Ciencia Latina Revista Científica Multidisciplinar
Septiembre-Octubre, 2023, Volumen 7, Número 5
https://doi.org/10.37811/cl_rcm.v7i5.7961

Fabrication of a Functionally Graded Material by ex situ Centrifugal Casting Method

Ing. Luis Gustavo Huilca Caisalitín Msc. [1]
luis.huilca@epn.edu.ec
https://orcid.org/0000-0002-6366-0706
Escuela Politécnica Nacional
de Quito Ecuador
National Polytechnic University
from Quito – Ecuador

Ing. Fausto Hernán Oviedo Fierro Msc.
fausto.oviedo@epn.edu.ec
https://orcid.org/0000-0002-1973-7577
Escuela Politécnica Nacional
de Quito Ecuador
National Polytechnic University
from Quito - Ecuador

ABSTRACT

This study focuses on the fabrication of a functionally graded material (FGM) with an aluminum matrix and silicon carbide reinforcement particles using the horizontal centrifugal casting method. The equipment used was the Stir Casting, and centrifugal casting machine. The fabrication of the FGM was carried out by prioritizing specific parameters such as temperature and mold rotation speed, molten matrix temperature, size and weight percentage of the SiC particles (mesh #400 and #320 respectively); once the parameters were defined, the material was fabricated by the horizontal centrifugal casting method ex-situ. A molten Al 365 alloy was used as matrix material and subsequent homogenization with SiC particles, a mixture under the required parameters was poured in the horizontal rotating mold at speeds of 1000 and 1200 rpm respectively, the permanent rotative mold allowed for obtaining a functionally graded tube from which specimens were extracted and characterized by metallographic analysis and microhardness.

Keywords: *ex situ centrifugal casting; functionally graded material; silicon carbide; microhardness*

[1] Autor principal
Correspondencia: luis.huilca@epn.edu.ec

Fabricación de un Material Funcionalmente Graduado por el Método de Colado Centrífugo Ex Situ

RESUMEN

Este estudio se centra en la fabricación de un material funcionalmente graduado (FGM) con una matriz de aluminio y partículas de refuerzo de carburo de silicio utilizando el método de colado centrífugo horizontal. El equipo utilizado fue el Stir Casting, y la máquina de colado centrífugo. La fabricación del FGM se llevó a cabo priorizando parámetros específicos como la temperatura, velocidad de rotación del molde, temperatura de la matriz fundida, tamaño y porcentaje en peso de las partículas de SiC (malla #400 y #320 respectivamente); una vez definidos los parámetros, el material se fabricó por el método de colada centrífuga horizontal ex-situ. Se utilizó una aleación fundida de Al 365 como material matriz y posterior homogeneización con partículas de SiC, se vertió una mezcla bajo los parámetros requeridos en el molde rotativo horizontal a velocidades de 1000 y 1200 rpm respectivamente, el molde rotativo permanente permitió obtener un tubo funcionalmente graduado del cual se extrajeron probetas que fueron caracterizadas por análisis metalográfico y microdureza.

Palabras clave: *fundición centrífuga ex situ; material funcionalmente graduado; carburo de silicio; microdureza.*

Artículo recibido 19 agosto: 2023

Aceptado para publicación: 29 setiembre 2023

INTRODUCTION AND BACKGROUND

The study focuses on obtaining a functionally graded material (FGM) that combines different constituents to create a material with unique properties. FGMs are attractive for various applications, among which the automotive and aerospace industries stand out, due to their improved physical and mechanical properties. Researchers have drawn inspiration from natural structures to design advanced materials.

Definition and importance of functionally graded materials (FGMs)

FGMs are materials composed of two or more constituents with significantly different properties, which combine to create a material with characteristics corresponding to each constituent [1]. FGMs offer improved strength, modulus, and high-temperature resistance compared to monolithic materials and are important for various engineering applications [2], [3].

Significance of FGMs in aerospace and automotive industries

FGMs are particularly attractive for the aerospace and automotive industries due to their improved physical and mechanical properties. FGMs provide a combination of metallic properties (ductility and toughness) from the matrix and ceramic properties (high strength and modulus) from the reinforcement. The use of FGMs in these industries can result in higher strength, modulus, and ability to withstand high temperatures compared to traditional materials [4]–[6]. Although several experiments exist for the in-situ centrifugal casting method, few exist for the method discussed in this paper.

Comparison with natural structures for designing advanced materials

Researchers have found functional structures with gradient properties in nature formations. This inspiration has allowed researchers to design similar models of advanced materials. The increasing importance of Industry 4.0 has also contributed to the development of advanced materials based on natural structures [6].

MATERIAL SELECTION

The materials used for the manufacture of functionally graded materials (FGMs) are metals with alloy percentages that allow the matrix to acquire suitable properties for different engineering applications. The most commonly used matrix material for FGMs is aluminum due to its adequate mechanical properties such as hardness, wear resistance, specific modulus, and a low coefficient of thermal expansion [4].

Properties required for the matrix material in FGMs:

The matrix material in FGMs should have properties like ductility and toughness (metallic properties) as well as high strength and modulus (ceramic properties).The addition of reinforcement particles improves the mechanical properties of the matrix material, such as resistance to high temperatures, adequate Young's modulus, and high tensile strength [4].

Advantages of using aluminum as the matrix material:

Aluminum casting provides a significant mass-saving compared to gray cast iron, making it suitable for the development of FGMs in various areas of research and industry. Aluminum has properties such as resistance to wear, corrosion resistance, good thermal conductivity, low density, and high strength, making it an attractive choice for FGMs [7]. For the manufacture of the FGM, an aluminum matrix was used that is within the 3xx.x alloy series (ANSI AA 365.0), which is identified through the ANSI H35.1 standards [8], It must be fulfilled that it is a matrix used in industrial environments of the automotive sector or the manufacturing sector, according to the ANSI standard, the matrices of greater use in the selection of alloys are 3xx.x, 4xx.x, and 4xxx [7].

Role of reinforcement particles (e.g., silicon carbide):

Silicon carbide (SiC) is a commonly used ceramic reinforcement particle in the production of composite materials. SiC particles are added to the aluminum matrix to improve the mechanical, wear, and high-temperature resistance properties of functionally graded materials. SiC particles have high thermal resistance, hardness, wear resistance, and corrosion resistance [9].

Rotary Machine Mold Features

Centrifugal force casting mold consists of an inlet nozzle, guides, liner, and end caps. It is used according to the shape and amount of material intended to be cast [9]. The mold of centrifugal casting machine consists of an A36 steel tube with a length of 60.96 cm, an outer diameter of 12.54 cm, and an inner diameter of 9.98 cm. The A36 steel has properties suitable to withstand high temperatures, which is required for the centrifugal casting process [10]–[13].

Centrifugal force casting method

Casting by centrifugal force is a liquid state method, the parameters involved in the process are: rotational speed, feed rate, mold preheating, ceramic reinforcement particle size, and weight percentage fraction [4], [13].

In-situ centrifugal force casting process

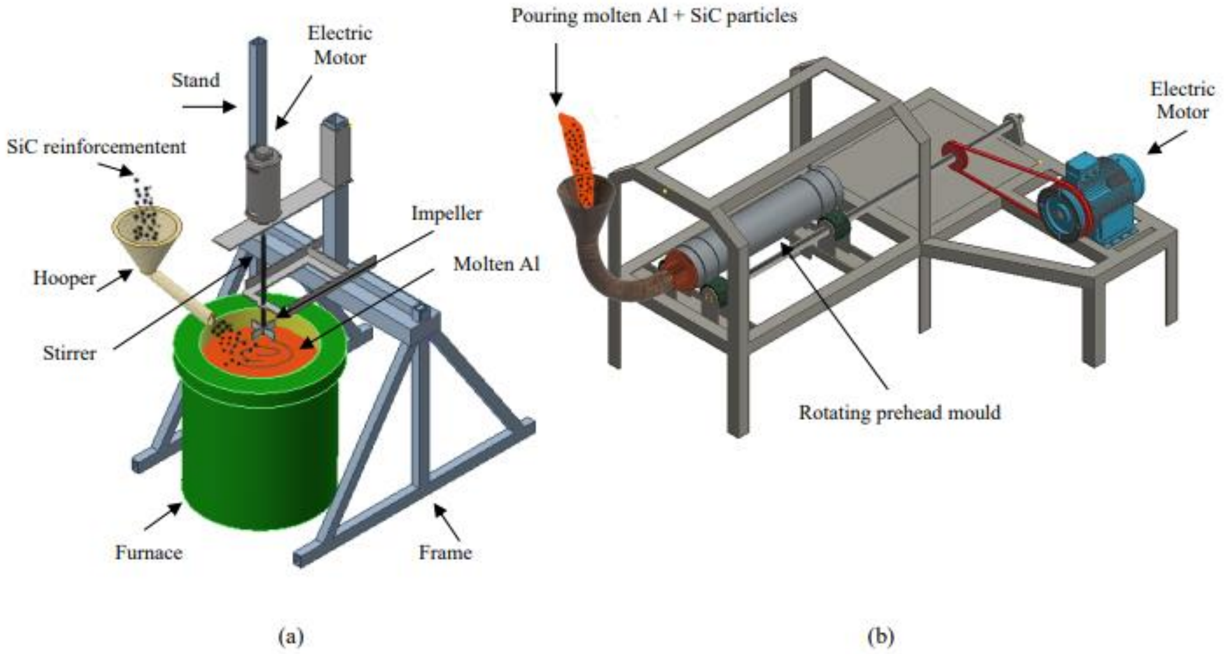
The in-situ centrifugal force casting process is a method in which the reinforcement particles take place inside the matrix during process. The first step is the matrix casting and the ceramic particles are added to be mixed with the casting and subsequently homogenize the mixture as shown in figure 1a, then it has to be cast in the centrifugal casting machine to obtain the FGM as shown in figure 1b [9].

Casting method by centrifugal force with solid particles or ex-situ

To produce a tube with graded properties, reinforcing materials with a melting temperature higher than the temperature of the matrix are used, i.e., the particles remain solid during the process prior to centrifugal casting and then, together with the matrix, are distributed in a mold along the radial direction under the influence of centrifugal force. The hard particles are distributed on the outer or inner surface forming a functionally graded tube, depending on the density between the base metal or matrix and the particles [4].

Figure 1

Procedure for obtaining an FGM by ex situ method: (a) Mixing of reinforcement particles with molten metal matrix; (b) Synthesis of FGM through horizontal centrifugal casting



METHODOLOGY:

Description of the ex-situ horizontal centrifugal casting method:

The ex-situ horizontal centrifugal casting method involves the matrix (ANSI AA 365.0 alloy). Ceramic SiC particles are added to the molten matrix and mixed using Stir Casting equipment and after pouring the mixture into the horizontal centrifugal casting machine mold in which the melted and homogenized mixture is poured in a progressive and fast manner.

Composition of the matrix material (ANSI AA 365.0 alloy):

The matrix material used for manufacturing the functionally graded material is the ANSI AA 365.0 alloy, which is an aluminum alloy with a percentage of 10.32% of silicon. Their chemical composition is shown in table 1:

Table 1. Aluminum matrix chemical composition ANSI AA 365.0 [14].

Numerical series			**Chemical composition in Wt%**											
ANSI AA Standart	**EN AC Standart**	**EN AC standart in composition**	**Type**	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Ti**	**Sn**	**Other unspecified items**	
													Every one	**Total**
365.0	43500	AlSi10Mn	Chem. Comp.	10.32	0.23	0.01	0.35	0.29	0.01	0.02	0.03	---		
			Sstandart limit	9.5-11.5	0.15	0.03	0.5-0.8	0.1-0.5	---	0.07	0.04-0.15	0.03	0.03	0.1

Characteristics of the SiC reinforcement particles:

The SiC reinforcement particles used in the study are ceramic particles with high thermal resistance, hardness, wear resistance, and corrosion resistance. They have an irregular polyhedral shape and are available in different sizes (e.g., #320 mesh and #400 mesh). The particle sizes range from 12.89 to 500 µm, and the weight fraction varies from 2.5 to 20%. The particles whose appearance can be seen in Figure 2 were subjected to laser particle size analysis to determine their average diameter, since particles do not have the same size, as can be seen in Table 2:

Figure 2

Silicon carbide particles used

Table 2

SiC particle diameters by laser granulometry

			SiC particle	diameter (μm)
Container	**(ni)**	**Parameters(di)**	**#320**	**#400**
n10	0,1	d10	12,2	9,5
n50	0,5	d50	35,5	20,4
n60	0,6	d60	40,2	23,1
n80	0,8	d80	52,9	30,3
n90	0,9	d90	65,6	37,0

The average diameter of SiC particles was done using equation 1 obtained from the reference Vision Analytical Inc [15], in which the results of granulometry analysis will be carried out as follows:

Average particle diameter:

$$D = \frac{(\sum n_i d_i)}{N} \quad \text{Eq. 1}$$

$$N = \sum n_i$$

Where D represents the average particle diameter, n_i is the container size, d_i is the representative diameter of each sample size, and n is the total container size count. By using the formula, it is established that the particle size for the indicated cases is as shown in table 3:

Table 3.

Values of particle diameter used.

	Diameter
320 mesh (μm)	49,81
400 mesh (μm)	28,46

Parameters and conditions for the casting process:

For manufacturing the functionally graded material with aluminum matrix and SiC ceramic particle reinforcement, the parameters presented in Table 4 were used:

Table 4

Parameters for the formation of the FGM

SiC Particles	#320 (49.81 µm)	#400(28.46 µm)
Aluminum Matrix (Pistons)	ANSI AA 365.0	
Weight percentage of SiC particles	6%	
Al-Si matrix temperature	750 - 780 ºC	
Mold preheat temperature	240 - 248 ºC	
Stir Casting Speed	500 - 600 rpm	
Casting time	8 min	
Centrifugal casting machine mold	A36 steel tube with a length of 60.96 cm and diameter 11.3 cm	
Melting furnace	Maximum temperature 1200°C, 7kg of capacity	
Centrifugal machine speed	1000 rpm	1200rpm

In relation to the above parameters, the following should also be taken into account the use of degassing and grain refiners during the casting process and the use of fluxes to protect the molten metal from oxidation and gas absorption.

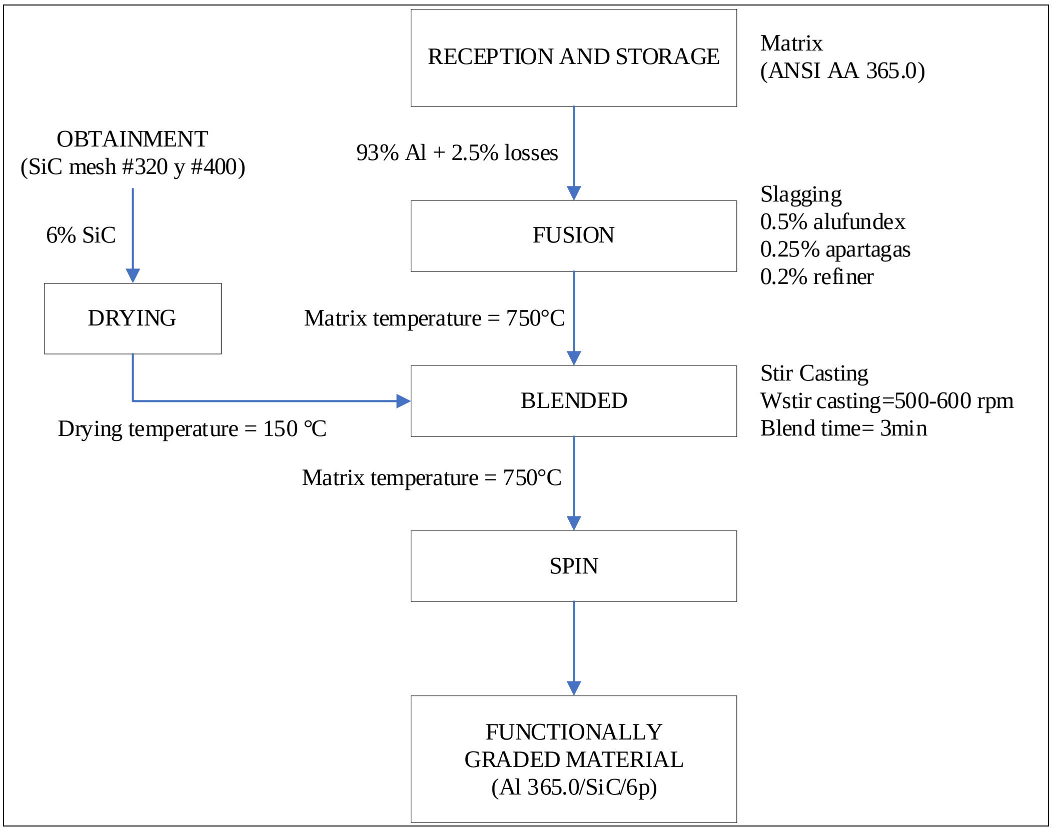
Experimental process:

The process is detailed in the diagram shown in Figure 3, where FGM manufacturing method is sequentially established

- Reception and storage of ANSI AA 365.0 aluminum pistons for later use.
- Melting process: Weighing 4777.5 g of aluminum pistons (matrix), 300 g of SiC particles (#320 and #400), 25 g of flux, 12.5 g of gasifier, and 10 g of grain refiner.
- Casting the pistons and removing the slag from the surface of the casting.
- Adding the degassing agent and then the refiner and drying the SiC particles.
- Mixing process using Stir Casting equipment to create a vortex in the molten matrix.
- Pouring the mixture into the preheated horizontal centrifugal casting machine mold at the specified speed (1000 rpm for #320 mesh particles and 1200 rpm for #400 mesh particles).
- Cutting two 1.5 cm rings from the obtained tube for analysis.
- Characterizing the material through metallographic testing and microhardness testing.

Figure 3

Process diagram for FGM manufacturing by the ex-situ horizontal centrifugal casting method

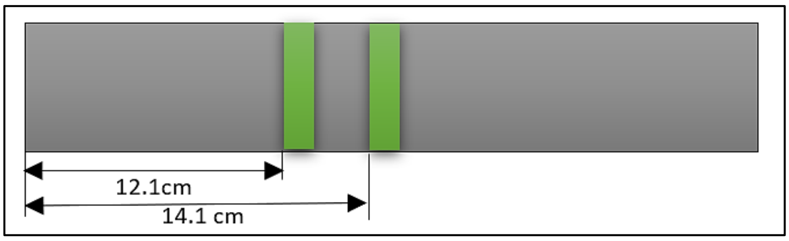


MECHANICAL CHARACTERIZATION

Once the tube was obtained from the horizontal centrifugal casting machine, two 1.5 cm rings were cut a distance of 12.1 cm and 14.1 cm as shown in Figure 8, which are the interest areas that will allow observing how SiC particles have been distributed along the cross-section of the functionally graded tube.

Figure 8

FGM tube cutting distance



Finally, 16 specimens were considered for analysis, as shown in Figure 4

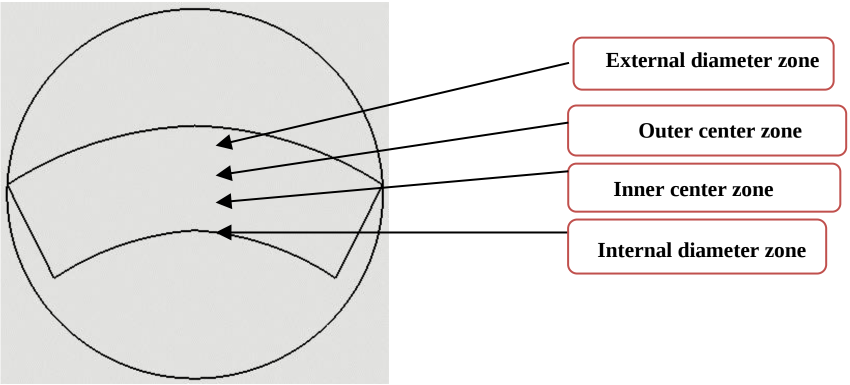
Figure 4

FGM specimens with SiC particles

For the characterization of the material obtained, we took into account the signaling shown in Figure 5, which shows the areas analyzed in the cross section of the functionally graded tube:

Figure 5

Analysis zones in the FGM specimen



Metallography test to examine the microstructure of the FGM

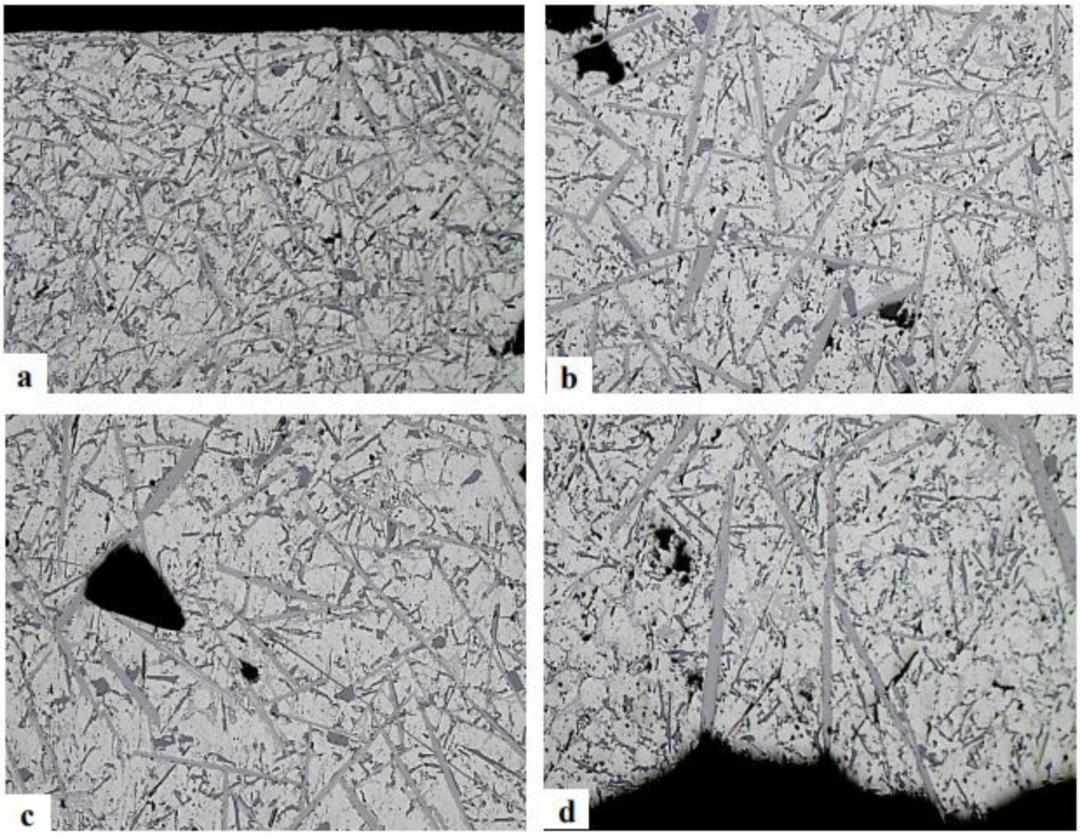
The metallography process was carried out using an Olympus GX41 optical microscope as shown in Figures 12 and 13, taking into consideration the same visualization line to appreciate the change that occurs in the microstructure along its cross-section. Taking into consideration the test was carried out in sections where the microstructure can be appreciated at a 100X magnification.

Material metallography for Al 365.0/SiC/6p for SiC mesh # 320 and 1000 rpm

The metallographs without chemical attack obtained were taken in represented zones in Figure 11, SiC particles have an irregular polyhedron shape of dark gray color, forming the characteristic distribution gradient of FGMs along the cross-section as can be seen in Figure 6. From the outer diameter zone (Figure 6a) to the central zone where it can be noticed there is an accumulation of particles (Figure 6b and Figure 6c), the microconstituents increase to the inner diameter zone (Figure 6d), taking into consideration that the SiC particles have reacted with the alloying elements belonging to the matrix and forming constituents. The distribution of the particles was produced due to the centrifugal force, emphasizing there was a considerable accumulation of larger particles in the central zone, while in the outer diameter zone, there is a small accumulation of particles with a smaller size.

Figure 6

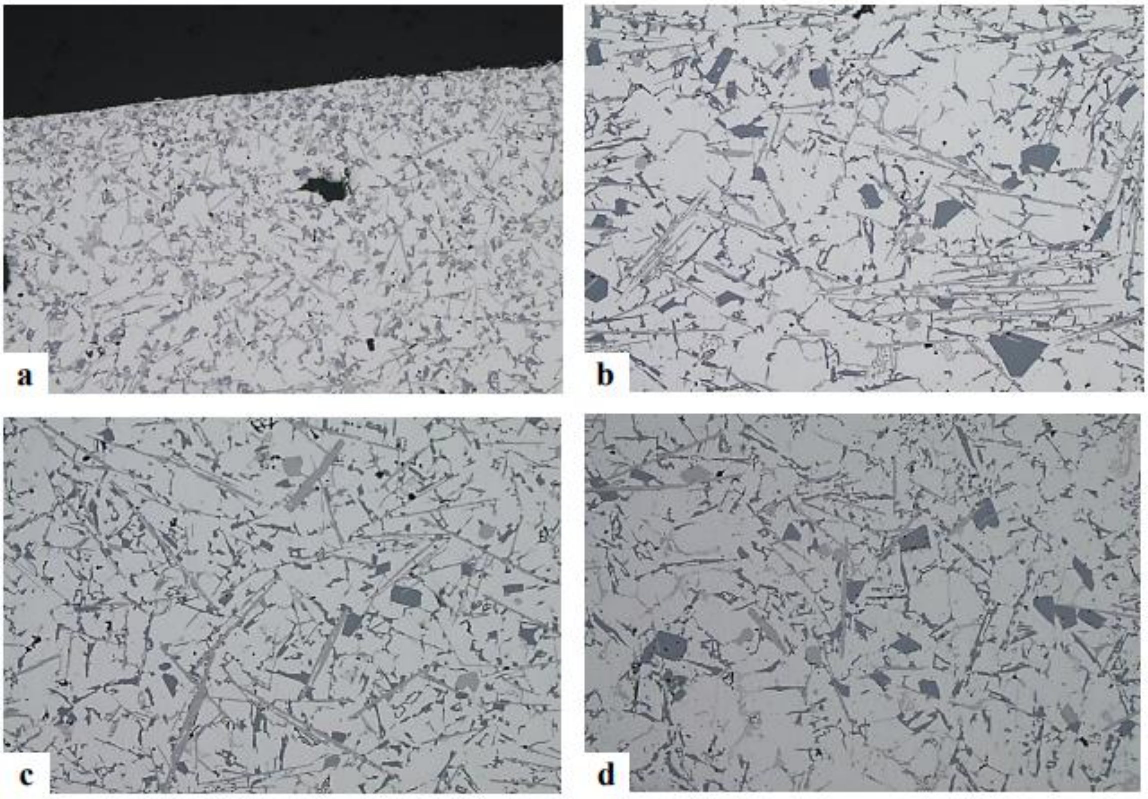
Metallography at 100X of distribution gradient along the FGM cross-section od the specimen with #320 mesh, silicon carbide, and 1000rpm: (a) Outside diameter zone; (b) and (c) intermediate zone, and (c) inside diameter zone



Material metallography for Al 365.0/SiC/6p for SiC mesh # 400 and 1200 rpm

As shown in Figure 7, the SiC particles are seen with an irregular polyhedral geometry, the distribution gradient of SiC particles is studied in the radial direction and goes in the order of smaller quantity from the inner diameter zone to a greater quantity in the outer diameter zone of the tube, at first sight it can be observed that the ceramic particles have a greater size in the inner diameter and as it advances to the central zone as to the upper zone, the size of these is reduced but there is a greater quantity, this is evident in the lower and upper central zones as SiC particles retain irregular polyhedral morphology but distributed in greater quantity, it must differentiate the silicon is also evident of the same color but this has different morphologies such as needle type, platelets and chinese writing, this amount of silicon is characteristic of the matrix, ceramic particles accumulation both on the outside and in the center are due to the radial forces that are generated by the centrifugal force. Certain microporosities are also observed, which are produced by the solidification temperatures of each of the FGM microconstituents. With this, it can be determined there is a gradient of particles which indicates the tube obtained is a functionally graded material. Tonality of silicon carbide particles and their morphology were identified based on the research carried out by I. Milosan [6].

Figure 7
Metallography at 100X of distribution gradient along the FGM cross-section of the specimen with #400 mesh SiC and 1200rpm: (a) Outside diameter zone; (b) and (c) intermediate zone and (c) inside diameter zone



Mechanical characterization

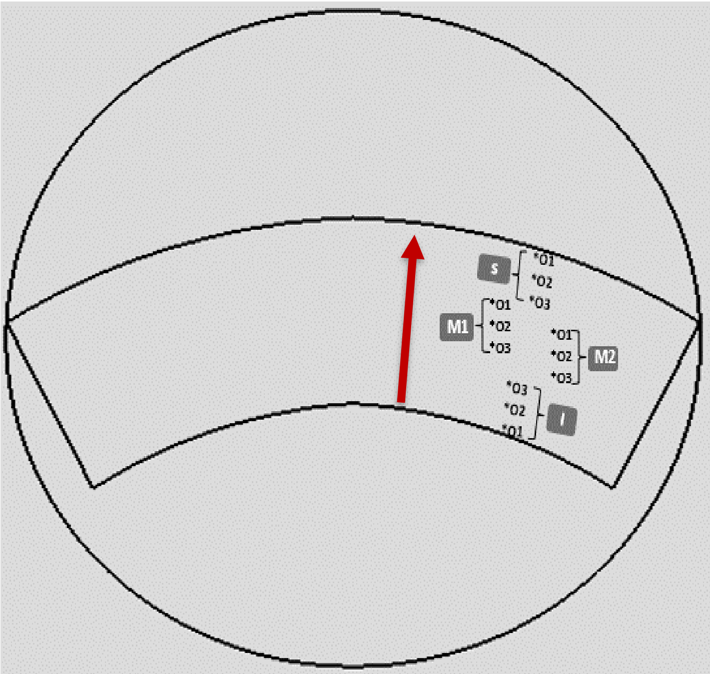
Vickers microhardness test

Measuring the microhardness in the cross section of tubes, particularly those made of composite materials such as silicon carbide-reinforced aluminum, offers valuable insights into the structure and quality of the material. This measurement can reveal the distribution of particles in the matrix, identifying possible gradients or uneven concentrations, which often arise from methods such as centrifugal casting. In addition, uniformity in microhardness can indicate the consistency and quality of the manufacturing process. Variations in hardness often correlate with other mechanical properties, providing a quick view of the tube's strength and modulus of elasticity. Subsequently, if subjected to heat treatments, measurements can evaluate the effectiveness of these treatments. In operations such as welding, microhardness identifies heat-affected zones. Overall, this evaluation is essential to ensure the quality and structural integrity of the material.

A total of 12 indentations distributed as shown in Figure 3.1.10 were performed on each of the selected specimens, applying a force of 50 gf for 15 seconds.

Figure 8

Indentation areas of Vickers microhardness test.



For the Vickers microhardness process, indenter used is a straight diameter pyramid with a square base, with an angle between faces of 136°. The test procedure was based on ASTM E92-16 and ASTM E384-17 standards corresponding to microhardness practice.

Parameters to be used for the test are a load of 50 gf (the range of values indicated in the standard is from 1 gf to 120 gf), and an application time of 15 seconds (the standard indicates a range of time values between 10 to 15 seconds). Finally, the test will be carried out with a DUROLINE-M microhardness tester, METKON brand.

The functionally graded material tube obtained by the centrifugal force casting process with denomination Al 365.0/SiC/6p (Figure 9) was analyzed, in this case, two specimens were selected (one for each ring) for the case of #320 mesh particles with 1000 rpm and the same number of specimens for #400 mesh particles with 1200 rpm respectively. In addition, it will be possible to compare the microhardness along the cross-section obtained from the Vickers test.

Figure 9

FGM tube with SiC particle reinforcement

Microhardness in Al 365.0/SiC/6p for the case of SiC mesh # 320 and 1000 rpm

Indentations were carried out in different zones along the section, resulting in the values shown in Table which are the results of the ring specimen that formed part of the resulting tube.

Table 5

Vickers microhardness values in the zones of FGM test piece ring.

Indentations	**S (HV)**	**M1 (HV)**	**M2 (HV)**	**I (HV)**
O1	76,01	105,81	115,25	53,95
O2	84,45	104,31	65,31	98,45
O3	65,39	157,26	104,51	105,97
Average	75,28	122,45	95,02	89,46

Microhardness in Al 365.0/SiC/6p for the case of SiC mesh # 400 and 1200 rpm

As in the previous case, the order in which the micro indentations were made was from the inner diameter to the outer, figure 16 it can be seen that the distribution gradient of the ceramic particles varies from the inner to the outer diameter, acquiring the shape of an FGM since ceramic particles are distributed from least to greatest amount having a maximum hardness value in the upper zone of 191.35 HV and a value of 56.42 HV in the inner zone

Table 6

Vickers microhardness values in the zones of FGM test piece-ring.

Indentations	**S (HV)**	**M1 (HV)**	**M2 (HV)**	**I (HV)**
O1	191,35	117,91	101,56	56,42
O2	183,68	138,58	89,80	83,36
O3	116,71	133,98	78,40	49,11
Average	75,28	122,45	95,02	89,46

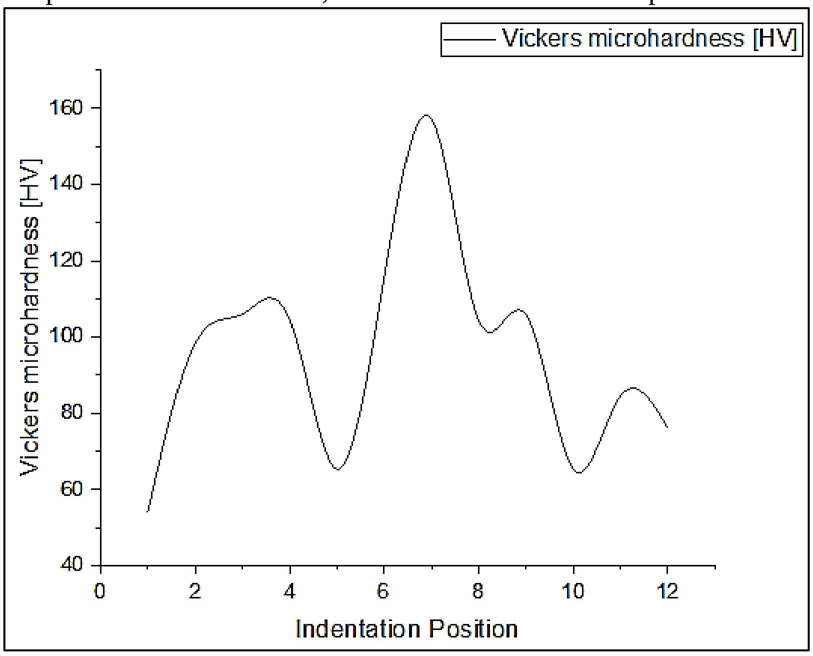
RESULTS AND DISCUSSION

In the following sections, two graphs illustrating the results of hardness tests performed using a Vickers hardness tester on the two specimens tested will be presented. The two graphs will show the relationship between the hardness and the cross-sectional distance of the material obtained, allowing to appreciate if this material property is the same as that corresponding to a FGM. This comparison will provide valuable insight into how advanced manufacturing techniques can be used to design and produce materials with graded properties to meet specific performance and application requirements.

Presentation of experimental results and data analysis

Microhardnesses in Al 365.0/SiC/6p for the case of SiC mesh # 320 and 1000 rpm

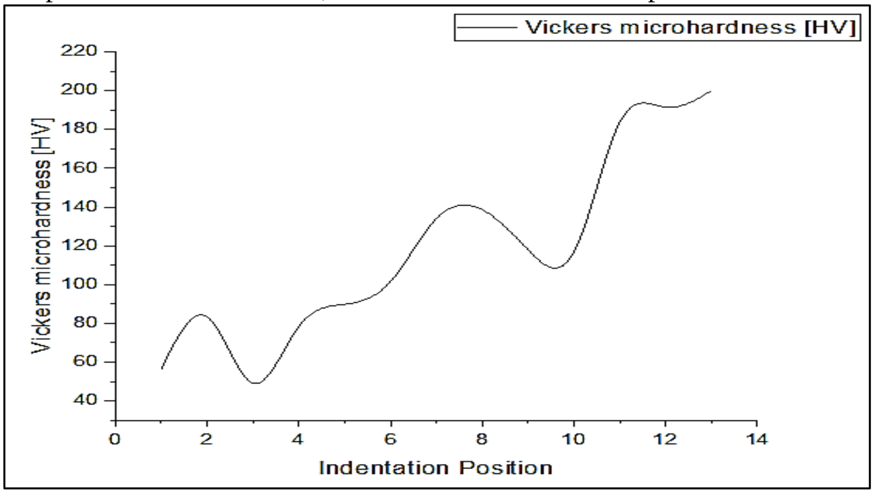
Figure 10
Graph of Vickers Hardness, SiC mesh # 320 and 1000rpm



As can be seen in figure 10, hardness increases from the inner diameter towards the center of the test piece, which is the area where most of the SiC particles accumulate, while in the area of the outer diameter, the hardness tends to decrease due to lack of concentration of tested specimen particles, indentations were established from the inside diameter to the outside of the specimen as indicated by the arrow in Figure 8.

Microhardness in Al 365.0/SiC/6p for the case of SiC mesh # 400 and 1200 rpm

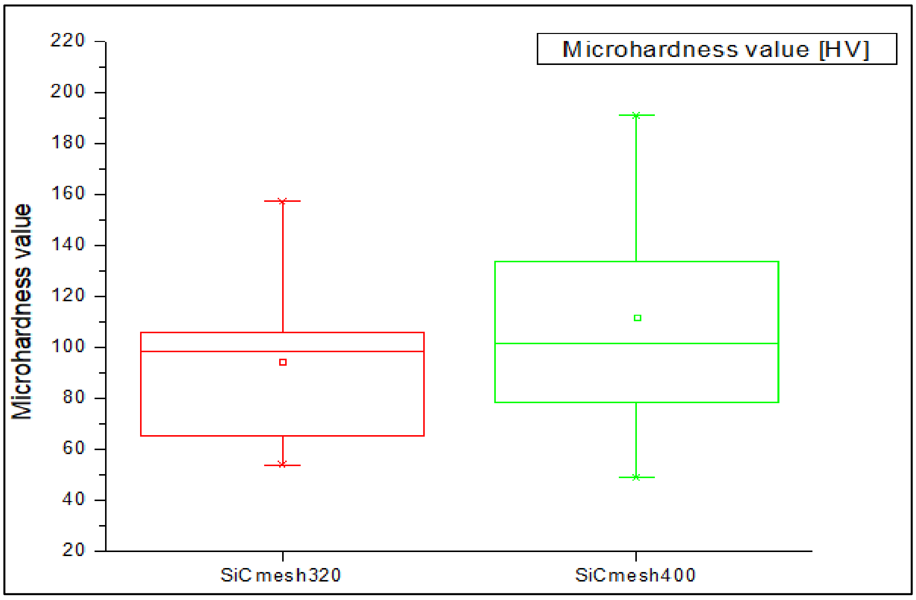
Figure 11
Graph of Vickers Hardness, SiC mesh # 400 and 1200rpm



As mentioned above, the purpose of the micro indentation is to know the influence caused by SiC particles in aluminum matrix, the particle composition gradient of a low concentration in the inner of the specimen that increases to the upper zone, it is observed in the graph of figure 11, the microhardness values go in the same direction as the concentration of SiC particles, as observed in the values of table 6 concerning each micro indented zone. In some cases, the Vickers indenter is placed in areas where there are silicon particles (or a concentration of them) and in areas where there is only the matrix.

Statistical analysis

The study addressed the fabrication of a functionally graded material (FGM) with an aluminum matrix and silicon carbide reinforcement particles. Through the horizontal centrifugal casting method, we sought to combine the intrinsic properties of aluminum and silicon carbide to obtain a material with improved characteristics. By varying parameters such as mold temperature and rotational speed, and SiC particle size, the distribution and orientation of the particles in the matrix is influenced, which is fundamental to the final properties of the FGM. Microhardness, a key measure of mechanical strength, was evaluated on specimens derived from tubes fabricated at two different rotational speeds and particle sizes.



Student's t-test was applied to discern differences in hardness properties between samples with #320 and #400 mesh SiC. The results showed no statistically significant differences in microhardness between the two configurations, suggesting that, under the conditions of the study, variation in particle size and mold speed did not drastically alter the hardness properties of the FGM. These findings have implications for the optimization of manufacturing parameters to achieve desired properties in composite materials.

CONCLUSIONS

The material was characterized as one of the FGM types because there is a distribution gradient of SiC ceramic particles, especially with the application of 1200 rpm and particle size of 28.46µm, which is observed in the respective metallography and graph. In the microhardness test, it was verified that the SiC particles were gradually distributed due to the centrifugal force.

The functionally graded tube manufactured with the name Al365.0/SiC/6p with an approximate length of 56.3 cm, an outer diameter of 9.98 cm, and a thickness of 0.86 cm, was manufactured taking into consideration parameters such as casting time, cooling, ambient temperature, mold preheating temperature, distance from the oven to the centrifugal machine, the size of the casting entry section, among other factors to consider.

The present literature for the manufacture of functionally graded materials with SiC particles through the ex-situ horizontal centrifugal casting process is limited in terms of the parameters and specifications of the machines that were used in the investigations related to this method, however, in the practice, the fundamental characteristic to be able to identify an FGM was noted, which is its distribution gradient.

From the data obtained, for the case of 1000rpm and particle size 49.81µm, there is evidence of an accumulation of SiC particles from the area of the inner diameter towards the central area of the cross-section of the specimens, with a similarity (in the tested specimens) of particles accumulation in the central area present, showing an incomplete distribution gradient due to the speed of rotation of the mold and the size and shape of the particles occupied, in addition to the particles reacted forming microconstituents that precipitated in the area of the inner diameter and part of the central area of the tested specimens.

In the case of 1200rpm and particle size 28.46µm, it is considered the appropriate ones to obtain an FGM, since there was an adequate and characteristic gradient of this type of material, in addition, the characteristic was verified with the measurement of the hardness in each zone of the material, which is proportional to the concentration of SiC particles.

BIBLIOGRAPHIC REFERENCES

D. K. Rajak, D. D. Pagar, R. Kumar, and C. I. Pruncu, "Recent progress of reinforcement materials: A comprehensive overview of composite materials," J. Mater. Res. Technol., vol. 8, no. 6, pp. 6354–6374, 2019, doi: 10.1016/j.jmrt.2019.09.068.

M. F. Forster, R. W. Hamilton, R. J. Dashwood, and P. D. Lee, "Centrifugal casting of aluminium containing in situ formed TiB2," Mater. Sci. Technol., vol. 19, no. 9, pp. 1215–1219, 2003, doi: 10.1179/026708303225005872.

M. Yousefi and H. Doostmohammadi, "Microstructural Evolution and Solidification Behavior of Functionally Graded In Situ Al–Cr Composites During Centrifugal Casting," Int. J. Met., vol. 15, no. 2, pp. 650–663, 2021, doi: 10.1007/s40962-020-00499-y.

B. Saleh et al., "30 Years of functionally graded materials: An overview of manufacturing methods, Applications and Future Challenges," Compos. Part B Eng., vol. 201, no. August, p. 108376, 2020, doi: 10.1016/j.compositesb.2020.108376.

R. Ambigai and S. Prabhu, "Characterization and Mechanical Analysis of Functionally Graded Al-Si3N4 Composites through Centrifugal Process," J. Mater. Eng. Perform., vol. 30, no. 10, pp. 7328–7342, 2021, doi: 10.1007/s11665-021-05963-2.

I. Milosan et al., "Characterization of aluminum alloy-silicon carbide functionally graded materials developed by centrifugal casting process," Appl. Sci., vol. 11, no. 4, pp. 1–14, 2021, doi: 10.3390/app11041625.

ASM, "ASM Handbook-Metallography and Microstructures," Technology, vol. 2, p. 3470, 2001.

J. G. Kaufman, Introduction to Aluminium Alloys and Tempers. 2000.

R. K. Verma, D. Parganiha, and M. Chopkar, "A review on fabrication and characteristics of functionally graded aluminum matrix composites fabricated by centrifugal casting method," SN Appl. Sci., vol. 3, no. 2, 2021, doi: 10.1007/s42452-021-04200-8.

A. Bedoya and J. Paúl, "Escuela Politécnica Nacional Facultad De Ingeniería Mecánica Rediseño Y Contrucción De La Máquina De Colado Centrífugo Horizontal Trabajo De Titulación Previo a La Obtención Del Título De Ingeniero Mecánico," 2020.

A. A. H. Faisal and L. A. Naji, "Simulation of Ammonia Nitrogen Removal from Simulated Wastewater by Sorption onto Waste Foundry Sand Using Artificial Neural Network," Assoc. Arab Univ. J. Eng. Sci., vol. 26, no. 1, pp. 28–34, 2019, doi: 10.33261/jaaru.2019.26.1.004.

. M. El-Galy, B. I. Saleh, and M. H. Ahmed, "Functionally graded materials classifications and development trends from industrial point of view," SN Appl. Sci., vol. 1, no. 11, 2019, doi: 10.1007/s42452-019-1413-4.

K. Wang, Z. M. Zhang, T. Yu, N. J. He, and Z. Z. Zhu, "The transfer behavior in centrifugal casting of SiCp/Al composites," J. Mater. Process. Technol., vol. 242, pp. 60–67, 2017, doi: 10.1016/j.jmatprotec.2016.11.019.

V. H. Sánchez Taco, "'Determinacion De La Metodologia Para La Obtencion De Aleaciones De Aluminio De Fundicion Maquinables Sin Porosidades'.," p. 168, 2011.

“An Introduction to Particle Characterization.”
https://www.azom.com/article.aspx?ArticleID=18502 (accessed Aug. 30, 2022).