 3: Elemental Constituent of the Fabricated Al-SiC Composites**

| Sample | Si (%) | C (%) | O (%) | Fe (%) | Al (%) |
|---|---|---|---|---|---|
| **A** | 0.85 | 5.81 | 1.28 | 0.95 | Remainder |
| **B** | 0.93 | 7.04 | 1.80 | 0.81 | Remainder |
| **C** | 1.37 | 16.98 | 3.12 | 0.62 | Remainder |
| **D** | - | 5.83 | 1.52 | 0.36 | Remainder |
| **E** | 0.80 | 5.84 | 1.30 | 0.87 | Remainder |
| **F** | 0.87 | 7.08 | 1.85 | 0.69 | Remainder |
| **G** | 1.29 | 16.85 | 3.24 | 0.48 | Remainder |

The SiC particles as observed under SEM imaging in figure 1 showed that the individual particles of the SiC reinforcements were irregularly shaped with jagged edges possibly as a result of crushing of the particles to desired sizes. The spacing between the silicon and carbon particles in a SiC atom is reported in literature to be about 1.46 Å.

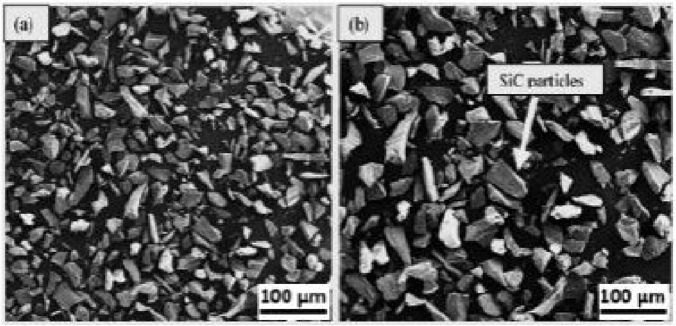


**Figure 1: SEM Morphology of (a) 7 µm and (b) 15 µm SiC Reinforcement Particles.**

SiC has been reported to possess properties such as high thermal stability, high wear resistance, hardness, and high melting temperature, and low manufacturing cost [27, 28], making it one of the most suitable reinforcement materials in the fabrication of metal matrix composites. Good wettability and relatively non-chemical reaction with reinforced matrix at elevated temperatures also lends support to the use of SiC as reinforcement [29, 30].

## 3. RESULTS AND DISCUSSION

Compression tests were carried out on the fabricated FGM samples to determine the impact of the size variance and weight-percent of the reinforcement particles on the cast samples. Readings obtained from the MTS universal testing machine for each sample were documented and compared against each other.

### 3.1 Compressive Strength of Fabricated FGM Composites

A compressive strength test was carried out on the prepared FGM samples at a constant load rate of 0.3 kN/s, using the MTS universal testing machine. The maximum loads at which each sample failed under compressive force were recorded and used in calculating their individual compressive strength values. Figure 2 shows the test samples after the compression test.

**Figure 2: Composite Samples after Compression Test.**

It was observed that the inclusion of SiC particles into the aluminum matrix improved the compressive strength of the composite. When the compressive strengths of samples which containing reinforcements of the same particle sizes were calculated, it was observed that the value of the compressive strength of the material increased as the weight-percent of the particle in the material increased. Samples A, B, and C, which contained 1 wt.%, 3 wt.%, and 5 wt.% of 7 µm of SiC reinforcement respectively, displayed a compressive strength of 2038 MPa, 2316 MPa, and 3107 MPa respectively. A similar pattern was observed for samples E, F, and G with 1 wt.%, 3 wt.%, and 5 wt.% of 15 µm of SiC reinforcement respectively having compressive strength of 1859 MPa, 2126 MPa, and 2271 MPa respectively. The compressive strength value of 1176 MPa was measured for sample D which had no SiC reinforcement. In summary, the results show that the sample with the combination of the smallest size, and the most percentage-weight of SiC particle reinforcement exhibited the highest compressive strength property as shown in figure 3. This result agrees with findings in literature [9, 31, 32] on the effects of particulate reinforcement addition on the compressive strength properties of aluminum matrix.

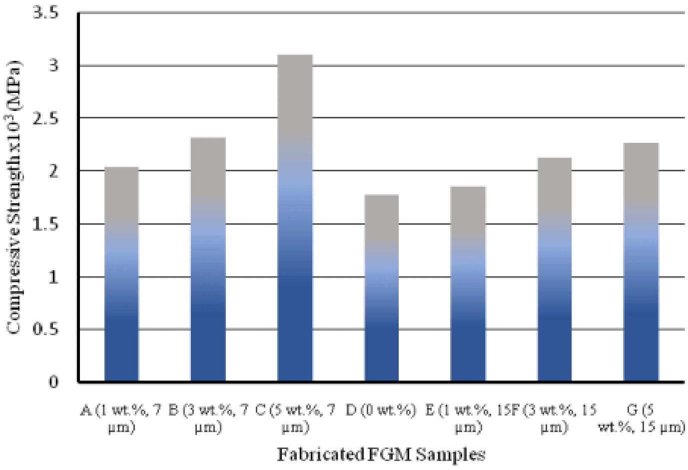


**Figure 3: Compressive Strength of Fabricated FGM Samples.**

### 3.2 Young's Modulus of Fabricated FGM Composites

The young's modulus of each fabricated composite sample, was calculated from the reading obtained from the UTM.

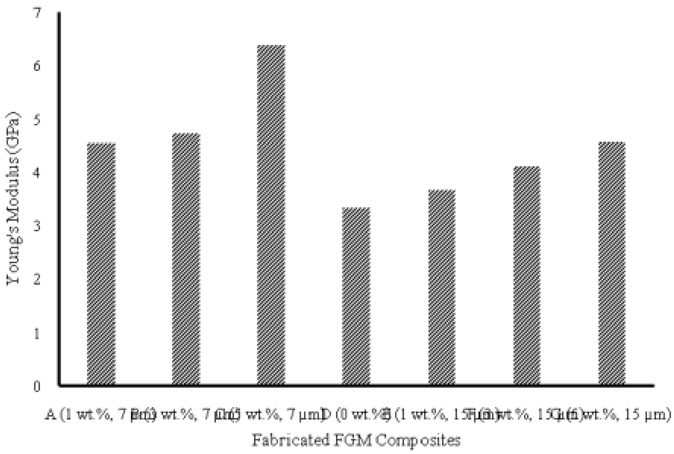


**Figure 4: Young's Modulus of Fabricated Composite.**

The Young's moduli of the fabricated composites were observed to follow a similar trend regarding the materials' compressive strength with the samples A, B, and C possessing Young's moduli of 4.54 GPa, 4.75 GPa, and 6.39 GPa respectively, while samples E, F, and G had Young's moduli values of 3.68 GPa, 4.12 GPa, and 4.57 GPa respectively. Sample D with no SiC reinforcement had a modulus value of 3.34 GPa. The composite sample which contained the combination of the finest particle size of 7 µm and the most weight-percent of 5 wt.% (sample C) had the highest young's modulus value of 6.39 GPa as shown in Figure 4.

### 3.3 Shear Strength and Modulus of Fabricated FGM Composites

The shear strength analysis was carried out using the MTS universal testing machine by applying a shear force perpendicular to the surface of the fabricated composites. The maximum force required to cause each composite to fail was recorded and was used to determine their shear strength values. Samples A, B, and C reinforced with SiC particle size of 7 µm and 1 %, 3 %, and 5 % by weight gave shear strength values of 8.79 GPa, 10.8 GPa, and 14.4 GPa respectively, while samples E, F, and G reinforced with SiC particle size of 15 µm and 1 wt.%, 3 wt.%, and 5 wt.% by weight displayed shear strength values of 6.97 GPa, 7.18 GPa, and 8.18 GPa respectively. Sample D having no reinforcement addition displayed the least shear strength value of 4.93 GPa. Figure 5 shows the composite samples after shearing while Figure 6 is a plot showing the shear strength and shear modulus all the fabricated FGM samples.

**Figure 5: Composite Samples after Shearing**

The cast composites' shear moduli shown as a line graph in figure 5 was obtained from data generated from the MTS universal testing machine during shear test. The shear moduli for samples A, B and C were 7.55 GPa, 8.47 GPa, and 9.29 GPa respectively, while samples E, F, and G had values of 7.15 GPa, 7.17 GPa, and 7.48 GPa respectively. Sample D with no reinforcement addition gave a modulus of 4.22 GPa.

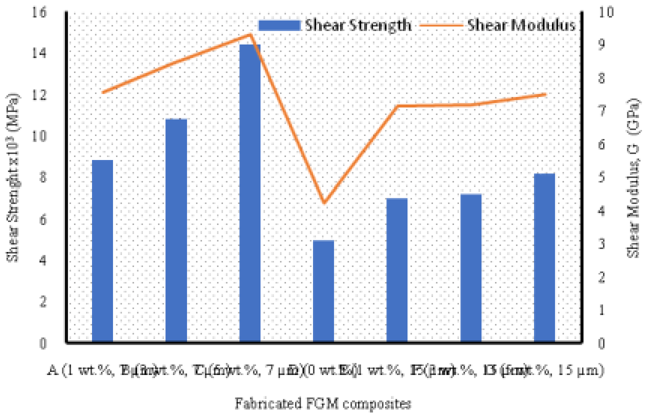


**Figure 6: Shear Strength and Shear Modulus all the Fabricated FGM Samples.**

The overall mechanical properties of sample C were observed to be higher than the other cast composites having shear strength and shear modulus values of 14.4 GPa and 9.29 GPa. The improved shear values can be attributed to the fine particle size and the high weight-percent of the reinforcement in the sample's matrix. This result agrees with results obtained from the work done by Ye, et al. [33] and Rahman and Al Rashed [34].

## 4. CONCLUSIONS

In this paper, functionally graded aluminum metal matrix composites were manufactured through a centrifugal casting technique using predetermined process parameters. The effect of SiC (particle size and weight percent) addition on the compressive and shear properties of the resulting Al-SiC composites were studied and the following conclusions were reached:

- Gradient distribution of SiC particles was achieved through the centrifugal force acting on the reinforcement particles during centrifugal casting process.
- The addition of SiC particle reinforcement to the matrix of aluminum alloy significantly improved the compressive and shear strength of the resulting FGM composites.
- Increasing the reinforcement particle ratio in the cast matrix produced a corresponding improvement in the strength of the cast FGM composites.
- The size of particle reinforcement influenced the properties of the cast composites. The composite samples reinforced with particle size of 7 µm of SiC displayed higher compressive and shear strength values when compared to corresponding composite samples reinforced with particle size of 15 µm of SiC.

## CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

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## 3.5 Chapter Summary

The mechanical properties of any engineering material determine the behavior of such materials when acted upon by external forces and stresses during service conditions. The properties desired of any materials is directly related to the expected area of application of that material. Properties of hardness, strength, toughness are usually required of materials that are constantly subjected to with external contact forces such as compression, tension or impact forces. The use of reinforcement particles to enhance the mechanical properties of engineering materials has become common practice in engineering research and industry alike. However, determining the right proportion and granularities of the reinforcement particles which will yield the optimal performance required of the composite materials during service is paramount.

The articles presented in this chapter have established the required reinforcement configuration of size and granularity to be adopted to obtain improved hardness, compressional strength, shear strength, and tensile strength for the cast Al-SiC composites. The hardness test was carried out using the ASTM 370 and standard while the compressive and shear strength test were carried out using the ASTM D 695 and ASTM D732-02 standard respectively. ASTM G133 – 05 standard and ASTM G99-95a standards test were adopted in carrying out the tribological analyses for the fabricated specimen. Within the premise of the varied parameters, sample C with 5 wt.% and 7 μm of reinforcement exhibited the most improved mechanical properties of all the cast composites.

# CHAPTER 4: TRIBOLOGICAL CHARACTERISTICS OF FABRICATED FGM SAMPLES

## 4.1 Chapter Synopsis

Wear resistance is an essential material property required for any application with moving parts. This property is important in material selection for automotive engine parts such as pistons, gears and crankshafts which are susceptible to high frictional force due to surfaces rubbing against each other. Hence, in the selection of suitable materials in the production of these parts, properties such as wear and frictional coefficient of the adopted material must be determined for the operating conditions under which they will be deployed.

The article presented in this chapter reports on the investigation of the effect of SiC reinforcement addition on the frictional coefficient of the fabricated composites. The high heat generated on the composites' surfaces in contact with the counterface ball during the test suggests a good dispersion of the reinforcement in the aluminium matrix. Likewise, the reduced heat generation observed on the surface of sample D is attributed to the absence of reinforcing particle. The published article can be found in the *International Journal of Mechanical and Production Engineering Research and Development (IJMPERD).*

**A. O. Owoputi**, F. L. Inambao, and W. S. Ebhota, "Examining the mechanical and tribological behavior of Al-SiC composite developed by centrifugal casting technique," International Journal of Mechanical and Production Engineering Research and Development (IJMPERD), vol. 11, Issue 2, pp. 119-130, 2021.

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## 4.2 Chapter 4 Article 1: Examining the Mechanical and Tribological Behavior of Al-SiC Composite Developed by Centrifugal Casting Technique

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# EXAMINING THE MECHANICAL AND TRIBOLOGICAL BEHAVIOR OF AL-SIC COMPOSITE DEVELOPED BY CENTRIFUGAL CASTING TECHNIQUE

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***ABSTRACT***

*The increasing interest in functionally graded materials for automobile, military, and aerospace structural applications in recent years is due to its admirable properties such as good resistance to thermal fluctuation, good formability, and good strength. This study investigates the tribological property of aluminum A356 composites reinforced with silicon carbide particles with varied weight-percents and particle sizes fabricated through centrifugal casting technique. Tribological, mechanical, and SEM analyses were carried out on fabricated composite samples, reinforced with $SiC_p$ of 7 μ and 15 μ particle sizes, respectively. The results indicated that the insertion of the reinforcement particles in the aluminum matrix improved the microstructural properties of the fabricated composites and enhanced their tribological properties. Furthermore, this study confirms that the size of the reinforcement particles influences the overall properties of aluminium metal matrix composites.*

***KEYWORDS:*** *Functionally graded materials, silicon carbide, frictional coefficient, tribology, aluminum matrix, centrifugal casting.*

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Original Article

## INTRODUCTION

Aluminum is the most abundant metal in the earth's crust. Its processing and use for industrial and domestic applications have significantly increased over the years. This increased application of aluminum and its alloys is not far removed from the excellent mechanical and tribological properties it possesses [1]. The ease of fabrication and relatively low cost also lend credence to its increased usage. Properties such as lightweight, low density, and toughness have also made alloys of aluminum the preferred material of choice in the automotive and aerospace industries [2]. However, in its pure state, aluminum is of little industrial use. Hence, the aluminum matrix composite concept introduces composites materials in controlled quantity into the aluminum matrix to improve its engineering properties such as abrasion resistance while leveraging on its excellent properties such as ductility and toughness [3, 4].

There have been various studies and research to develop a series of AMCs using different reinforcing materials such as $TiB_2$, SiC, $Al_2O_3$, Mg, Cu, CNT, ZnO, graphite, fly ash, and other elements. These reinforcing materials are adopted and used in varying weight-percent to produce a tailor-made material property suitable for specific applications [5, 6]. Furthermore, various manufacturing processes and techniques have been researched to fabricate the best materials for definite applications. The author has discussed these processes in a previous publication [7, 8]. AMCs have been found to possess a high strength to weight ratio and excellent tribological property, which makes them particularly suitable for structural, aerospace, and automobile application [9].

Functionally graded materials (FGMs) are materials with a gradient or varied concentration of reinforcement particles dispersed along the base material's matrix from one axis to the other. This advanced and novel material was developed to meet the ever-dynamic functional demands required in engineering applications such as low abrasion resistance, good machinability, thermal resistance, and the ability to withstand extreme and opposing conditions during service. FGM was birthed from a challenge to solve the thermal challenge faced by engineers from Japan when building the frame of a rocket in the mid-1980s. Since then, various FGM types have developed through several manufacturing techniques for automobile, military, aerospace, and structural applications.

The use of FGMs in the fabrication of automobile parts has been a focus for research in recent years, with different researchers exploring the potentials of various types of metal matrix composites (MMC) in solving specific automobile challenges. Polajnar, et al. [10] investigated the use of functionally graded ductile iron (FGDI), which contains Cr and Ni as reinforcing elements for brake pad application. Polajnar, et al. reported that improved wear property and a stable frictional coefficient were obtained on the FGDI due to the presence of the functionally graded zone and the formation of a thin oxidized layer on the pad, which aids in self-lubrication of the wear surface. Other researchers have also researched the use of Al-based MMC in the fabrication of FGMs [11-14]. Due to their high strength to weight ratio, low cost, and high wear resistance, aluminum matrix composites are widely manufactured and used in structural applications along with the aerospace and automobile industry. Also, a simple and cost-effective method for manufacturing the composites is essential for expanding their application. Reinforcements like particulate alumina, silicon carbide, graphite, fly ash, etc., can easily be incorporated into the melt using a simple yet innovative casting method.

Research into the various techniques and the development of novel ones in fabricating different metal-based FGMs have also garnered keen interest among researchers. The prospect of components manufactured through CCT, as opposed to the conventional gravity casting for structural application, was demonstrated by Chirita, et al. [15]. They submitted that the FGM produced through centrifugal process possessed improved mechanical properties such as strength and toughness compared to those produced via gravity casting. Consequently, various researchers have adopted unique techniques to fabricate functionally graded metal-matrix composites tailor-made for specific engineering applications. Pawar and Utpat [16] developed FGMs for spur gear application using aluminum metal as the base matrix and silicon carbide particulate as the reinforcements while adopting a stir casting technique. The percentage weight addition of reinforcements utilized in producing the FGMs was varied from 2.5% to 10%, and the variation's effect was examined. They submitted that properties of hardness and toughness of the FGMs were enhanced with increment in SiC reinforcement within the matrix.

In the quest to produce an ideal FGM suitable for any given application, researchers have studied the influence of various process parameters on specific mechanical behaviors desired of the FGM to be fabricated. A prime example of a mechanical property is the material's wear behavior.

The importance of the wear properties of engineering material used in automobile applications cannot be overstretched as moving parts in contact with each other are required to possess this property to mitigate uncontrolled material loss. The desire to improve on wear property of Al-based FGMs in automobile applications has necessitated the introduction of particle reinforcement such as silicon carbide into aluminum matrix to enhance this property. The adoption of silicon carbide as a choice reinforcing element for aluminum composites by various researchers stems from its relatively low cost, accessibility, and desirable abrasive properties. Silicon carbide particle exhibits a denser property compared to aluminum. When introduced into the aluminum matrix, properties such as abrasive strength and hardness of the resulting composite material are significantly improved [17]. Other influences of SiC addition to the aluminum matrix in varying amounts and under various fabrication techniques have been well researched and documented [18-21].

In research carried out by Pradhan, et al. [19], it was reported that the wear resistance of the aluminum metal matrix composite fabricated using the stir casting technique was greatly influenced by the addition of SiC reinforcements with controlled design parameter. Three sets of MMCs were fabricated and reinforced with 5 wt.%, 7.5 wt.%, and 10 wt.% of SiC particles. The pouring temperature for the cast was kept at 720 °C. Pradhan, et al. [19] reported a decrease in the frictional coefficient of reinforced MMC when compared to pure aluminum. Furthermore, a steady decrease in the frictional coefficients of the fabricated composites was observed as the weight-percent on the reinforcement increased.

Similarly, in the study conducted by Ozben, et al. [22], it was reported that the addition is $SiC_p$ as reinforcement to the Al matrix improved the strength and toughness of the composite material as the weight-percent is increased from 5% to 15%. However, beyond 10 wt.%, the composite's tensile strength gradually reduces as the material's hardness is observed to increase. Consequently, the wear behavior of the composite also reduces beyond 10 wt.% addition.

Other researchers have reported on the effect of other fabrication parameters such as stirring speed [23], pouring temperature, rotational speed, cooling rate, on other mechanical properties of FGMs produced through centrifugal and other casting methods. This paper seeks to highlight the influence of SiC particle size on the mechanical and wear property of the FGAMMC manufactured using the centrifugal casting technique.

## EXPERIMENTAL PROCEDURES

### Materials and Method

Aluminum alloy A356 ingots and particles of SiC were adopted as the base materials and reinforcements respectively in the research. The average particle size of the SiC reinforcements was 7 μm and 15 μm. Aluminum ingots were weighed and charged into the furnace and temperature set to 750 °C to melt the material. Dross formed on the melt was skimmed off while the SiC particle reinforcements are preheated in a muffle furnace to a temperature of 300 °C and introduced to the aluminum melt. Preheating is necessary to mitigate the rejection of the SiC particles from the melt due to a sharp temperature difference. Stirring the solution to enhance even dispersion of the SiC particles in the melt was carried out using a mechanical stirrer. The homogenous composite was poured into the cavity of a vertically rotated centrifugal machine for the casting process to begin. Due to the density difference between aluminum and silicon carbide, the centrifugal effect of the rotating mold was expected to force the SiC particles away from the center of the cast and towards the outer ends. Once solidification was completed, the cast sample was removed from the mold, and the process was repeated to produce other samples. Two sets of the sample were produced using two particle sizes of $SiC_p$ reinforcement - 7 μ and 15 μ. Each set of the cast sample contained 1 wt.%, 3 wt.%, and 5 wt.% addition of $SiC_p$. A control sample with 0 wt.% was also fabricated, bringing the cast samples to 7. The cast samples were labeled from 'A' to 'G' were produced. The casting process parameters are shown in Table 1, while Table 2 shows the chemical compositions of the as-cast Al-356 and the reinforcement particles' chemical composition. As analyzed using the Bruker mass spectrometer, the samples' chemical compositions are presented in Table 3.

**Table 1: Casting Parameters**

| | |
|---|---|
| Melting temperature | 750 °C |
| Melting Time | 10 Mins |
| Reinforcement preheated temp | 300 °C |
| Rotating speed of mold | 800 rpm |

**Table 2: Chemical Composition of As-Cast Aluminium alloy and Rein Forcing SiC**

| | Al | C | O | Fe | Si | Total |
|---|---|---|---|---|---|---|
| As-cast Aluminum Alloy (wt.%) (Sample D) | 92.3 | 5.83 | 1.52 | 0.36 | - | 100 |
| Reinforcement (wt.%) | - | 42.63 | 3.01 | - | 54.36 | 100 |

**Table 3: Chemical Compositions of the Cast Al-SiC Composites**

| Sample | Wt.%, µm | Si (%) | C (%) | O (%) | Fe (%) | Al (%) |
|---|---|---|---|---|---|---|
| A | 1 wt.%, 7 µm | 0.85 | 5.81 | 1.28 | 0.95 | Balance |
| B | 3 wt.%, 7 µm | 0.93 | 7.04 | 1.80 | 0.81 | Balance |
| C | 5 wt.%, 7 µm | 1.37 | 16.98 | 3.12 | 0.62 | Balance |
| D | - | - | 5.83 | 1.52 | 0.36 | Balance |
| E | 1 wt.%, 15 µm | 0.80 | 5.84 | 1.30 | 0.87 | Balance |
| F | 3 wt.%, 15 µm | 0.87 | 7.08 | 1.85 | 0.69 | Balance |
| G | 5 wt.%, 15 µm | 1.29 | 16.85 | 3.24 | 0.48 | Balance |

**Sample Preparation for Microstructural and Mechanical Analysis**

The cast samples produced from the casting process had dimensional configuration of 100 mm length and 20 mm diameter. The samples were sectioned and prepared for metallographic characterization. Each sectioned sample piece was mounted in Bakelite, and their surfaces were prepared using standard metallographic procedures. Grinding was carried out using 320-1200 grits of SiC grinding papers. Polishing was done using an automatic polishing machine with different microns of diamond suspensions and fumed silica on polishing cloths. The polishing process continued until a mirror-like surface was achieved. The samples' surfaces were further etched using Keller's reagent to reveal adequate details during the microstructural examination. The mechanical properties of hardness, tensile strength, and wear behavior of the FGM cast samples were also investigated. The individual sectioned samples were subjected to a hardness test to determine the effect of the different particle sizes with the varying concentrations of the reinforcement particles along each sample's length on their respective hardness properties. The hardness test was carried out using the LECO® M-400-H1 hardness testing machine with a load of 100 g and a dwell time of 15 sec. The hardness value for each sample was determined by taking the average values obtained from five indentations on the sample's surface to be examined. The uniquely developed FGAMMC presented in this paper was subjected to tribological analysis using a pin-on-disc Anton Paar tribometer. A stainless steel counterface with a surface roughness of 15 nm, a load of 5 N, a sliding distance of 400 m, and a motor speed of 100 rev/min was used to determine the tribological property of the samples. The samples' worn surfaces were further examined using SEM to investigate the wear tracks formed and the interaction between the counterface material and samples' surface.

## RESULTS AND DISCUSSION

### Morphology of SiC Starting Powder

The morphology of the SiC reinforcement was examined using SEM. Before this examination, the SiC particles were prepared by coating it with gold dust in a Quorum Q150A ES sputtering machine, which improves their conductivity. Figure 1 highlights the morphology of the reinforcement powders. The particles of Figure 1a and 1b displays a rocky and irregular shape. Several researchers have reported silicon carbide having a tetrahedral layer accompanied by a polyhedral structure. However, as observed in Figure 1a, the fragmented and elongated shape can be attributed to the crushing of the SiC particles into smaller sizes. The atoms of silicon carbide have been reported in literature to have a spacing of 1.46 Å between the particles of silicon and carbon, which are the primary elements present in the powder.

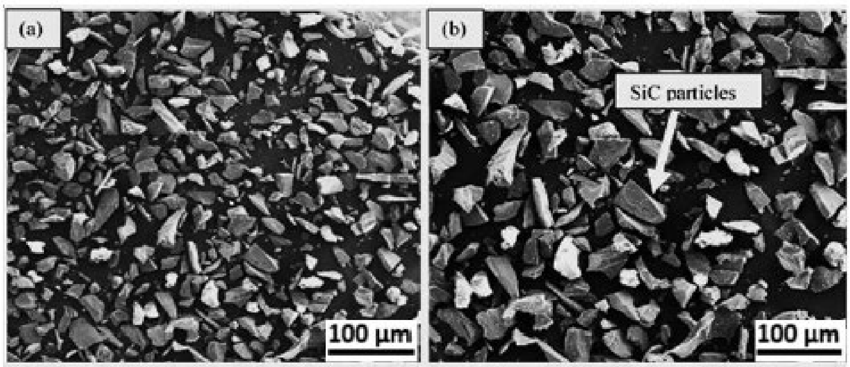


**Figure 1: SEM Morphology of (a) 7 µm and (b) 15 µm SiC Reinforcement Particles**

### Microstructural Analysis of FGM Samples

The SEM morphology of the FGM samples is presented in Figure 2. Figure 2a shows the existence of the eutectic α-Al phase, formed during the solidification of aluminum. The dendrites evident in the aluminum alloy matrix are less visible in the micrographs shown in Figure 2b-2d. The reduction of dendrites can be ascribed to the incorporation of SiC reinforcement particles with varying particle sizes [24]. The homogeneous distribution of the reinforcement phases within the aluminum matrix is observed in Figure 2. Figures 2b and 2c with respective addition of 3 wt.% and 5 wt.% of 7 µ SiC reinforcements show a clear interface and excellent bonding between the reinforcement and matrix phases, which could improve the load-bearing property of the fabricated composite during service. This observation is corroborated by the study carried out by Akinwamide, et al. [25]. The utilization of centrifugal casting is observed to be a successful technique as large sizes of SiC particles (15 µ) are seen to be effectively dispersed within the matrix of aluminum, as presented in Figure 2d. Furthermore, the level of strengthening offered by the reinforcement particles depends on factors, such as the particle size of reinforcement and the type of bond existing between the reinforcement and matrix phases [26].

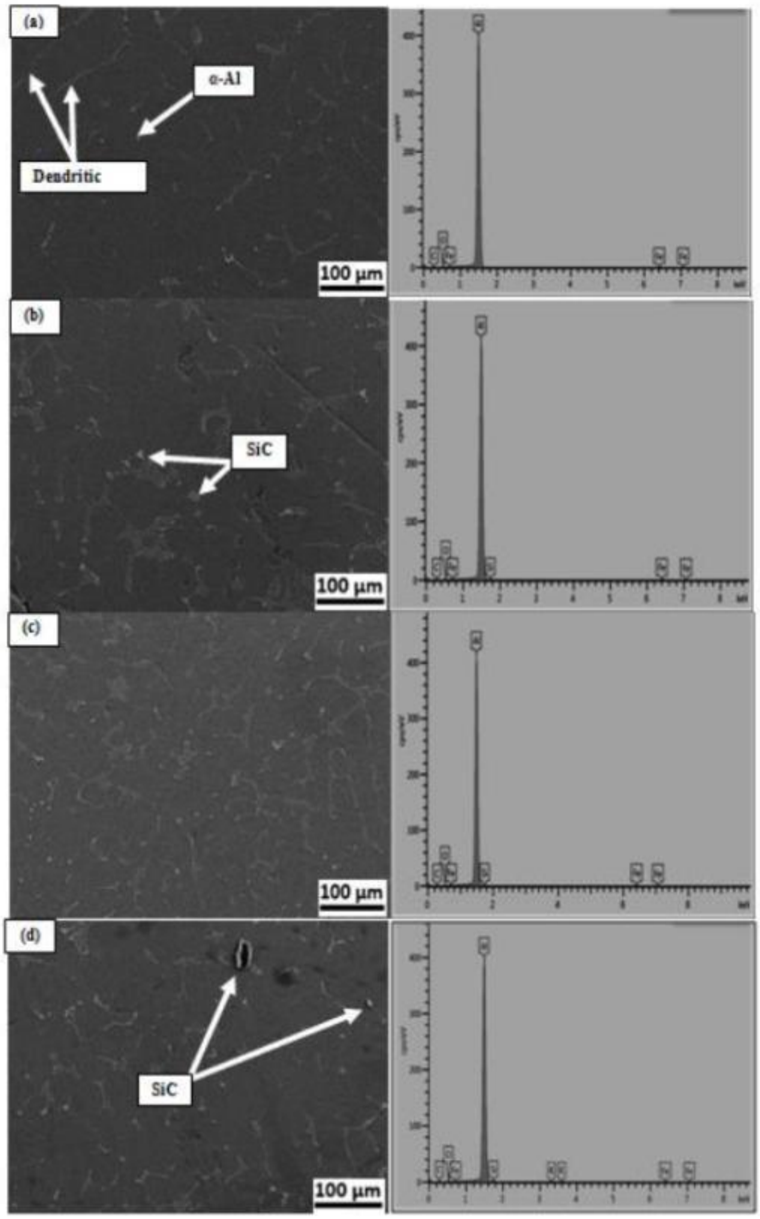


**Figure 2: SEM Micrographs and EDX Analysis of (a) Al alloy (b) Al+3wt.% SiC (7 µ) (c) Al+5wt.% SiC (7 µ) (d) Al +1wt.% SiC (15 µ)**

**Mechanical Properties of Al- 356 FGM**

In a previous study, the authors have been able to establish the effect of particle size and percentage weight concentration of the SiC reinforcements within the matrix of the aluminum A356 alloy on the mechanical properties of hardness tensile strength. Samples A, B, and C were reinforced with SiC particles with an average size of 7 µ at 1 wt.%, 3 wt.%, and 5 wt.% of the aluminum A356 alloys. The cast samples were observed to possess hardness values of 106.8 HV100, 111

HV100, and 112.7 HV100, respectively. Sample D (control), with no reinforcement added to it, exhibited a hardness value of 102 HV100. Furthermore, samples E, F, G, which contained SiC reinforcements of average particle size of 15 µm at 1 wt.%, 3 wt.%, and 5 wt.% of the Al-356 alloys, showed hardness values of 104 HV100, 106.1 HV100, and 108.4 HV100, respectively. Using the cast composite samples' obtained hardness values, corresponding tensile strength values were calculated with the aid of an online engineering software database [27]. Tensile strength values obtained were cross-referenced with values obtained from the ASTM A370 / ASME SA-370 standard manual, and a strong relationship was established [21, 28]. The influence of the difference in SiC particle sizes on the matrix of cast aluminium composite in the mechanical properties (tensile and hardness) was fully established in the previously published articles. The reinforced composites with the larger particle size of SiC reinforcements (15 µ) recorded reduced mechanical properties as it allows easy movement of dislocation. However, the improved mechanical properties exhibited by the cast samples that were reinforced with 7 µ SiC particles are attributed to excellent bonding and the effective load-bearing mechanism characteristic of the smaller size reinforcement particles.

**Frictional Coefficient of as-Cast Aluminum Alloy and Composites**

The plot of the coefficient of friction of samples with 7 µ and 15 µ particle sizes against sliding time is shown in Figure 3 and Figure 4, respectively. From Figure 3, the lowest frictional coefficient is evident in the sample without any reinforcement particle (0 wt.%). The sudden rise in the frictional coefficient observed in the sample after the first 80 s can be ascribed to heat generation between the stainless-steel counterface and the sample [29]. However, a uniform trend with increased fluctuation, observed in the samples with 1 wt.%, 3 wt.%, and 5 wt.% SiC particles can be attributed to a reduction in the abrasive force generated between the two surfaces in contact during the test [30]. The slight increase in the frictional coefficient of the sample reinforced with 3 wt.% SiC reinforcement after the first 300 s is due to the rapid removal of the surface layer resulting from the contact between the sample surface and the counterface ball. This observation is in agreement with a study by Akinwamide et al. [31]. Figure 4 shows the dispersion effect of varying proportions of 15 µ SiC particles on the samples' resistance to wear under a static load. The sturdy fluctuations observed in the sample reinforced with 1 wt.% SiC particles can be a result of contact between the dispersed large-sized SiC particles and the stainless steel counterface ball. This is in contrast with a uniform trend observed in the samples reinforced with higher proportions of SiC particles (3 wt.% and 5 wt.%). The higher frictional coefficient recorded by the samples with reinforcements results from the repeated generation of heat and opposition offered by the reinforcement particles to the sliding of the stainless steel counterface over the sample surface [32]. It should also be noted that SiC particles have been reported to assist with forming passive films on the surface of the reinforced samples, thereby decreasing the rate of wear during metal to metal interaction. [33, 34].

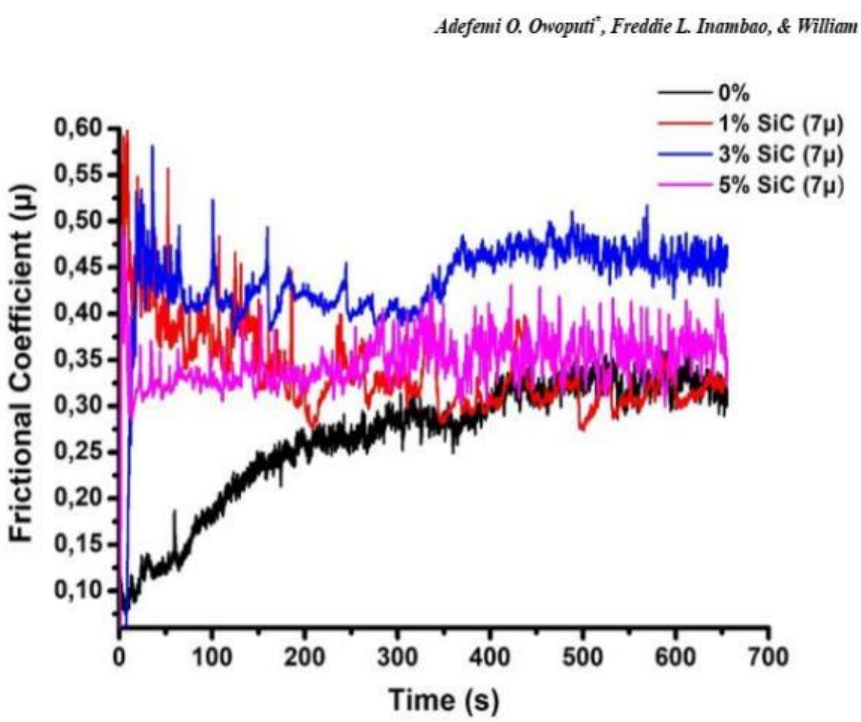


**Figure 3: Frictional Coefficient of as-Cast Aluminium Alloy and composites with 7 μ SiC reinforcements**

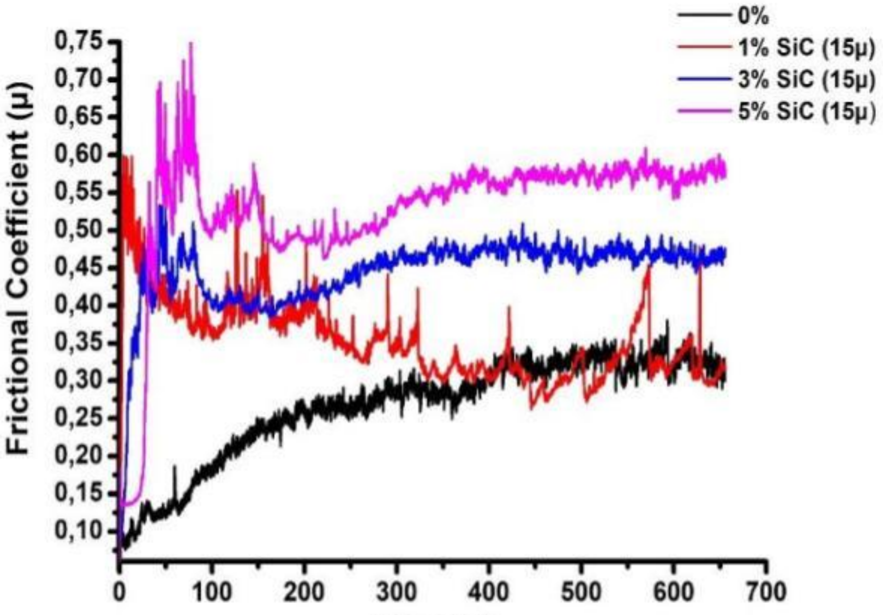


**Figure 4: Frictional Coefficient of as-Cast Aluminum Alloy and Composites with 15 μ SiC**

The SEM of the wear tracks formed from the interaction between the sample surface and the tribometer pin are shown in Figure 5. Figure 5a shows that the plastic deformation of the unreinforced alloy, leading to the sample surface's delamination, is evident. The grooves visible across the wear track indicate abrasive wear [32, 35]. Figure 5b-5c shows a laminar flow that resulted from ductile shearing on the wear tracks. Consequently, the samples' surfaces were damaged due to the SiC particles' resistance to the tribometer pin's sliding movement on the surfaces [36]. The formation of chippings resulting from the continuous ploughing surface of the samples containing larger size SiC particle reinforcements was observed. Similar chip formations have previously been reported in a study by Dwivedi [37]

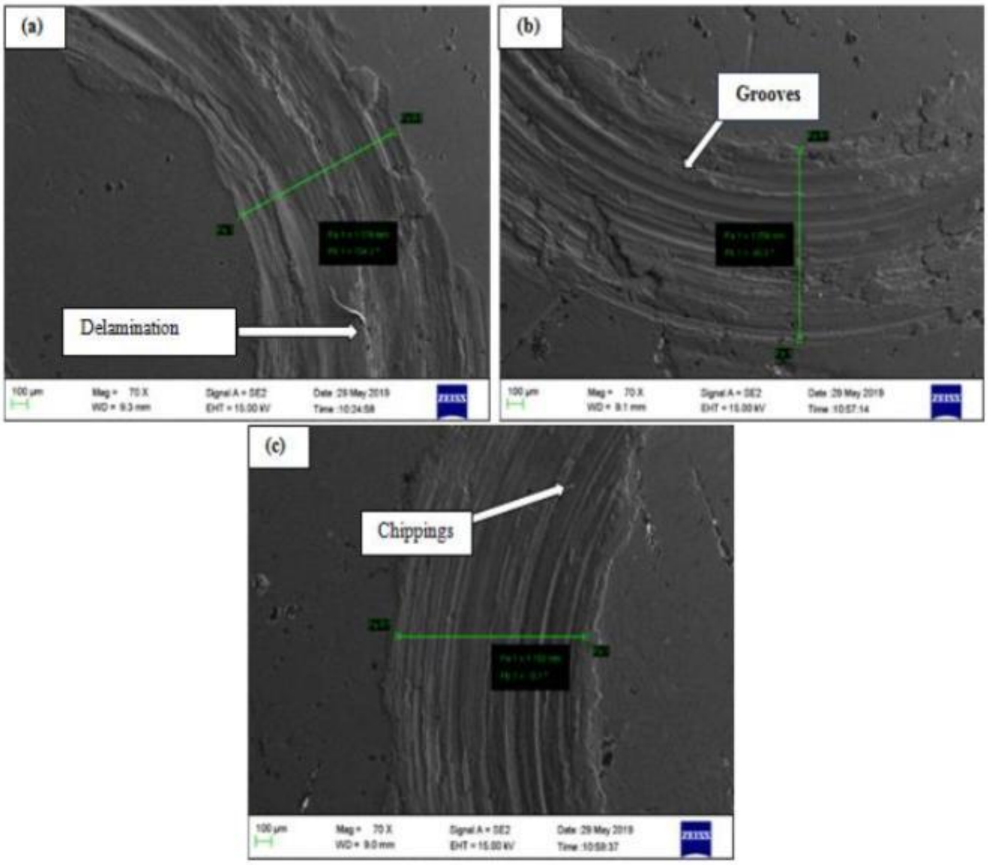


**Figure 5: Wear Tracks of (a) Al alloy (b) Al + 3 wt.% SiC (7 µ) (c) Al + 3 wt.% SiC (15 µ)**

## CONCLUSIONS

The effect of the varying particle size on the microstructural and tribological properties of Al alloy and $SiC_p$ was investigated in this study, and the following conclusions were made.

- An improved bonding interface was observed in the composite reinforced with 7 µ when compared to composites reinforced with 15 µ. This was confirmed by the microstructural and mechanical analysis performed on the samples.
- The incorporation of SiC particles as reinforcement into the aluminum matrix resulted in an increased heat generation on the surface of the samples during the tribological test. This indicates that the particles of SiC offered significant resistance to the sliding force from the stainless steel counterface.

- The improvement in the tribological property of reinforced composites was ascribed to the formation of thin oxide layer on the surface of the composite.
- Resistance to the sliding movement of the tribology pin on the samples' surface was observed to be greater in the composites with 7 µ reinforcement particle size than in composites with 15 µ reinforcement particle sizes

**Conflict of Interest**

The authors declare no conflict of interest associated with this study.

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## 4.3 Wear Analysis of Fabricated Al-SiC Composite

The wear behavior of the fabricated composites was examined with the aid of a room temperature tribometer shown in Figure 4-1. The mass difference of the composite material was obtained using an electronic weight scale by recording the initial and final mass of the material before and after the wear process. The wear rate was then calculated using Equation 1:

$$K_i = \frac{v}{F_n S} \tag{1}$$

Where $K_i$ is wear rate of the material, $v$ is change in mass, $F_n$ is the applied force and $S$ is the sliding distance of the counterface ball.

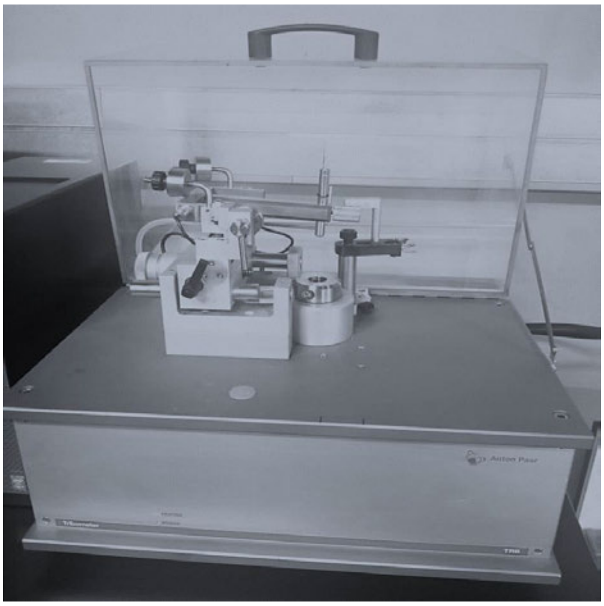

**Figure 4-1: Tribological setup**

The result of the wear analysis for the Al-SiC composites as shown in Figure 4-2, suggests that the sample A having 1 wt.% and 7 µm of the silicon carbide reinforcement addition had the highest wear rate of all the reinforced composite samples with 3.8 x $10^{-5}$ $mm^3/Nm$. The least wear rate of 2.8 x $10^{-5}$ $mm^3/Nm$ among the reinforced samples was recorded for sample C with 5 wt.% and 7 µm of SiC reinforcement while a wear rate of 4.2 x $10^{-5}$ $mm^3/Nm$ was recorded for the unreinforced composite sample D.

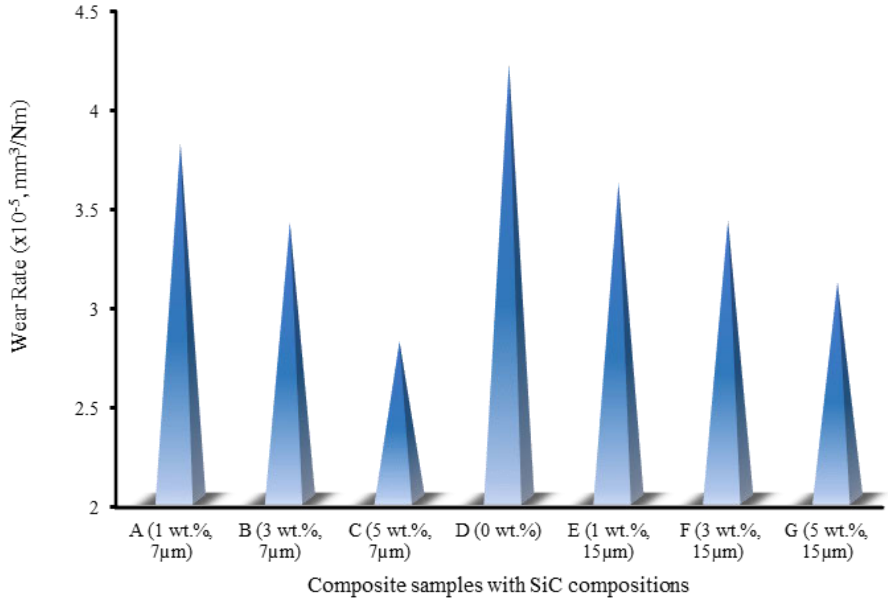


**Figure 4-2: Wear rate of fabricated Al-SiC samples**

Samples C and G both displayed admirable wear properties when compared to the rest of the fabricated composite. This can be attributed to the high percentage weight contained in their matrices with respect to the reinforcement size. However, when compared against each other, sample C displayed a better wear property than sample G due to its smaller particle size and better dispersion within the matrix of the composite. The improved wear rate of sample C is linked to the increase in the frictional coefficient observed between the sample surface and the counterface ball of the tribometer.

## 4.4 Chapter Summary

The continuous rubbing of mechanical moving parts during service leads to excessive heat generation at the point of contact as well as gradual material loss. The above stated effect is undesirable as it leads to decreased efficiency and overall performance of the materials used in the production of the mechanical moving parts. The introduction of SiC into the matrix of the fabricated composites resulted in an improvement in their tribological properties. The result revealed that sample C with 5 wt.% and 7 µm exhibited the least wear rate of $2.8 \times 10^{-5}$ $mm^3/Nm$ due to the weight-percent and size of the SiC reinforcement in the composite's matrix.

# CHAPTER 5: THERMAL ANALYSIS OF FABRICATED FUNCTIONALLY GRADED AL-SIC COMPOSITE

## 5.1 Chapter Synopsis

Thermal stability is the ability of an engineering material to resist detrimental changes to its structure and composition due to thermal fluctuations. The thermal integrity of engineering materials for intended application in high temperature regions of an automobile is a crucial factor to be considered when determining the material type, processing route, processing parameters, reinforcement materials, among other factors, to be adopted for the proposed application. The physical and chemical properties of most engineering materials are influenced by thermal changes and most materials will perform optimally within a certain temperature range. However, the addition of reinforcements into the matrix of engineering materials improves their thermal capacity when subjected to thermal fluctuations during service.

The article presented in this chapter gives a report on the thermal degradation and heat flow rate properties of fabricated Al-SiC composites when subjected to thermal evaluation using the thermogravimetric analyzer SDT Q600. The least thermal degradation with respect to weight was recorded for material sample C which contained 5 wt.% of reinforcement with particle size 7 $\mu$m, while the unreinforced sample recorded the highest percentage weight loss. The published article can be found in the *International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)* with details as follows:

> **A. O. Owoputi**, F. L. Inambao, and W. S. Ebhota, "Thermal evaluation of Al-SiC Metal matrix composite fabricated through liquid metallurgy process," International Journal of Mechanical and Production Engineering Research and Development (IJMPERD), vol. 11, Issue 3, pp. 349-356, 2021.

**Available Online:** http://www.tjprc.org/publishpapers/2-67-1620801002-29IJMPERDJUN202129.pdf

## 5.2 Chapter 5 Article 1: Thermal Evaluation of Al-Sic Metal Matrix Composite Fabricated Through Liquid Metallurgy Process

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# THERMAL EVALUATION OF AL-SIC METAL MATRIX COMPOSITE FABRICATED THROUGH LIQUID METALLURGY PROCESS

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***ABSTRACT***

***The importance of the thermal stability of aluminum alloys and composites used in the manufacturing of automobile engine parts cannot be overemphasized. In this study, the thermal analysis of fabricated aluminum matrix composites manufactured by centrifugal casting technique proposed for high-temperature automobile part applications is investigated. The thermogravimetric curve obtained from this study's thermal analysis showed the samples' weight response to temperature increase. At a temperature region below 655°C, the composites' heat flow rate is lower than at the temperature region beyond 655°C. From the DSC curve generated, the sample reinforced with 5 wt.% and 15 µm of the SiC particle (Sample G), is observed to give the most desired thermal behavior at the temperature region beyond 655°C, having the lowest heat flow rate of 0.004 w/g at a maximum experiment temperature. However, the percentage weight loss of all the fabricated samples obtained from the TGA curve is negligible within the experiment's temperature parameters.***

***KEYWORDS: Metal Matrix Composites, Thermogravimetric Analysis, Differential Scanning Calorimetry, Silicon Carbide & Heat Flow Rate***

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**Original Article**

## 1. INTRODUCTION

The response of engineering materials used in automobile engine applications to temperature changes and increases in heating rate has evoked keen interest from researchers in the recent past. Being one of the most abundant metals in nature and owing to its good properties, aluminum alloys are favored by researchers as the material of choice in the fabrication of automobile engine parts like piston heads, cylinder walls, crankshafts, and engine blocks [1]. The constant movement and rubbing of mechanical parts against each other generate heat, affecting the material's performance during service [2]. Thus, thermal stability and thermal degradation properties are vital in determining composite materials' suitability for high-temperature applications. The choice of aluminum as the preferred engineering metal in automobile applications is justified by the excellent mechanical, physical, and thermal properties it exhibits when reinforced with oxides, carbides, or nitrides of other materials [3, 4]. Silicon carbide (SiC) particles possess an excellent combination of good abrasive and mechanical properties, making them a unique choice of reinforcement in the fabrication of aluminum-based composites.

Researchers have reported in literature how incorporating SiC particles into the matrices of aluminum alloys influences the resultant composites' properties. In a study conducted by Xiaoyu, et al. [5], SiC particles were adopted as the reinforcement of choice in the fabrication of pistons by centrifugal casting technique. Their study concluded that casting parameters such as reinforcement particle concentration, melt temperature, and rotation speed of mold contributed significantly to the cast piston's observed mechanical and thermal properties.

Furthermore, a comparative study of the properties between pistons fabricated by a centrifugal casting technique and those manufactured through gravity casting showed that the former process produces improved hardness and wear resistance properties compared to the latter. A similar outcome was achieved in a study conducted by Arsha, et al. [6] when a functionally graded aluminum piston was fabricated by vertically oriented centrifugal casting technique using Si particles as reinforcement. Characterization of the fabricated piston showed improved properties of hardness and wear resistance at the piston head, where a high concentration of the reinforcing materials is. It is notable that, in addition to the presence of reinforcement in the matrix of composite material, the particle size of the reinforcement, and the weight ratio of the reinforcement within the matrix also play a significant role in the overall properties of the fabricated material [7-11].

The response of engineering materials to temperature changes depends on heat capacity, the thermal stability of the composite's elemental composition, and density. Thermogravimetric analysis (TGA) is a technique that accounts for the change in mass of materials and the heat flow through them as the materials' temperature rises. For an engineering material to perform optimally in predetermined thermal conditions, the material's stability in this boundary condition must be guaranteed. A hybrid aluminum metal matrix composite was analyzed using thermogravimetric analysis by Sangeetha, et al. [12]. They adopted a heating rate of 5 °C/min and a maximum temperature of 700 °C and reported a decrease in the composite's weight as the temperature increases. The DSC analysis conducted at 10 °C/min and a maximum temperature of 300 °C revealed an increased heat flow through the material at a lower temperature. A further increase in temperature to 300 °C brought about a gradual decrease in the heat flow recorded. In another study, thermal decomposition of aluminum precursor fibers was observed by Gao, et al. [13] when it was subjected to a heating rate of 5 °C to a maximum temperature of 700 °C in a thermal analyzer, resulting in a weight loss of 65% of the fiber.

Aluminum composites have been the material of preference by engineering researchers and manufacturers alike in the production of components of automobile engines such as flywheels, pistons, and cylinder walls, owing to properties such as ease of fabrication, lightweight, corrosion resistance, toughness, and the high strength-to-weight ratio [14, 15]. Automobile engine components such as pistons are constantly being subjected to thermal change and abrasive and compressional forces during service, thereby making the thermal, chemical, and mechanical stability of materials used in fabricating such components of great importance.

This paper presents a report on the response of aluminum metal matrix composite fabricated through centrifugal casting to periodic increment in temperature to a maximum of 1000 °C.

## 2. MATERIALS AND METHOD

In fabricating the functionally graded composite, aluminum ingots with trace amounts of alloying elements were impregnated with silicon carbide particles. The fabrication technique of choice was the centrifugal casting technique due to relative ease of processing and comparative cost advantage for mass part production [16]. The as-received aluminum alloy was charged into the furnace, and melting was achieved at a temperature of 750 °C. Mechanical stirring of the melt was done to create a vortex where SiC particles, preheated in an induction furnace at 300 °C, were introduced. Stirring was continued after impregnating the aluminum matrix to ensure even dispersion of the particles in the melt. The liquid composite was poured into the cavity of the rotating mold of a centrifugal machine. The cast sample was allowed to solidify in the rotating mold. The spatial positions of the individual particles within the matrix of a sample were determined by the amount of the centrifugal force acting on it and the drag they encounter due to the melt's viscosity and density. The impact of the centrifugal force exerted on the reinforcement particles is governed by Stokes' law expressed in Eq. (1).

$$v = \frac{d^2(p_p - p_l)g}{18\mu} \quad (1)$$

Where:

$v$ Particle velocity,

$d$ Particle diameter,

$\mu$ Viscosity of liquid metal,

$\rho_l$ Density of liquid metal, and

$\rho_p$ Density of the particle.

Using variations of SiC weight percent and particle sizes, six composite test samples were fabricated and prepared for analysis. A control sample (sample D) with no reinforcement particle was also fabricated. Samples A, B, and C contained 1 wt.%, 3 wt.%, and 5 wt.% of reinforcement with an average particle size of 7 $\mu$m while samples E, F, and G had 1 wt.%, 3 wt.%, and 5 wt.% of reinforcement with an average particle size of 15 $\mu$m respectively. Sample D is not reinforced with SiC particles. The thermogravimetric analyzer SDT Q600 shown in Figure 1 was used to investigate the fabricated composite samples' behavior under varied temperature and heat change.

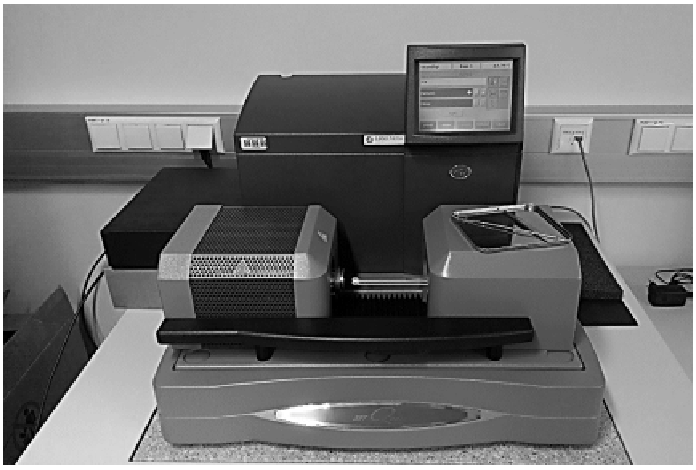

**Figure 1: Thermogravimetric Analyzer SDT Q600.**

The elemental composition of fabricated samples and reinforcement particles obtained from EDS analysis is presented in Tables 1 and 2 respectively, while the parameters adopted for the samples' TGA analysis are shown in Table 3.

**Table 1: Elemental Compositions of the Fabricated Samples**

| | Si (%) | C (%) | O (%) | Fe (%) | Al (%) |
|---|---|---|---|---|---|
| **Sample A** | 0.85 | 5.81 | 1.28 | 0.95 | Remaining |
| **Sample B** | 0.93 | 7.04 | 1.80 | 0.81 | Remaining |
| **Sample C** | 1.37 | 16.98 | 3.12 | 0.62 | Remaining |
| **Sample D** | - | 5.83 | 1.52 | 0.36 | Remaining |
| **Sample E** | 0.80 | 5.84 | 1.30 | 0.87 | Remaining |
| **Sample F** | 0.87 | 7.08 | 1.85 | 0.69 | Remaining |
| **Sample G** | 1.29 | 16.85 | 3.24 | 0.48 | Remaining |

Table 2: Elemental Composition of the SiC Particle Reinforcement

| | Al | C | O | Fe | Si | Total |
|---|---|---|---|---|---|---|
| Reinforcement (wt.%) | - | 42.63 | 3.01 | - | 54.36 | 100 |

Table 3: TGA Test Parameters

| Gas used | Flow Rate | Temperature Range | Heating Rate |
|---|---|---|---|
| Argon | 100 ml/min | 25 °C to 1000 °C | 10 °C/min |

## 3. RESULTS AND DISCUSSION

In the authors' prior work, the effect of the addition of varied particulate size and weight percent of $SiC_p$ reinforcement on mechanical and wear properties of the Al-$SiC_p$ composites was discussed extensively [8, 17, 18]. This study seeks to highlight the response of the fabricated composites' thermal changes when subjected to elevated temperature. Although most engineering and automobile applications aluminum composites are intended for temperature regions below 400 °C[19], this study seeks to determine the behavior of the fabricated composites at a much higher temperature region.

### 3.1 Thermogravimetric Analysis of Fabricated FGM Samples

The thermogravimetric analysis of the cast samples shown in Figure 2 represents the materials' weight response to temperature increase from 25 °C to 1000 °C. It is evident that the fabricated aluminum composites exhibited negligible multistage weight loss over the given temperature range. This is attributed to the relative thermal stability of aluminum alloy within the temperature region in which the test was carried out. However, the extent of weight loss is different for each sample, as shown in Figure 3. At a temperature region of about 655 °C (where aluminum starts to melt), it is observed that sample C, which contained 5 wt.% of reinforcement with particle size 7 $\mu$mhad the least amount of weight loss of 0.37 % compared to the other samples. Samples A (with SiC reinforcement of 1 wt.%, 7 $\mu$m) and sample D (with SiC reinforcement of 0 %) had the most weight loss of 1 % recorded by the materials.

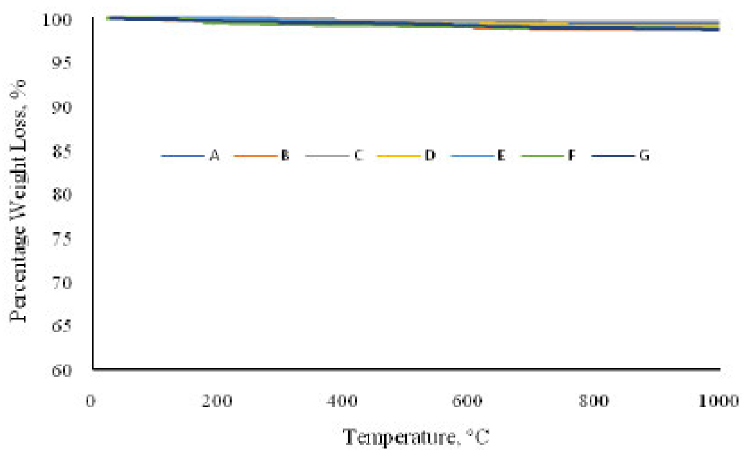


Figure 2: TGA Graph of the Fabricated Al-SiC Composites.

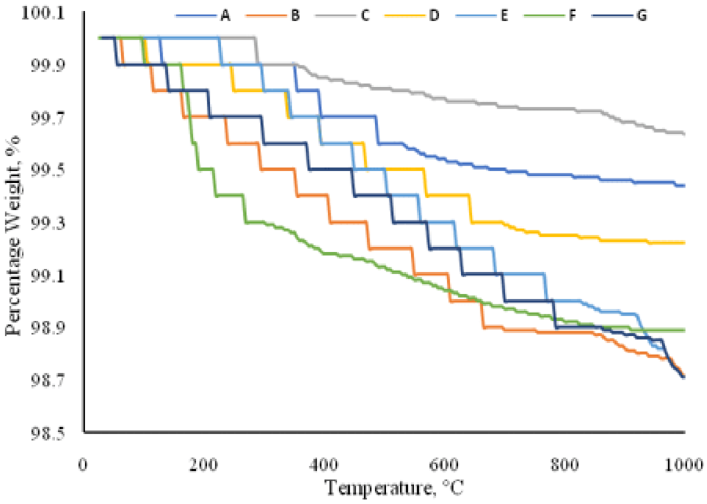


**Figure 3: Expanded TGA Graph of the Fabricated Al-SiCp Composites.**

**3.2 Differential Scanning Calorimetric Analysis of Fabricated FGM Samples**

The differential scanning calorimetric analysis examines the heat flow through the samples as the temperature increases. The DCS curves of the fabricated composite samples were obtained at a heating rate of 10 °C/min in an inert Argon atmosphere is shown in Figure 4.

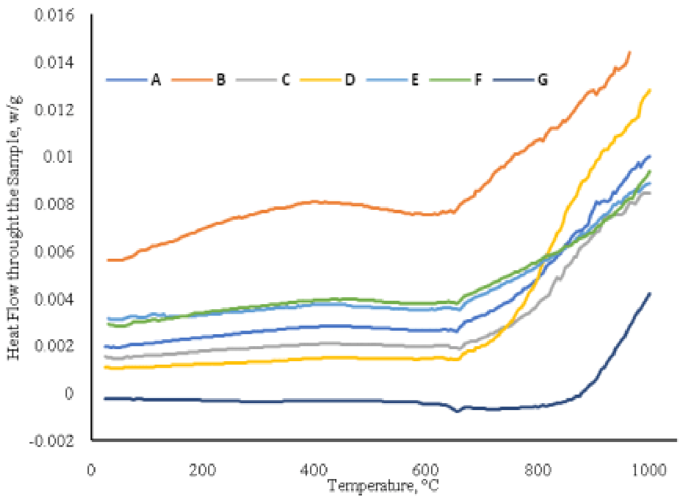


**Figure 4: DSC Curves Showing Heat Flow in Fabricated Al-SiC Composites.**

A slow increase in the heating rate is observed for the samples at a lower temperature region. Further increase in the temperature towards melting temperature brought about a slight decrease in the heat flow through the materials. Similar behavior was reported in work done by Sangeetha, et al. [12] when a hybrid aluminum metal matrix composite was subjected to thermal analysis. As the temperature continues to rise, a distinct endothermic peak can be observed for all the samples at 655 °C, which corresponds to the aluminum alloy's melting temperature region. Beyond 655 °C to 1000°C, the samples' heat flow rate is observed to increases sharply. Sample G with 15$\mu$m and 5 wt.% of the $SiC_p$ reinforcements displayed the lowest heat flow rate of 0.004 w/g at 1000 °C. This low heat flow rate could be due to the amount and particle size of the reinforcement in the sample's matrix.

## 4. CONCLUSIONS

In this study, a thermogravimetric analysis of aluminum metal matrix composites fabricated through centrifugal casting was carried out. The results of thermal analysis of the materials obtained from this study inform the conclusions, which are as follows:

- The overall percentage weight loss resulting from increased temperature to 1000 °C is negligible as the maximum process temperature is significantly lower than the composites' boiling temperature and that of its individual components.
- The particle size and weight percent of the $SiC_p$ reinforcement in the composite matrixes influence the heat retention capacity and heat flow through them at elevated temperatures.
- A slow increase in the materials' heat flow occurs at the temperature region below the melting temperature. In contrast, a sharp rise in the materials' heat flow occurs at a temperature beyond the melting temperature.
- With a combination of 15$\mu$m and 5 wt.% of the $SiC_p$ reinforcements, sample G displayed the best thermal resistant property at an elevated temperature having the lowest heat flow rate of 0.004 w/g at 1000 °C.

**Conflict of Interest**

The authors have no conflicts of interest to declare.

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17. A. O. Owoputi, F. L. Inambao, and W. S. Ebhota, "Influence of SiCp Reinforcement on the Mechanical Properties of Functionally Graded Aluminum Metal Matrix Composites Fabricated by Centrifugal Casting Technique," International Journal of Mechanical Engineering and Technology, vol. 10, pp. 306-316, 2019.
18. A. O. Owoputi, F. L. Inambao, and W. S. Ebhota, "Examining the mechanical and tribological behavior of Al-SiC composite developed by centrifugal casting technique," International Journal of Mechanical and Production Engineering Research and Development, vol. 11, pp. 119-130, 2021.
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# CHAPTER 6: DISCUSSION OF RESULTS

## 6.1 Results and Discussion

The aim of this research was to design and fabricate functionally graded aluminium metal matrix composites suitable to be used for auto engine components exposed to mechanical wear and thermal conditions during service. The piston component of an automobile engine is one such component.

Chapters 2 to 5 were developed to meet the objectives of the research as stated in section 1.6 of Chapter 1 of this thesis. A review of classification of functionally graded material, namely, bulk and thin FGM and their processing techniques was presented in Chapter 2. The merits and demerit of various processing techniques and the areas of application of FGMs were also discussed, as well as the current trends and outlook for FGMs. The outcome of Chapter 2 satisfies the research objective i in section 1.6 of Chapter 1 of this thesis and the associated article has been peer reviewed and subsequently published.

Chapter 3 describes the fabrication process of choice as well as the process parameters adopted. The experimental procedure carried out in Chapter 3 was designed to test the mechanical behavior of the fabricated composite when subjected to external forces of hardness, compression, tension, and shear. The results obtained suggest that the mechanical properties of hardness, compression, shear and tension for the fabricated composites were influenced to varying degree dependent on the granularity and the weight-fraction of the SiC reinforcement present in the composite's matrix. The increase in the weight-percent of the reinforcement composition resulted in a corresponding improvement in the hardness, compressive, shear strength and modulus of the material. The results from the mechanical analysis of the cast composites presented in sections 3.2, 3.3, and 3.4 of Chapter 3 met the research objectives ii, iii, and iv in section 1.6 of Chapter 1 of this thesis. The associated articles have been peer reviewed and subsequently published. A process flowchart detailing the steps taken in fabricating Al-SiC composites for mechanical analysis is shown in Figure 6-1.

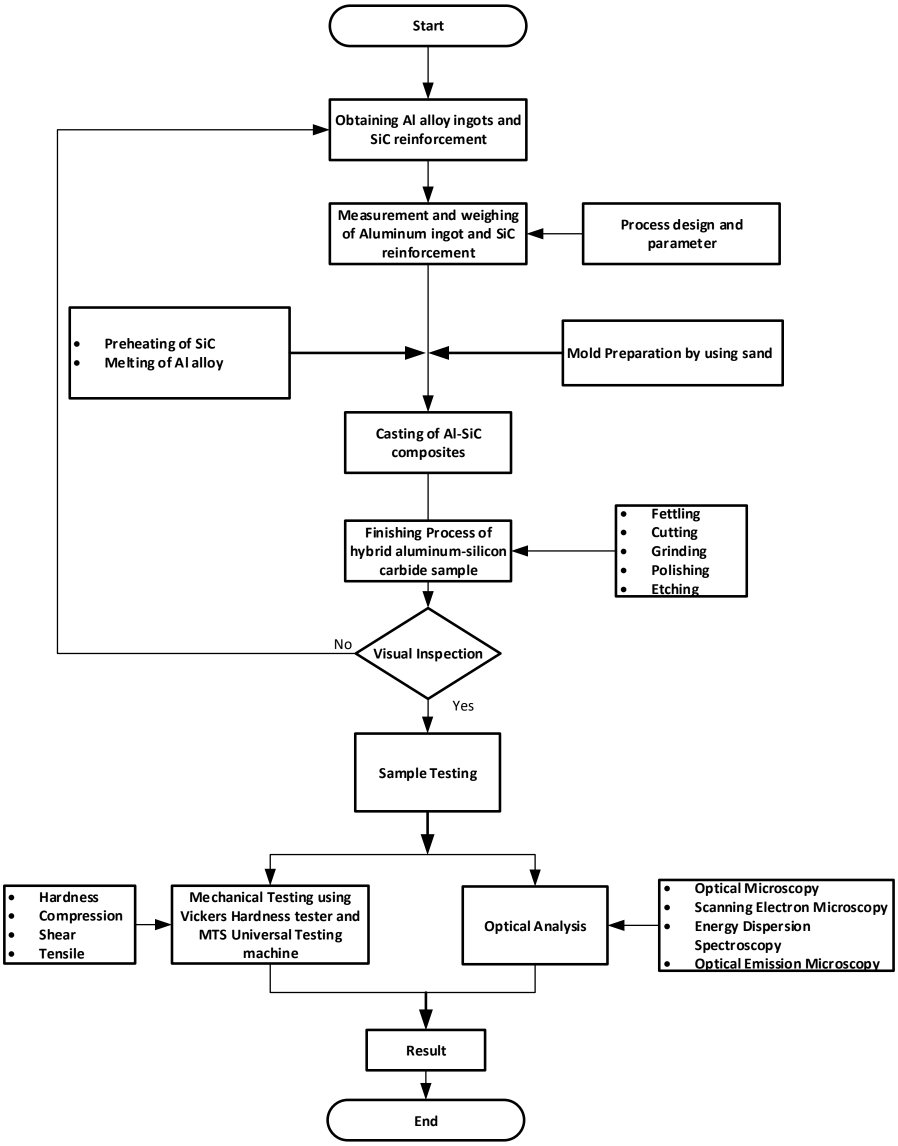


**Figure 6-1: Flowchart to obtaining and Al-SiC composites for mechanical analysis**

The result presented in Chapter 4 showed the fabricated composite materials' responses to abrasive force by subjecting them to a tribological analysis. The wear rate and frictional coefficient of each composite were determined and compared against each other. The greater the reinforcement content in the composite's matrix, the better the wear properties. Similarly, improved wear property was observed when the reinforcement particle size is smaller. Sample C with 5 wt.% and 7 µm of SiC particle reinforcement was observed to possess the least wear rate of all the fabricated composites with different SiC reinforcement configurations. The results from the tribological evaluation of the cast composites presented in section 4.2 and 4.3 met research objective v in section 1.6 of chapter 1 of this thesis. The associated article has been peer reviewed and subsequently published. The process flowchart showing the steps taken in fabricating Al-SiC composites for tribological analysis is shown in Figure 6-2.

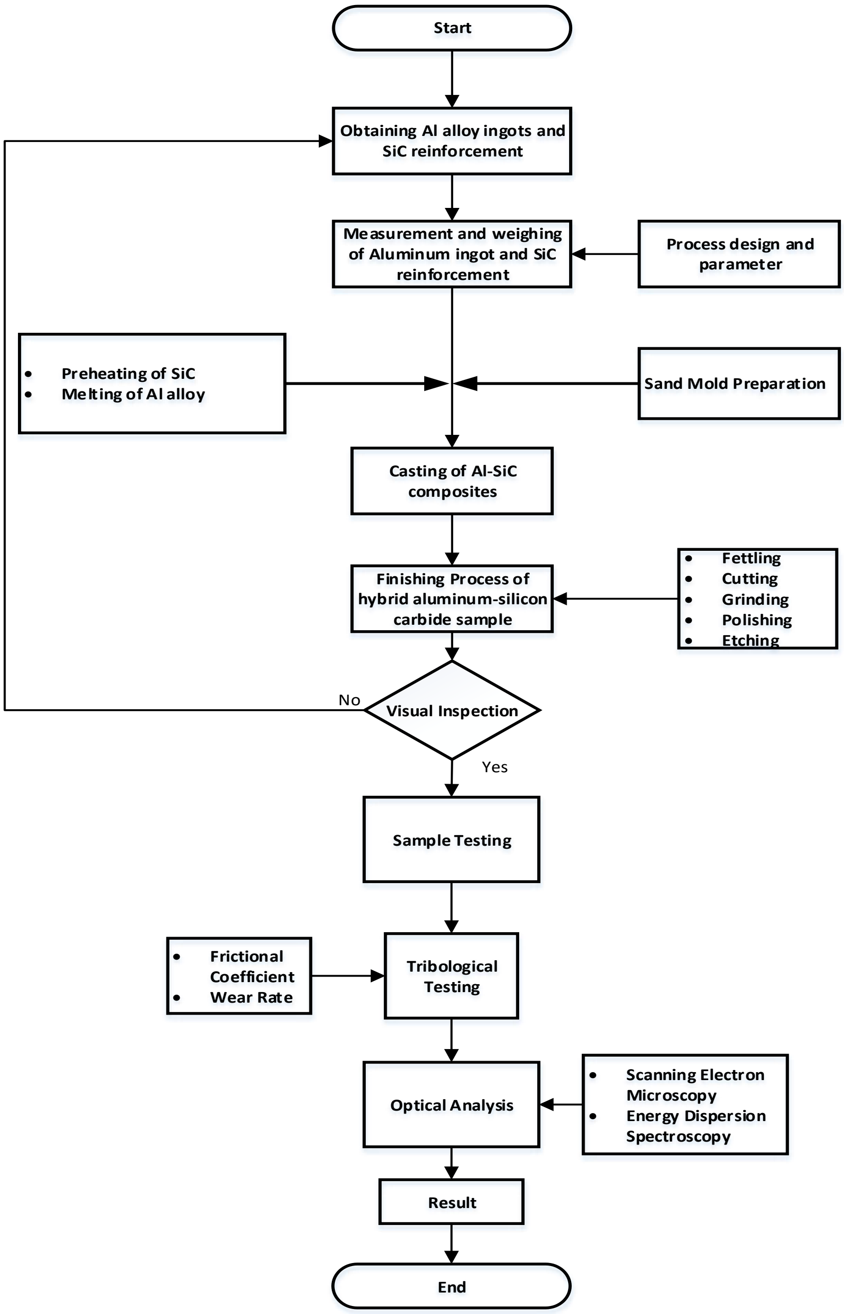


**Figure 6-2: Flowchart to obtaining and Al-SiC composites for tribological analysis**

The thermal properties of the fabricated composites presented in Chapter 5 were determined by subjecting the samples to incremental temperature from 25 °C to 1000 °C. The rate of heat flow and the percentage material weight loss due to thermal degradation was observed and reported. Findings showed that the reinforcement particles in the matrix of each cast sample had an influence on the rate of heat flow through the material. Although the thermal degradation of the cast samples was minimal, the effect of the reinforcement configuration with respect to particle size and weight-fraction was evident with the composite sample containing 5 wt.% and 7 µm SiC particles recording the least weight loss. The results from the thermal evaluation of the cast composites were presented in section 5.2, and met research objective vi in section 1.6 of chapter 1 of this thesis. The process flow diagram details the steps taken to fabricate and analyze the thermal properties of the cast composites is shown in Figure 6-3. The associated article has been peer reviewed and subsequently published.

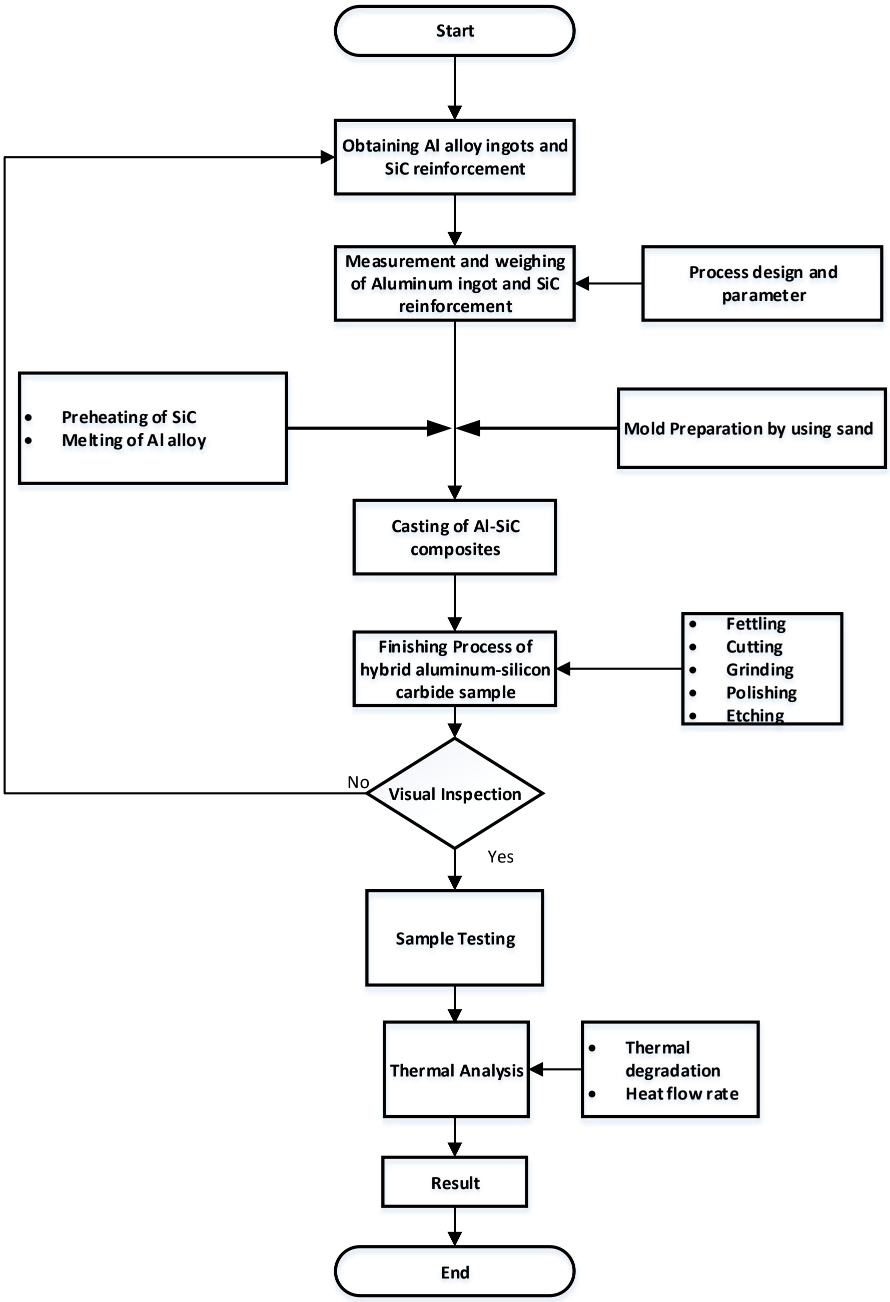


**Figure 6-3: Flowchart to obtaining and Al-SiC composites for thermal analysis**

## 6.2 Research Rationale

The engine is an essential part of an automobile and consists of several moving components that are subjected to external stresses due to their working conditions. The automobile piston is a component that is constantly subjected to mechanical, thermal and abrasive stresses / forces during service. This makes the selection and fabrication process of potential material for the manufacturing of the piston component of great importance. It is imperative that the material adopted for this application be able to withstand compressive force, not easily deform, have good thermal characteristics, and be able to withstand abrasive force. These requirements informed the analyses carried out on the fabricated Al-SiC composites.

The results obtained from the tests and analyses carried out on the fabricated samples suggest the suitability of sample C for automobile engine piston application, due to the overall improved mechanical, tribological and thermal properties the sample exhibited compared to the other fabricated samples.

# CHAPTER 7: CONCLUSION AND RECOMMENDATION

## 7.1 Conclusion

The aim of this study was to develop FGAMMC composites for use in the automobile industry. In achieving this, varying proportions of SiC reinforcement particles with average particle sizes of 7 µm and 15 µm were dispersed within the matrix of industrially sourced aluminium alloy. Seven functionally graded Al-SiC metal matrix composites were developed using centrifugal casting technique.

The cast composites were subjected to microstructural, mechanical, tribological and thermal analysis to determine their respective properties with respect to the reinforcement configuration within their various matrices. Microstructural examination from a scanning electron microscope revealed even dispersion of the reinforcement particles within the aluminium matrix. This further confirmed the efficiency of the fabrication technique adopted. Results from the mechanical testing of the fabricated specimens showed an improvement in the hardness, compressive and shear strength as well as thermal and tribological properties of the cast composites. These improved properties were attributed to the homogeneous dispersion of the SiC reinforcement.

The composite sample C with SiC reinforcement of 7 µm and 5 wt.% displayed the highest properties by recording hardness, compressive strength, Young's modulus, shear strength, and shear modulus values of 112.7 HV100, 3107 MPa, 6.39 GPa, 14.4 GPa, and 9.29 GPa, respectively. Moreover, the TGA / DSC analysis of the samples revealed that this sample also exhibited the least percentage weight loss of 0.37 % and thermal resistance capacity at maximum temperature (1000 °C) when compared the samples containing less volume of reinforcement in their matrices.

## 7.2 Contribution to Knowledge

The piston is an important component of the automobile engine which harnesses heat energy generated from compressed gas in the engine and transforms the energy into mechanical energy. As a result, the flat surface of the piston head is subjected to immense thermal, mechanical and tribological pressure due to constant upward and downward movement and air-fuel explosions within the engine cylinder. The Al-SiC composite materials developed in this research displayed significant improvement in thermomechanical and tribological properties which are crucial factors in the production of automobile pistons. When subjected to thermal analysis, the composite samples C and G with 7 µm, 5 wt.% and 15 µm, 5 wt.% of SiC reinforcement respectively, showed a high thermal capacity and low thermal degradation property at maximum experimental temperature compared to other samples. The tribomechanical behavior of the material sample C, when subjected to mechanical and wear test, showed significant improvement when compared to other samples. This overall improvement in thermo-tribomechanical properties of sample C makes it a prime candidate in the proposed production of automobile pistons with improved thermal and mechanical properties.

## 7.3 Recommendations for Future Work

To date there has been limited study of high temperature thermal degradation of aluminium metal composites for use in automobile applications. In the course of this research, the manufactured composites were subjected to thermal analysis at a temperature in the region of 1000 °C. The recommendation in this case is for thermal characterization of aluminium metal matrix composites at temperature regions higher than the materials' boiling points. This will ensure the integrity of the materials during service when subjected to extreme temperature conditions. The present research explored the reinforcement of aluminium matrix with different particle sizes and weight percentages of SiC particles. However, the overall properties of titanium show that it can serve as a perfect replacement for aluminium-based composites. Further research is therefore proposed on the possibility of replacing aluminium matrix composites with other metal-based matrix composites in the automobile industry.

# APPENDIXES

## Appendix I: Editing Certificates

**Appendix A: Chapter 1, Chapter 2, Chapter 6, and Chapter 7**


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**EDITING CERTIFICATE**

Re: **Adefemi O. Owoputi**
For Chapters 1, 2, 6, 7 of PhD thesis: **DEVELOPMENT AND FABRICATION OF FUNCTIONALLY GRADED ALUMINUM METAL MATRIX COMPOSITE FOR AUTOMOBILE COMPONENT APPLICATIONS**

I confirm that I have edited this article and the references for clarity, language and layout. I returned the document to the author with track changes so correct implementation of the changes and clarifications requested in the text and references is the responsibility of the author. I am a freelance editor specialising in proofreading and editing academic documents. My original tertiary degree which I obtained at the University of Cape Town was a B.A. with English as a major and I went on to complete an H.D.E. (P.G.) Sec. with English as my teaching subject. I obtained a distinction for my M.Tech. dissertation in the Department of Homoeopathy at Technikon Natal in 1999 (now the Durban University of Technology). I was a part-time lecturer in the Department of Homoeopathy at the Durban University of Technology for 13 years and supervised many master's degree dissertations during that period.

Dr Richard Steele
**7 June 2021**
*per email*

**Appendix B: Chapter 3 (Paper 1)**

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**EDITING CERTIFICATE**

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I confirm that I have edited this article and the references for clarity, language and layout. I returned the document to the author with track changes so correct implementation of the changes and clarifications requested in the text and references is the responsibility of the author. I am a freelance editor specialising in proofreading and editing academic documents. My original tertiary degree which I obtained at the University of Cape Town was a B.A. with English as a major and I went on to complete an H.D.E. (P.G.) Sec. with English as my teaching subject. I obtained a distinction for my M.Tech. dissertation in the Department of Homoeopathy at Technikon Natal in 1999 (now the Durban University of Technology). I was a part-time lecturer in the Department of Homoeopathy at the Durban University of Technology for 13 years and supervised many master's degree dissertations during that period.

Dr Richard Steele
**19 July 2019**
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Re: **Adefemi O. Owoputi**
Journal article: **Effect of percentage weight and particle size of $SiC_p$ reinforcement on the mechanical behavior of functionally graded aluminum metal matrix composite**

I confirm that I have edited this article and the references for clarity, language and layout. I returned the document to the author with track changes so correct implementation of the changes and clarifications requested in the text and references is the responsibility of the author. I am a freelance editor specialising in proofreading and editing academic documents. My original tertiary degree which I obtained at the University of Cape Town was a B.A. with English as a major and I went on to complete an H.D.E. (P.G.) Sec. with English as my teaching subject. I obtained a distinction for my M.Tech. dissertation in the Department of Homeopathy at Technikon Natal in 1999 (now the Durban University of Technology). I was a part-time lecturer in the Department of Homoeopathy at the Durban University of Technology for 13 years.

Dr Richard Steele
**26 September 2019**
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## EDITING CERTIFICATE

Re: **Adefemi O. Owoputi**
Journal article: **Analyzing the Impact of Reinforcement Addition on the Mechanical Properties of Aluminum A356 Alloy**

I confirm that I have edited this article and the references for clarity, language and layout. I returned the document to the author with track changes so correct implementation of the changes and clarifications requested in the text and references is the responsibility of the author. I am a freelance editor specialising in proofreading and editing academic documents. My original tertiary degree which I obtained at the University of Cape Town was a B.A. with English as a major and I went on to complete an H.D.E. (P.G.) Sec. with English as my teaching subject. I obtained a distinction for my M.Tech. dissertation in the Department of Homoeopathy at Technikon Natal in 1999 (now the Durban University of Technology). I was a part-time lecturer in the Department of Homoeopathy at the Durban University of Technology for 13 years and supervised many master's degree dissertations during that period.

Dr Richard Steele
**19 April 2021**
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**Appendix F: Chapter 5 (Paper 1)**

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**EDITING CERTIFICATE**

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Dr Richard Steele
**29 March 2021**
*per email*

# Appendix II: Acceptance Letters

## Appendix A: Paper 1

**Adefemi Owoputi (214585093)**

| | |
|---|---|
| **From:** | Freddie Inambao |
| **Sent:** | Tuesday, 06 July 2021 15:00 |
| **To:** | Adefemi Owoputi (214585093) |
| **Cc:** | Freddie Inambao |
| **Subject:** | FW: REMINDER : Paper Accepted for IJAER Paper Code: 66017 |
| **Attachments:** | 66017-IJAER.pdf; 66017 RIP Copyright Form Paper code 66017 final.pdf |

Acceptance letter

**From:** Research India Publications <ijaereditor@gmail.com>
**Sent:** Tuesday, 28 August 2018 11:32
**To:** Freddie Inambao <Inambaof@ukzn.ac.za>
**Subject:** REMINDER : Paper Accepted for IJAER Paper Code: 66017

Dear **Professor Freddie Inambao,**

**Paper Code: 66017**

We are very pleased to inform you that your paper "**A REVIEW OF FUNCTIONALLY GRADED MATERIALS: FABRICATION PROCESSES AND APPLICATIONS**" is accepted by our Editor-in-chief for our journal **International Journal of Applied Engineering Research (IJAER).**

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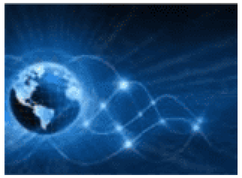
**Paper ID: IJMET_10_08_024** **Date: 28-August-2019**

## *Certificate of Publication*

This is to certify that the research paper entitled **"INFLUENCE OF SICP REINFORCEMENT ON THE MECHANICAL PROPERTIES OF FUNCTIONALLY GRADED ALUMINUM METAL MATRIX COMPOSITES FABRICATED BY CENTRIFUGAL CASTING TECHNIQUE"** authored by **"Adefemi O. Owoputi, Freddie L. Inambao William S. Ebhota"** had been reviewed by the Editorial Board and published in **"International Journal of Mechanical Engineering & Technology (IJMET), Volume 10, Issue 8, August 2019, pp. 306-316; ISSN Print: 0976-6340 and ISSN Online: 0976-6359; Journal Impact Factor (2019): 10.6879 Calculated by GISI (www.jifactor.com)".**



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Chief Editor

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## Appendix C: Paper 3



Gmail

**Adefemi Owoputi <adefemiowoputi@gmail.com>**

### IJERT - Effect of percentage weight and particle size of SiCp reinforcement on the mechanical behaviour of functionally graded aluminum metal matrix composite

**International Research Publication House** <irpeditor@gmail.com> Sun, Oct 13, 2019 at 4:17 PM
To: Adefemi Owoputi <adefemiowoputi@gmail.com>

Dear Dr. Adefemi owoputi,

Paper Code: 18765-IJERT

We are very pleased to inform you that your paper "Effect of percentage weight and particle size of SiC p reinforcement on the mechanical behaviour of functionally graded aluminum metal matrix" is accepted by Editor for publication in our journal International Journal of Engineering Research and Technology (IJERT) ISSN 09743154, scopus indexed, active in 2019.

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## Appendix D: Paper 4

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**Apr 28, 2021**

**To**

**Professor Freddie L. Inambao,**
UNIVERSITY OF KWAZULU NATAL
PRIVATE BAG X54001
DURBAN
4000
SOUTH AFRICA
VAT NUMBER – 4860209305

**Dear Professor Freddie L. Inambao,**

Greetings.

<u>**Subject**</u>: Acceptance of research paper for publication in our International Journal

It's our pleasure to inform you that, after the peer review of your paper, **Titled:** "**Analyzing the impact of reinforcement addition on the mechanical properties of aluminum A356 alloy"** authored by **"Adefemi O. Owoputi, Freddie L. Inambao & William S. Ebhota"** submitted to us for an evaluation by you on **26th Apr 2021** has been accepted by the Review Board for publishing in **"International Journal of Mechanical and Production Engineering Research and Development (IJMPERD) Journal with ISSN (Print): 2249-6890; ISSN (Online): 2249-8001; Impact Factor (JCC): 9.6246; NAAS Rating: 3.11; IBI Factor: 3.2; ICV 2015:60.6"**

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Paper Id: IJMPERDAUG20214

Date: 06/14/2021

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[redacted]

**Associate Editor-TJPRC**

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**Chief Editor-TJPRC**

**Appendix E: Paper 5**

Paper Id: IJMPERDAPR202111

Date: 03/08/2021

# Certificate of Publication

*This is to certify that the research paper entitled " EXAMINING THE MECHANICAL AND TRIBOLOGICAL BEHAVIOR OF AL-SIC COMPOSITE DEVELOPED BY CENTRIFUGAL CASTING TECHNIQUE " authored by " ADEFEMI O. OWOPUTI*, FREDDIE L. INAMBAO, & WILLIAM S. EBHOTA " had been reviewed by the board and published in " INTERNATIONAL JOURNAL OF MECHANICAL AND PRODUCTION ENGINEERING RESEARCH AND DEVELOPMENT (IJMPERD); ISSN (ONLINE): 2249-8001; ISSN (PRINT): 2249-6890; IMPACT FACTOR(JCC) (2020): 9.6246; INDEX COPERNICUS VALUE (ICV) - (2016): 60.6; NAAS RATING: 3.11; VOL - 11, ISSUE - 2; EDITION: APR - 2021 "*

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Chief Editor-TJPRC

## Appendix F: Paper 6

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**Apr 07, 2021**

**To**


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**Dear Scholar. Professor Freddie Inambao,**

**Subject**: Acceptance of research paper for publication in our International Journal

Greetings.

It's our pleasure to inform you that, after the peer review of your paper, **Titled:** "**THERMAL EVALUATION OF AL-SIC METAL MATRIX COMPOSITE FABRICATED THROUGH LIQUID METALLURGY PROCESS**" authored by **"Adefemi O. Owoputi, Professor Freddie Inambao & William S. Ebhota"** submitted to us for an evaluation by you on **Apr 04, 2021** has been provisionally accepted by the Review Board for publishing in **"International Journal of Mechanical and Production Engineering Research and Development (IJMPERD) journal with ISSN (Print): 2249-6890; ISSN (Online): 2249-8001; Impact Factor (JCC): 9.6246; NAAS Rating: 3.11; IBI Factor: 3.2; ICV 2015:60.6.**

Again, thank you for working with TRANSSTELLAR. We believe that our collaboration will help to accelerate the global knowledge creation and sharing one step further. TRANSSTELLAR looks forward to your final publication package. Please do not hesitate to contact us if you have any further questions.

Thanking you,

Yours sincerely,

For Transstellar Journal Publications & Research Consultancy Pvt. Ltd.

[redacted]

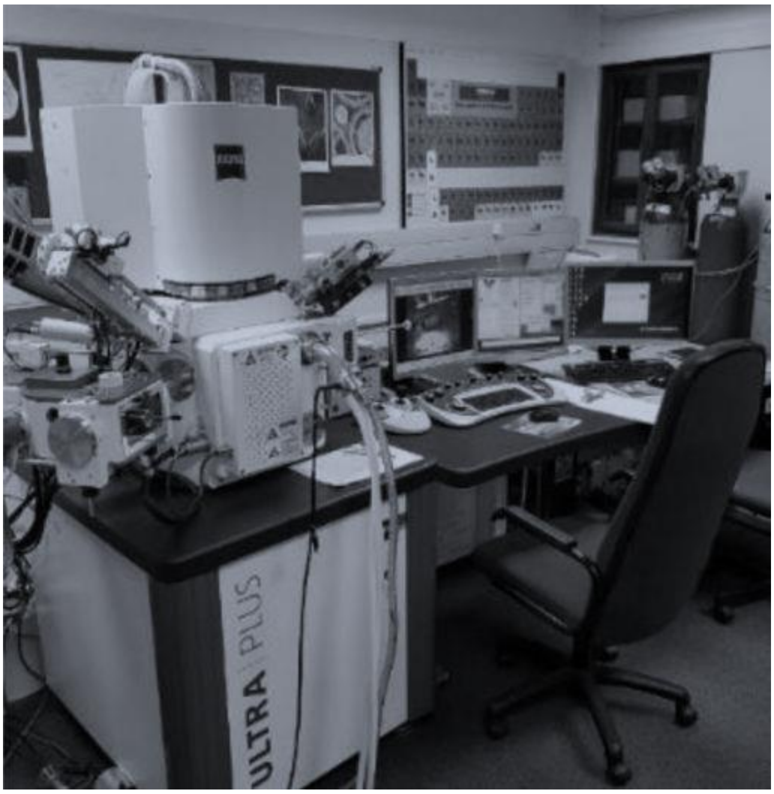
Authorized Signatory

**Associate Editor**

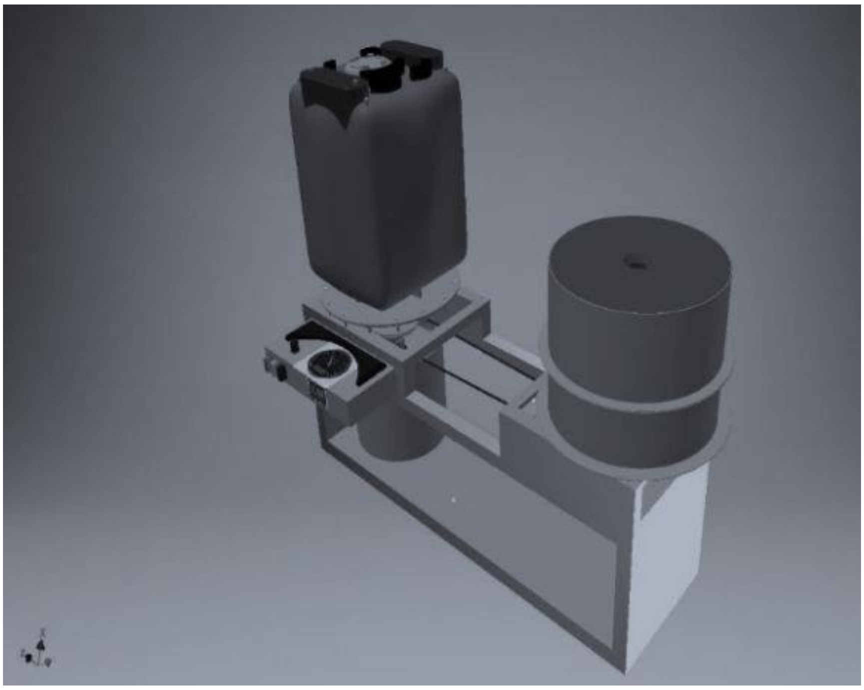
**TJPRC Pvt Ltd.**

## Appendix III: Additional Images

Appendix III 1 Thermal Gravimetric Analyzer




Appendix III 2 FEG-SEM Setup



**Appendix III 3 3-D Diagram of casting machine**

**Appendix III 4 Centrifugal Casting Setup**

**Appendix III 5 Sputtering machine**

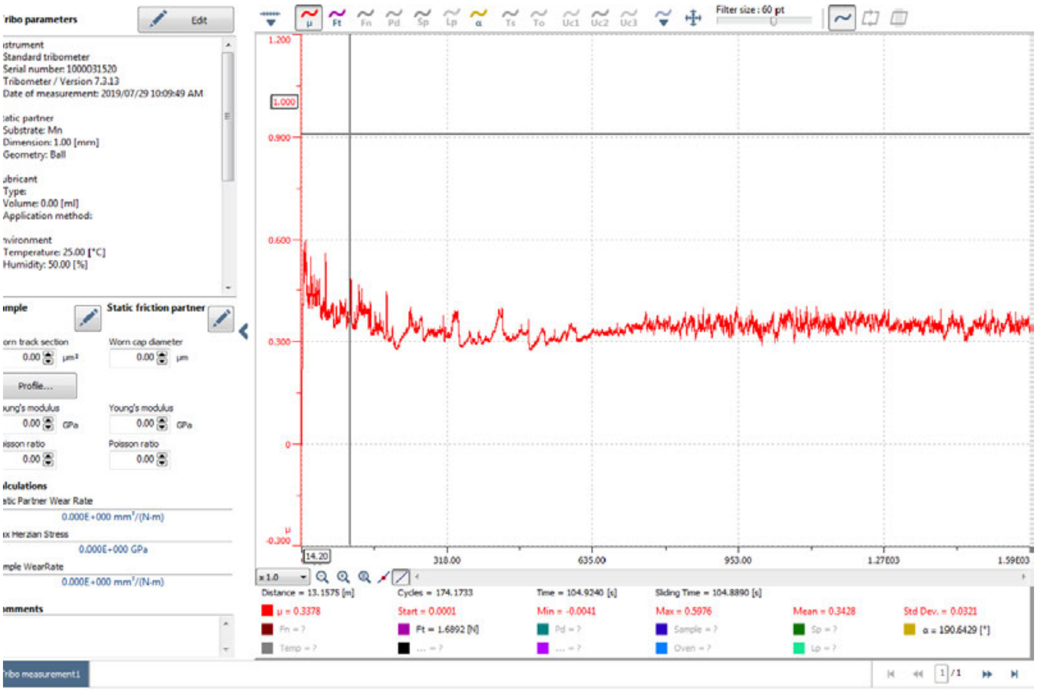

**Appendix III 6 Hot-Mounting Setup**


**Appendix III 7Manual grinder and polisher**

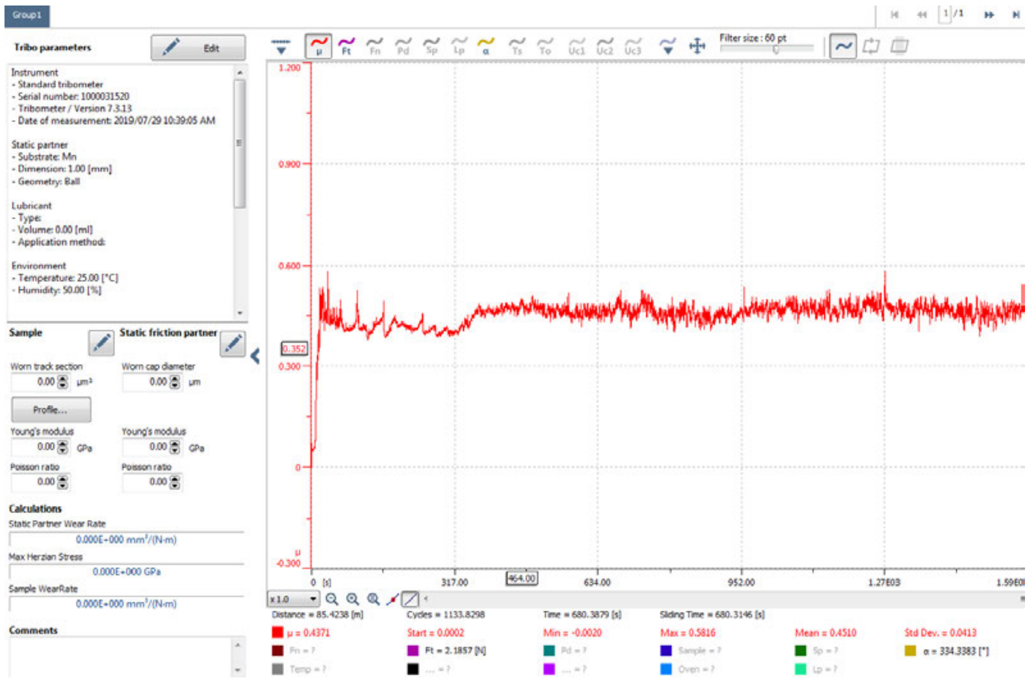

**Appendix III 8 Automated grinding and polishing machine**

**Appendix III 9 Vicker's hardness testing machine**

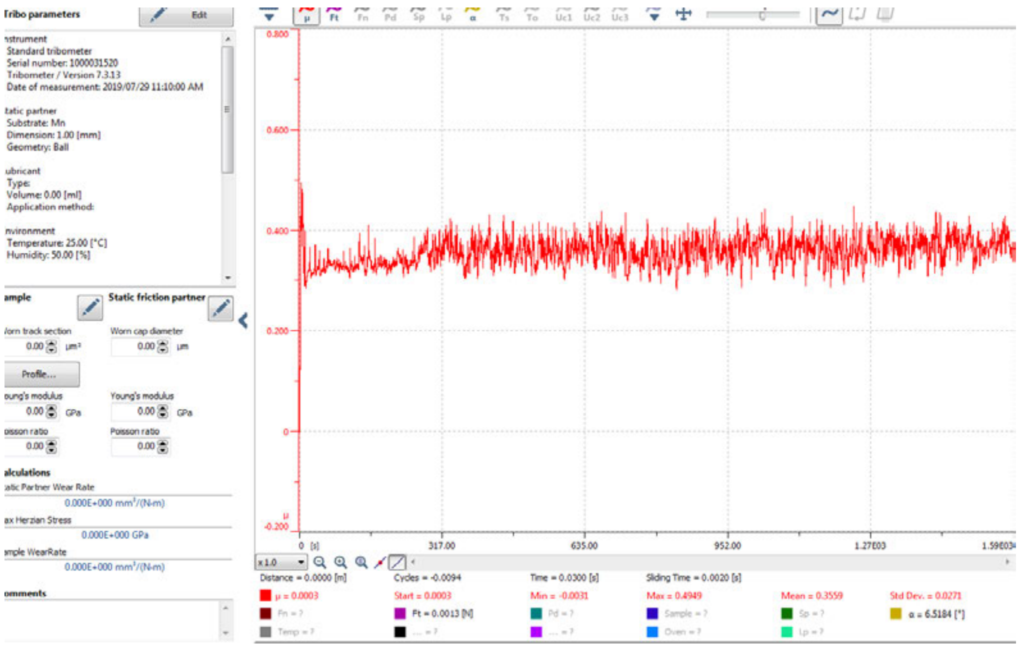

**Appendix III 10 Optical Microscope and setup**



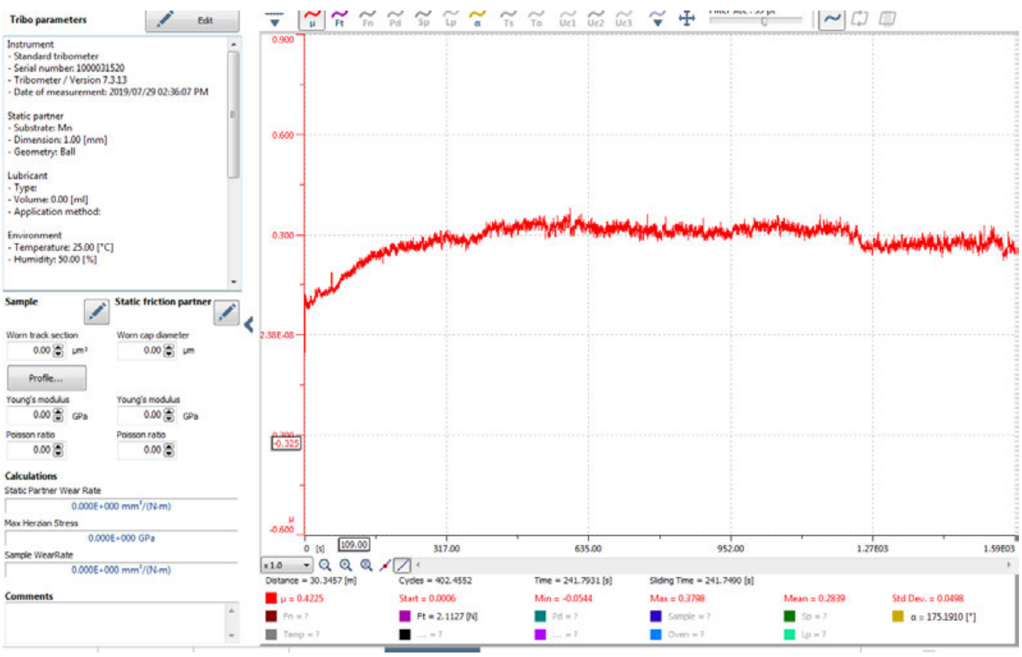
**Appendix III 11 Origin plot of frictional coefficient for composite sample A**



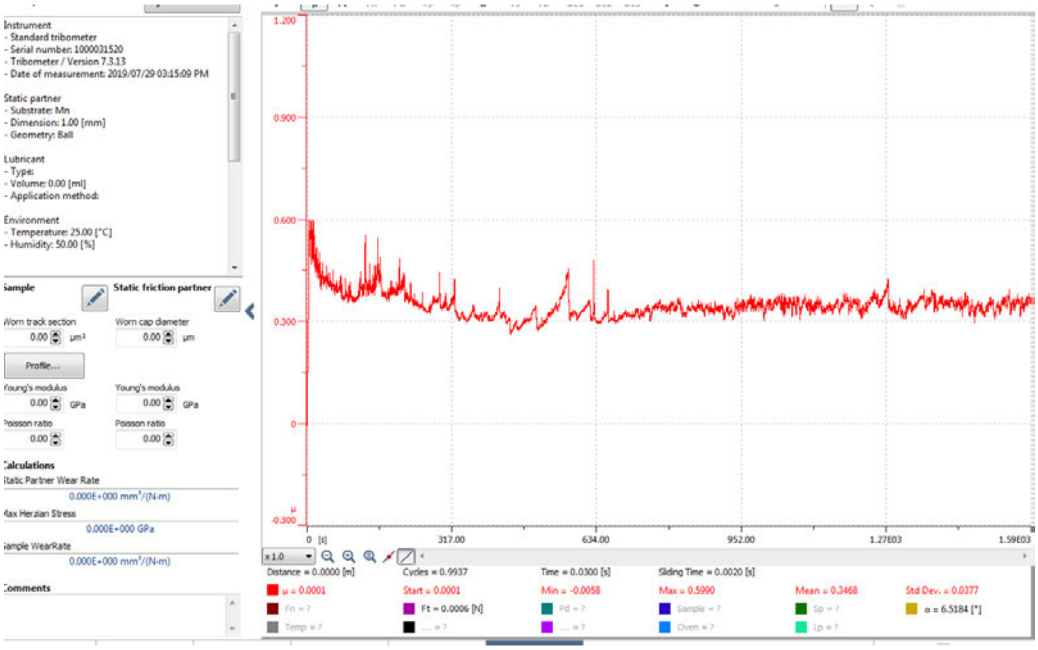
**Appendix III 12 Origin plot of frictional coefficient for composite sample B**



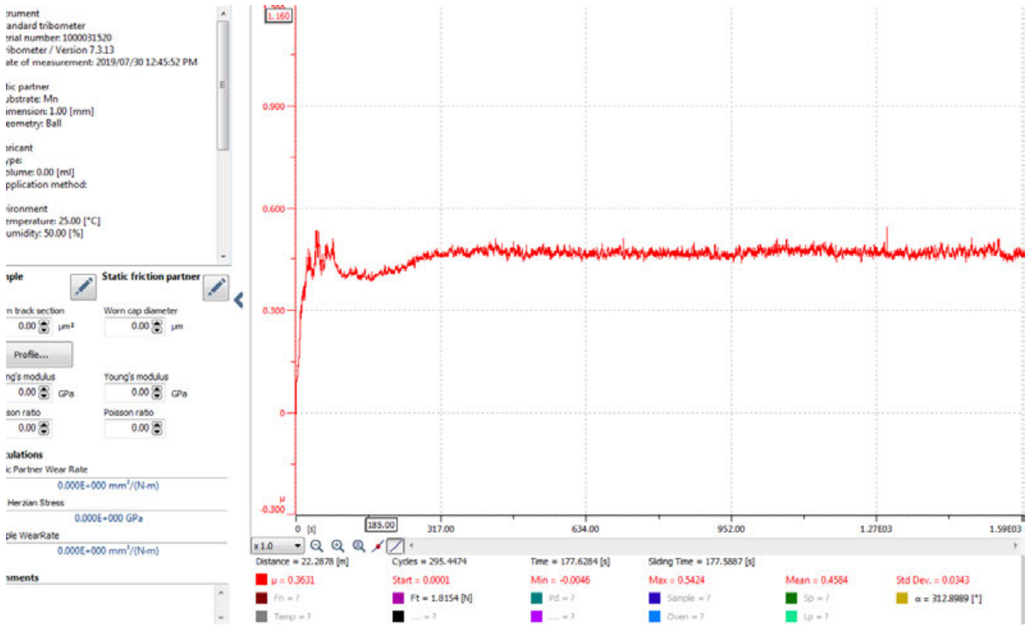
**Appendix III 13 Origin plot of frictional coefficient for composite sample C**



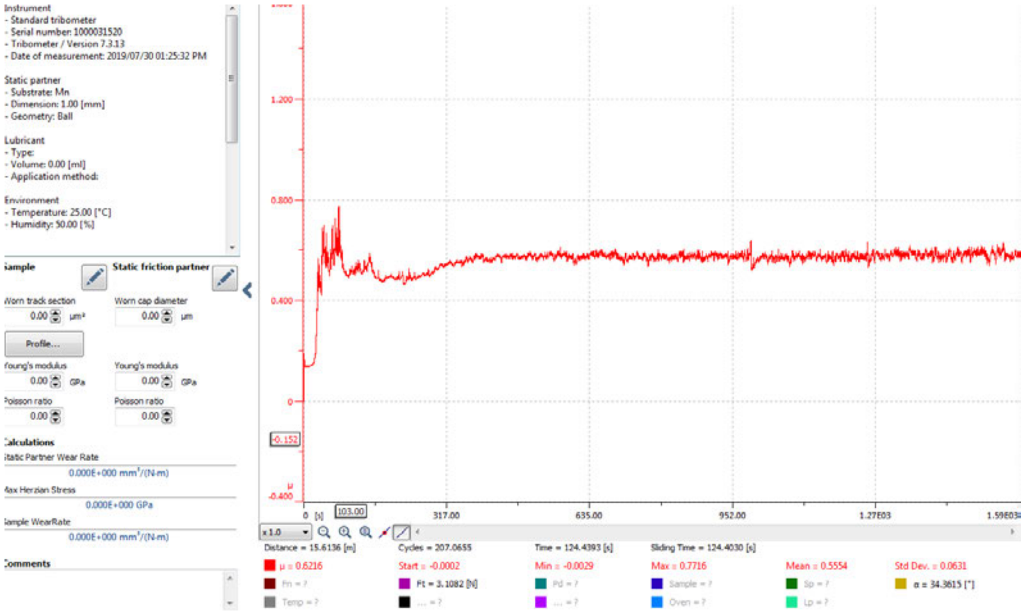
**Appendix III 14 Origin plot of frictional coefficient for composite sample D**




**Appendix III 15 Origin plot of frictional coefficient for composite sample E**




**Appendix III 16 Origin plot of frictional coefficient for composite sample F**




**Appendix III 17 Origin plot of frictional coefficient for composite sample G**

**Appendix III 18 Pre-cast Aluminium alloy ingots**