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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):

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

where η is the viscosity of the base matrix, R_r is the reinforcement particle size, ρ_r and ρ_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):

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

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; η 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

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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.

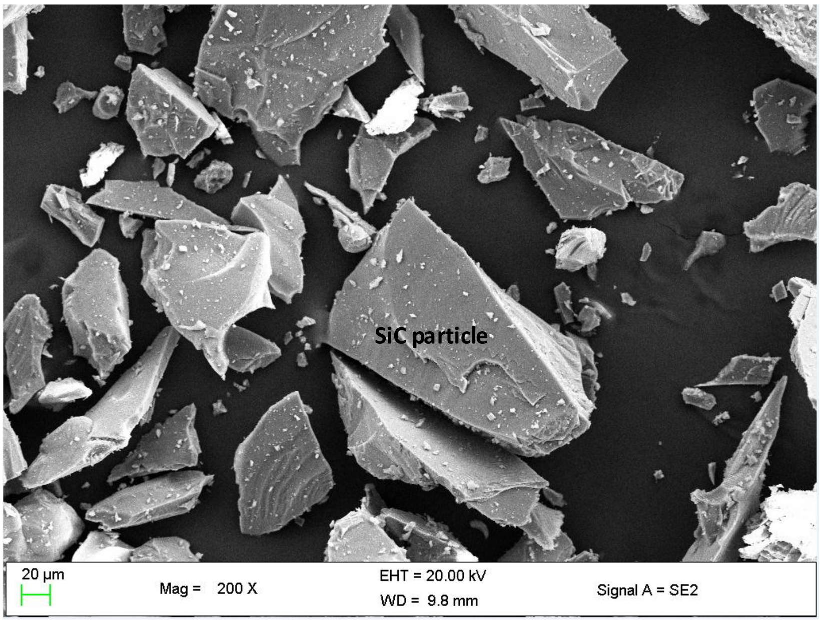

Figure 3. SEM images for the reinforcement particles

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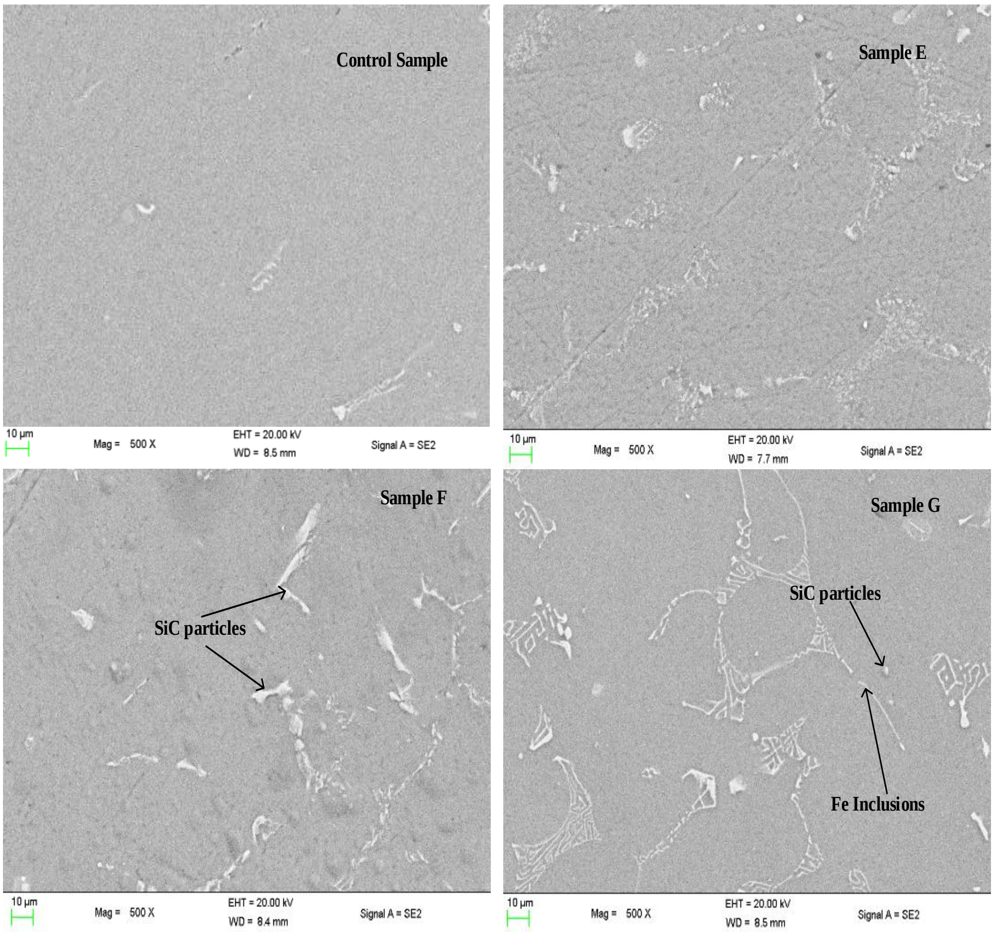

Figure 4. SEM micrograph of FGM with different weight-percent of SiC reinforcement

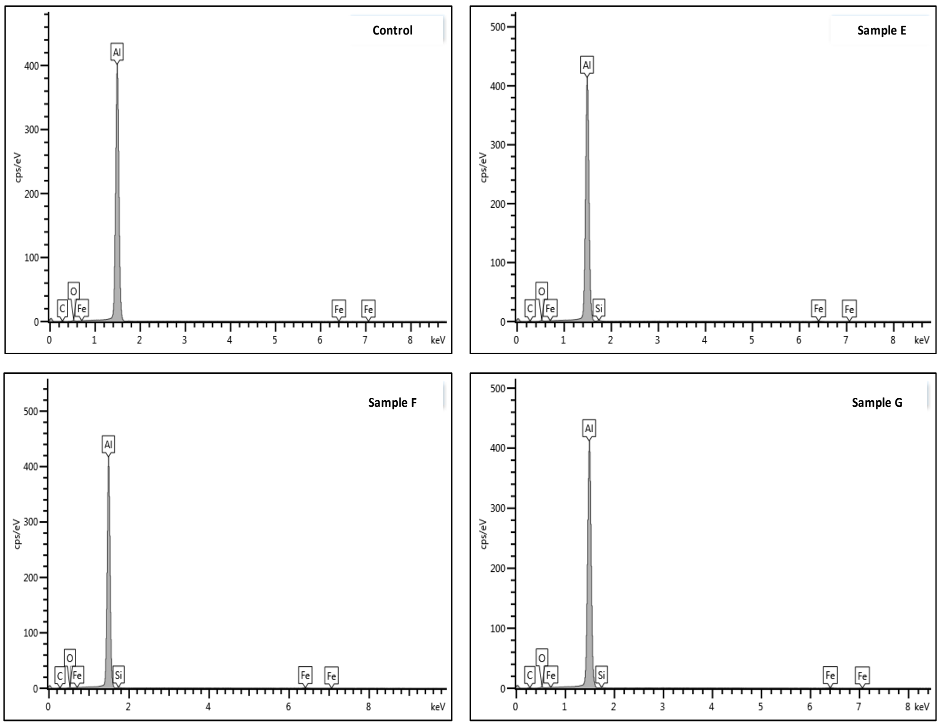

Figure 5. EDX images obtained from SEM analysis

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.

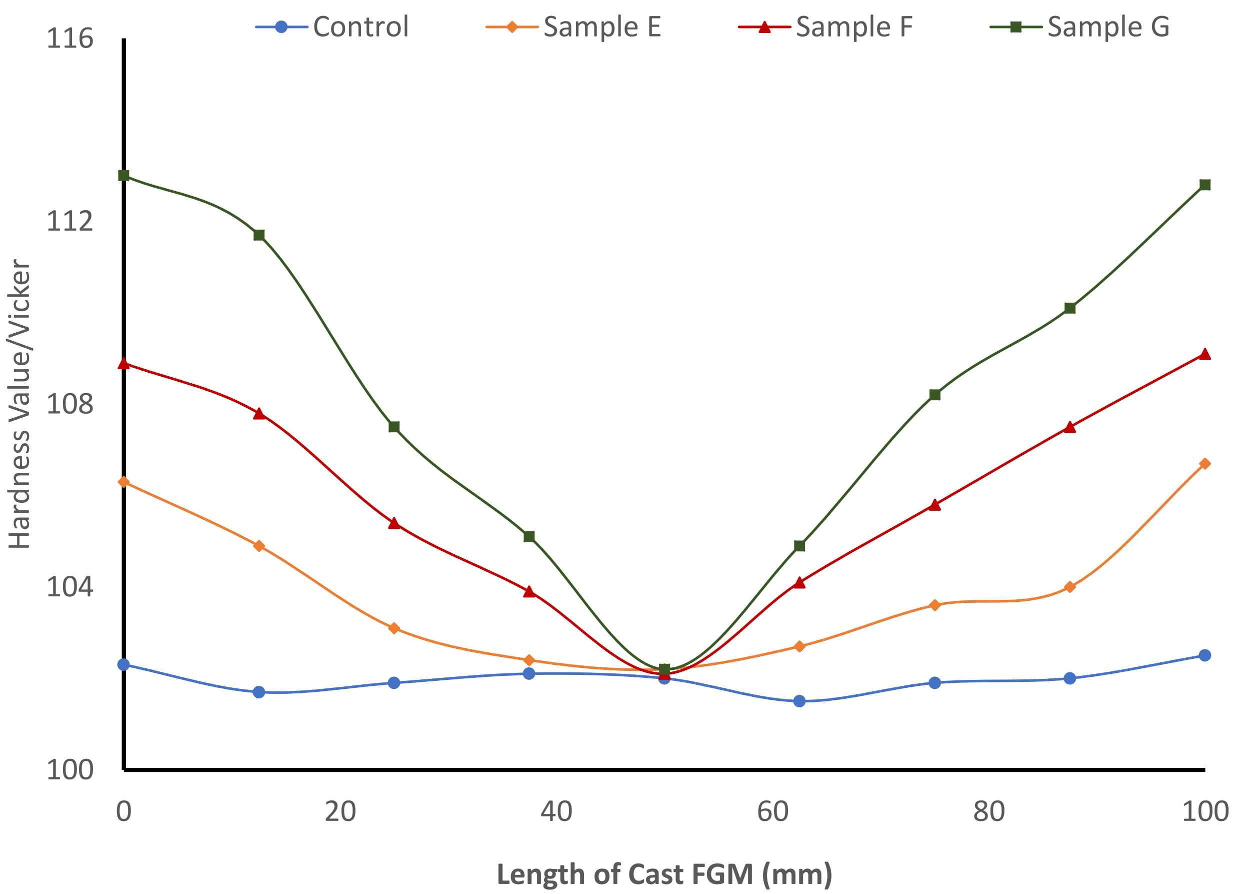

Figure 6. Hardness values measured along the length of cast FGM samples

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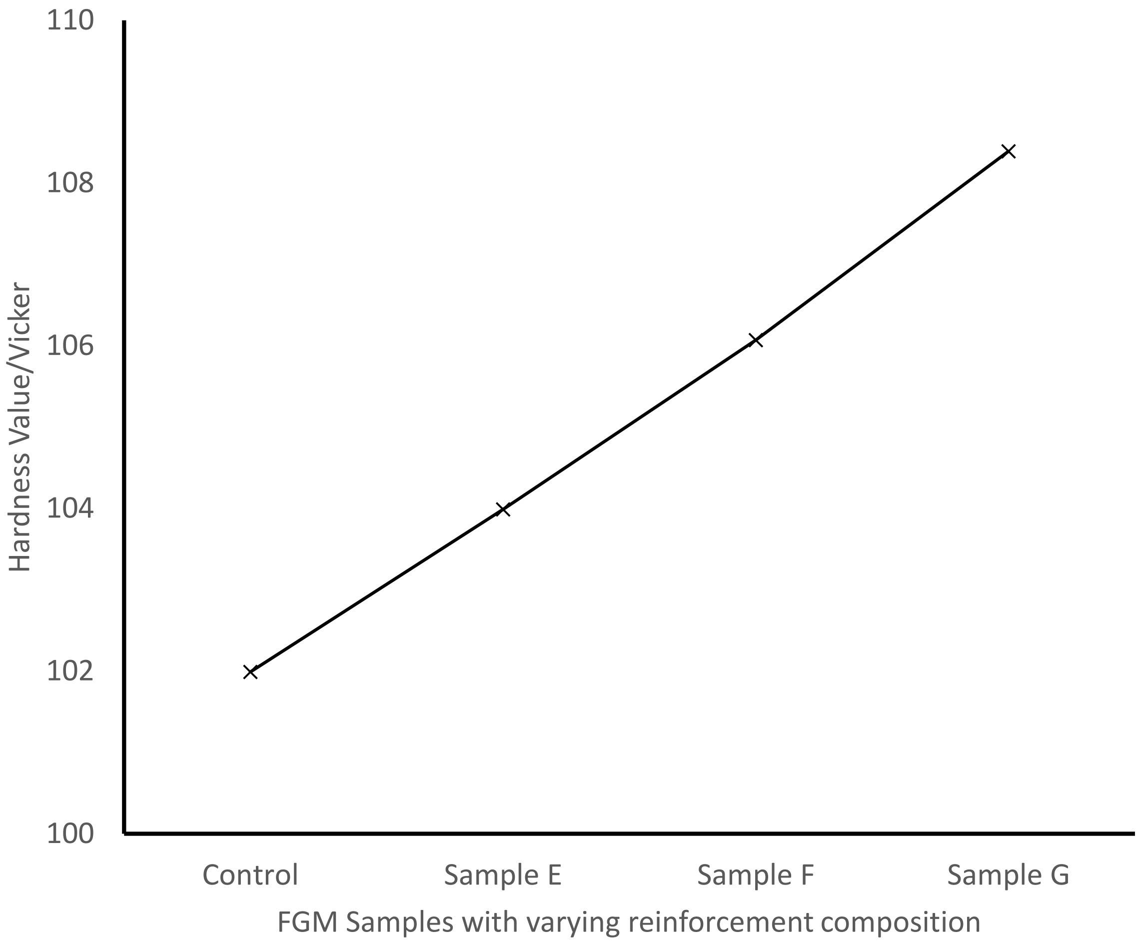

Figure 7. Hardness values of cast FGM samples

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.

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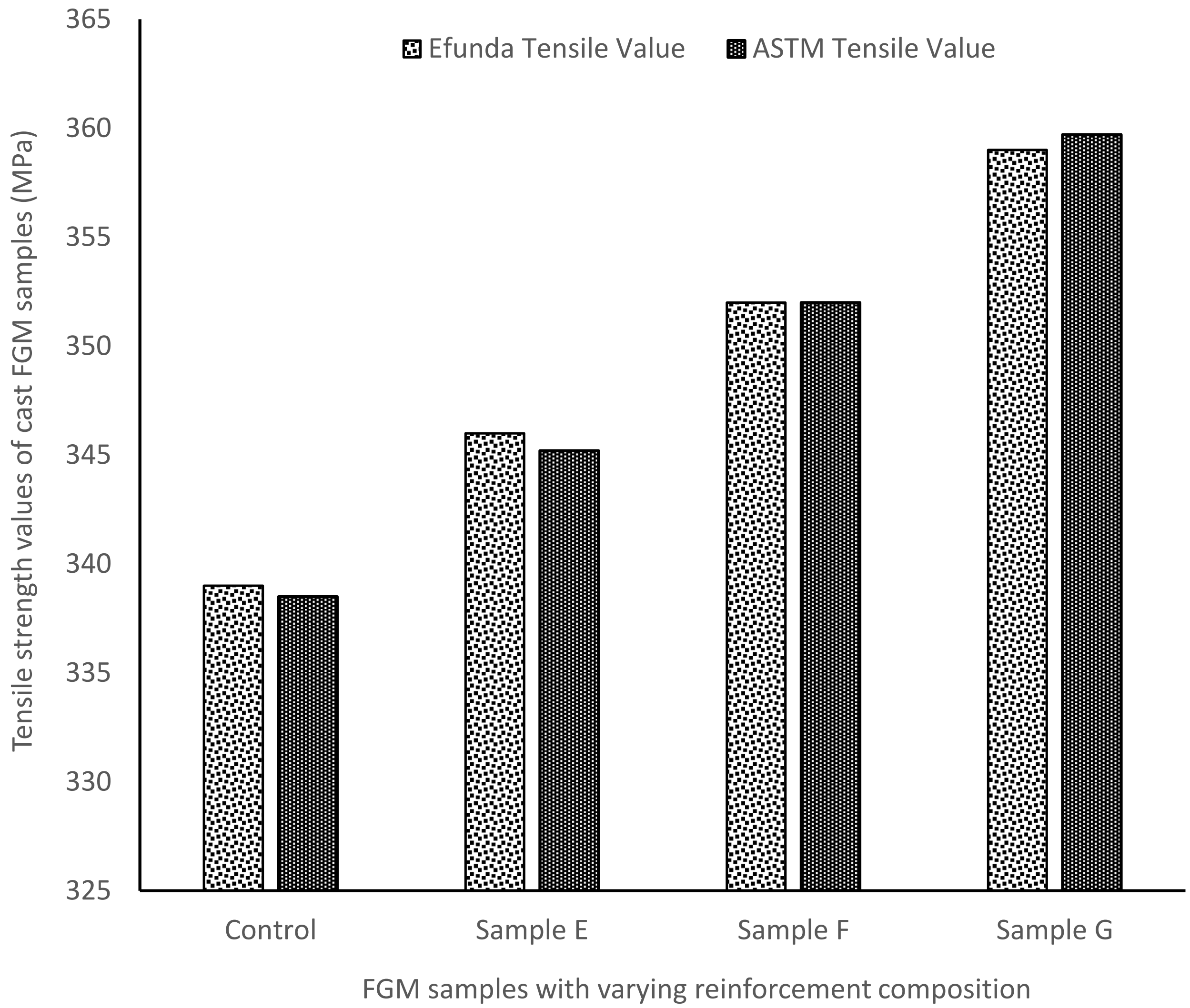

Figure 8. Comparative tensile strength property of the cast materials.

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.

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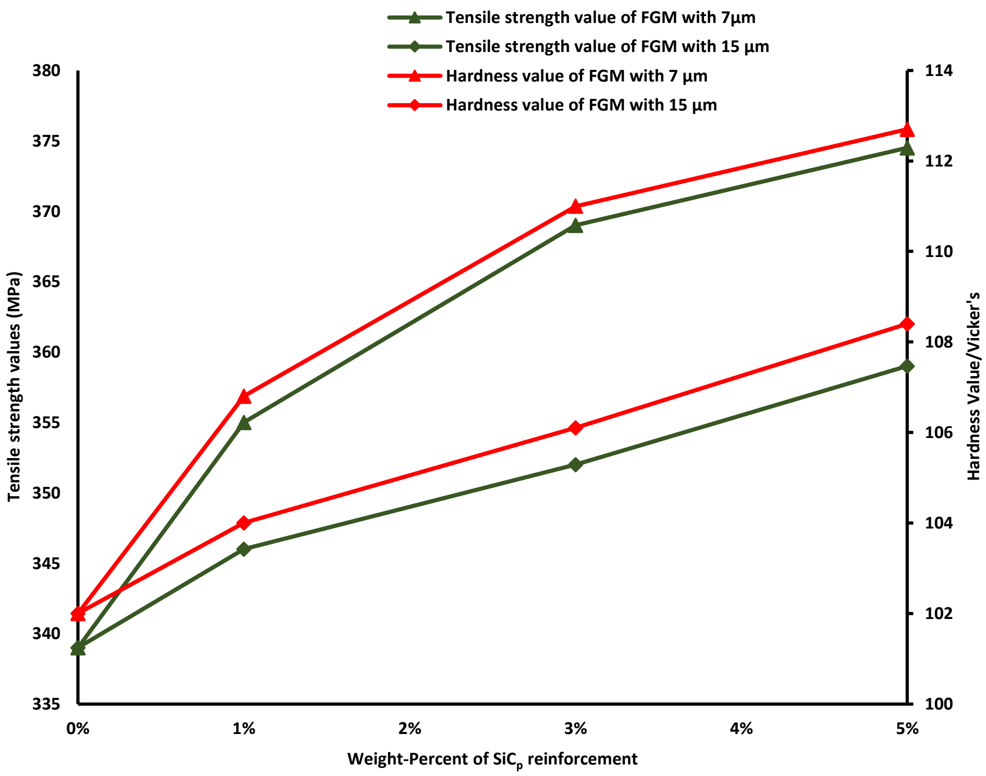

Figure 9. Effect of particle size of reinforcements on hardness property of cast FGM

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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