

Development of hydroxyapatite-reinforced magnesium matrix composites: effect of reinforcement ratio on wear and corrosion properties

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ABSTRACT

In this study, magnesium matrix composites reinforced with different weight percentages (1, 3, and 5 wt.%) of hydroxyapatite (HA) were fabricated via powder metallurgy to evaluate their suitability for biomedical applications. The effects of HA content on microstructure, mechanical behavior, wear resistance, and corrosion performance were systematically investigated. SEM and EDX analyses confirmed that while HA was uniformly dispersed at lower concentrations, 5 wt.% HA led to significant particle agglomeration, particularly along grain boundaries. The composite containing 3 wt.% HA exhibited the most favorable properties, including the highest hardness (36.30 HV), lowest wear rate ($13.2 \times 10^{-3} \text{ mm}^3/\text{m}$), and significantly improved corrosion resistance (1.00 mm/year). In contrast, the 5 wt.% HA composite showed reduced hardness (29.34 HV), increased wear rate ($19.6 \times 10^{-3} \text{ mm}^3/\text{m}$), and a drastic rise in corrosion rate (6.68 mm/year), highlighting the detrimental effect of excessive reinforcement and poor dispersion. These findings demonstrate that a controlled addition of 3 wt.% HA optimizes the balance between mechanical strength, tribological stability, and biodegradation resistance, making it a promising candidate for bioresorbable implant materials.

Keywords: *Magnesium, powder metallurgy, hydroxyapatite, wear, corrosion.*

1. INTRODUCTION

Magnesium and its alloys have garnered considerable interest in recent years owing to their unique combination of low density, high specific strength, and excellent biocompatibility, making them promising candidates for biodegradable implants and lightweight structural components in aerospace, automotive, and especially biomedical fields [1,2]. However, the

practical use of magnesium is limited by its relatively low mechanical strength, elastic modulus, and, more critically, its rapid degradation and poor corrosion resistance in physiological environments [3]. To address these challenges, researchers have focused on various enhancement strategies, including alloying, surface modification, and particularly the development of metal matrix composites [4].

Among the diverse reinforcement materials investigated, hydroxyapatite (HA)—a naturally occurring calcium phosphate mineral and the primary inorganic component of bone and teeth—has emerged as a particularly attractive candidate. HA is renowned for its excellent biocompatibility, osteoconductivity, and bioactivity, which collectively promote bone ingrowth and facilitate osseointegration of implanted materials [5,6]. When integrated into a magnesium matrix, hydroxyapatite not only improves the composite's mechanical properties and corrosion resistance but also enhances its biological functionality, accelerating bone regeneration and healing through synergistic effects [7,8].

The development of hydroxyapatite-reinforced magnesium matrix composites thus represents a promising direction for next-generation biomaterials, particularly in orthopedic and dental implant applications where load-bearing capacity, controlled degradation, and tissue integration are critical. Magnesium's natural biodegradability further eliminates the need for secondary surgeries to remove the implant, reducing patient risk and healthcare costs [9].

One of the most efficient approaches for fabricating such composites is powder metallurgy, a versatile and cost-effective technique that enables precise control over microstructure and composition [10,11]. This process involves blending magnesium and hydroxyapatite powders, compacting them into a desired form, and subsequently sintering at elevated temperatures to achieve densification and bonding through solid-state diffusion. By fine-tuning parameters such as powder size, mixing uniformity, compaction pressure, and sintering temperature, composites with tailored mechanical and biological properties can be produced to meet specific application requirements.

In summary, magnesium-hydroxyapatite composites offer a unique combination of bioactivity, biodegradability, and mechanical integrity. These characteristics render them highly suitable for load-bearing biomedical applications, including orthopedic implants, bone tissue engineering scaffolds, and bioresorbable fixation devices. The current study aims to explore the effect of hydroxyapatite reinforcement ratio on the wear and corrosion properties of magnesium matrix composites, with the goal of identifying optimal compositions for biomedical use.

2. EXPERIMENTAL STUDIES

2.1. Raw Materials

The magnesium powders (purity: 99.95%, size: 35 μm) serving as matrix material and the hydroxyapatite powders (purity: 99.5%, size: 40-50 μm) serving as the reinforcement were both procured from Nanografi LLC.

2.2. Sample Fabrication

The powders were first mixed for 1 h using a three-dimensional Turbula T2F mixer according to the compositions specified in Table 1. The resulting powder mixtures were then compacted in a mini mold made of 1.0718-grade steel using a manual hydraulic press. A uniaxial pressure of 20 N/mm^2 was applied to ensure the uniform formation of the specimens. Following compaction, the green specimens were wrapped in aluminum foil and sintered in a Protherm furnace at 600 $^{\circ}\text{C}$ for 2 h. To prevent oxidation of the Mg-based specimens during heat treatment, they were placed in sealed glass or quartz containers under a protective argon atmosphere or vacuum. The heating rate was set to 100 $^{\circ}\text{C/h}$. After sintering, the specimens were allowed to cool naturally to room temperature inside the furnace. The cooling process took approximately 12 h.

Table 1. Chemical compositions of samples.

Samples	Mg (wt.%)	HA (wt.%)
Mg	100	0
Mg+1 wt.% HA	99	1
Mg+3 wt.% HA	97	3
Mg+5 wt.% HA	95	5

2.3. Characterization

A field-emission scanning electron microscope equipped with energy-dispersive X-ray (EDX) spectroscopy was utilized to characterize the samples' microstructure and worn surfaces. The apparent density was determined via the Archimedes principle, in accordance with the ISO 3923/1-2018 standard, by comparing the samples' weights in air and water. Vickers hardness measurements were performed at five different locations on each specimen under a load of 1 kg and a dwell time of 15 s using a QNESS Q10A+ hardness tester. The hardness results are reported as mean $\pm$ standard deviation. Tribological properties were evaluated using a reciprocating ball-on-flat tribometer in accordance with ASTM G133-05. The wear tests were conducted in simulated body fluid (SBF) at room temperature. A 6 mm diameter AISI 52100 steel ball was used as the counter-body. The tests were performed under a normal load of 5 N, with a stroke length of 5 mm, a sliding speed of 0.04 m/s, and a total sliding distance of 100 m. After testing, the wear-track profiles were measured using a surface profilometer, and the wear

volumes were determined from the measured cross-sectional profiles. The wear rates were subsequently calculated using the wear volume and total sliding distance. Corrosion behavior was assessed through potentiodynamic polarization in a SBF solution, employing a potentiostat with a three-electrode setup. The corrosion potential (E_{corr}), corrosion current (I), and corrosion current density (I_{corr}) were obtained from the polarization measurements. The corrosion current density was calculated by normalizing the corrosion current to the exposed specimen area, and the corrosion rate was determined in accordance with ASTM G102–89 using Faraday's law. The density/porosity, wear, and electrochemical corrosion tests were conducted once for each composition. Therefore, these results are reported as single experimental values, and standard deviations or inferential statistical analyses were not calculated for these measurements.

3. RESULTS AND DISCUSSIONS

3.1 Microstructural Analysis and Density Results

Figure 1 presents SEM micrographs of magnesium matrix composites reinforced with varying weight percentages of hydroxyapatite (HA), illustrating the evolution of microstructure as a function of reinforcement content. In the unreinforced sample (Figure 1a), the microstructure is relatively homogeneous, with clearly defined grain boundaries and typical of pure sintered magnesium. Upon the addition of 1 wt.% HA (Figure 1b), HA-rich particles become visible both near the apparent boundaries of the Mg particles/grains and within the matrix regions, indicating increasing interactions between the reinforcement and the Mg matrix. Based on mechanisms previously reported for particle-reinforced metal matrix composites, these particles may locally restrict boundary movement during sintering [12,13]. However, quantitative grain-size measurements were not performed in the present study, and the SEM micrographs alone do not allow reliable confirmation of grain refinement or grain-growth inhibition. At 3 wt.% HA (Figure 1c), the reinforcement appears to be more uniformly distributed throughout the matrix. This more homogeneous distribution may contribute to improved mechanical and corrosion properties by reducing localized reinforcement-deficient or reinforcement-rich regions [14].

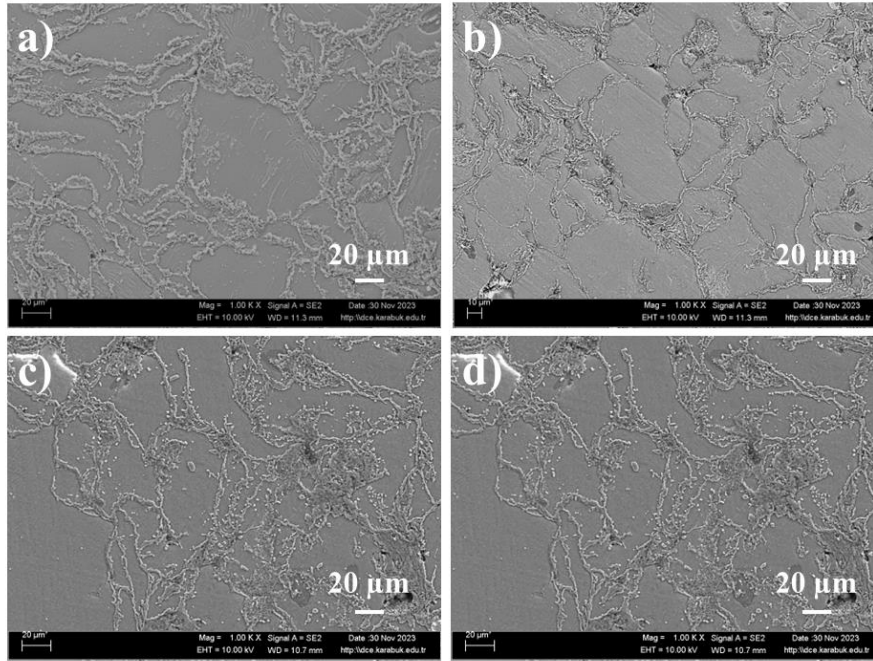


Figure 1. Microstructural SEM images of a) Mg, b) Mg+1wt.% HA, c) Mg+3wt.% HA, and d) Mg+5wt.% HA

However, in the sample containing 5 wt.% HA (Figure 1d), although HA particles are more abundant, signs of agglomeration become evident. These clustered regions may act as stress concentration zones and hinder the mechanical performance due to poor load transfer efficiency. Overall, the SEM observations indicate that moderate HA content, particularly 3 wt.%, results in a more homogeneous distribution of the reinforcement, whereas excessive HA addition promotes particle agglomeration and microstructural heterogeneity. The reinforcement-distribution trend observed in the present study is generally consistent with previous investigations showing that HA dispersion becomes more difficult as its content increases. Del Campo et al. [15] similarly observed that agglomerated Ca/P/O-rich regions were already evident at 5 wt.% HA. The lower apparent agglomeration threshold may be associated with differences in reinforcement size, mixing conditions, compaction, and the absence of a subsequent extrusion step. This comparison demonstrates that the critical HA content is not universal but depends strongly on the processing route and its ability to break up and redistribute reinforcement clusters. Gu et al. reported a relatively uniform HA distribution in a Mg–10 wt.% HA composite, occasional clustering at 20 wt.% HA, and severe agglomeration at 30 wt.% [16].

Figure 2 illustrates the elemental mapping results obtained from EDX analysis of the Mg–5 wt.% HA composite, providing spatial distribution data for magnesium (Mg), calcium (Ca), phosphorus (P), and oxygen (O). These elements correspond respectively to the matrix (Mg)

and the hydroxyapatite ($\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$) reinforcement phase. The magnesium signal (in red) appears homogeneously distributed, outlining the matrix phase. In contrast, the Ca, P, and O signals—originating from hydroxyapatite—exhibit localized concentrations, particularly in certain clustered regions. This observation strongly supports the SEM findings from Figure 1d, where visible agglomerations were identified at higher HA content. The co-localization of Ca, P, and O indicates the presence of HA-rich or calcium-phosphate-rich regions. Furthermore, the oxygen signal (in green) shows a patterned distribution that coincides with HA clusters, reinforcing the conclusion that the hydroxyapatite is present in particulate agglomerates rather than as uniformly distributed nanophases. Such agglomeration may create microstructural discontinuities, compromising mechanical integrity and interfacial bonding strength [17], as previously discussed in microstructural analysis.

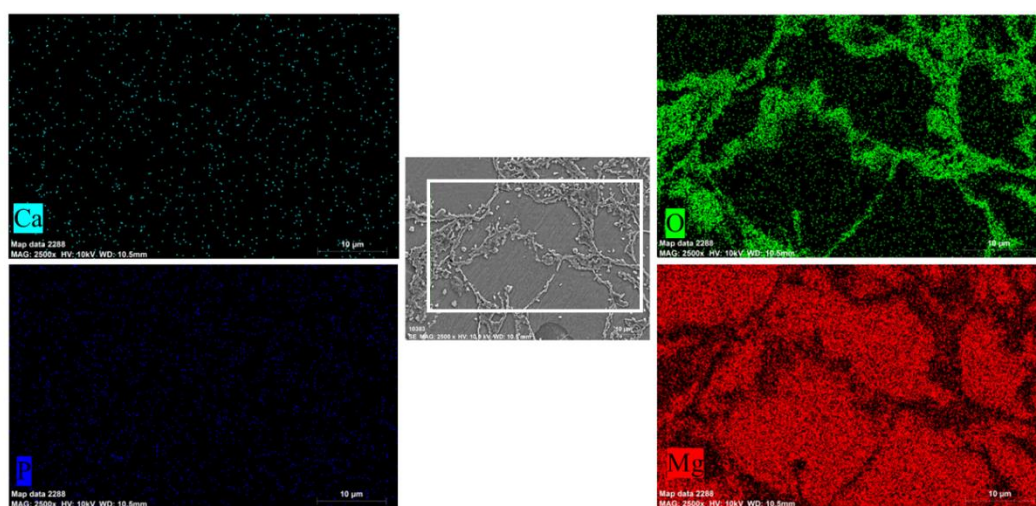


Figure 2. Mapping EDX analysis of Mg+5wt.% HA

Figure 3 presents a line EDX analysis of the Mg–5 wt.% HA composite, providing further evidence regarding the spatial distribution of hydroxyapatite within the microstructure. The corresponding EDX line scan graph on the right reveals two significant peaks in calcium (Ca), phosphorus (P), and oxygen (O) concentrations at positions coinciding with the HA-rich zones, while the magnesium (Mg) signal exhibits a sharp decrease in these same regions. The simultaneous increase in Ca, P, and O signals, accompanied by a decrease in the Mg signal, confirms the presence of Ca/P/O-rich regions. These regions are consistent with the localization of the added HA reinforcement; however, their exact crystalline phase composition cannot be determined from EDX analysis alone. These results validate the earlier mapping data shown in Figure 2, which highlighted elemental localization, and reinforce the conclusion that HA particles tend to accumulate at grain boundaries when added at higher concentrations such as 5 wt.%. This boundary-localized reinforcement distribution is critical in interpreting the

composite's mechanical and corrosion performance [18]. In contrast, excessive accumulation of HA may introduce interfacial weaknesses and potential crack-initiation sites under mechanical loading.

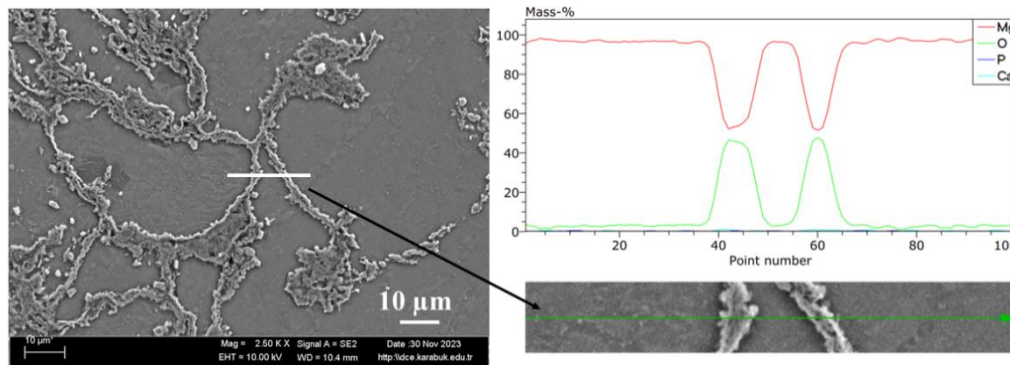


Figure 3. Line EDX analysis of Mg+5wt.% HA

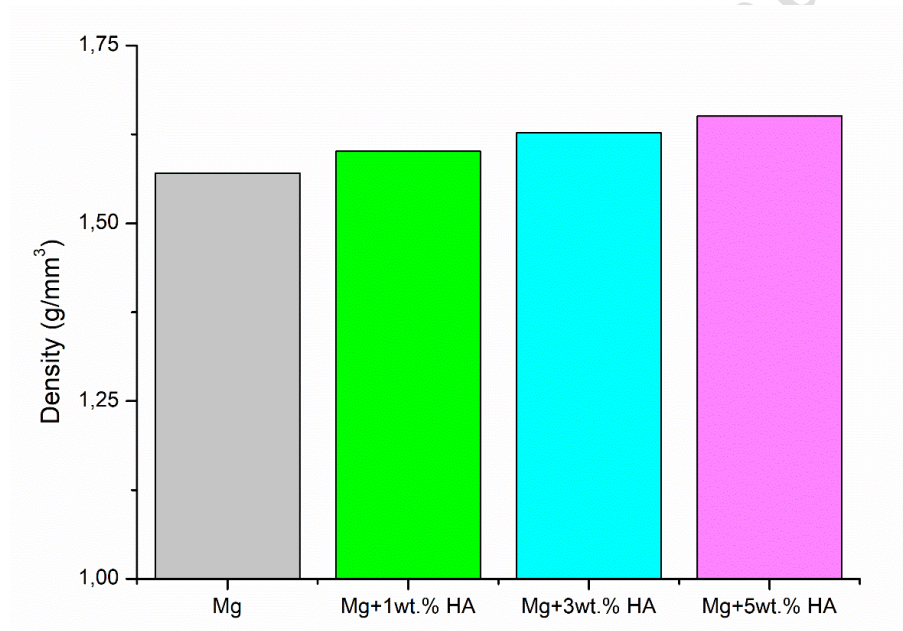


Figure 4. Density measurement results of the composites

Figure 4 illustrates the effect of HA reinforcement on the measured density and porosity of the magnesium matrix composites. The density progressively increased from 1.5704 g/cm³ for pure Mg to 1.6508 g/cm³ for the Mg + 5 wt.% HA composite. This trend is primarily associated with the higher theoretical density of HA, approximately 3.16 g/cm³, compared with approximately 1.74 g/cm³ for Mg. The porosity decreased from 9.64% in pure Mg to 8.61% in both the Mg + 1 wt.% HA and Mg + 3 wt.% HA composites, suggesting improved particle packing at low and moderate reinforcement contents. A slight increase in porosity to 8.74% was observed at 5 wt.% HA, which may be associated with reduced compaction efficiency caused by HA agglomeration. Nevertheless, this relatively small increase in porosity was insufficient to offset

the density increase resulting from the higher HA fraction. Therefore, the measured density continued to rise despite the slight increase in porosity at 5 wt.% HA.

3.2 Hardness Results

Figure 5 presents the Vickers hardness values of the magnesium matrix composites reinforced with varying amounts of HA, while the corresponding numerical values are summarized in Table 2. The results indicate that the mean hardness increased from 32.14 HV for pure Mg to 36.30 HV for the Mg + 3 wt.% HA composite, corresponding to an approximately 13% numerical increase which can be attributed to the effective dispersion of HA particles within the matrix, as previously observed in the SEM image (Figure 1c) and supported by EDX mapping (Figure 2). The homogeneously distributed HA particles likely act as effective barriers against dislocation motion [19], thereby enhancing the composite's resistance to localized plastic deformation. Also, it is well known that hard second-phase particles typically leads to improved hardness in metal matrix composites [20]. This trend agrees with the results of Del Campo et al. [15], who reported increased microhardness after incorporating HA into Mg, although the corresponding compression behavior was also influenced by texture and porosity. However, a noticeable decline in hardness is observed at 5 wt.% HA, despite the increase in density reported in Figure 4. This reduction can be explained by the particle agglomeration identified in Figure 1d and further confirmed by elemental mapping (Figure 2) and line analysis (Figure 3). Such clustering of HA particles at higher concentrations may introduce microstructural defects and interfacial weaknesses, reduce the efficiency of load transfer and compromising the composite's overall mechanical integrity. These findings emphasize that while moderate HA addition enhances hardness through dispersion strengthening mechanisms, excessive reinforcement content may have a detrimental effect due to poor particle distribution and agglomeration. Therefore, 3 wt.% HA appears to be an optimal reinforcement ratio for maximizing hardness in these composites.

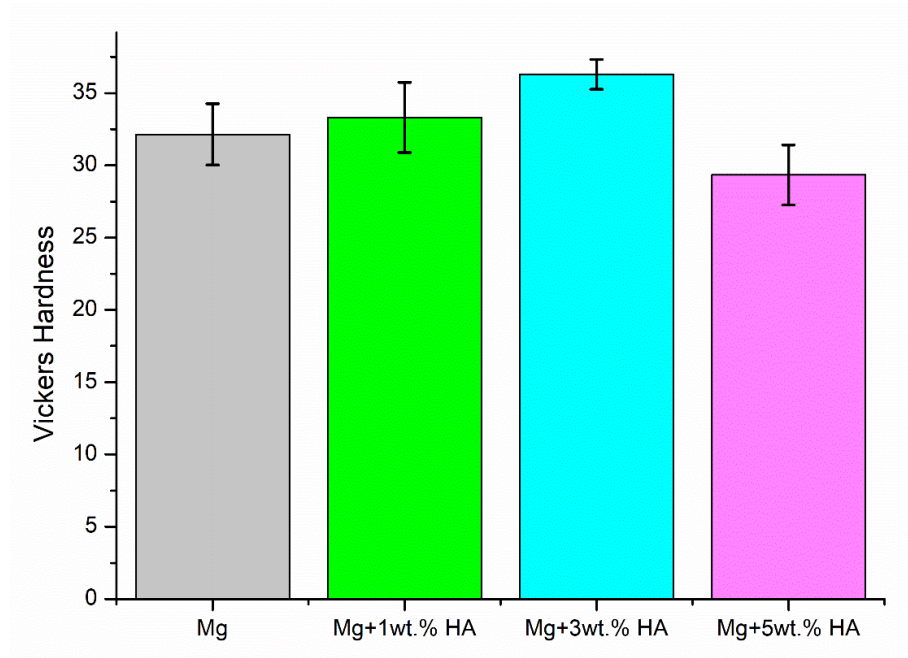


Figure 5. Hardness test results of the alloys

3.3 Tribological Properties

Figure 6 presents the wear rate values of pure magnesium and the Mg–HA composites with varying reinforcement ratios, and the corresponding numerical results are summarized in Table 2. The wear rate decreased from $16.5 \times 10^{-3} \text{ mm}^3/\text{m}$ for pure Mg to $13.2 \times 10^{-3} \text{ mm}^3/\text{m}$ for the Mg + 3 wt.% HA composite, representing an approximately 20% reduction in the measured wear rate. The lower wear rate is consistent with the simultaneous increase in mean hardness and the comparatively homogeneous distribution of HA particles. Specifically, the lowest wear rate is observed in the Mg + 3 wt.% HA sample, which correlates well Archards Law which exhibits that softer material has lower wear resistance than harder materials [21]. This improvement is primarily attributed to the uniform dispersion of HA particles which may act as a rigid load-bearing phase within the matrix (Figure 1c) [22], effectively resisting plastic deformation and surface material removal under sliding conditions. In contrast, the sharp increase in wear rate at 5 wt.% HA despite the composite having the highest density (Figure 4) suggests that microstructural factors such as HA agglomeration (as evidenced in Figures 1d, 2, and 3) significantly impair wear performance. Clusters of HA at grain boundaries may act as weak spots under tribological stress, leading to particle pull-out, microcracking, and interfacial debonding, all of which contribute to accelerated material loss [23]. This behavior highlights a critical balance between reinforcement content and its distribution; while moderate HA addition enhances wear resistance through dispersion strengthening, excessive loading undermines this effect due to poor microstructural integrity. Jayasathyakawin et al. [24] also reported that HA

content influenced the hardness and abrasive wear behavior of powder-metallurgy-processed Mg–3Al/HA composites. However, direct numerical comparison between the two studies is limited because of differences in matrix composition, counter-body, applied load, sliding conditions, and test environment. In particular, the present tests were performed in SBF, where mechanical wear, corrosion, and possible tribochemical reactions occur simultaneously. In summary, the wear test results reinforce earlier findings and confirm that 3 wt.% HA provides the most favorable combination of microstructural uniformity, hardness, and wear resistance.

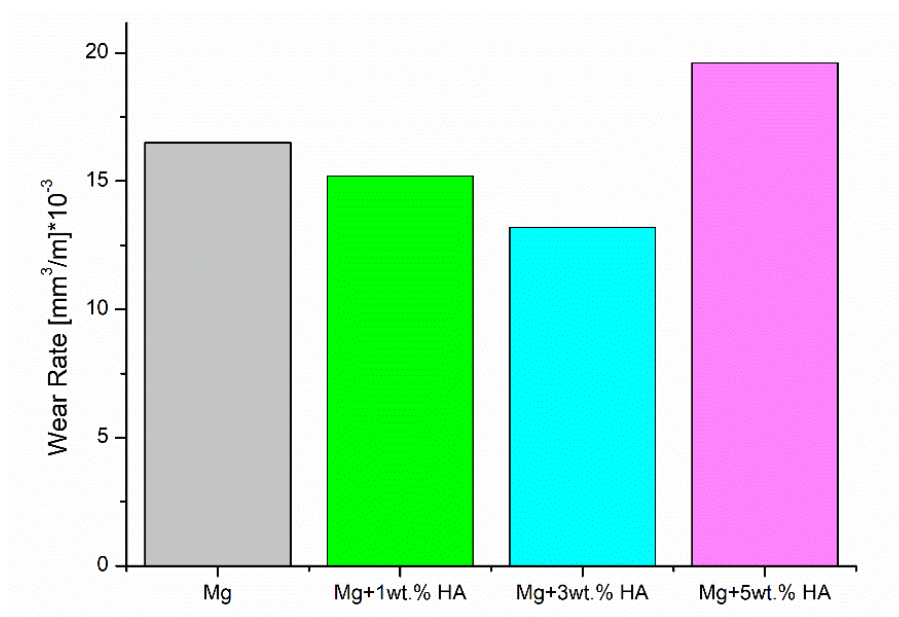


Figure 6. Graphical wear rate comparisons

Figure 7 presents SEM micrographs of worn surfaces for pure magnesium and Mg–HA composites following wear tests conducted in simulated body fluid (SBF), providing insight into the wear mechanisms. In the case of pure magnesium (Figure 7a), the worn surface shows distinct grooves and plastic deformation features, typical of adhesive and abrasive wear mechanisms [25]. These features indicate limited resistance to sliding wear and the absence of reinforcing phases that could hinder material removal. With the addition of 1 wt.% HA (Figure 7b), the surface becomes slightly smoother, and fewer deep grooves are observed. The presence of HA particles likely contributes to moderate improvement in wear resistance by partially inhibiting plastic flow and enhancing surface hardness, consistent with the slight decrease in wear rate (Figure 6) and modest increase in hardness (Figure 5). The Mg + 3 wt.% HA composite exhibited a comparatively smooth worn surface with fewer pronounced grooves and less visible wear debris, consistent with its lower measured wear rate. This behavior may be partly associated with the more homogeneous distribution of the hard HA particles, which can restrict localized plastic deformation and material removal during sliding. However, because

the wear tests were conducted in SBF, tribochemical and corrosion-related reactions may also have influenced the worn-surface morphology [26]. Previous studies have shown that Ca–P-containing compounds or apatite-like deposits can form on Mg–HA surfaces during exposure to SBF [27]. The formation or retention of such reaction products within the wear track could partially fill surface irregularities and reduce direct interaction between the steel counter-body and the Mg matrix, thereby contributing to the smoother surface appearance. This indicates an effective load transfer mechanism and improved tribological stability in the physiological medium, consistent with the lowest wear rate measured. In contrast, the worn surface of the Mg + 5 wt.% HA composite (Figure 7d) exhibits severe surface damage, including crack formations, brittle fracture regions, and clustered debris. These defects suggest that the agglomerated HA particles previously confirmed through mapping (Figure 2) and line analysis (Figure 3) create microstructural weaknesses that fail under sliding contact. The poor bonding at HA-rich grain boundaries likely promotes interfacial debonding and particle pull-out, leading to elevated wear rate (Figure 6) and reduced hardness (Figure 5). Overall, the worn surface morphologies confirm the trend that 3 wt.% HA yields the most favorable tribological behavior in simulated body conditions, whereas excessive HA loading (5 wt.%) leads to surface degradation due to particle clustering and weak interfacial integrity. These findings underscore the importance of optimizing reinforcement content not only for mechanical enhancement but also for stable in vivo wear performance.

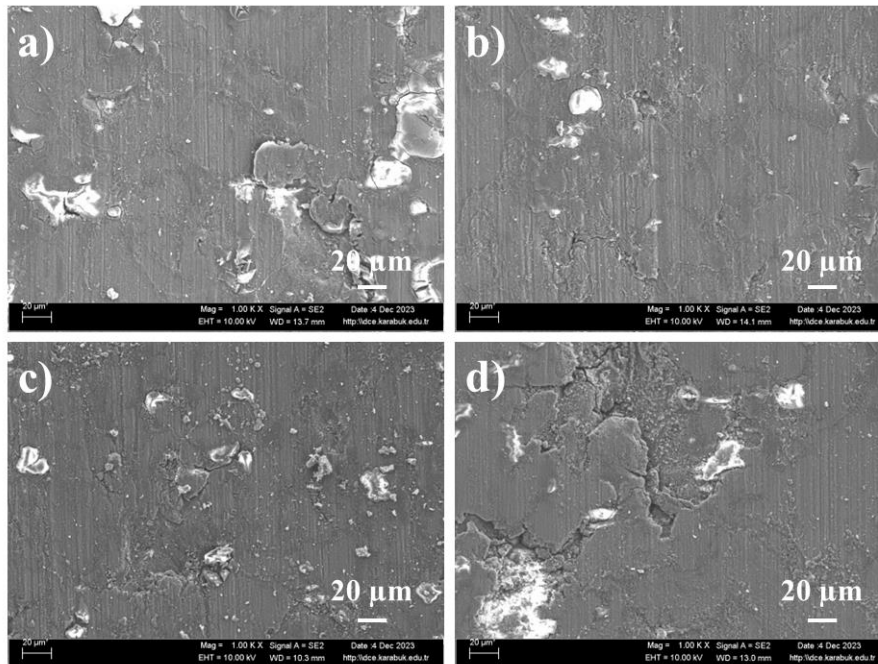


Figure 7. SEM micrographs of worn surfaces a) Mg, b) Mg+1wt.% HA, c) Mg+3wt.% HA, and d) Mg+5wt.% HA

The porosity, hardness, wear rate results of all investigated compositions are collectively summarized in Table 2.

Table 2. Porosity, hardness, wear rate results of compositions.

Specimen	Hardness (Vickers)	Wear Rate (mm ³ /m)*10 ⁻³	Porosity (%)
Mg	32.14±2.11	16.5	9.64
Mg+1wt.% HA	33.32±2.42	15.2	8.61
Mg+3wt.% HA	36.30±1.04	13.2	8.61
Mg+5wt.% HA	29.34±2.07	19.6	8.74

3.4 Corrosion Behavior

The electrochemical parameters obtained from the potentiodynamic polarization tests are summarized in Table 3. In addition to the corrosion-rate results, the corrosion current density provides a direct indication of the electrochemical dissolution kinetics of the investigated composites. The Mg + 3 wt.% HA composite exhibited the lowest corrosion current density of 40.43 $\mu\text{A}/\text{cm}^2$, consistent with its lowest corrosion rate of 1.00 mm/year. This result indicates a lower electrochemical dissolution tendency under the investigated SBF conditions. This positive trend is closely associated with the microstructural uniform dispersion of HA particles together with the lower porosity measured for the Mg + 1 wt.% HA and Mg + 3 wt.% HA composites. The HA phase, being chemically stable and bioactive, likely forms a partial passive layer that [28],[29] slows down the kinetics of the corrosion reactions [30]. In contrast, the Mg + 5 wt.% HA composite showed the highest corrosion current density of 269.36 $\mu\text{A}/\text{cm}^2$ and the highest corrosion rate of 6.68 mm/year, confirming the pronounced deterioration in corrosion resistance at the highest HA content. The sharp increase in corrosion rate observed for the Mg + 5 wt.% HA composite may be associated with the agglomeration of HA particles previously identified in the microstructural analyses. Such agglomerated regions can generate microstructural heterogeneity and possible interfacial discontinuities between the reinforcement and the Mg matrix, which may facilitate localized corrosion. In addition, these heterogeneous regions may contribute to differences in local electrochemical activity. Furthermore, the microcracks and surface damage seen in the worn surfaces of Mg + 5 wt.% HA (Figure 7d) suggest that poor interfacial bonding and brittle fracture can further accelerate corrosion through crack-assisted penetration of electrolyte. In conclusion, the corrosion data

reinforces earlier findings by highlighting that 3 wt.% HA offers an optimal balance providing both mechanical reinforcement and corrosion resistance while excessive HA addition (5 wt.%) undermines structural integrity and accelerates degradation.

The E_{corr} values shifted from 1.50 V for pure Mg to 1.49 V for the Mg + 3 wt.% HA and 1.65 V for the Mg + 5 wt.% HA composites. Although E_{corr} provides information about the relative thermodynamic tendency for corrosion, it should not be interpreted independently as a direct measure of corrosion resistance. Therefore, the corrosion performance was evaluated primarily by considering I_{corr} and corrosion rate together. The combined electrochemical results indicate that moderate HA addition reduced the measured corrosion activity, whereas excessive HA addition produced a more electrochemically active and heterogeneous composite structure.

Table 3. Electrochemical parameters of pure Mg and Mg–HA composites obtained from potentiodynamic polarization tests in SBF.

Specimen	Corrosion Current (μA)	Corrosion Current Density ($\mu\text{A}/\text{cm}^2$)	Corrosion Rate (mm/year)	E_{corr} (V)
Mg	-32.46	115.93	2.88	-1.50
Mg+1wt.% HA	-25.83	92.25	2.29	-1.49
Mg+3wt.% HA	-11.32	40.43	1.00	-1.65
Mg+5wt.% HA	-75.42	269.36	6.68	-1.41

The non-linear corrosion response observed in the present study is comparable with the contrasting trends reported for Mg–HA systems in the literature. Del Campo et al. [15] found that Mg–5 wt.% HA exhibited better corrosion resistance than pure Mg and composites containing 10 and 15 wt.% HA in PBS, emphasizing the roles of porosity and microstructural characteristics. Conversely, Gu et al. [16] reported increasing corrosion rates with increasing HA content in Mg composites containing 10–30 wt.% HA. Xiong et al. [31], however, observed improved corrosion resistance for microwave-sintered Mg–HA composites compared with pure Mg. These apparently different findings indicate that HA content alone does not determine corrosion behavior; reinforcement dispersion, porosity, interfacial integrity, matrix composition, and processing conditions are also critical.

4. CONCLUSIONS

In this study, hydroxyapatite (HA)-reinforced magnesium matrix composites were successfully fabricated using the powder metallurgy method, and the effects of varying HA content (1, 3, and 5 wt.%) on the microstructural, mechanical, tribological, and corrosion properties were systematically investigated. SEM and EDX analyses indicated that low and moderate HA additions, particularly 1–3 wt.%, resulted in a relatively homogeneous reinforcement distribution, whereas excessive reinforcement at 5 wt.% led to significant HA agglomeration, particularly near the apparent matrix boundaries. This non-uniformity adversely affected the material's overall performance. Mechanical testing demonstrated that the incorporation of HA increased the Vickers hardness up to a reinforcement content of 3 wt.%. The higher hardness of the Mg + 3 wt.% HA composite may be associated with the relatively homogeneous distribution of the hard HA particles, which can restrict localized plastic deformation and dislocation movement within the Mg matrix. Wear test results were in agreement, with the 3 wt.% HA composite showing the lowest wear rate and the smoothest worn surface morphology, indicating enhanced wear resistance under simulated body fluid conditions. In contrast, the 5 wt.% HA composite showed increased wear damage, consistent with the presence of brittle fracture regions and reinforcement clustering. Corrosion behavior followed a similar trend. The corrosion rate decreased with increasing HA content up to 3 wt.%, suggesting that HA acts as a protective barrier and contributes to surface passivation. However, at 5 wt.% HA, corrosion resistance deteriorated significantly due to poor interfacial bonding and micro galvanic effects caused by agglomerated HA particles. In summary, the findings clearly indicate that 3 wt.% HA represents an optimal reinforcement level for balancing mechanical strength, wear resistance, and corrosion performance in Mg–HA composites. Beyond this threshold, the detrimental effects of particle agglomeration outweigh the potential benefits. These results underscore the importance of controlling reinforcement dispersion in designing high-performance biodegradable magnesium-based materials for biomedical applications, particularly for load bearing and corrosion-sensitive environments.

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DECLARATION OF COMPETING INTEREST

The authors affirm that there are no known financial conflicts of interest or personal relationships that could have potentially influenced the findings presented in this paper.

ETHICS DECLARATION

Not applicable

DECLARATION OF AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the author(s) used OpenAI's ChatGPT to assist with language refinement and to enhance the readability of the manuscript. After utilizing this tool, the authors thoroughly reviewed and edited the content to ensure accuracy and clarity and take full responsibility for the content of the published article.

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