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* **Corresponding author**.

anilkumar@srkrec.ac.in

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Effect of Three Layered Centrifugal Casting on Tribological and Microstructural Characteristics of Mg Based Functionally Graded Material Alloy

M Anil Kumar[1]*, V Srinivasan[2], P Ramamurthy Raju[3]

1 Research Scholar, Department of Manufacturing Engineering, Faculty of Engineering and Technology, Annamalai University, Annamalai Nagar, 608 002, Tamil Nadu, India
2 Associate Professor, Department of Manufacturing Engineering, Faculty of Engineering and Technology, Annamalai University, Annamalai Nagar, 608 002, Tamil Nadu, India
3 Professor, SRKR Engineering College, Bhimavaram, Andhra Pradesh, India

Abstract

Objectives: The aim of this study is to examine the tribological properties and microstructural of functionally graded material (FGM) composites based on magnesium (Mg) base material. Magnesium alloys are commonly employed in the development of biomaterials for implant applications owing to their favorable corrosion properties. The research objective is to produce Zn/Mo reinforced functionally graded magnesium composites using the centrifugal casting. **Methods:** A centrifugal process was employed to fabricate a functionally graded material (FGM) consisting of three layers with a cylindrical shape. The base material used for this FGM was Magnesium, which was alloyed with 10% of Zn and 10% of Mo. The developed FGMs have been analyzed for their mechanical and microstructural characteristics. The microstructure of the samples were analyzed via the Optical Microscope (OM). It is identified that denser particle molybdenum (Mo) have influenced the mechanical and microstructural characteristics of the FGM composites. **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 observed that the minimum wear loss for sliding wear samples A, B & C of Mg based FGM alloy were found to be 0.0018 g, 0.028 g and 0.031 g respectively, while the maximum wear loss for sliding wear samples A, B & C of FGM alloy were found to be 0.0021 g, 0.41 g and 0.31 g respectively. **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 would be 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; Tribological characteristics; microstructural behavior; and bioimplants

1 Introduction

The ongoing expansion of modern industries in the field of material technology, along with the progress made in scientific research, has resulted in a continuous demand for increasingly advanced and intelligent materials possessing the necessary properties and characteristics. In recent times, material processing has played a pivotal role in the emergence of Functionally Graded Materials (FGM), which represent a complex type of multilayered materials. It is worth noting that FGM often consists of two phases or materials that gradually transfer their characteristics from one part of the sample to another. This gradual evolution leads to the development of exceptional features that are free from any mechanical fragility[(1)]. According to Micheal et al. (2012), a large number of individuals benefit from biomaterials as they regain their mobility and functionality through the repair or replacement of damaged bones and joints. Chemical stability, biocompatibility, and mechanical characteristics are among the key factors for the successful application of a biomaterial. Interestingly, FGM has recently gained significant attention from the automotive and biomedical sectors for the manufacturing of various 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)]. The aim of this study was to develop a Mg-based functionally graded material (FGM) with a composition consisting of 80% weight of Mg as the base material, 10% of Zn as alloying elements, and 10% of Mo as reinforcement. Extensive research on this topic revealed a limited amount of available literature. In comparison to biomaterials like Titanium and Stainless steel, the expected lifespan of implants within the human body is significantly reduced due to their rapid degradable characteristics and the presence of defects such as porosity, which are inevitable. The FGM samples underwent mechanical, microstructural, and tribological characterization using various experimental procedures.

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 1.75g/cc (108.6 lb/ft3) and 650 C of melting point with 55.0 -05 Hv of hardness.[6,7]

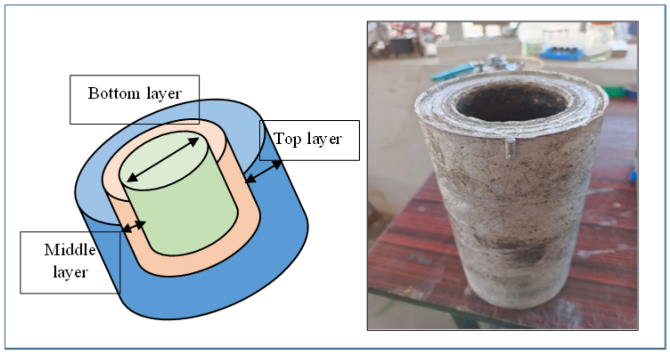

Fig 1. CAD design and FGM fabricated component

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. After completing the cleaning process, the crucible, stirrer, and drain channel of the casting furnace are coated with a layer of graphite paste[8].

The furnace is activated, and the temperature is continuously monitored through the utilization of a thermocouple. Upon reaching a temperature of 700°C, 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. Once all the necessary preparations have been completed, the molten liquid is poured into the rotating die by opening the furnace valve. As a result of the centrifugal action, the molten melt is propelled towards the die wall in a radial direction, thereby initiating the process of solidification.[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 identical process was replicated for each sample. The design specifications of the centrifugally casted samples are illustrated in Figure 2.

2.2 Microstructure

The microstructures of the fabricated FGMs were examined using the Optical microscope (OM). To enable microstructural observations, the samples experienced both mechanical and chemical polishing. The hollow cylinder was longitudinally cut along its axis to obtain thin strips measuring 10mm width. The mount underwent a polishing process using a sequence of emery paper, varying in coarseness from rough to fine, and was then further refined using a velvet cloth to attain a polished mirror-like surface. Following this, the microstructures were analyzed. The MetalPlus software was employed at different positions to ascertain the grain size and phase volume in all areas for each sample.[11]

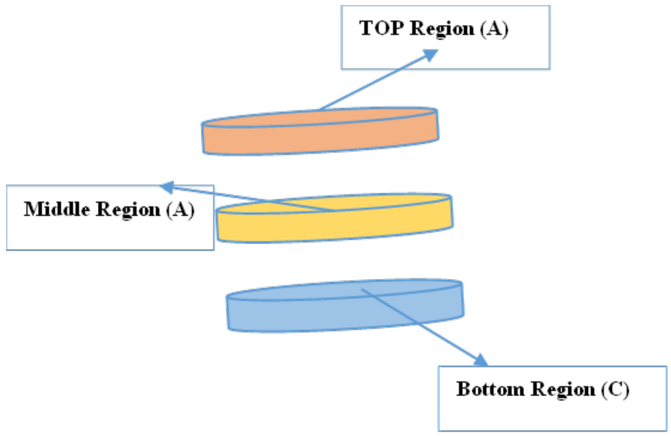

Fig 2. Casted Component Design

2.3 Mechanical properties

The hardness of a casted sample was assessed using a Micro hardness Tester. A force of 500g was exerted for a duration of 10 seconds. Subsequently, the specimen was longitudinally divided along its axis and converted into slender strips. These strips were then cut to a length of 5mm in the perpendicular direction, while ensuring a 1mm gap from the uppermost surface. In order to attain a sleek and even surface, the specimen underwent a process of mounting and polishing. Subsequently, the hardness of the material was assessed in a radial manner within the outer region, situated at a distance of 1mm from the unrestricted surface. The middle and inner regions, on the other hand, were positioned at a distance of 5mm x 10mm away from the unrestricted surface, respectively. To guarantee precision, a total of five measurements were recorded at nine distinct longitudinal positions. The average values obtained from these readings were reported.

2.4 Wear Characteristics

Sliding wear samples were tested under a pin on disc friction tester using Ducom Pod 4.5 with standard specifications of ASTM standards. Maintained normal load of 100 N and micro hardness at the cross section of samples was measured using the Vickers micro hardness test at a load of 500 g applied for a period of 10 sec[(12)].

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, 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 less dense Primary Mg is propelled towards the bottom region of the core as shown in Figure 3 **a**.

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. 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 Figure 3**b, d, e** and **f** exhibits the different regions of microstructure top, middle and bottom respectively**.**

3.2 Micro-Hardness Investigation

Figure 4 shows the micro hardness comparison between top, middle and bottom region Mg based FGM alloy. It is observed that micro hardness is higher in the outer zone, specifically the top surface, in comparison to the inner zone, which corresponds to

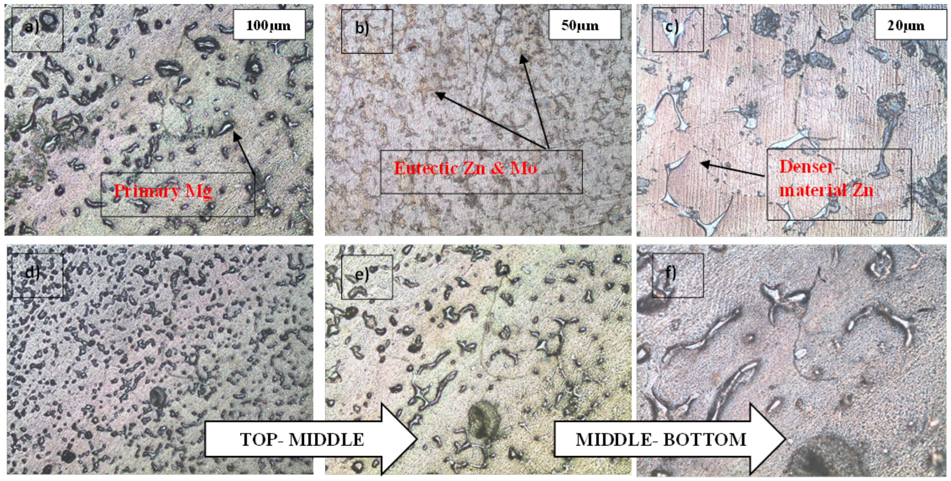

Fig 3. Microstructural analysis and pores identification

the bottom surface. The centrifugal force exerted during the centrifugal casting process leads to the radial outward projection of denser particles.

Hence, this occurrence results in the elemental segregation of zinc and molybdenum particles towards the outer edge, leading to a greater accumulation of Mo elemental segregation in the external area and a lesser concentration in the internal area. Additionally, the emergence of laves phase, which arises from the elemental segregation, adversely affects the specimen's ductility and enhances its hardness. The hardness of the sample from the top region is measured at 243±10 Hv, which is 19% higher than the hardness of the sample from the middle region and 21% higher than the hardness of the sample from the bottom region.

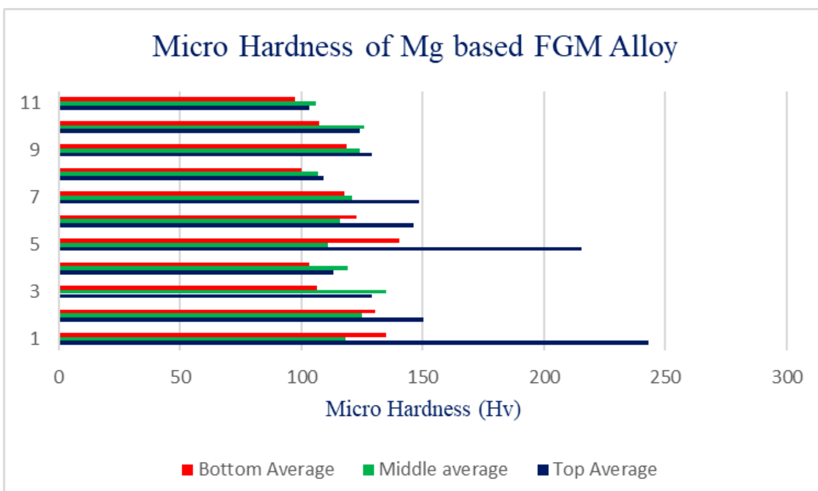

Fig 4. Comparison of Micro Hardness

3.3 Sliding Wear Characteristics

Dry sliding wear behavior of Mg based FGM alloy was studied under varying loads, sliding velocity, and the results are discussed in the following sections.

3.4 Impact of Load

The sliding results of top, middle and bottom Mg based FGM samples and Figure 5**a** and **b** displays the impact of normal load on the wear behavior of both top region sample A and bottom B and middle C region samples of FGM alloy. The maximum coefficient of friction values for samples A B & C sliding wear samples of FGM based alloy were found to be 0.281, 0.36 and 0.610 respectively. The minimum wear loss for sliding wear samples A, B & C of Mg based FGM alloy were found to be 0.0018 g, 0.028 g and 0.031 g respectively, while the maximum wear loss for sliding wear samples A, B & C of Mg based FGM alloy were found to be 0.0021 g, 0.41 g and 0.31 g respectively.[13]

According to a study conducted by V. Srinivasan et al., it was observed that the coefficient of friction decreases as the load increases. This phenomenon can be explained by the fact that at higher loads, the melt present at the interface acts as a lubricant, resulting in a significant reduction in the coefficient of friction. However, it was also noted that the wear continues to increase with an increase in load. This can be attributed to the hydrodynamic loading of the melt at the interface. Interestingly, the coefficient of friction in this study was found to be inversely proportional to the wear loss of all the samples.

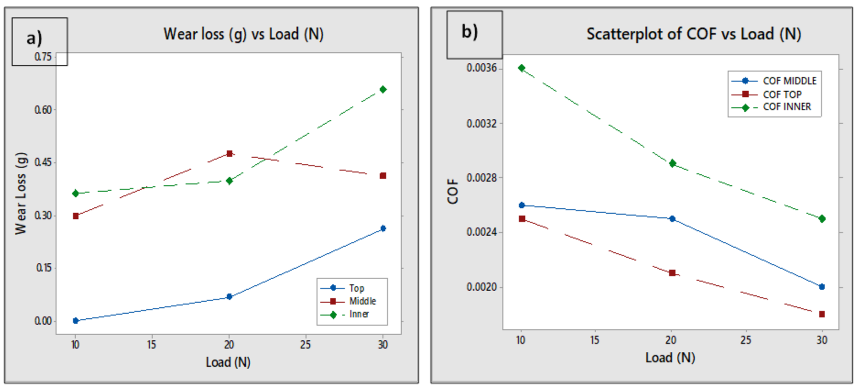

Fig 5. Impact of load on (a) COF and (b) wear loss

It was observed that the COF increased with increase in the applied load, in addition the wear resistance of the bottom region samples B & C was determined to be higher than the top region sample A with the increase of applied load.

3.5 Effect of Sliding Velocity

Figure 6 **a** and **b** shows the impact of sliding velocity on the wear behavior of bottom region samples B & C and top region sample A of FGM alloy. It is apparent that the applied velocity excreted a key role in influencing the obtainable wear performance.

On increasing velocity from 0.3 m/s to 0.9 m/s, the material loss was increased by increasing velocity, the wear loss of middle region sample B slightly increased from 0.36 to 0.64 while for sample C wear loss slightly increased from 0.28 to 0.403 and the wear loss of top region sample A increased from 0.0018 to 0.0031. It has been observed that the amount of wear experienced rises as the sliding velocity increases. This could be attributed to the fact that at higher velocities, the elimination of wear debris occurs at a faster pace, and the dislodged wear debris may have functioned as an abrasive agent, thereby considerably augmenting the coefficient of friction at the interface (Rasool et al., 2017).

High sliding velocities can produce high temperature due to frictional heating which may cause the Mg based FGM samples to degrade. However, in some cases higher temperatures might be beneficial to the lubricating process. Furthermore, the augmentation of contact asperity's locations at the contact tip due to the growing presence of a harder phase results in the stimulation of the stick-slip phenomenon. This, in turn, leads to an increase in the magnitude of the coefficient of friction, thereby boosting the frictional forces.[14]

It is noticed that, in top region sample A, wear loss was decreased by increasing denser particle distribution, which is due to the fact that, addition of material increases the hardness as forms a robust interfacial bond with the subsequent layers. This hardness increment enhances the load and velocity bearing capacity which in turn augments the wear resistance capacity (Kataria et al. 2010).

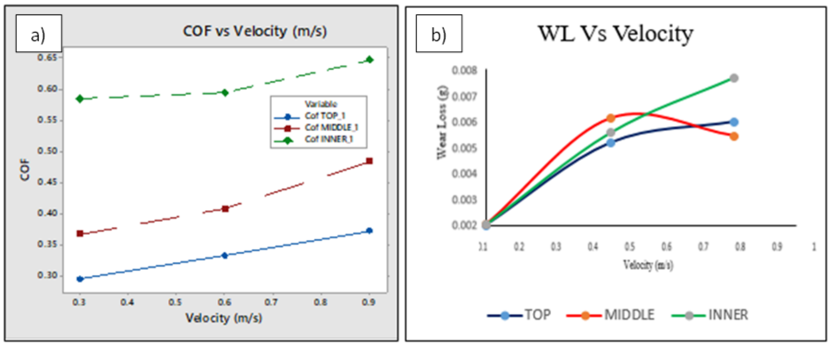

Fig 6. Impact of sliding velocity on (a) COF and (b) wear loss

3.6 Wear Transition Maps

The wear rate maps serve the purpose of examining and forecasting the wear patterns exhibited by materials when subjected to varying speeds and loads during sliding. These maps are essential in identifying the distinctive wear attributes of a particular material under a range of sliding conditions. The primary aim of the graphical representation is to investigate the impact of parameters like normal load and sliding velocity on the wear loss through the utilization of contours. The mode of wear, whether it be mild, severe, or ultra-severe, can be determined by analyzing the change in direction of the contour lines. To construct the contour wear rate map, Minitab software was utilized. The map was created by plotting the normal load on the Y-axis, sliding velocity on the X-axis, and the resulting wear values on the Z-axis. Each contour line on the map represents wear data corresponding to different combinations of normal load and sliding velocity conditions. Figure 7 **a**, **b** and **c** depict the wear distribution of the upper, middle, and lower sliding wear samples of the FGM alloy. The horizontal contour lines in the figures indicate their influence on the vertical axis, while the vertical contours represent their impact on the horizontal axis. The investigation conducted by Srinivasan et.al, confirms that the wear values of the Mg-based FGM alloy are minimized under lower magnitude conditions and maximized under higher applied sliding velocity conditions.

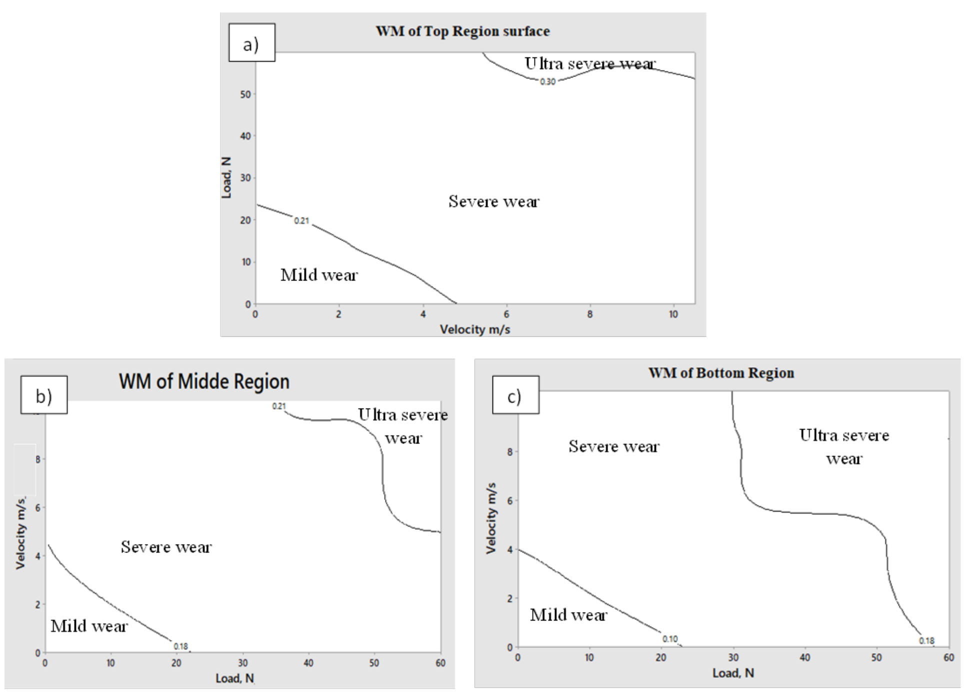

Fig 7. Wear Transition map for Top, Middle and Bottom Region FGM samples

The formation of transition boundary surfaces occurred between mild wear and severe wear, as well as between severe wear and ultra-severe wear. The transition maps clearly demonstrate the dominant shifts in wear mechanisms from one to another. Additionally, these transitions can be identified by quantifying the changes in wear values.

Under the condition of steady state, the process of wear takes place. As the loading and sliding conditions undergo changes, the rate of wear experiences a rapid increase, progressing from mild wear to severe wear and then to ultra-severe wear. These findings suggest that there is a substantial increase in wear that occurs concurrently with the shift in wear mechanisms associated with this transition in wear. Consequently, the transition map reveals that the mild wear regime for sample A in the top region exhibits a significant increase compared to samples B and C in the middle and bottom regions, enabling the specimens to withstand higher operating conditions. [15]

The mild wear regime can be considered the most secure regime due to its typically low wear rates. Conversely, the severe wear and ultra-severe regimes in the upper region of sample A experienced significant reduction. Consequently, the mild wear regimes can be deemed acceptable, while transitions to subsequent regimes are regarded as unacceptable.

4 Conclusion

For the purpose of this investigation, a cylindrical functionally graded material (FGM) was created using a centrifugal method. The FGM was composed of an alloy containing 80% Mg, 10% Zn, and 10% Mo. The following section provides an overview of the study's findings.

- 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.
- Dry sliding wear behavior of Mg based FGM alloy was studied under varying loads, sliding velocity, and observed that the load is significantly influenced the wear mechanisms.
- It is observed that the minimum wear loss for sliding wear samples A, B & C of Mg based FGM alloy were found to be 0.0018 g, 0.028 g and 0.031 g respectively, while the maximum wear loss for sliding wear samples A, B & C of FGM alloy were found to be 0.0021 g, 0.41 g and 0.31 g respectively.
- The transition map reveals a significant increase in the mild wear regime at the top region of sample A, in comparison to samples B and C located in the middle and bottom regions. This implies that the specimens can withstand higher operating conditions.
- Mg based FGM alloy of top region surface exhibited relatively good sliding wear performance with minimal grooves or cracks as compared to the bottom and middle region sample B & C. The future research and development bio implant and bone replacement have vast opportunities for five layered centrifugal casting which enhancing the properties and advancements in bio implants and automobile industries.

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