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Development of Controller-Based Interchangeable Axis Centrifugal Casting Machine and Characterization of Aluminum-Silicon Carbide (Al-SiC) Functional Graded Composite

Naveen Kumar SN [1] , Devarajaiah RM [1] , Manjunath Attel [1] , Nagaraja KC [2]

1. Mechatronics Engineering, Acharya Institute of Technology, Bangalore, IND 2. Mechanical Engineering, Acharya Institute of Technology, Bangalore, IND

Corresponding author: Devarajaiah RM, devarajaiah99@gmail.com

Abstract

Centrifugal casting is one of the prominent and simple methods to produce functionally graded composites (FGC). Functionally graded composites are a class of materials which possess continuously varying properties along the radial direction. Functionally graded composites have a wide variety of applications in different fields of engineering. The processing method of functionally graded composite plays a vital role in defining its properties. Centrifugal casts can be produced in vertical (for short annular casts of larger diameters) and horizontal (for long annular casts of smaller diameters) axis machines. Two different machines are being used to cast FGCs based on the application. This work is about the development of controller based centrifugal casting machine, which can be used both in vertical and horizontal orientations to produce annular casts. The characterisation of Silicon Carbide reinforced aluminium matrix functionally graded composite produced from the developed machine is also carried out. The results depict that the hollow cylindrical cast produced from the machine possesses varying characteristics along the inner and outer regions of the cast. The hardness and the wear characteristics of the outer region are found to be better than those of the inner region of the FGCs. The outer region of the FGC sample (95% Al-5% SiC) exhibited a higher average hardness of 35.68BHN, compared to 32.2BHN in the inner region with the same composition. This indicates improved surface hardness in the outer layer due to structural gradient effects. At 40N load, the inner sample exhibited a maximum wear rate of approximately 0.00018mg/m, while the outer sample showed a lower rate of about 0.000094mg/m. Across all loads (10-40N), the inner region consistently recorded higher wear rates, confirming enhanced wear resistance in the outer FGC layer.

Categories: Advanced Manufacturing Technologies, Advanced Materials, Materials Engineering
Keywords: centrifugal casting, functional graded composite, scanning electron microscope, wear test, aluminium composites

Introduction

Centrifugal casting is a special casting technique that is employed to produce cylindrical parts with high material integrity and structural uniformity. In this method, the mould is made to rotate at high rpm. Once the molten metal is poured into the rotating mould, the molten metal gets uniformly distributed along the walls of the mould due to the centrifugal force generated by the rotation of the mould. This results in material with superior metallurgical properties in comparison with the conventional casting process [1-6]. This rotational motion not only aids in the filling of intricate mould geometries but also facilitates directional solidification, which can lead to improved mechanical properties and reduced casting defects [5-7].

Functionally graded composites (FGCs) are a special category of composites in which the material properties change along a particular (radial) direction. This variation is due to the changes in composition or microstructure along that direction. These functionally graded composites can be processed using different methods such as powder metallurgy, coating, cladding, centrifugal casting, thermal spraying, and other similar techniques. Based on the requirements, functionally graded composites can be processed by controlling the reinforcement parameters such as size, density, quantity, and quantity of the reinforcement within the matrix material [8].

In the context of FGCs, centrifugal casting offers a promising avenue for processing components with tailored material compositions and properties [1]. FGCs are engineered materials designed to exhibit gradual variations in composition and microstructure, offering better performance characteristics such as wear resistance, thermal resistance, and corrosion resistance. By leveraging the controlled solidification process inherent in centrifugal casting, researchers can precisely control the distribution of different materials within a single component, thereby optimizing its functionality and performance under diverse operating conditions [9,10].

The centrifugal casting process is generally classified into true centrifugal casting, semi-centrifugal casting, and centrifuge. In true centrifugal casting, a cylindrical mould is used, which rotates about the central axis [11]. In the semi-centrifugal casting process, non-cylindrical but symmetrical parts are produced by rotating similar shaped moulds around the rotating axis of the casting machine. The centrifuge is a type of centrifugal casting machine in which non cylindrical and non-symmetrical parts are produced by using similarly shaped moulds. The molten metal enters the mould cavity through the sprue to enter the non-symmetrical mould. True centrifugal casting can be further classified into horizontal centrifugal casting and vertical centrifugal casting based on the axis of rotation of the mould. Horizontal centrifugal casting is used when the length of the material to be produced is more than the diameter of the mould, and vertical centrifugal casting is used when the diameter of the mould is more than the length of the mould to maintain the uniform thickness of the part produced [12-16].

Literature has shown that the casts produced from centrifugal casting machines with reinforcements such as aluminium oxide (Al_2O_3), silicon carbide (SiC), tungsten carbide (WC), and boron carbide (B_4C) in aluminium matrix possess enhanced hardness and wear resistance [6-8]. There have been attempts to analyze the impact of hybrid composites (multiple reinforcements with aluminium matrix). Even such hybrid composites have shown improvements in mechanical and tribological performance [9].

This work aimed at the development of a controller-based centrifugal casting machine with interchangeable orientations (horizontal/vertical). As a part of the work, a mobile app was also developed for the user to interact with the machine to control the process parameters such as speed and orientation.

This work also includes processing of SiC (silicon carbide) reinforced aluminium-based FGCs (by employing the horizontal orientation) and subsequent characterization of the produced casts.

Materials And Methods

Development of the centrifugal casting machine

The centrifugal casting technique relies on using the centrifugal force generated by mould rotation to evenly distribute molten metal, resulting in high-quality castings. The significant controlling parameter of the centrifugal casting process is the speed of rotation of the mould [9]. When the mould rotates along a horizontal or vertical axis, centrifugal force pushes the molten metal toward the outer edges of the mould cavity due to radial acceleration. As the molten metal is pushed toward the mould walls, it begins to solidify from the outer surface inward, a process known as directional solidification [10]. This controlled solidification ensures a refined grain structure and enhances the mechanical properties of the casting. If there is a density difference between the materials within the mould, the denser material experiences higher centrifugal force and moves toward the outer periphery of the cast, and the lighter materials remain toward the inner periphery of the cast.

This work aims at developing a centrifugal casting machine, taking into account the necessary parameters such as speed and orientation. This machine is capable of processing both vertical and horizontal centrifugal casts. The objective of the work is to develop a controller-based centrifugal casting machine that can work in both horizontal and vertical orientations of the mould.

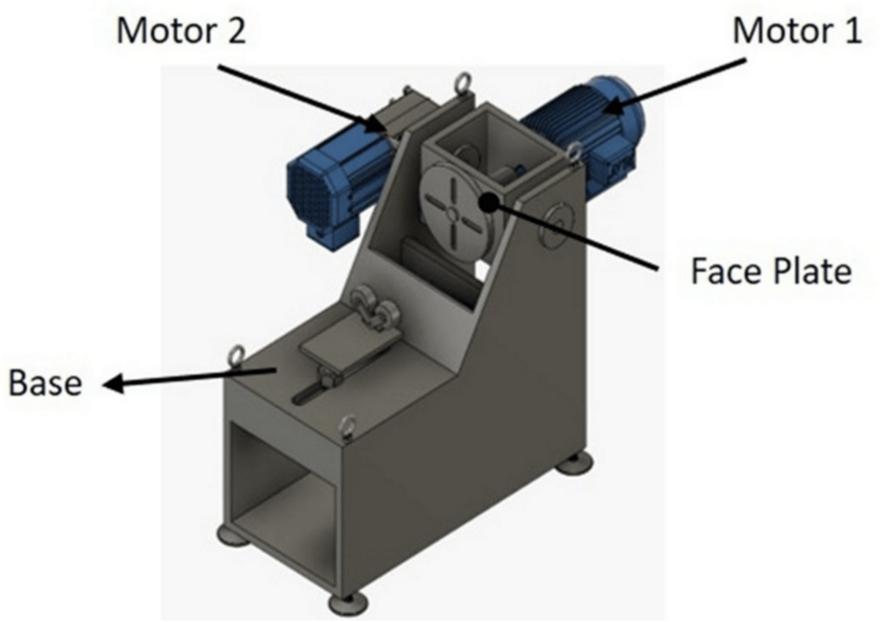

FIGURE 1: CAD model of the centrifugal casting machine

CAD, Computer-Aided Design

The components of the centrifugal casting machine are a solid base for housing the different components of the machine, and two motors, one for the rotation of the mould and the other for changing the axis of the mould. Figure 1 shows the Computer-Aided Design model of the centrifugal casting machine. Motor 1 is used to rotate the faceplate to which different-sized moulds can be attached. The face plate has slotted holes to accommodate different-sized moulds with an outer side diameter up to 140 mm. The shaft of Motor 1 shaft is connected to the face plate through a proper bearing and fixture. This complete assembly is housed above the supporting base. The Motor2, which is used to change the orientation of the machine, is placed on one side of the base. This motor is a geared motor is used to change the orientation of the machine. Two proximity sensors are used to provide input signals when the orientation reaches horizontal and vertical positions.

An exclusive control panel is used in the machine that contains all the control components like an HMI (human machine interface), Miniature Circuit Breakers, Programmable Logic Controller (PLC), Arduino controller, relays, Variable Frequency Drive, and control switches. Figure 2a shows the components in the control panel, and Figure 2b shows the circuit diagram of the control panel to control the speed and orientation of the machine. The control panel shows different components assembled within it.

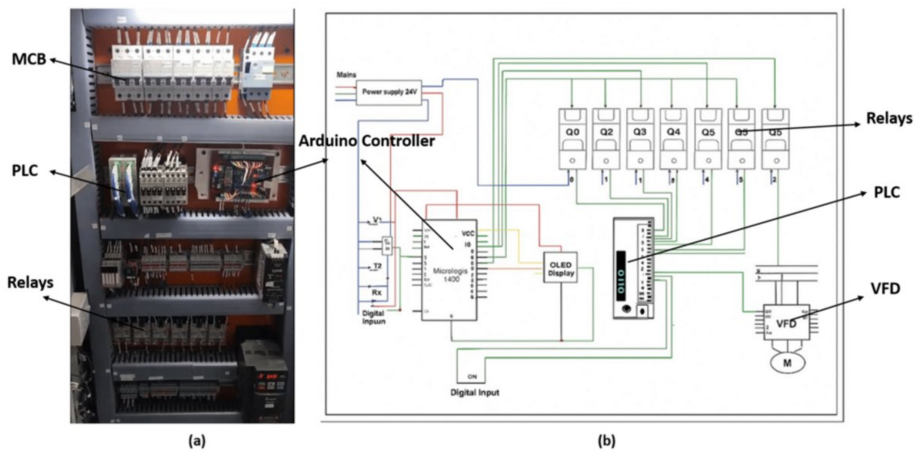

FIGURE 2: (a) Components of the control panel; (b) control circuit

Inputs can be given to the controller in two different ways, one is from the mobile phone app, and the other is from the HMI touch display attached to the control panel. There is an option on the controller to switch between the HMI and the mobile app. If the switch is in HMI mode, the first step is to log in to the controller through the login ID and password. After login, the user can enter the speed values in the settings option. Once the speed is set, the user can switch the motor on and off or change the configuration of the machine on the home screen. The input given from the HMI is sent to the PLC. From the PLC, the signal is sent to the motors based on the input parameters.

In the current work, a mobile app is also developed to give the inputs remotely to the machine. To give input from the mobile app, the user should first install the mobile app on the phone. In the controller, mobile app mode should be chosen to control the machine wirelessly. Through this mobile app, the first step is to connect the mobile phone to the controller using Bluetooth. Figure 3 shows the mobile app interface. The speed range of the machine is from 0 to 1450 rpm. In the mobile app, the maximum speed is mapped to 100% and the minimum speed is mapped to 0%. The rotational speed of the mould should be entered in percentage, starting from 0 to 100% for the speed range of 0 to 1450 rpm. The entered speed in terms of percentage will be shown in rpm on the screen. Once the required speed is set, the start button has to be pressed to start motor 1 to rotate the mould. Similarly, there are two options to choose from the orientation, one is horizontal and the other is vertical. The input given from the mobile app is transferred to the Arduino controller through the Bluetooth module. Then the signal is sent to the PLC. Based on the sensor signal and the input given to the controller, the PLC sends an actuating signal to the motors.

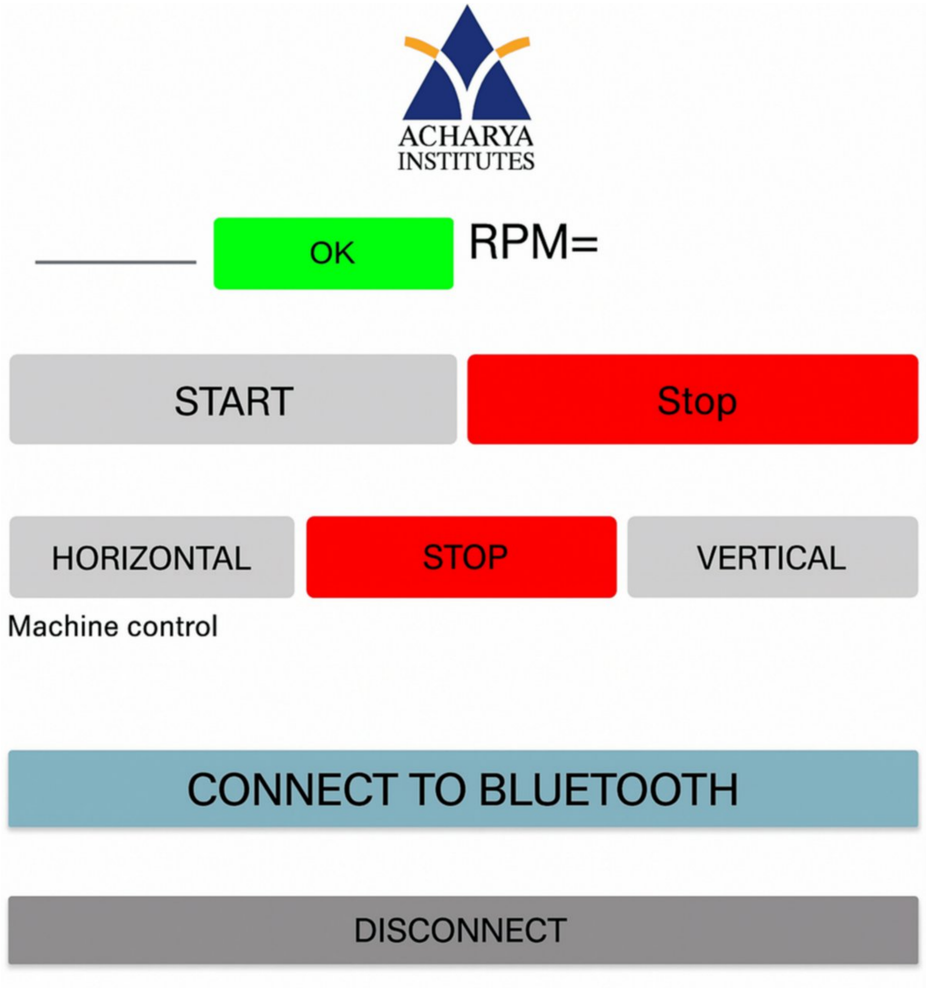

FIGURE 3: Mobile app interface

Processing of FGC

FGCs are a class of composite materials that possess continuously varying properties along a particular direction. In this work, an effort is made to produce a functionally graded composite with aluminium as the matrix material and silicon carbide (SiC) as reinforcement. To produce a functionally graded composite, we have considered 95% aluminium and 5% silicon carbide (SiC) (by volume fraction) based on literature studies. The processing is done using the centrifugal casting machine developed in-house.

The mould is attached to the face plate. For pouring molten metal into the mould, a pouring assembly is built. The pouring assembly can be adjusted to different heights using vertical and horizontal supports as shown in Figure 4a. Figure 4b shows the mould with the mould cover and the bottom plate to fix the mould with the faceplate.

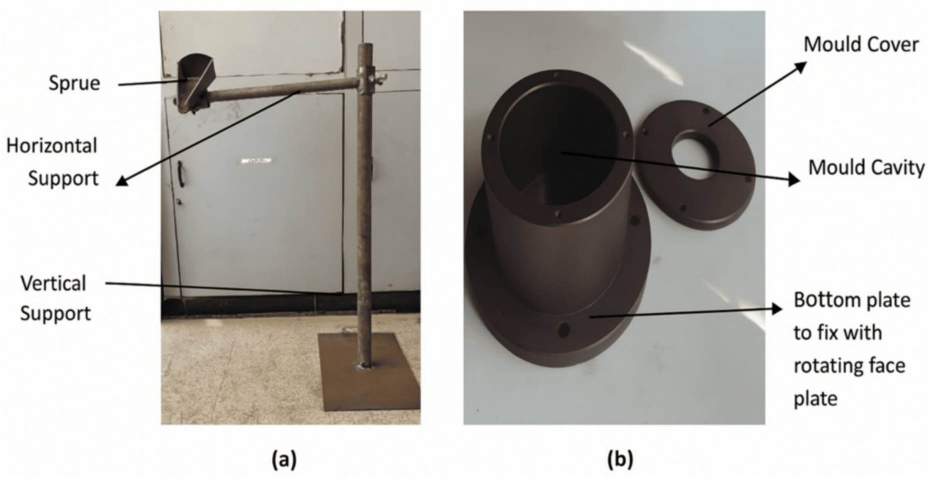

FIGURE 4: (a) Pouring assembly and (b) the mould

Based on the dimensions of the mould cavity and the thickness of the cast to be produced, the amount of the aluminium matrix and silicon carbide (SiC) reinforcement is calculated. Commercially available pure aluminium (aluminium 1100) is used as the matrix material. Aluminium 1100 sheets were purchased and cut into small pieces. Table 1 shows the composition of commercially available pure aluminium.

Elements	Al	Fe	Si	Cu	Ti	Zn	Mn	Mg
Weight %	99.97	0.015	0.015	0.004	0.002	0.001	0.001	0.001

TABLE 1: Composition of commercially available pure aluminium

Refer to reference [9].

In this work, aluminium is chosen as the matrix and silicon carbide (SiC) is chosen as matrix and reinforcement, respectively. Table 2 below shows the physical parameters of the constituents of the FGCs produced. Based on the literature, we have chosen aluminium and SiC, which have different densities between the matrix and reinforcement, to control the distribution of SiC in the aluminium matrix.

Properties	Aluminium	Silicon Carbide
Physical state	Sheets	Powder
Density	2.73 g/cm^3	3.21 g/cm^3
Particle size	Solid sheets are melted	10 μm
Composition	95%	5%

TABLE 2: Constituents of FGC

FGC, functionally graded composite

Silicon carbide (SiC) microparticles with an average particle size of 10 μm are purchased for reinforcement. Cut pieces of aluminium are weighed and placed into the melting furnace as shown in Figure *5a*. The required amount of SiC was weighed and preheated to a temperature of 250°C as shown in Figure *5b* and c. Once the aluminium is completely melted, the preheated SiC is poured into the molten aluminium and stirred so that the SiC completely mixes with the molten aluminium with continuous stirring. A mechanical stirrer is used to mix the reinforcement SiC, as shown in Figure *5d*. Figure *5e* shows the pouring of the aluminium and SiC mixture into the rotating mould using the pouring mechanism. From the literature, the quality of the cast produced from centrifugal casting is good for a speed range of 700 rpm to 1500 rpm. For this study, a constant mould speed of 1000 rpm is maintained.

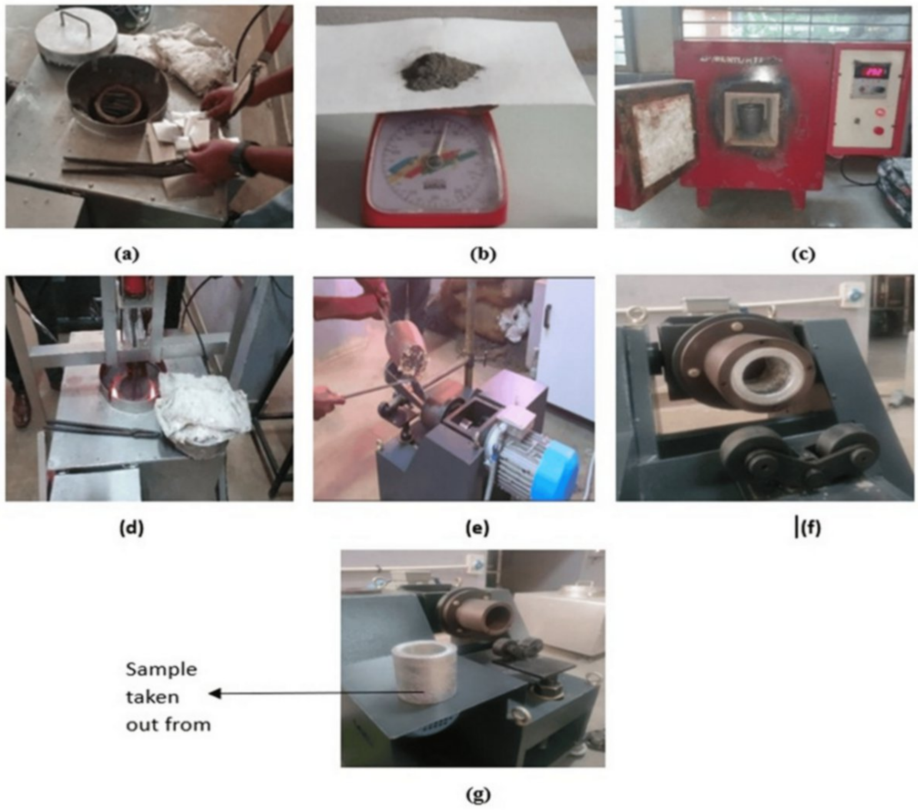

FIGURE 5: Experimental setup and process sequence of Al-SiC composite fabrication using the developed centrifugal casting machine: (a) Cut pieces of aluminium placed in the melting furnace, (b) Weighing of SiC reinforcement, (c) Preheating of SiC particles to 250°C, (d) Stirring of molten aluminium with SiC using a mechanical stirrer, (e) Pouring of the molten Al-SiC mixture into the rotating mould through the pouring mechanism, (f) Produced functionally graded composite (FGC) sample inside the mould, (g) Extracted FGC sample after cooling.

The cast is allowed to solidify within the rotating mould for around 5 minutes and then cooled to room temperature naturally. Then the sample is removed from the mould as shown in Figure *5f* and g. A hollow cylindrical cast is processed from the centrifugal casting process with 95% of aluminium matrix and 5% of SiC reinforcement by volume.

Results And Discussion

For the characterization of processed cast, two regions along the radial direction of the cast are considered, one toward the inner periphery and the other toward the outer periphery. To validate the FGCs, the specimen from the two regions of the processed cast is subjected to microstructural characterization, hardness test, and wear test. The results of the tests are discussed below.

Analysis of microstructure using Scanning Electron Microscope (SEM)

SEM images of the processed SiC reinforced FGCs were captured at different magnifications to analyze the distribution of SiC particles in the aluminium matrix at two different regions, namely the inner and outer regions. The SEM analysis was done at the CENSE center, IISc Bangalore.

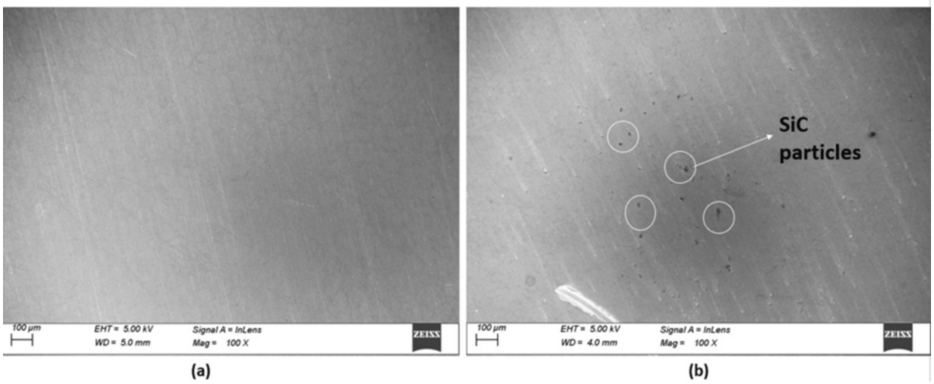

FIGURE 6: SEM images of SiC-reinforced aluminium matrix FGC at 100× magnification: (a) Inner region, (b) Outer region

SEM, Scanning Electron Microscope; FGC, functionally graded composite

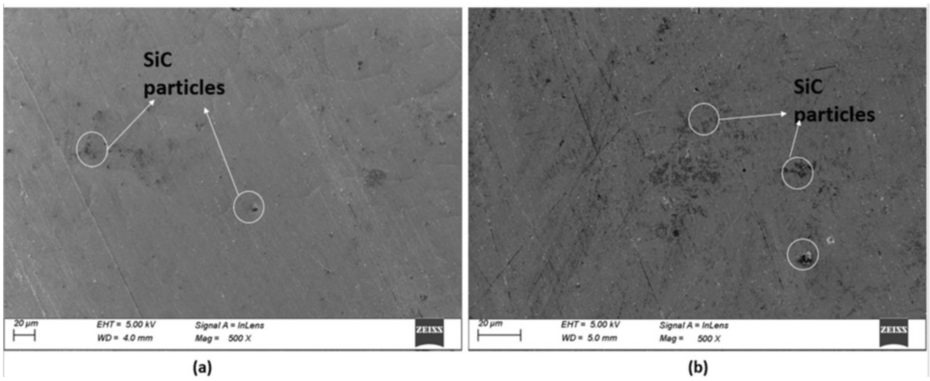

FIGURE 7: SEM images of SiC-reinforced aluminium matrix FGC at 500× magnification: (a) Inner region, (b) Outer region

SEM, Scanning Electron Microscope; FGC, functionally graded composite

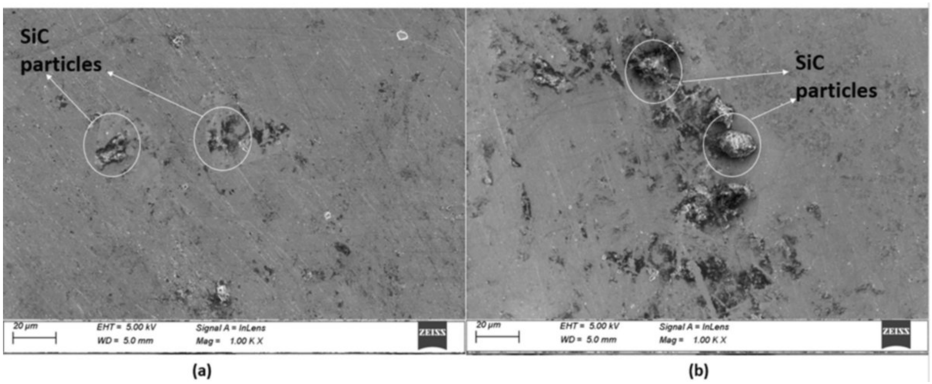

FIGURE 8: SEM images of SiC-reinforced aluminium matrix FGC at 1000× magnification: (a) Inner region, (b) Outer region

SEM, Scanning Electron Microscope; FGC, functionally graded composite

Figures 6, 7, and 8 show the SEM images of SiC-reinforced aluminium matrix FGC. Figure 6a shows the inner region of the FGC at 100× magnification. Figure 6b shows the outer region of FGC at 100× magnification. In these images, we can see small black dots that are more in the outer region than in the inner region. These black regions are SiC particles distributed in the grey aluminium matrix regions.

Figures 7 and 8 show the processed FGC at 500× and 1000× magnification, respectively. In both images, the outer region shows more SiC particles, which is because of the density difference between reinforcement SiC and the matrix aluminium. As the SiC particles have a higher density, higher centrifugal force pushes these particles toward the outer region of the specimen. This is witnessed in the SEM images.

Hardness test

Hardness of any material can be defined as the ability of the material to resist scratches on it. It is one of the important mechanical properties of materials. To measure the hardness of the material, a Brinell hardness test was performed. The type of indenter used is ball indentation to apply the force. The force applied in the test for indentation on the sample is 250 kgf, and the ball diameter is 5 mm, according to the ASTM E10 standard. The following Table 3 shows the results of both inner and outer samples.

S. No.	Composition		Region	BHN					
	Al	SiC		1	2	3	4	5	Average
1	95%	5%	Outer	36	34.5	36	35.8	36.1	35.68
2	95%	5%	Inner	32.1	32.6	31.6	32.5	32.2	32.2

TABLE 3: Hardness test (Brinell Test) results

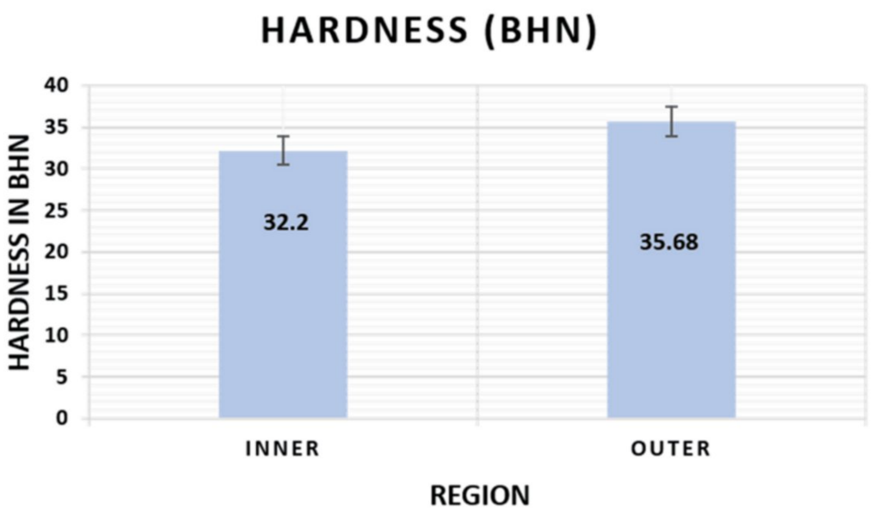

FIGURE 9: Comparison of hardness

From the results, we can see that the hardness of the outer region of the FGC is higher than that of the inner region. In the processed FGC, the hardness of the outer region is found to be 10.8% higher than in the inner region. This is due to the higher concentration of SiC particles in the outer region. It can be noted here that the density of SiC is 3.21 g/cm^3 and that of aluminium is 2.73 g/cm^3. To get these data, the results are captured at five different points within the same region, and the average of those five readings is considered as hardness. The error bar in the form of the standard deviation of those readings is also included in Figure 9. Hardness of a material is also directly proportional to its wear resistance. The results are similar to previous works that showed the varying hardness along the radial direction of the FGC [17-19].

Wear test

The objective of the wear test was to evaluate the wear resistance of SiC reinforced aluminium-based FGC samples. The specimens were chosen from the inner and outer regions of the cast. A pin-on disc two body adhesive wear test was conducted according to ASTM G99-17 standards.

The wear tests were conducted under controlled conditions to ensure accuracy and repeatability. The sliding distance for each test was 1800 m, with a sliding velocity of 2 m/s, on a track of 100 mm diameter.

The wear loss was determined for different loads of 10 N, 20 N, 30 N, and 40 N. These conditions were selected based on the literature and to simulate practical wear scenarios and to extract meaningful data for comparison.

Mass loss

The wear test results for both outer and inner samples are summarized in Figure *10*, based on the mass measured before and after each test. It can be noticed from the graph that the mass loss at every load in the outer region is smaller than that in the inner region. These results correlate with the hardness results, as plotted in Figure *9*.

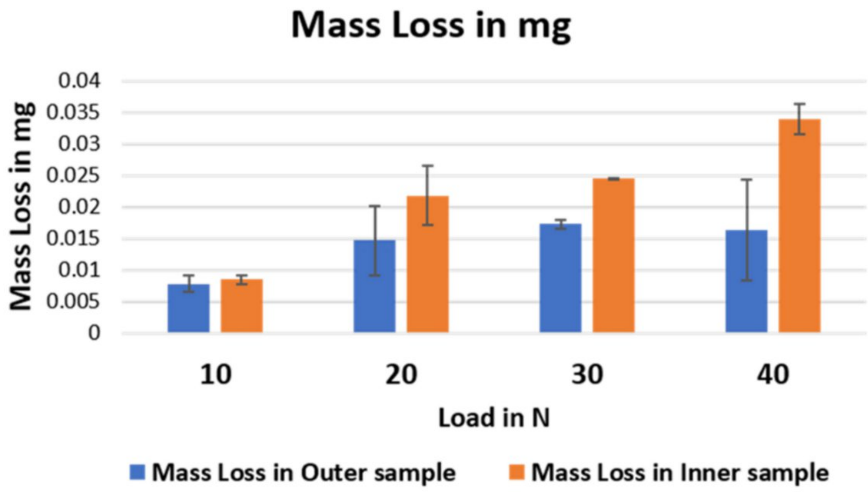

FIGURE 10: Mass loss during wear test at different load conditions

For the outer sample, the wear test under a 10 N load indicated a mass loss of 0.0078 g. When the load was increased to 20 N, a mass loss of 0.0140 g was observed. At a load of 30 N, a mass loss of 0.0177 g was observed. Finally, under a load of 40 N, a mass loss of 0.0167 g was captured. These data indicate that the mass loss increased with the applied load, though there was a slight decrease in mass loss at the highest load, suggesting a possible threshold.

For the inner sample, under a 10 N load, a mass loss of 0.0084 g was observed. When the load was increased to 20 N, a mass loss of 0.0217 g was observed. At a load of 30 N, a mass loss of 0.0244 g was captured. Finally, under a load of 40 N, a mass loss of 0.033 g was observed.

These data indicate that the inner sample exhibited slightly higher mass loss values compared to the outer sample, especially at higher loads. The wear rate surged at 30 N and 40 N loads.

Wear rate

Wear rate is nothing but the amount of material lost when subjected to wear at a constant load and specific distance. The wear rate represents the gradual loss of material due to friction. It quantifies the amount of material lost when subjected to wear at constant load and over a specific distance. The equation below gives the formula for the wear rate

$$[\text{Wear Rate} = \frac{W_1 - W_2}{D} \quad \begin{cases} W_1 = \text{initial weight (mg)} \\ W_2 = \text{final weight (mg)} \\ D = \text{sliding distance (m)} \end{cases} \quad]$$

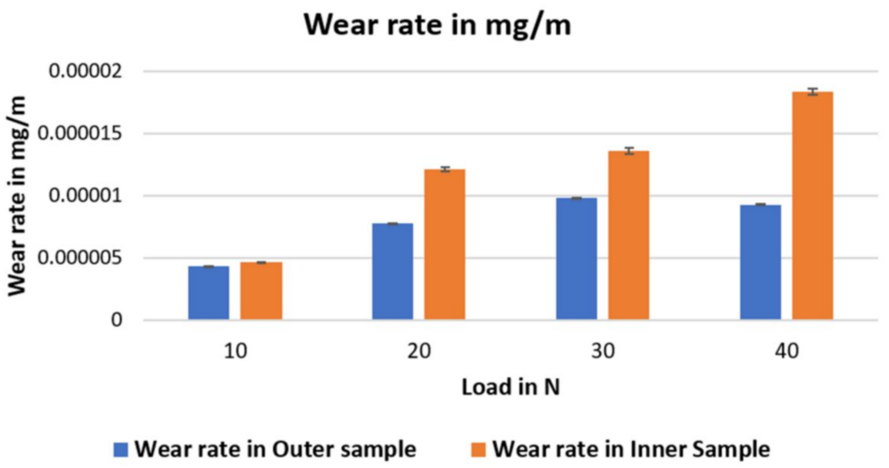

FIGURE 11: Wear rate at different load conditions

Figure *11* shows the wear rate comparison of the outer and inner samples of the FGC at different loading conditions. From this, we can observe that the wear rate of the inner sample is higher compared to the outer sample. For both the outer and inner regions, as the load increases, the wear rate increases. But, wear rate is notably higher in the inner region in comparison with the outer region. It is because of the difference in the presence of reinforcement between the inner and outer regions. In the same results, we can observe that as load increases in the wear test, the wear rate increases in both the outer and inner regions of the FGC samples. At lower load conditions, the wear rate is almost similar. As the load increases, the difference in wear rate also increases between the outer and inner samples. Few of the previous works show similar results in the wear behavior of the FGCs [17-19].

These results imply that the outer sample has better wear resistance in comparison with the inner sample. This can be attributed to the higher concentration of SiC in the outer samples, due to the higher concentration of SiC. This may be the main reason for the change in wear behavior of the two samples. The sample with higher SiC particles has shown better wear resistance than the inner sample.

Conclusions

Centrifugal casting is one of the oldest and simplest methods for the processing of functionally graded materials. True centrifugal casting processes can be done by keeping the axis of rotation either horizontally or vertically. Conventionally, industries use separate machines for both horizontal and vertical centrifugal casting machines. This work was aimed at:

Development of a controller-based centrifugal casting machine that can be used in both horizontal and vertical orientations.

Processing of SiC-reinforced aluminium matrix FGC material using the developed centrifugal casting machine.

Characterization of processed FGC for microstructure, hardness, and wear rates for inner and outer regions of the samples.

SEM images confirmed a higher concentration of SiC reinforcement in the outer region of the specimen. The hardness results of the inner and outer regions also validate the processing of a functionally graded composite. Further wear tests were conducted at four different loading conditions. From the results, it is evident that the distribution of SiC particles is higher at the outer region in comparison with the inner region, providing the functionally graded properties to the sample. The presence of SiC has improved the hardness and wear characteristics of the sample in the outer region. A FGC of SiC-reinforced aluminium-based FGC is processed using a centrifugal casting machine. The experimental analysis of FGC samples revealed a distinct variation in mechanical performance across the gradient. The outer region demonstrated superior hardness (35.68BHN) and lower wear rate (0.000094mg/m at 40N) compared to the inner region, highlighting the benefits of compositional grading. These results show around 10% increase in hardness and around 7% lower wear rate at 40 N load in the outer region in comparison with the inner region. These findings confirm that tailored material distribution in FGCs enhances surface durability under mechanical stress.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Naveen Kumar SN, Devarajaiah RM, Manjunath Attel, Nagaraja KC

Acquisition, analysis, or interpretation of data: Naveen Kumar SN, Devarajaiah RM, Manjunath Attel, Nagaraja KC

Drafting of the manuscript: Naveen Kumar SN, Manjunath Attel, Nagaraja KC

Critical review of the manuscript for important intellectual content: Naveen Kumar SN, Devarajaiah RM, Manjunath Attel, Nagaraja KC

Supervision: Devarajaiah RM, Manjunath Attel, Nagaraja KC

Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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