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Research Article

# Development and Evaluation of an AZ31 Magnesium Alloy and Eggshell Powder Composite for Orthopedic Surgical Implants

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**Abstract:** This research investigates the development and evaluation of a novel composite material composed of AZ31 magnesium alloy and eggshell powder, designed for use in surgical bone implants. The primary objective is to enhance the mechanical properties and biocompatibility of AZ31 by incorporating eggshell powder, which is known for its hardness and strength. The composite is fabricated using the stir casting technique, where the molten magnesium is mixed with finely ground eggshell powder to achieve uniform dispersion. The resulting samples are subjected to rigorous mechanical testing, including tensile and compressive strength evaluations, as well as hardness measurements. Additionally, the internal structure and particle distribution of the composite are analyzed using scanning electron microscopy and X-ray diffraction, respectively. This study aims to provide a comprehensive understanding of the material properties and structural characteristics of the composite, with a focus on its potential applications in orthopedic load-bearing implants and fixation devices, such as bone plates, joint replacements, screws, rods, dental implants, and cardiac stents. The findings are expected to contribute to the development of improved biomaterials for medical applications, leveraging the unique benefits of both magnesium alloy and eggshell powder.

***Keywords*:** hybrid composite; stir casting; mechanical properties; orthopedic applications

## 1. Introduction

Magnesium alloys, particularly AZ31, are becoming increasingly important in biomedical applications due to their favorable properties, including lightweight, high strength, and biodegradability. These characteristics make magnesium alloys suitable for developing implants that can gradually degrade and be absorbed by the body, thereby eliminating the need for a second surgery to remove the implant. However, pure magnesium alloys often face challenges such as rapid corrosion rates and insufficient mechanical strength for certain load-bearing applications. To address these challenges, researchers are exploring the addition of various reinforcements to magnesium alloys to enhance their properties. Eggshell powder, primarily composed of calcium carbonate, has emerged as a promising additive due to its inherent hardness, strength, and biocompatibility. The use of eggshell powder not only improves the mechanical properties of the composite but also leverages a sustainable and low-cost waste material. This study focuses on the development and testing of an AZ31 magnesium alloy and eggshell powder composite specifically designed for surgical bone implants. The primary objective is to evaluate the mechanical properties and internal structure of the composite to determine its suitability for orthopedic applications. The fabrication process involves mixing the magnesium alloy with eggshell powder using the stir casting technique, ensuring a uniform distribution of the reinforcement within the matrix. Subsequent mechanical testing, including tensile and compressive strength measurements as well as hardness testing, will provide insights


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into the material's performance under physiological conditions. Additionally, the internal structure and particle distribution will be examined using scanning electron microscopy (SEM) and X-ray diffraction (XRD) to ensure the composite's structural integrity and uniformity. The results of this research are expected to contribute to the development of improved biomaterials for medical applications, particularly in the creation of orthopedic load-bearing implants and fixation devices such as bone plates, joint replacements, screws, rods, dental implants, and cardiac stents. By enhancing the properties of AZ31 magnesium alloy with eggshell powder, this study aims to pave the way for more effective and sustainable solutions in surgical bone repair and replacement.

## 2. Literature Review

Magnesium alloys have gained significant attention in various industries due to their unique properties, such as lightweight, high specific strength, low specific weight, good quenching properties, and stable machinability. These characteristics make magnesium alloys suitable for applications in aerospace, biomedical, military, automotive, and electronic industries [1–3]. In the automotive sector, cast magnesium alloys are employed in numerous components of modern vehicles, including high-performance cars. Die-cast magnesium is also popular in the production of camera bodies and lenses, benefiting from its low cost and excellent castability.The biomedical field has particularly shown interest in magnesium-based materials for orthopedic applications. Magnesium and its alloys are recognized for their excellent mechanical properties, biocompatibility, and ability to degrade safely within the body, which makes them ideal candidates for temporary implants [4]. However, pure magnesium alloys face challenges such as rapid corrosion and insufficient mechanical strength, which can limit their use in load-bearing applications [5–7]. To address these limitations, researchers have investigated the incorporation of various reinforcements into magnesium alloys. One promising reinforcement material is eggshell powder, which is predominantly composed of calcium carbonate. Eggshell powder has been shown to improve the hardness, strength, and overall mechanical properties of composites while being a sustainable and low-cost material [8]. Studies have demonstrated that the addition of calcium carbonate-based reinforcements can enhance the corrosion resistance and mechanical integrity of magnesium composites [9]. The fabrication of magnesium composites often involves techniques such as stir casting, which ensures a uniform distribution of reinforcement particles within the matrix. Stir casting is a cost-effective and scalable method that has been successfully employed in the production of metal matrix composites [10]. The resulting composites are then subjected to various mechanical tests to evaluate their performance under different loading conditions. Tensile strength, compressive strength, and hardness are critical parameters that determine the suitability of these materials for biomedical applications [11]. Microstructural analysis techniques such as scanning electron microscopy (SEM) and X-ray diffraction (XRD) are essential for understanding the internal structure and phase composition of the composites. SEM provides detailed images of the material's morphology, revealing the distribution and interaction of reinforcement particles within the magnesium matrix. XRD analysis identifies the phases present in the composite and confirms the uniformity of particle dispersion [12, 13]. Finite element-based simulation processes are also employed to predict the stress distribution and performance of magnesium-based fracture fixation devices. These simulations help in optimizing the design of orthopedic implants to ensure they can withstand the physiological loads encountered in the human body [14–16]. The integration of eggshell powder into AZ31 magnesium alloy composites has shown promising results in enhancing the mechanical properties and biocompatibility of the material. This study aims to build on this foundation by developing and testing an AZ31 magnesium alloy and eggshell powder composite specifically for surgical bone implants. The goal is to provide a comprehensive understanding of the material's properties and its potential applications in orthopedic load-bearing implants and fixation devices.

## 3. Materials and Methods

### 3.1 *Materials*

In this work, a metal-matrix composite using a magnesium alloy (AZ31) as the base material and purchased India mart supplier at Cheanni. They are using eggshells in powder form as a reinforcement material. The eggshells collected from hotel messes have been chemically modified, processed by ball milling, and converted into powder. The size of the eggshell powder used in the composite is 320 mm. To make it easier to handle, the magnesium alloy ingot is cut into small pieces measuring 1cm × 1cm × 3cm. These smaller pieces can then be placed in the hot work melting chamber. The tensile properties of the magnesium alloy at elevated temperatures are influenced by the condition (heat treatment) of the casting and the duration at the elevated temperatures. Despite being of low density, the magnesium alloy exhibits high elongations and excellent formability at ambient temperature. It also forms a strong basal texture. The chemical composition of the magnesium alloy is 97% magnesium, 2.5% aluminum, and 0.5% other elements. The eggshell powder used as reinforcement is a low-cost material with a high melting point of 2750°C, making it refractory. It is also stable against the action of many melted metals. The eggshell powder is shown in Fig. 1.

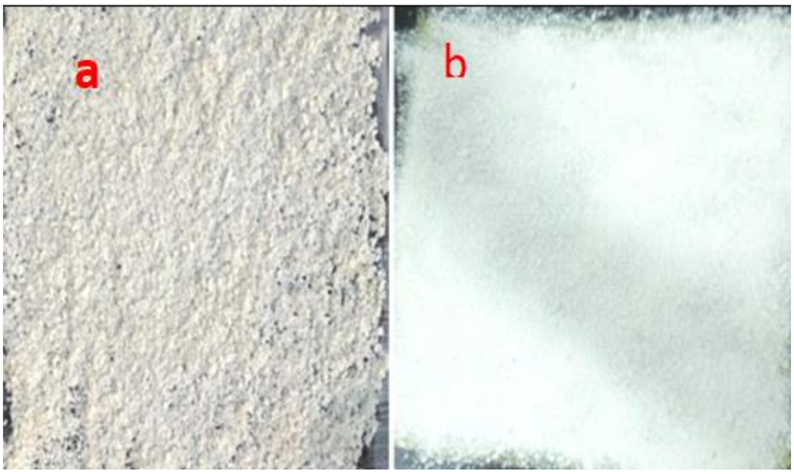


**Figure 1.** Chemically modified eggshell and eggshell powder (a. Eggshell, b. Eggshell powder)

The application of eggshell powder in metal-matrix composites, particularly with AZ31 magnesium alloy, presents a promising approach to developing materials with enhanced performance characteristics. AZ31 magnesium alloy exhibits a tensile strength of 260 MPa, a density of 1.8 g/cm³, a coefficient of thermal expansion of -0.03 × 10^6/°C, and a modulus of elasticity of 42 GPa, making it suitable for high-strength and low-weight applications. Eggshell powder offers high-temperature resistance, stability in alkaline-metal vapor and liquid metals, and resistance to $CO_2$ and $H_2O$, expanding its use in various industrial processes. However, while the inclusion of eggshell powder enhances the strength of the composite, it also increases brittleness, requiring careful management based on specific application requirements. The combination of AZ31 magnesium alloy and eggshell powder results in a composite material with improved mechanical properties and stability, making it particularly suitable for aerospace components, automotive parts, and industrial equipment operating in high-temperature or chemically aggressive environments. Balancing the increased brittleness is essential to fully leverage the benefits of this innovative material in practical applications.

## 3.2 *Fabrication method*

The fabrication process of AZ31 magnesium and eggshell-reinforced composites involves stir casting, a primary process for composite production. In this process, molten base metal (magnesium alloy) is continuously stirred while introducing reinforcements (eggshell powder). The resulting mixture is then poured into a die and allowed to solidify.

The experimental arrangement consists of a main furnace equipped with four mild steel stirrer blades. The process begins with preheating, where the empty crucible and the reinforcement powders (Eggshell powder and magnesium alloy) are separately heated to a temperature close to the main process temperature. The magnesium alloy (95%) is melted inside the furnace, with the ingot preheated for 3–4 hours at 550°C. Simultaneously, the eggshell powder and magnesium powder are preheated to 400°C in separate containers. The crucible containing the magnesium alloy is heated to 830°C, while the preheated powders are mechanically mixed below their melting points. This metal matrix is then placed in the furnace at the same temperature. The furnace melts the magnesium alloy pieces and the calcium oxide powder. The stirring mechanism is lowered into the crucible inside the furnace and set at the desired depth. The materials are vigorously stirred for mixing of composition. Fig.2. shown the fabrication process of magnesium-based matrix composite.


**Figure 2.** Fabrication procedure of AZ31 magnesium and eggshell-reinforced composite (a) Die with composite materials, b.) Open section of die, c.) Final composite materials, d.) A complete view of die)

# 4. Experimental Testing

The following tests are conducted on the magnesium AZ31 composite to know their mechanical properties.

## 4.1 *Tensile Test*

Mechanical testing, crucial for assessing material strength, is conducted using a universal testing machine, adhering to ASTM standards (ASTM E8 M). Tensile tests are performed on three samples each of AZ31 magnesium and eggshell-reinforced composite. Samples are clamped into the machine, and subjected to tension until fracture, and data on load and displacement are recorded. Average tensile stress is calculated for each material set, ensuring representative values. Comparative analysis of tensile stress aids in evaluating relative material performance.

## 4.2 *Compression Test*

Compression testing, akin to tensile testing, employs cubic or cylindrical specimens to ensure uniform loading. Specimens are sandwiched between compression plates on a universal testing machine, and subjected to gradually applied compressive loads. Deformation, typically measured as length change or displacement, informs analysis. Compressive properties, including strength and modulus, are derived from load-deformation data. Failure modes encompass buckling or shearing. Compression testing (ASTM E9) is indispensable for evaluating material behavior in engineering applications.

## 4.3 *Brinell hardness Test*

The Brinell hardness test (ASTM E10) assesses a material's resistance to indentation using a known load and a hardened steel ball. A 10 mm diameter ball is pressed against the material's surface with loads ranging from 500 kg to 3000 kg. Indentation diameter, measured after 10-15 seconds, determines material hardness, calculated as the applied load divided by the indentation area. This method is commonly used for evaluating the hardness of metals and alloys.

# 5. Result and Discussion

## 5.1 *Tensile strength*

In mechanical strength tests adhering to ASTM standards (ASTM E8 M), three distinct composition samples were examined. Sample I comprised 85% AZ31 and 15% eggshell powder, Sample II consisted of 90% AZ31 and 10% eggshell powder, and Sample III contained 95% AZ31 and 5% eggshell powder. Comparative analysis revealed that Sample III exhibited superior mechanical strength, suggesting that a lower percentage of eggshell powder reinforcement enhances tensile strength in the composite. Figure 3 illustrates the typical shape and dimensions of the tensile specimen for the AZ31 magnesium-eggshell powder-reinforced composite, while Figure 4 presents the corresponding tensile strength results. These results underscore the significant influence of eggshell powder content on the composite's mechanical properties. each sample was taken from 5 specimens and evaluated average value of tensile strength.

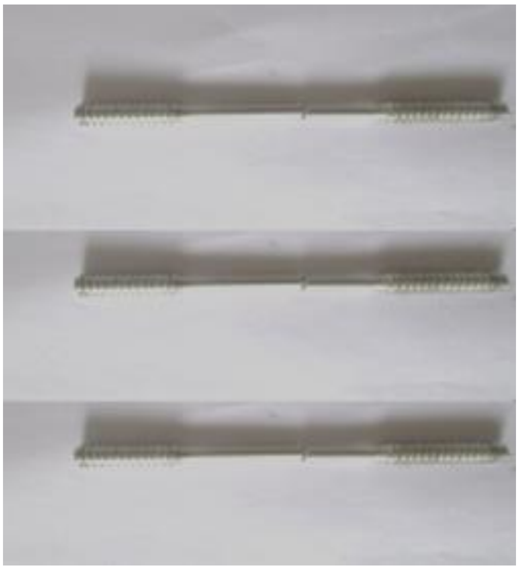

**Figure 3.** Tensile testing specimens

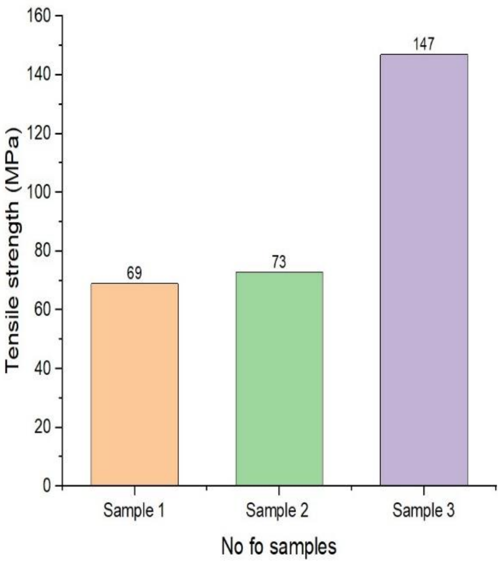


**Figure 4.** Tensile Strength of the Samples

## 5.2 *Compression strength*

The study involved preparing different compositions of composite samples by reinforcing the AZ31 magnesium matrix with varying percentages of eggshell powder, following ASTM standards (ASTM E9). These samples were then tested for their compressive strength. The compression tests were conducted using a universal testing machine, with the loads applied gradually to ensure accurate measurement of compressive strength. Among the samples tested, it was found that sample 3 exhibited the highest compressive strength of 153 MPa compared to the other samples. This sample demonstrated the capability to withstand the desired loads of 28 kN without failure. Figure 5 displays the compressive strength of various compositions of magnesium matrix composite specimens. The results of the study indicated that a lower percentage of eggshell powder reinforcement resulted in higher compressive strength. This was evident as sample 3, with a lower eggshell powder content, showed superior compressive performance. During the compression tests, the compressive loads were applied gradually, starting from an initial load of 5 kN and increasing incrementally by 1 kN until the failure of the specimen. This method ensured that the load was uniformly distributed, and the compressive strength of each sample was accurately determined.

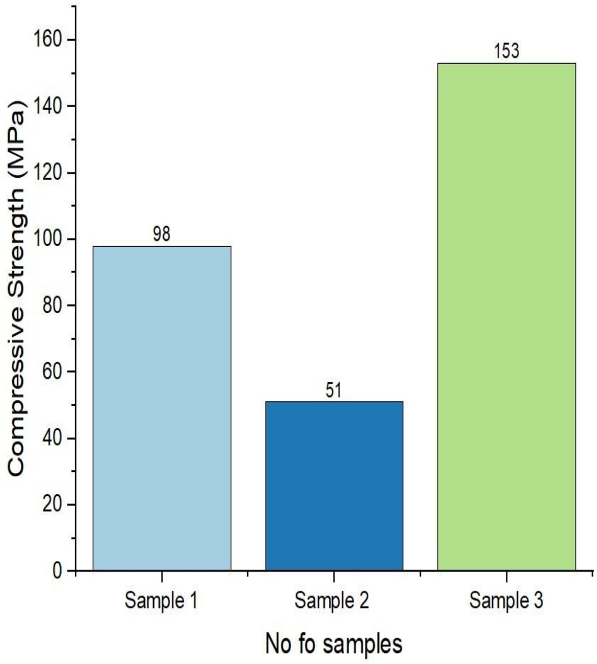


**Figure 5.** The compression strength of samples

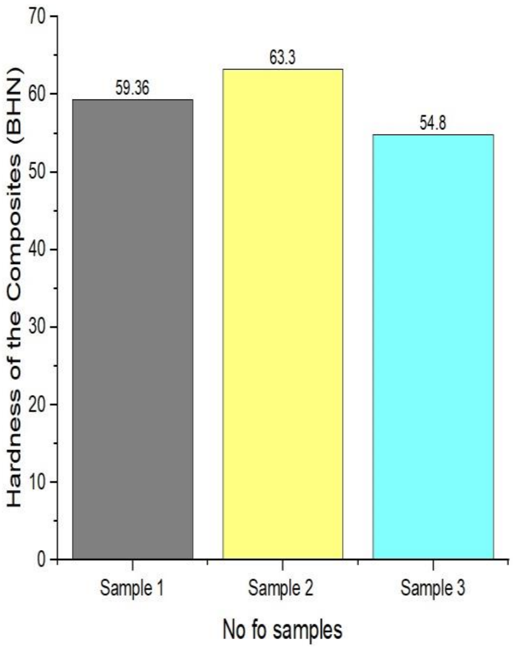


**Figure 6.** The hardness of the samples

## 6. Brinell Hardness Test

The hardness test was conducted on the prepared composite samples using a Brinell hardness test machine (ASTM E10), under a continuous load of 250 kg and a 5 mm ball. Each sample was subjected to this test to evaluate the effect of reinforcement on hardness. The results revealed that Sample 2 had the highest hardness number of 63.3 BHN, compared to Sample 1 (59.36 BHN) and Sample 3 (54.8 BHN), as illustrated in Figure 6. These findings suggest that the reinforcement of the AZ31 magnesium matrix with eggshell powder enhances hardness, but the relationship between reinforcement percentage and hardness is non-linear. This trend can be compared with previous studies which have demonstrated that an optimal level of reinforcement improves hardness due to the hard nature of the reinforcement material. However, beyond a certain point, the hardness may decrease due to particle agglomeration and poor matrix-reinforcement bonding.

## 7. Morphological Analysis

An optical microscope analyzed the microstructure of AZ31 magnesium and Eggshell powder-reinforced matrix composite. Fig. 7 shows the microstructure of magnesium matrix composite sample 3.

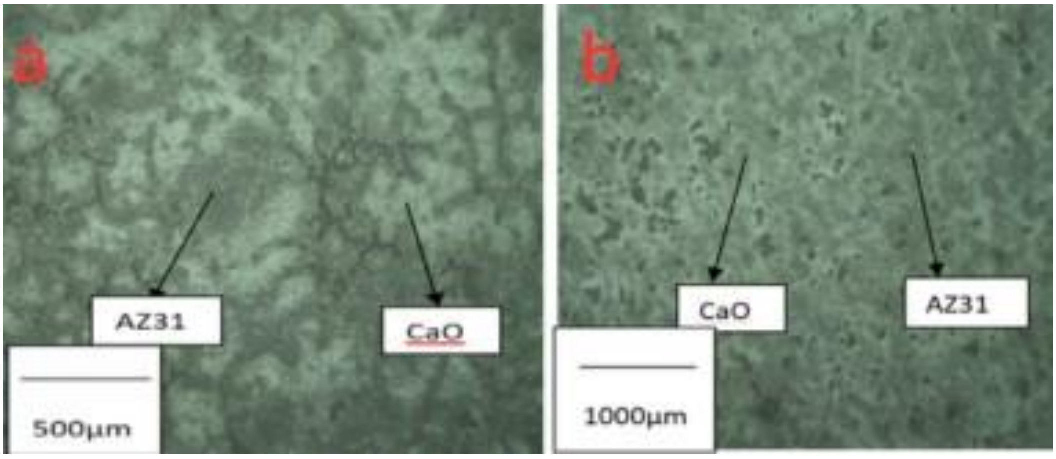


**Figure 7.** Optical microscope view of Sample 3 (a.500µm image, b.1000µm image)

In this sample3 a white layer surface found in the optical micrograph indicates the presence of AZ31 and a black color porous layer indicates the presence of eggshell powder and few traces of Al2O3 were observed over the surface and some of the porosity is observed in all samples that result in an inhomogeneous distribution of reinforcement and aggregation of reinforcement in some selective regions Energy dispersive X-ray analysis (EDAX)) is a technique used characterization of materials and composites. The figure shows the energy-dispersive X-ray analysis of the magnesium-reinforced eggshell powder matrix composite. the figure explores the weight and atom percentage of the magnesium matrix composite. Mg has 85.60% and oxide of 14.38 %, and other 3.78% (Al&Si). Fig 8. Shows the magnesium alloy matrix composite characterization and component presence.

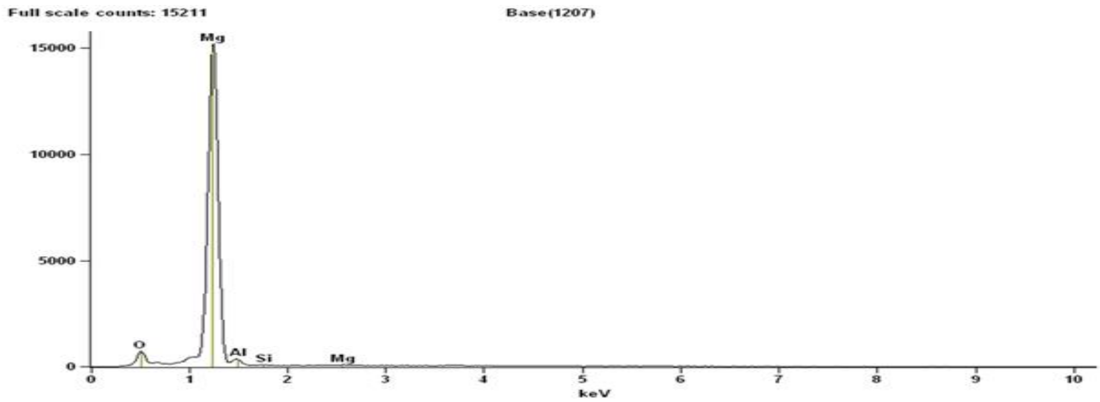


**Figure 8.** Sample 3 (AZ31=95%, Eggshell powder =5%) at energy dispersive X-Ray analysis

The scanning electron microscope analyzed the microstructure of the current composite and identified the presence of composition materials.

In Figure 9. we can able to observe the presence of the eggshell powder and AZ31 in the sample. the eggshell is observed in the form of the white porous layer and few porosities are obtained in the dimpled layer. the AZ31 is observed in the form of black layers. Magnesium-based matrix composites are utilized in bone implant applications. Specifically, magnesium-reinforced eggshell powder matrix composites are employed in orthopedic applications such as compression screws, cardiovascular stands, and cortex screws. These composites are well-suited for medical use due to their mechanical strength, stability in biological environments, non-toxicity, and degradation rate. Magnesium (Mg) also plays crucial roles in various cellular functions, including protein and nucleic acid synthesis, mitochondrial functions and integrity, ion channel modulation, plasma membrane stabilization, and translation processes[9–13]. Fig10. Shows the cardiovascular stent and bone screws for orthopedic bone implantation applications.

The microstructural analysis of the AZ31 magnesium matrix composite reinforced with eggshell powder reveals a heterogeneous structure, with eggshell powder evident as a black porous layer alongside the magnesium matrix. Energy dispersive X-ray analysis confirms the composite's composition, with magnesium comprising 85.60%, calcium oxide as the primary oxide component at 14.38%, and minor elements such as aluminum and silicon at 3.78%. Scanning electron microscope images further support these findings, highlighting eggshell powder as a white porous layer and AZ31 magnesium as black layers, with additional porosity observed. These analyses affirm the composite's potential for orthopedic applications, emphasizing its mechanical strength, biocompatibility, and controlled degradation rate in biomedical engineering.

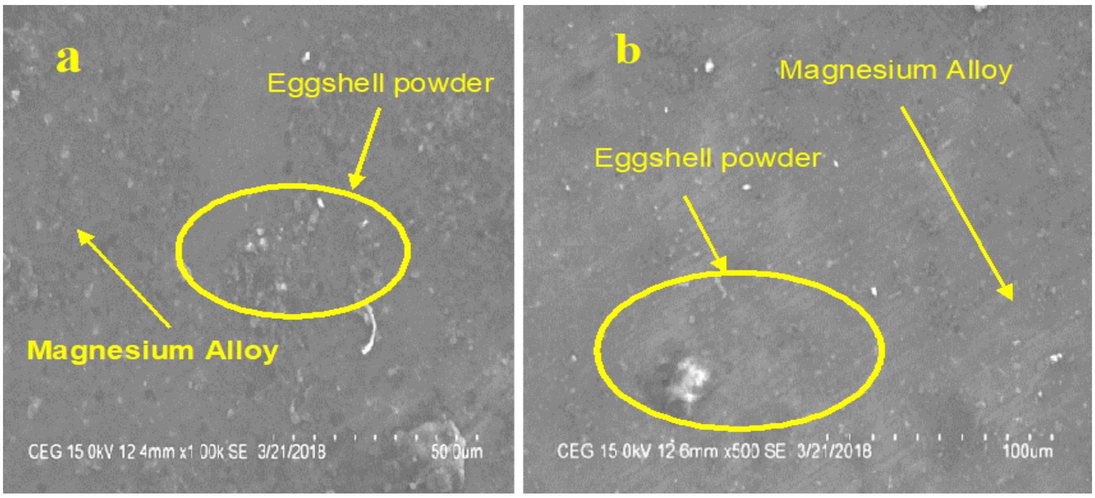


**Figure 9.** SEM image of composite (a. 500µm image, b. 1000µm image)

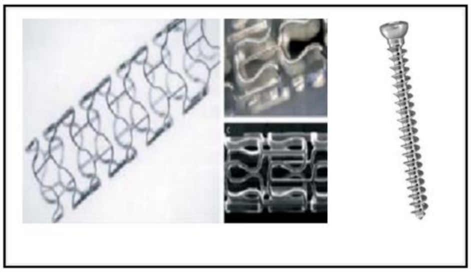

**Figure 10.** Cardiovascular stands and bone screws used in bone implantation

## 8. Conclusion

In this study, three distinct samples were fabricated and subjected to various mechanical tests to evaluate their performance. It was observed that sample 3 exhibited a slightly higher tensile strength compared to the other two samples, likely attributed to its higher magnesium content. However, sample 2 demonstrated higher tensile strength (74 MPa) compared to sample 1 (64 MPa), suggesting that the addition of reinforcement generally enhances the ultimate tensile strength and yield strength of alloys within a specific range. Additionally, the yield strength and elastic modulus of the magnesium matrix composite were found to increase linearly with the volume fraction of the composite reinforcement. Sample 3, with 5% eggshell powder (CaO) reinforcement and 95% AZ31, demonstrated the highest tensile strength among all samples, indicating the beneficial effects of ceramic reinforcement in improving the composite's mechanical properties. Furthermore, this composite exhibited enhanced ductility, attributed to a reduced likelihood of particle and interface fracture. The Brinell hardness results revealed minor variations among the samples, with sample 2 exhibiting the highest hardness (63.3) and sample 3 slightly lower (54.3) but still demonstrating favorable hardness characteristics. Microstructure analysis confirmed a uniform distribution of reinforcement in the matrix, with the presence of AZ31 indicated by the white layers observed. Finally, the fabricated composite shows promise for biomedical applications in orthopedic bone implants, including use as bone screws, cardiovascular stents, cortex screws, and transverse plates, highlighting its potential versatility and relevance in the biomedical engineering field. These findings align with expectations and earlier research, underscoring the importance of reinforcement and compositional optimization in enhancing the mechanical properties of magnesium matrix composites for biomedical applications.

## Conflict of interest

There is no conflict of interest for this study.

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