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Microstructural and Mechanical Characterization of the Mg Based Functionally Graded Material Fabricated through Centrifugal Casting Process

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Abstract

Objectives: The aim of this study is to examine the mechanical and microstructural properties of functionally graded material (FGM) composites based on magnesium (Mg). Magnesium alloys are commonly employed in the development of biomaterials for implant applications owing to their favorable corrosion properties. The research objective is to study the microstructural and mechanical properties and produce Zn/Mo reinforced functionally graded magnesium composites using the centrifugal casting. **Methods:** A triple layered cylindrical shaped Mg based functionally graded material (FGM) was fabricated through a centrifugal process from (Mg (80%) +Zn (10%) + Mo (10%) alloy. The developed FGMs have been analyzed for their mechanical and microstructural characteristics. The microstructure was analyzed via the OM AND SEM microscope. It is identified that denser particle molybdenum (Mo) have influenced the mechanical and microstructural characteristics. **Findings:** Results recommend that, all the three layered testing's, Mg (80%) +Zn (10%) + Mo (10%) composite exhibited favorable mechanical and microstructural properties. It is identified that denser particle of Mo which is influenced the microstructural characteristics. The alteration in micro hardness in the direction of centrifugal force is observed, and it is perceived that top surface has higher hardness as compared to the middle and bottom region. The flexural strength of top surface sample is 254 MPa, which is 10% greater than middle surface sample and 12.36% greater than bottom surface sample. Compressive strength of 385 MPa, surpassing the middle surface sample by 17.11% and the bottom surface sample by 19.36%. **Novelty:** In this study, a novel three-layered centrifugal casting technique was devised. Owing to its rapid degradability, the anticipated duration of the implants within the human body is significantly shorter in comparison to alternative biomaterials such as

Titanium and Stainless steel. Furthermore, the findings from the conducted tests strongly advocate for the utilization of this technique in biomedical implantations.

Keywords: Functionally graded material (FGM); Centrifugal casting; Mechanical properties; Microstructural behavior and bioimplants

1 Introduction

The continuing expansion of modern industries in the field of material technology and the advancement of science have led to an ongoing demand for ever-more-advanced and intelligent materials with the necessary properties and characteristics. Recently, material processing has contributed to the emergence of FGM (Functionally Graded Materials), a second intricate type of multilayered materials. Moreover, FGM frequently consists of two phases or materials that progressively transfer their characteristics from one aspect of the sample to another[1]. According to Micheal et al. (2012), numerous individuals benefit from biomaterials by regaining mobility and usefulness by fixing or replacing damaged bones and joints. Among the most important factors for a successful biomaterial are chemical stability, biocompatibility, and mechanical characteristics. Interestingly, FGM started to attract substantial demand from the automotive and biomedical sector for manufacturing parts.[2]

Due to its biodegradability and biocompatibility, Magnesium has gained prominence as a viable material for biomedical implants. Magnesium can break down quickly in physiological conditions, which could lead to corrosion and eventual implant failure. Therefore, it is crucial to develop new alloys with improved mechanical properties and corrosion resistance. This article investigates number of material combinations, including alloys of magnesium, zinc, and molybdenum[3]. A master alloy's mass percentage composition was Mg-80%, Zn-10%, and M0-10%. These metals could be combined to reinforce biomedical components or to provide metal to metal joint contact. The mechanical advantages include improved stress shielding in the surrounding bone and increased load support with smaller geometries. Engineered materials, on the other hand, have minor and common faults that can be done through numerous trials, as well as some undesired properties such as minimal creep resistance, restricted cold forming ability, and poor corrosion resistance[4].

FGM casting orientation and dense layers (Outer, middle and bottom) are key aspects to consider while exploring the mechanical and microstructure characteristics of FGM-based alloys. In this investigation microstructural, Vickers micro hardness of the manufactured FGM are all systematically investigated. These alloys have shown promising results in terms of corrosion resistance, mechanical strength, and biocompatibility. Furthermore, efforts are being made to understand the underlying mechanisms of mechanical behavior in magnesium based alloys and to develop effective surface treatments that can enhance their performance. [5]. In this study Mg based FGM was developed using 80% weight, base material Mg and 10% alloying elements as Zn and 10% reinforcement as Mo. After conducting an extensive investigation, it was discovered that there is a limited amount of research available on this topic. In comparison to biomaterials like Titanium and Stainless steel, the expected lifespan of implants within the human body is considerably shortened due to their rapid degradable characteristics and defects like porosity are inevitable. The FGM based samples were subjected to mechanical and microstructural characterization using various experimental procedure.

2 Methodology

2.1 Material

In this investigation, magnesium powder with 99% of purity index and particle size of 50 microns was used as the matrix material. Because of their greater quantity and lower density, magnesium metal was chosen and a pure, 98.7% Mg, with 20 micron-sized reinforcing powder of zinc and molybdenum was employed in an 80:10:10 ratio of Mg (80%) +Zn (10%) + Mo (10%). Magnesium grade of AZ31 was used for the metal matrix, density with 1740 kg/m3 (108.6 lb/ft3) and 650 °C of melting point with 55.0 -05 Hv of hardness.[(6,7)]

Zinc and molybdenum were reinforced with Mg is used with size of and 50 μm and under draining gravity die stir casting apparatus. Where Mg melts and the alloying element, reinforcement material were added. Hence, the molten material is subsequently transferred to the centrifugal casting mold system in order to achieve the desired graded distribution. This process is facilitated by an integrated software for stir casting, and fabricated samples were depicted in Figure 1.

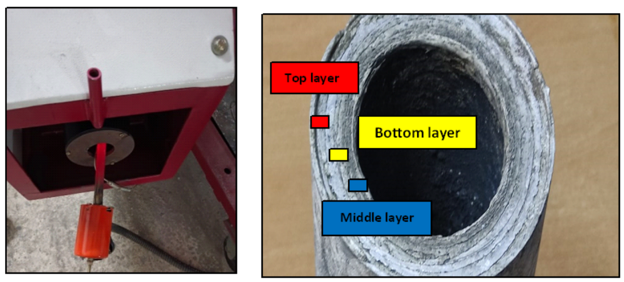

Fig 1. Bottom squishing and centrifugal casting machinery for stir casting & FGM fabricated component

Following the cleaning procedure, a layer of graphite paste is applied onto the crucible, stirrer, and drain channel of the casting furnace.[(8)]. The furnace is activated, and the temperature is continuously monitored through the utilization of a thermocouple. Upon reaching a temperature of 700 degrees Celsius, the magnesium substance is introduced into the furnace, followed by the subsequent closure of the crucible's lid. In order to achieve a homogeneous mixture of the desired grading zinc and molybdenum powder, it was necessary to preheat them to a temperature of 300 °C.

This preheating process effectively eliminated any excess moisture content. Subsequently, the prepared melt was introduced to the stirrer, which was set at a speed of 450 rpm. The reinforcement material was then gradually incorporated into the vortex of the melt, while simultaneously moving the stirrer in an up and down motion.[(9)]

To achieve a consistent dispersion of reinforcements within the molten magnesium, the molten liquid is poured into a preheated centrifugal die at a temperature of 450 °C. The centrifugal die is then set to a speed of 1400 RPM to prevent abrupt solidification. The furnace valve is opened to allow the molten liquid to be poured into the rotating die once all the necessary preparations have been completed. After being subjected to centrifugal action, the molten melt will be propelled in a radial direction towards the die wall, initiating the solidification process.[(10)] Adequate time is allocated for the cooling of the centrifugal cast, which is subsequently extracted from the die, cleaned, and prepared for further testing through the cutting of samples. The experimental parameters utilized in this study are presented in Table 1, and the identical process was replicated for each sample. The design specifications of the centrifugally casted samples are illustrated in Figure 2.[(11)]

Table 1. FGM fabrication parameters

Casting Parameters	Values
Stirrer RPM	450 RPM while mixing & 750 RPM while casting with vertical movement for 30mm
Furnace Temperature	700 °C
Melt Temperature	720 °C
Die Temperature	450 °C
Centrifugal RPM	1400 RPM

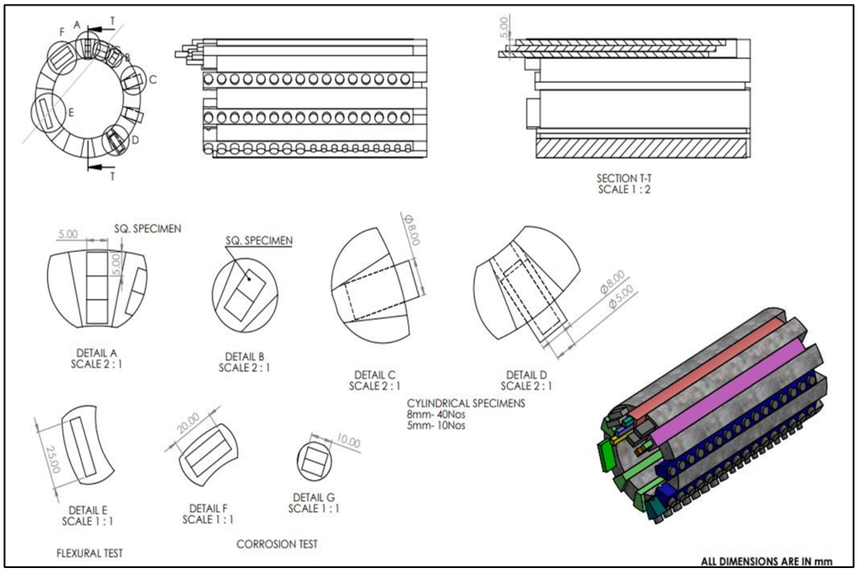

Fig 2. FGM design chart

2.2 Microstructure

The scanning electron microscope (SEM) was utilized to observe the microstructures of the fabricated FGMs. In order to conduct microstructural observations, the samples underwent both mechanical and chemical polishing. Additionally, energy dispersive X-ray (EDX) analysis was carried out to uncover the elemental composition gradient present in the samples. Thin strips were obtained from the hollow cylinder by cutting them longitudinally along the axis, with a width of 10 mm. Subsequently, the strip was further cut to a length of 15 mm, leaving a distance of 10 mm from the top surface in the transverse direction. A strip measuring $15 \times 10 \times 10$ mm was then mounted in a manner that allowed for the observation of the radial distribution of particles. The outer region of the strip was in contact with the wall of the mold, while the inner region was closer to the core axis of the cylinder[(12)].

After polishing the mount using a series of emery paper ranging from rough to smooth grade, followed by the use of velvet cloth to achieve a smooth mirror finish, the microstructures were examined. Subsequently, the mount was washed in running water. The microstructural images were captured at three distinct zones, namely the outer, middle, and inner regions. For the outer region, the images were taken while leaving a 0.5 mm distance from the periphery. On the other hand, for the middle and inner regions, the images were taken at a distance of 5mm x 10mm from the periphery. In order to determine the grain size and phase volume in all regions for all samples, the MetalPlus software was employed at the same position[(13)].

2.3 Mechanical properties

The hardness of a casted sample was determined using a Micro hardness Tester, with a load of 500g applied for a dwell period of 10 seconds. The sample was then cut longitudinally along the axis and made into thin strips, which were subsequently cut to a length of 5mm in the transverse direction, leaving 1mm from the top surface. After mounting and polishing to achieve a smooth surface, the hardness was measured radially in the outer region, which was 1mm away from the free surface. The middle and inner regions were located 5mm x 10mm away from the free surface, respectively. To obtain accurate results, five readings were taken in nine different positions longitudinally, and the average values were reported[(14)].

The cutting of flat surfaces and division of long specimens into smaller cubical pieces for compression testing was carried out using an ATM Brillant 250 wet abrasive cut-off machine. For the flexural test at room temperature, an MTS model bionic servo-hydraulic test system with a maximum force capacity of 25 kN was utilized. The placement and movement of fixtures were facilitated by a hydraulic wedge grip incorporated in the machine. Additionally, the compression test was conducted using a Mtest-647 modeled hydraulic material test system, capable of exerting a maximum force of 100 kN. Total of nine flexural samples (10 x 25 x 10 mm) were casted in accordance with ASTM standards and examined using a 3 point bending equipment was assessed for investigations. Scanning electron microscopy (SEM) JEOL was employed to analyse the flexural tests at 500 x.[(15)]

3 Results and Discussions

3.1 Microstructural Investigation

Microstructural analysis was conducted on the material casted using centrifugal force at a speed of 1400 rpm. The analysis involved varying magnifications for three distinct radial zones, namely the outer, middle, and inner regions. At elevated rotational speeds, the reinforced materials exhibit a higher concentration and are thrown with greater force, resulting in the shearing and breaking of Zn dendrites. This phenomenon leads to the formation of smaller grains, as depicted in Figure 3**(b), (c) & (d)**, due to the opposing force generated by centrifugal action. Additionally, the centrifugal force creates a squeezing effect that further contributes to the formation of smaller grains. The Primary Mg is propelled towards the bottom region of the core as shown in Figure 3 **(a)**.

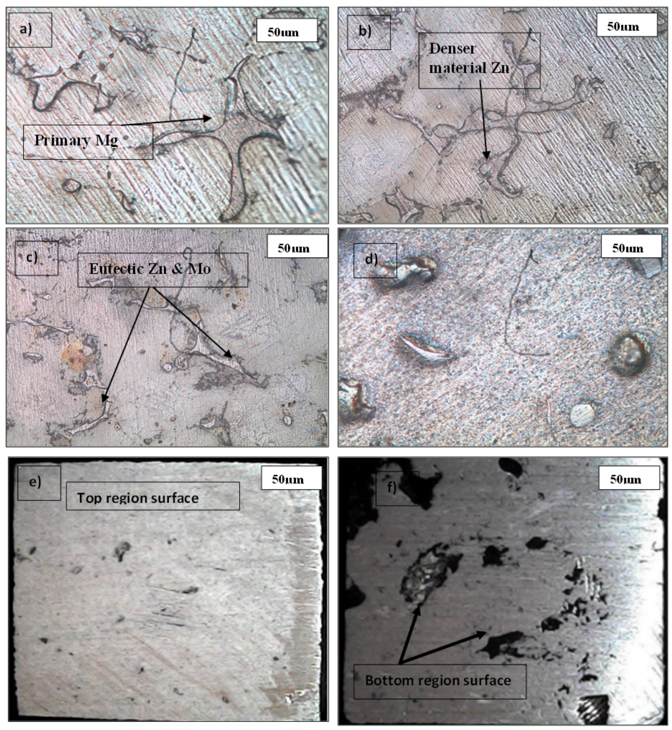

Fig 3. Microstructural analysis and pores identification

The microscopic image reveals a notable dispersion of magnesium, which can be attributed to the tendency of larger particles to gradually release heat, thereby prolonging the solidification process [16]. This prolonged solidification time ultimately leads to a more even distribution of reinforcement throughout the material. **Fathi et al.**, reported that The Formation and segregation of β-Mg phases in the top/outer surface (reinforcement zone) have been more dominant and denser as compared to the inner region surface, which exhibit better mechanical properties. Figure 3**(e) & (f)** are the pore structure between outer and bottom region surfaces. Figure 4 exhibits the different regions of microstructure top, middle and bottom respectively**.**Table 2 and Figure 5 shows the EDS analysis of the samples to confirm the presence of different elements propelled from bottom to top region.

3.2 Micro-Hardness Investigation

It can be deduced from the data presented in Figure 6 that the hardness of all the samples is higher in the outer zone, specifically the top surface, in comparison to the inner zone, which corresponds to the bottom surface. The centrifugal force exerted during the centrifugal casting process leads to the radial outward projection of denser particles. Consequently, this phenomenon results in the segregation of zinc and molybdenum particles towards the periphery, leading to a higher concentration of Mo elemental segregation in the outer region and a lower concentration in the inner region. It can also be observed that the elemental segregation formed laves phase which is detrimental to the ductility with increased the specimen's hardness [17]. Hardness of

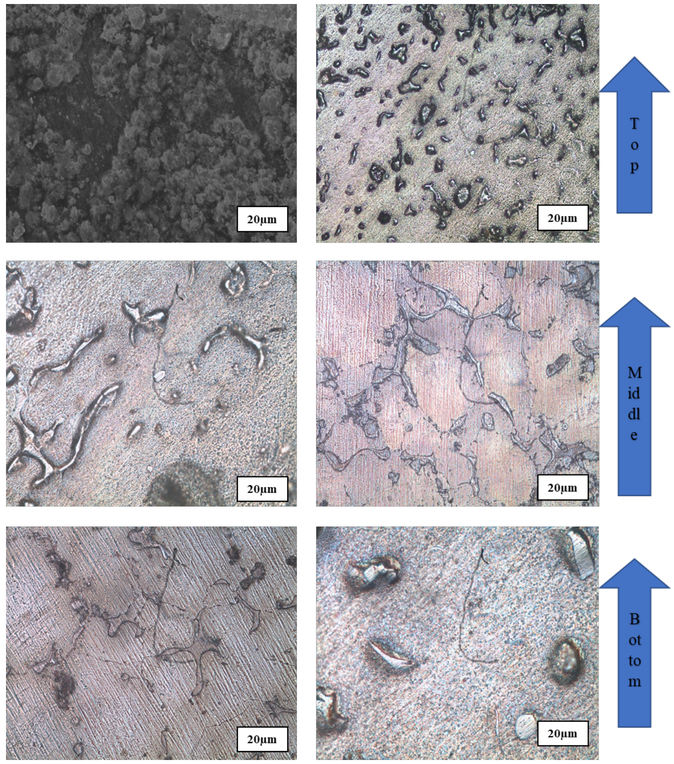

Fig 4. Microstructures of Top, Middle, Bottom region specimens

Table 2. Chemical Composition at each region (mass %)

Samples	Region	Mg	Zn	Mo
Sample 1	Top	69.06	8.76	5.42
	Middle	72.18	9.1	1.6
	Bottom	79.2	8.97	0.2
Sample 2	Top	70.53	10.11	6.51
	Middle	81.36	11.01	2.1
	Bottom	87.19	10.95	0.9
Sample 3	Top	77.43	9.21	4.47
	Middle	82.53	11.01	1.3
	Bottom	88.68	12.29	0.16

the top region sample is 243$\pm$10 Hv which is 19% greater than the hardness of middle region sample and 21 % greater than hardness of bottom region samples. These results proved that denser particle has higher micro hardness in top region surface.

3.3 The impact of the compressive strength of FGM Based Alloy

The compressive strength of the material is depicted graphically in Figure 7, revealing a noticeable disparity between the outer and inner regions of all samples. This variation can be attributed to the particles' ability to absorb the load, as they possess superior shock resistance and load bearing capacity in comparison to the middle and bottom regions. These observations align with the research conducted by[18].

The compressive strength in the top region is greater due to the higher concentration of reinforcement in the outer region. Additionally, the material exhibits a distinctive advanced property, characterized by its high toughness. This unique property can be attributed to the resultant microstructure formed as a result of the high cooling rates employed in the Centrifugal casting process. Conversely, the rupture value of samples from the top region displays lower ductility when compared to the middle

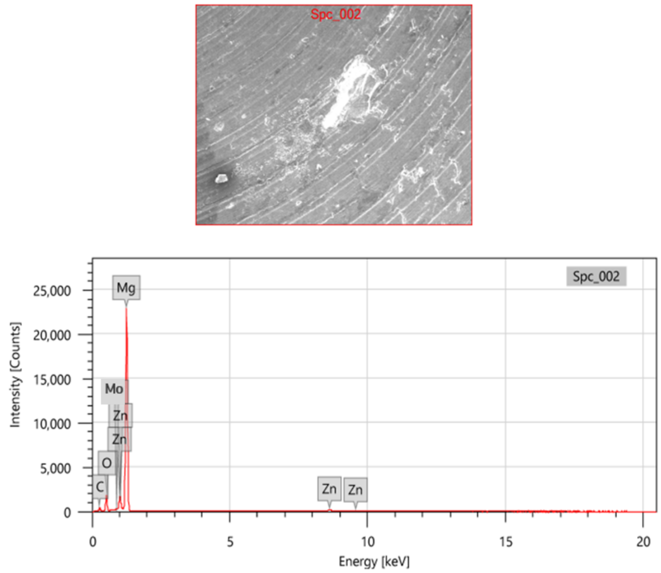

Fig 5. EDS analysis of FGM based Component

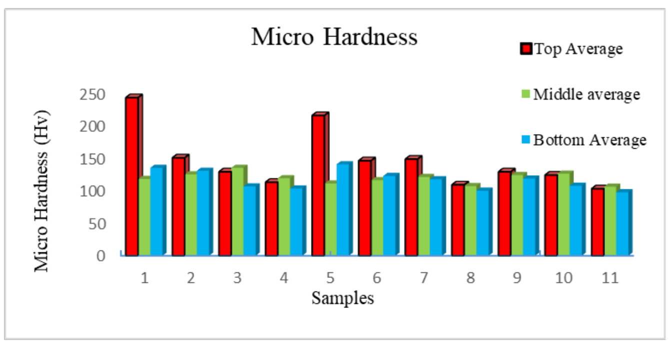

Fig 6. Comparison of Micro Hardness

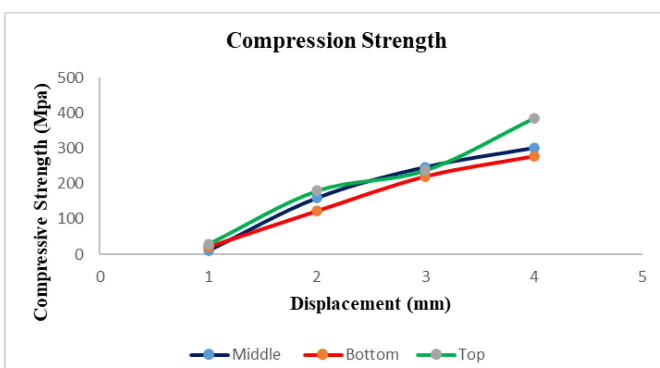

Fig 7. Comparison of inner and outer layer compression test

and bottom samples. This reduced ductility can be attributed to the slight embrittlement of the samples, which is caused by the formation of interdendritic regions containing minimal Laves phase.

The superior compressive strength and elongation of the top surface sample in comparison to the middle and bottom region samples are clearly evident. The compressive strength of the top surface sample measures 385 MPa, representing a 17.11% increase compared to the middle surface sample and a 19.36% increase compared to the bottom surface sample. Additionally, the percentage elongation of the top region sample is 18% lower than that of the middle region sample and 10.5% lower than that of the bottom region sample. Consequently, it can be observed that an increase in concentration leads to an increase in porosity, while the formation of agglomerations tends to decrease the compressive strength.

3.4 The impact of the Flexural Strength of FGM Based Alloy

The graphical depiction of the flexural strength of the alloy casted through centrifugal means is illustrated in Figure 8 . Evidently, the stress distribution profiles within the bending specimens are computed, considering the distinct regions of the casted material, namely the top, middle, and bottom regions.

Figure 8 illustrates the stress distributions as a function of specific thickness under an applied load of 100 N, enabling a comparison of general trends. The variations in the stress profiles are contingent upon the changes in Young's modulus. It is observed that Young's modulus escalates as the distance from the crack initiation plane increases, consequently leading to an increase in stress compared to that in a homogeneous material. In contrast, for concave profiles, the Young's modulus exhibits a decline as the distance from the crack initiation plane increases. Moreover, the rate of stress reduction surpasses that observed in a homogeneous material. Consequently, the fracture strength or fracture load demonstrates an augmentation along the inner and outer surface of the specimen.

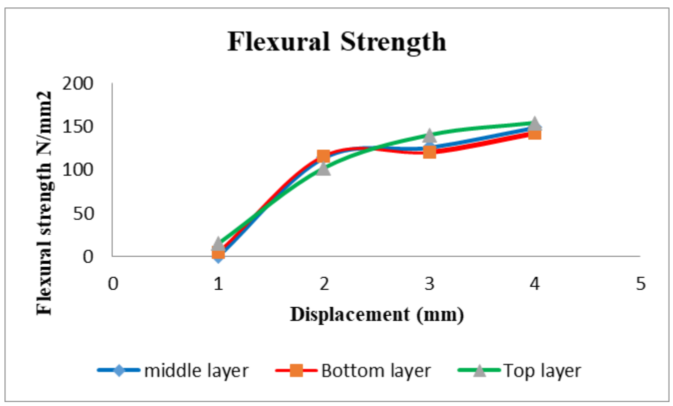

Fig 8. Flexural Strength of Inner and outer area of FGM alloy

From the graphical trends, it is observed that top surface sample exhibits better flexural strength and elongation in comparison with middle and bottom region samples. According to **Farahmand et al.** [19] research findings, the flexural strength of a magnesium alloy with a functionally graded material (FGM) was determined to be 209 MPa during three-point bending tests. In this context we were attained the flexural strength of top surface sample is 254MPa, which is nearly 10% greater than middle surface sample and 12.36% greater than bottom surface sample. The top region sample exhibits a reduction in percentage elongation by 29% compared to the middle region sample and a decrease of 20.5% compared to the bottom region sample.

4 Conclusion

A functionally graded material (FGM) with a cylindrical shape, composed of an alloy of Mg (80%), Zn (10%), and Mo (10%), was produced through a centrifugal method for the purpose of this investigation. The findings of the study are presented below.

- The microstructure of the Mg based functionally graded material were directly influenced by the geometry of the casting direction and it is identified that denser particle of Mo which is influenced the mechanical and microstructural characteristics.
- The FGM exhibits a rise in Mo concentration towards the centrifugal force direction, whereas the chemical compositional gradient of Zn remains negligible or insignificant.

- The alteration in micro hardness in the direction of centrifugal force is observed, and it is observed that top surface has higher hardness as compared to the middle and bottom region.
- The flexural strength of top surface sample is 254MPa, which is 10% greater than middle surface sample and 12.36% greater than bottom surface sample. The top region sample exhibits a reduction in percentage elongation by 29% compared to the middle region sample, and a further decrease of 20.5% compared to the bottom region sample.
- The top surface sample exhibits a compressive strength of 385 MPa, surpassing the middle surface sample by 17.11% and the bottom surface sample by 19.36%. In contrast, the percentage elongation of the top region sample is 18% lower than that of the middle region sample and 10.5% lower than that of the bottom region sample.
- The future research and development for Gyroid structure have vast opportunities for in Additive manufacturing. By enhancing the properties of these FGM layered samples, there is potential for significant advancements in screw fit in dental implant and biocompatibility.

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