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Investigation on Mechanical and Corrosion behavior of Mg based Mo/Zn Functionally Graded Composites for Biomedical Implants

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Abstract: A functionally graded material (FGM) with a triple-layered cylindrical shape, based on magnesium (80%), zinc (10%), and molybdenum (10%), was produced using a centrifugal process. The mechanical and microstructural properties of the developed FGMs were examined, with the microstructure being analyzed using optical microscopy (OM) and scanning electron microscopy (SEM). It was observed that the denser molybdenum particles had an impact on the mechanical and tribological characteristics of the magnesium-based FGMs. The study suggests that the Mg (80%) +Zn (10%) + Mo (10%) composite, subjected to three-layered testing, displayed promising mechanical and microstructural characteristics. An increase in micro hardness was noted in the direction of centrifugal force, with the average impact strength of the functionally graded magnesium composite measuring 58 joules, showing a 10% improvement compared to the middle region and a 19.26% improvement compared to the bottom region of FGM samples. The corrosion rates for the samples were determined to be 3.264E+1mm/yr for the bottom sample, 2.734E+1mm/yr for the middle region sample, and 2.6068E+1mm/yr for the top sample.

Keywords: *Functionally graded material (FGM), Centrifugal casting, mechanical properties, microstructural behavior, and bio-implants.*

1. Introduction

The ongoing expansion of modern industries in material technology and scientific advancements has created a growing need for more advanced and intelligent materials with specific properties. Material processing has led to the development of FGM (Functionally Graded Materials), a complex type of multilayered materials consisting of two phases that gradually transition their characteristics from one part of the sample to another [1]. According to Mallick et al. (2012**),** biomaterials have enabled many individuals to regain mobility and functionality by repairing or replacing damaged bones and joints. Key factors for successful biomaterials include chemical stability, biocompatibility, and mechanical properties. Notably, FGM has begun to attract significant demand from the automotive and biomedical industries for part manufacturing [2].

Magnesium is a promising material for biomedical implants due to its biodegradability and biocompatibility, but its quick breakdown in physiological conditions can lead to corrosion and implant failure. To address this issue, it is essential to develop new alloys with enhanced mechanical properties and corrosion resistance, such as magnesium-zinc-molybdenum combinations. A master alloy with a composition of Mg-80%, Zn-10%, and Mo-10% can be used to strengthen biomedical components and improve load support with smaller geometries. However, engineered materials may have drawbacks like minimal creep resistance, limited cold forming ability, and poor corrosion resistance, which can be mitigated through multiple trials and modifications [3-4].

The investigation focused on the importance of FGM casting orientation and dense layers in understanding the mechanical and microstructure characteristics of FGM-based alloys. The study systematically examined the microstructural features and Vickers micro hardness of the manufactured FGM alloys, which displayed promising results in terms of corrosion resistance, mechanical strength, and biocompatibility. Efforts are being made to comprehend the mechanical behavior of magnesium-based alloys and develop surface treatments to enhance their performance.

The study developed Mg-based FGM with specific weight percentages of base material Mg, alloying elements Zn, and reinforcement Mo, revealing a lack of research in this area. Compared to biomaterials like Titanium and Stainless steel, FGM-based alloys show potential for shorter implant lifespans due to rapid degradability, highlighting the need for further research on mechanical and microstructural characterization. **[5]**

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2. Materials & Methods

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].

Fig. 1. FGM fabricated components

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 and fabricated samples were depicted in Figure 1. 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 ºC.

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 ºC. 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 and the identical process was replicated for each sample.

2.2. 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 [11].

The impact specimens with dimension of 10 X10 X 55 mm were subjected to Charpy test with a prescribed notch of 0.25 depth for an inclination angle of 450 with accordance of ASTME23 standards (Zhang et al. 2021). Then the fractured samples were prepared for microscopic examinations. As per the standards totally nine samples were studied, three for each regions and their values with standard deviation are clearly explained.

2.3. Corrosion Behaviour

The electrochemical characteristics of Mg based FGM alloy of top, middle and bottom region of porosity are investigated using Potentiodynamic testing. The experiment is performed using a solution of simulated bodily fluid (SBF) at a temperature of 37° C. The substrates were examined utilizing three electrodes: the sample served as the working electrode with an area of 100 mm2, platinum mesh was employed as the counter electrode, and the calomel electrode was used as the reference electrode. The composition of the simulated bodily fluid (SBF) included NaCl, NaHCO3, KCl, K2HPO4.3H2O, Na2SO4, MgCl2.6H2O, CaCl2, HCl (1M) and Tris Buffer NH2C (CH2OH) 3. The Potentiodynamic analysis was conducted with a scan rate of 2.5 mV/s within the voltage range of -2000 mV to 1500 mV. The corrosion current density (Icorr) and corrosion potential (Ecorr) were examined based on the test results [12].

3. Results and Discussions

3.1 Mechanical Characteristics

It is observed that for all the samples the hardness is more in the outer zone (top surface) compared to the inner zone (bottom surface). In centrifugal casting due to centrifugal force, the denser particles will be thrown radially outward. This action causes the denser zinc and molybdenum particles to be thrown towards the periphery causing the Mo elemental segregation on the outer region and least in the inner region. It can also be observed that the elemental segregation formed laves phase which is detrimental to the ductility with increases the specimen's hardness. The hardness of the top region sample is 243±10 Hv which is 19% greater than the hardness of the middle region sample and 21 % greater than hardness of the bottom region samples. These results proved that larger particle has more hardness in the outer region. Figure.2a). Shows the graphical representation of FGM samples

It is clearly observed that the impact energy of the material is higher for the outer regions as compared to the inner region for all the samples. The particles play a crucial role by absorbing the load.

This is mainly due to the particles has fact that this Mo particle located at top region has higher shock resistance or load-bearing capacity compared to the middle and bottom region samples. As the concentration of the reinforcement is higher in the outer region the impact strength is more in the top region. Also, the material has unique advanced properties like high impact toughness.

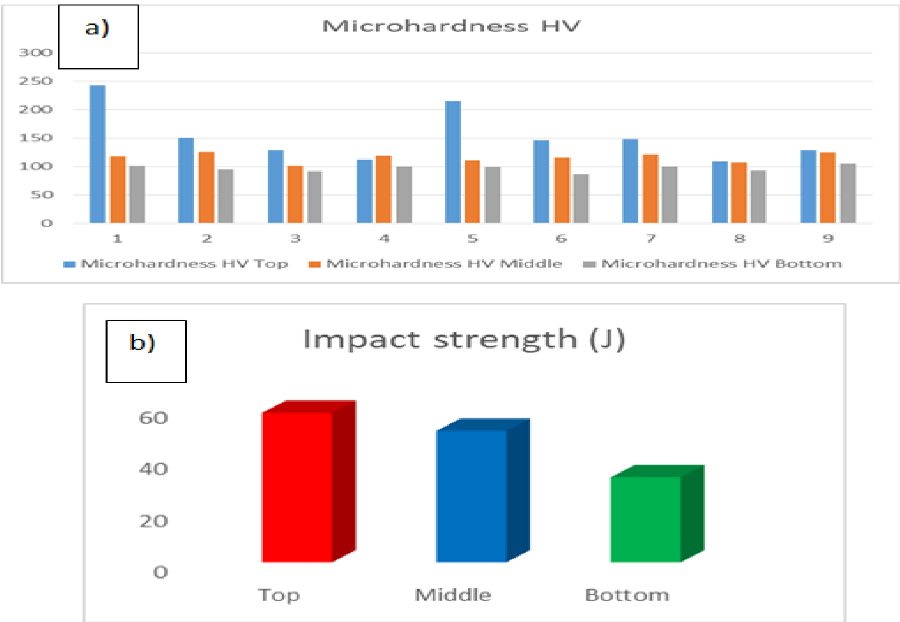

Fig. 2. a) Graphical Representation of Micro-hardness, b) Graphical Representation of Impact test

This may be ascribed to the resultant microstructure caused by the high cooling rates involved in the Centrifugal casting. On the other hand, the value of top region samples rupture shows a lower ductility in comparison with middle and bottom of FGM samples, which is attributed to the slight embrittlement of samples due to the formation of interdendritic regions with minimal Laves phase. It is clearly evident that the top surface sample exhibits better impact strength and low elongation in comparison with middle and bottom region samples. The impact strength of the top surface sample is 58J for three layered specimens, which is 10.11 % greater than the middle surface sample and 9.36% greater than the bottom surface sample.

Figure.2a). Shows the graphical representation of impact FGM samples.

3.2 Corrosion behavior

A Potentiodynamic polarization test was conducted to assess the protective ability of the substrates. The Potentiodynamic polarization curves for samples in the SBF environment are depicted in Figure 3.(a) and (b) respectively. It is observed that top region samples, which has a higher concentration of Mo particles, forms an oxide layer that acts as a barrier, resulting in enhanced corrosion resistance compared to bottom and middle region samples. This is achieved by reducing the electrochemical process on the surface. **[13]**

Fig. 3. (a) Machine apparatus and (b) testing samples

The study emphasized the inherent tradeoffs between optimizing the layered casting and the behaviour of corrosion. It discovered a potential parabolic relationship between the volume of voids, the surface area, and the corrosion process. [14] Figure 4 depicts the Tafel curves derived from potentiodynamic polarization curves of the FGM samples. The experiments were conducted in a corrosive medium called Simulated Body Fluid (SBF) at a temperature of 35°C. The electrochemical corrosion parameters, including Ecorr, Icorr, and linear polarization resistance, for the three samples are presented in Table 1. A reduced corrosion current density, Icorr, indicates improved corrosion resistance in the material. Furthermore, materials with superior corrosion resistance would have elevated levels of linear polarization resistance (ohms)

The top sample has the highest polarization resistance of 9.636E+1 (ohm) and lower Icorr of 1.997E-4 (μA/cm2) when compared with the other bottom and middle region samples. The lower corrosion value of the top region sample can be attributed to the superior surface integrity of the material. Top region sample exhibits a greater corrosion potential (Ecorr) and lower current density (Icorr) compared to the other samples. The FGM alloy has inherent corrosion resistance due to the formation of a spontaneous oxide layer on its surface. The formation of this oxide layer occurs by a process known as passivation, when the metal surface undergoes a reaction with atmospheric oxygen to generate a thin coating of oxide. The polarization resistance of bottom and middle region samples is significantly lower than that of top sample [15-16].

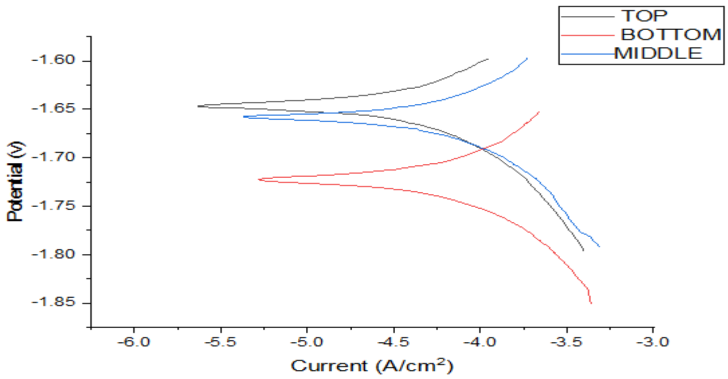

Fig. 4. Potentiodynamic polarization curves of FGM samples.

The polarization resistance increases due to the decrease in the potential drop (IR), which weakens the force that drives of activation polarization. As a result, the anodic and cathodic operations become less efficient, resulting to a decrease in the rate of corrosion. Bottom exhibits the lowest polarization resistance, measuring 8.944E+1 ohms, whereas middle has a polarization. Resistance of 9.108E+1ohms. Bottom region sample exhibited the greatest Icorr value of 3.152E-4 (µA/cm2), whereas middle region sample has an Icorr value of 2.641E-4 (µA/cm2). From these corrosion results the top region sample is having superior corrosion resistance than other two samples.

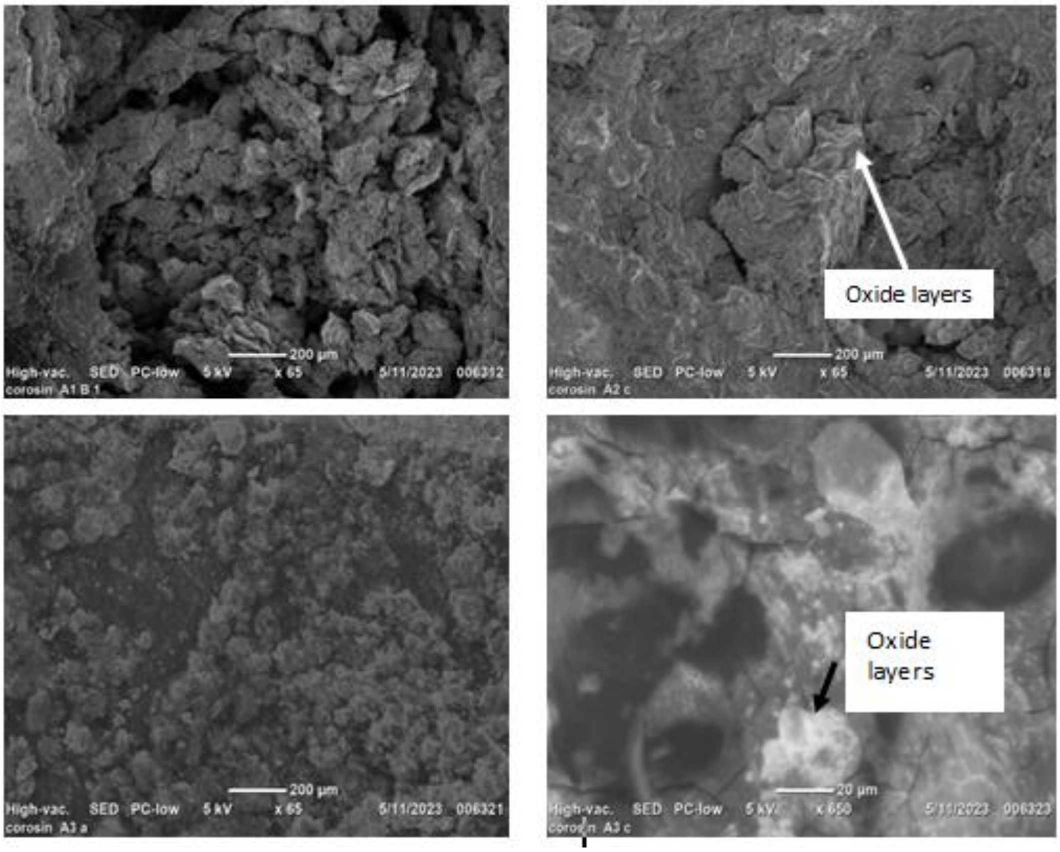

Fig. 5. SEM analysis on Corrosion Test samples

Table 1. Electrochemical Corrosion values of FGM samples from Polarization curves

Sample .NO	**Sample Name**	**icorr value (A/cm^2)**	**Ecorr value (obs)(V)**	**βa (V/dec)**	**βc (V/dec)**	**Rp (ohm)**	**Corrosion rate (mm/year)**
1	**Bottom**	3.152E-4	-1.608	0.14	0.116	8.944E+1	3.264E+1
2	**Middle**	2.641E-4	-1.723	0.147	0.115	9.108E+1	2.734E+1
3	**Top**	1.997E-4	-1.658	0.108	0.103	9.636E+1	2.068E+1

It is observed that oxide layer has been formed on the top region as a protective layer. The correlation between a material's microstructure, hardness, and its resistance to chemical or electrochemical assault is the underlying cause for the enhancement of corrosion resistance by hardness. Studies have demonstrated a positive correlation between an augmentation in hardness and enhanced resistance to corrosion [17]. Since the top region sample has more hardness than other bottom and middle region samples. It is also the reason for enhanced corrosion resistance in the sample. It is also the reason for enhanced corrosion resistance in the top region sample. It has been confirmed that the formation of oxide layer may acts as a barrier for the corrosion in the top region sample which can be shown in the SEM image. Hardness is more in the top region sample and the micro structures can also influencing the better corrosion resistance in the top 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.

- Vickers hardness changes along the centrifugal force direction, and it is observed that top surface has higher hardness as compared to the middle and bottom region. The alteration in micro hardness in the direction of centrifugal force is observed.
- The average impact strength of the functionally graded magnesium composite is 58 joules which is 10% greater than the middle region and 19.26 % greater than the bottom region of FGM samples.
- The corrosion rate for the samples was found as 3.264E+1mm/yr for the bottom sample, the middle region sample has the corrosion rate of 2.734E+1mm/yr and the top sample has the corrosion rate of 2.6068E+1mm/yr.
- The centrifugally casted Mg based FGMs has significantly decreased the corrosion current density and corrosion rate and increases the corrosion potential and linear polarization resistance of top, middle and bottom region samples.
- The top sample has better corrosion resistance that other region samples respectively. It has been confirmed that the formation of oxide layer may acts as a barrier for the higher corrosion resistance in the top region than middle and bottom region samples.

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