

Review

Not peer-reviewed version

---

# Biodegradable Magnesium Alloys for Biomedical Implants: Properties, Challenges, and Surface Modifications

---

Kevin Thomas , [Mah Noor Zafar](#) , [William G. Pitt](#) , [Ghaleb Hussein](#) \*

Posted Date: 24 October 2023

doi: 10.20944/preprints202310.1485.v1

Keywords: magnesium alloys; biomaterials; biomedical implants



Preprints.org is a free multidiscipline platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This is an open access article distributed under the Creative Commons Attribution License which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Review

# Biodegradable Magnesium Alloys for Biomedical Implants: Properties, Challenges, and Surface Modifications

Kevin Koshy Thomas <sup>1</sup>, Mah Noor Zafar <sup>2</sup>, William G. Pitt <sup>3</sup> and Ghaleb A. Husseini <sup>1,2,4,\*</sup>

<sup>1</sup> Materials Science and Engineering Program, College of Arts and Sciences, American University of Sharjah, Sharjah P.O. Box. 26666; UAE; b00085892@alumni.aus.edu (K.K.T.), ghusseini@aus.edu

<sup>2</sup> Biomedical Engineering Program, American University of Sharjah, Sharjah, United Arab Emirates (UAE); g00092920@aus.edu (M.N.Z), ghusseini@aus.edu

<sup>3</sup> Department of Chemical Engineering, Brigham Young University, Provo, UT 84602, United States of America; pitt@byu.edu

<sup>4</sup> Department of Chemical and Biological Engineering, American University of Sharjah, Sharjah P.O. Box. 26666; UAE; ghusseini@aus.edu (GAH)

\* Correspondence: ghusseini@aus.edu

**Abstract:** Biomedical devices made from high-modulus and hardness materials play a critical role in enhancing the quality of life for individuals with bone-related ailments. While these materials have been successfully used in orthopedic applications, concerns including stress-shielding have necessitated the exploration of alternative solutions. An ideal biomedical implant requires a delicate balance of mechanical performance, corrosion resistance, tissue biocompatibility, and other properties such as tribological performance and osseointegration. This review explores the suitability of biodegradable magnesium (Mg) alloys as a promising material for biomedical implants. It delves into the essential properties of biomedical implants, emphasizing the importance of matching mechanical characteristics with human bone properties to mitigate stress shielding. The corrosion properties of implant materials are discussed, highlighting the need for controlled degradation to ensure the safety and longevity of implants. The focus then shifts to the potential of magnesium alloys as biomedical implants, examining their benefits, limitations, and the challenges associated with their high degradation rates and less-than-satisfactory mechanical properties. Alloying with elements such as aluminum, zinc, and others is explored to improve magnesium alloys' mechanical performance and corrosion resistance. Furthermore, this review discusses surface modification techniques, including chemical conversion coatings and biomimetic deposition, as effective strategies to enhance the corrosion resistance and biocompatibility of magnesium and its alloys. These modifications offer opportunities to improve the long-term performance of magnesium-based biomedical implants. This paper provides a comprehensive overview of the properties, challenges, and potential solutions associated with biodegradable magnesium alloys as a promising material for biomedical implants. It underscores the importance of addressing issues related to mechanical performance, corrosion resistance, and biocompatibility to advance the development of safe and effective biomedical implant materials.

**Keywords:** magnesium alloys; biomaterials; biomedical implants

## 1. Introduction

Many biomedical devices are constructed from natural or synthetic materials characterized by high modulus and hardness, often serving as implants to enhance the well-being of individuals afflicted with damaged or missing bone structures [1,2]. These sturdy materials find potential applications elsewhere in the human body, such as heart valves and intravascular stents, depending on the specific medical needs [3–7]. Elderly individuals are more likely to encounter orthopedic health issues like arthritis, often necessitating the use of implanted devices to replace compromised biological structures [8]. Conditions such as osteoporosis, osteoarthritis, and trauma further compound the challenges older patients face, potentially leading to localized pain and physical

deterioration in the functionality of hard tissues [9]. Addressing this issue has involved substantial time and effort invested over several decades in the development of various orthopedic implants [10]. Metal-based implants crafted from materials like titanium-based, cobalt-based, or stainless-steel alloys have emerged as prominent choices in load-bearing orthopedic applications due to their high-modulus mechanical properties. However, research has revealed that these implant materials are susceptible to stress-shielding, a side-effect wherein a high-modulus orthopedic implant bears such a substantial load that the adjacent bone, lacking its typical load, undergoes deterioration [11]. Ideal biomedical implants must possess three fundamental characteristics: mechanical performance, corrosion resistance, and tissue biocompatibility, alongside other essential attributes, including tribological behavior, osseointegration, and non-toxicity [12].

Introducing a biomedical implant into the body involves multiple interactions at the tissue-implant interface. These interactions define the biocompatibility of an implant, significantly impacting its biological and mechanical performance [13–15]. For instance, if an orthopedic material releases toxic elements, it cannot be considered biocompatible. Therefore, selecting materials for biomedical implants necessitates a paramount focus on non-toxic, biocompatible substances that closely mimic the elastic modulus and strength of human bone [16–21].

Apart from materials designed for permanent implants, there is a growing interest in durable biomaterials that can gradually biodegrade over time, allowing for the regeneration of bone or other tissues to fulfill their original functions. Materials such as stainless steel, titanium, and cobalt alloys remain non-degradable throughout the implant's lifespan. In contrast, certain magnesium alloys can be engineered to degrade safely and under controlled conditions within the body. This review examines biodegradable magnesium (Mg) alloys as a promising material for biomedical implants, scrutinizing their bulk and surface properties and their overall performance.

- 1.1 Main Properties of Biodegradable and Biomedical Implants:

Generally, implants serve as medical devices that facilitate interaction with biological systems [22]. Their proximity to bodily tissues holds both medical applications and implications. As previously mentioned, an ideal implant material must exhibit requisite mechanical properties, excellent biocompatibility, and a low corrosion rate suitable for the mechanical and biological demands of the application at hand. For example, titanium alloys find use in joint replacements due to their lower elastic stiffness and excellent compatibility with bone [10]. Consequently, the design of a safe and dependable implant material necessitates a meticulous blending of mechanical, chemical, physical, and biological properties to ensure prolonged functionality without the need for replacement surgeries. A more comprehensive exploration of desirable properties in medical implants and biomaterials, in general, is presented below.

- 1.2 Mechanical Properties:

A critical requirement for any load-bearing implant material is aligning its mechanical characteristics with those of human bone. Whether composed of metal, ceramic, polymer, or their combinations, the material's mechanical performance must be tailored based on tissue characteristics and load requirements at the specific implantation site [23]. To this end, some very general and exemplary mechanical and durability prerequisites are summarized in Tables 1 and 2.

**Table 1.** Mechanical and durability requirements for general biomedical material design [24].

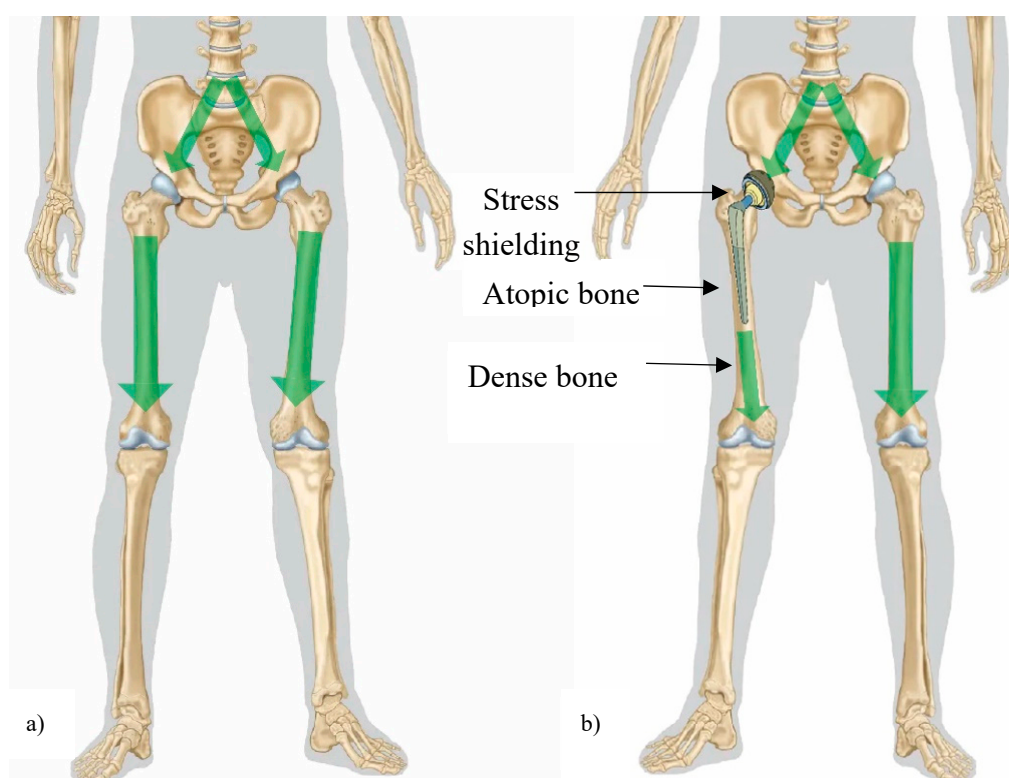
Mechanical performance	
Biomaterial	Mechanical Characteristics
Hip prosthesis	Strong and rigid
Tendon material	Strong and flexible
Heart valve leaflet	Flexible and tough
Articular cartilage	Soft and elastomeric

**Table 2.** Durability condition for biomedical implant design [24].

Mechanical performance	
Biomaterial	Durability
Bone plate	Six months or longer
Hip joint	Ten years or longer under heavy loads
Heart valve leaflet	Able to fully flex 60 times/min without undergoing failure for several decades

The key mechanical properties essential for evaluating an implant include tensile modulus, yield strength, hardness, compressive and shear strength, toughness, fatigue strength, and elongation [28]. These mechanical characteristics should closely match those of human bone to withstand decades of use and minimize the phenomenon of stress shielding. The choice of materials for implants is often guided by their specific mechanical properties, tailored to their intended applications within the human body. For instance, Titanium-based alloys are commonly employed in bone fixation devices and high-load scenarios like hip prosthetics, whereas cobalt-based alloys are preferred for joint replacement [25,26]. An implant material must exhibit an adequate modulus and yield strength to fulfill its intended function. Furthermore, for implants like hip and knee replacements, robust fatigue resistance under substantial loads is imperative [27]. Additionally, implant materials should exhibit outstanding wear resistance, especially for articulating surfaces such as hip and knee prostheses, often associated with surface hardness. Minimizing the formation and propagation of cracks is also vital in high-load applications [29].

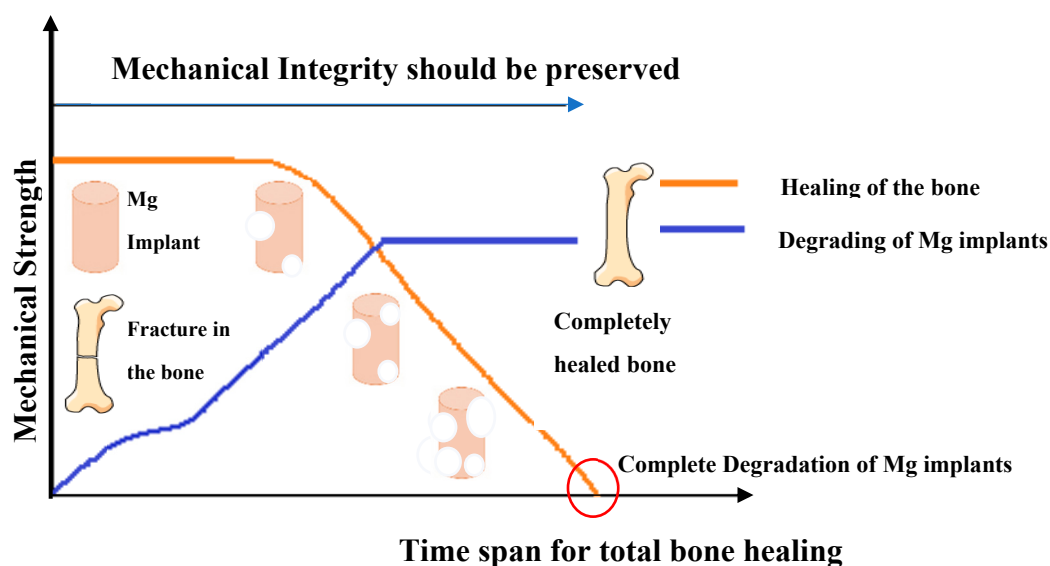
As previously mentioned, an elevation in the mechanical properties of the implant, particularly the modulus, in comparison to the surrounding human bone, frequently results in stress reduction within the neighboring bone, which typically would bear the full load [30]. Consequently, regions experiencing reduced loading may suffer from atrophic bone density and mass loss. This bone mass and strength decline can lead to implant loosening or even fracture, necessitating premature revision surgery [31]. The phenomenon of stress shielding is visually depicted in Figure 1. To mitigate the impact of stress shielding, innovative implant design approaches that consider material stiffness, geometry, and shape adjustments become imperative [32].



**Figure 1.** (a) Normal distribution of load in human bone; (b) region of alteration of load on a bone due to stress shielding by a high modulus implant.

## 2. Corrosion properties

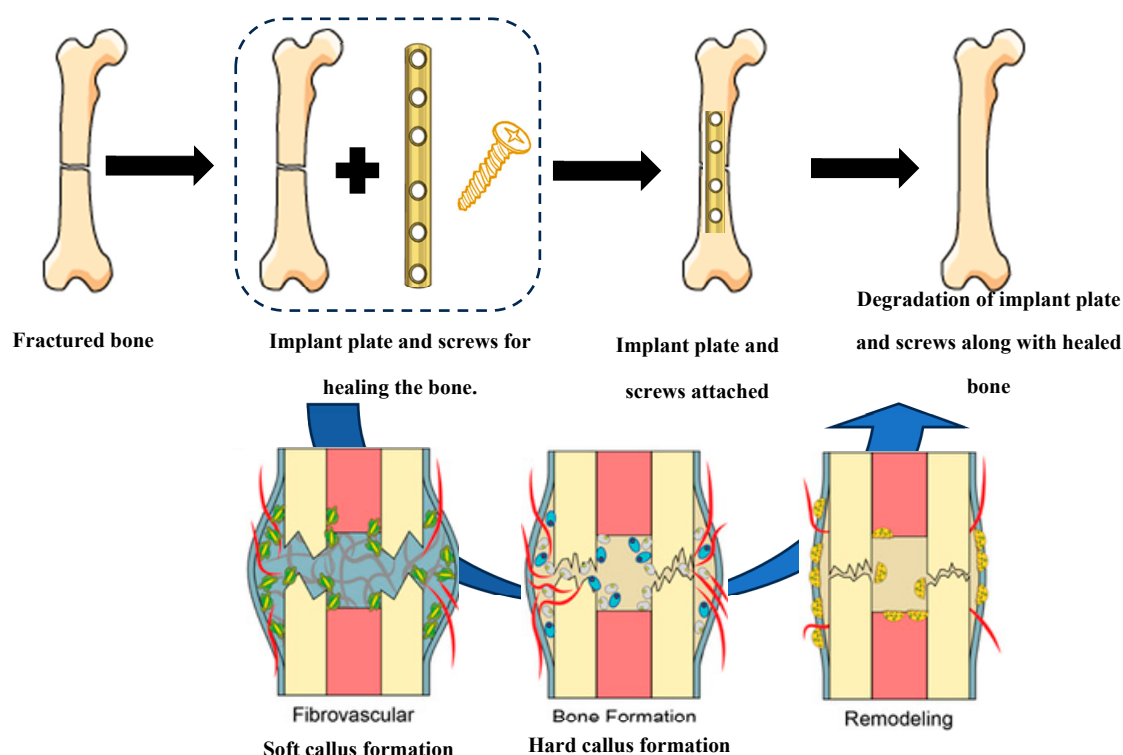
As one of the critical properties of Mg alloys is controlled degradation through corrosion, we present a brief overview of corrosion principles. Programmed degradation, often referred to as controlled biodegradation, serves to meet temporary load-bearing requirements without interfering with the healing and regeneration of local tissues. However, once local wound healing has occurred, the implant gradually degrades, transferring the load to the adjacent bone tissue, as illustrated in Figure 2 [34]. Conversely, undesired but often normal degradation of any alloy can be manifest in the form of surface corrosion, oxidation, and mechanical wear of the implant material. Such undesirable degradation can compromise the structural integrity of the implant, release potentially toxic metallic ions, and generate wear debris particles, resulting in unfavorable biological reactions in neighboring tissues or in mechanical impediment of articulating joints. The preferred model for biodegradable implants within the body involves the degradation or corrosion of metals that are non- to minimally harmful, or that can be rapidly eliminated from the body through physiological processes without local concentrations exceeding any toxic thresholds during the corrosion process [35]. A critical consideration when designing biodegradable implants is achieving a controlled degradation rate that aligns with the timeline of tissue restoration, as depicted in Figure 3. Magnesium (Mg) alloys are among the materials employed for biodegradable purposes. This is particularly relevant in hard material prostheses because  $Mg^{2+}$  ions are non-toxic at normal concentrations, and the corrosion rate can be controlled [36].



**Figure 2.** Degradation process for biodegradable Mg implant.

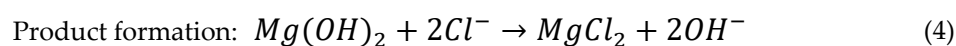
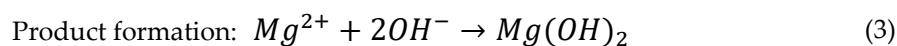
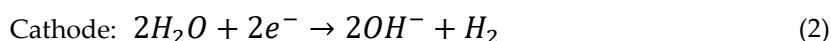
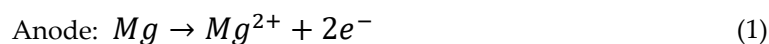
From a toxicological standpoint, an implant material should not release toxic ions into the body unless such release is intentionally desired. Thus, the implant material should exhibit controlled chemical stability in the complex chemical environment of the human body [50]. Nevertheless, released toxic elements entering body tissues are virtually inevitable, even if implant materials are believed to possess robust corrosion resistance [51,52]. Studies have demonstrated that the release of metal ions due to implant wear in the human body is a leading cause of toxic effects related to implant materials, including tissue sensitization, damage to local blood vessels supplying the bone, bone necrosis, and more [53,54]. The deposition of non-matching metallic ions at the implantation site can trigger allergic and toxic responses, leading to inflammatory reactions and tissue damage [55]. Generally, the  $Mg^{2+}$  ion is naturally present throughout the body and plays a crucial role in numerous biochemical reactions. More than half of the magnesium in the human body is in the bones.

Incorporating magnesium as a significant metallic element in the design of biomaterial alloys can aid in achieving favorable degradation of a biodegradable implant, as demonstrated in Figure 3, and contribute to bone healing through cellular repair mechanisms [37]. Typically, Mg is not a cause for concern; however, pure Mg lacks adequate mechanical properties and thus is frequently alloyed with other elements to enhance strength and modulus and reduce brittleness. Biodegradable alloys are generally considered safe, biocompatible, and non-cytotoxic when the viability of cells adjacent to corroding metals surpasses 70% compared to a control group. For instance, the Mg-Zr-Sr-Sc alloy is considered biocompatible because cell viability remains at least 83% [57]. Toxicity is typically attributed to released ions other than  $Mg^{2+}$ .



**Figure 3.** The mechanism for biodegradable implants [1].

When Mg is inserted into the biological environment,  $Mg^{2+}$  ions are produced on the Mg surface due to the anodic reaction of the metal. Simultaneously,  $H_2$  and  $OH^-$  ions are produced by the cathodic reaction occurring on other nearby surfaces, and the  $OH^-$  ions react with the  $Mg^{2+}$  to form  $Mg(OH)_2$  film. The reaction produces a  $Mg(OH)_2$  film covering the magnesium alloy surface. In a biological setting, chloride ions are always present, which react with magnesium hydroxide to form soluble  $MgCl_2$ , exposing fresh Mg surface for further corrosion [24]. These reactions are summarized below.



Undesired degradation of certain implants could be dangerous when placed in the human body if the ions being released are toxic; they could cause the discoloration of the implant or the adjacent tissue [39,40]. Furthermore, unwanted corrosion may compromise the mechanical properties of the implant. Types of unwanted corrosive behavior in implants include galvanic, pitting, crevice, and fatigue corrosion. In one such example from a fractured stainless-steel implant inside a patient's thigh, Farzad et al. found extensive structural damage, including crack initiation from pitting, intergranular surface cracking inside the crevice, and more [41]. Galvanic corrosion has been observed in dental implants when two metal elements (like Co-Cr alloy) are combined to manufacture implants [42]. In orthopedic applications, crevice corrosion has been observed in bone fixation implants at the contact interface between bone plates or between screws and bone tissue. Studies have shown that a larger crevice size leads to a higher implant corrosion rate [43]. Due to the adverse effects of toxic products on patients leading to implant restriction or denial, there is a growing need for corrosion-resistance materials to ensure the longevity of implant materials in physiological conditions.

As mentioned, for controlled degradation to be safe, the metal ions released from corrosion need to be either non-toxic; but an acceptable alternate is that they are released at a slow enough rate that the local concentration in the adjacent tissues never exceeds the safe toxic limit. Yet, this may create conflicting objectives since often one of the objectives is to degrade at the same rate as tissue is restored in vivo [38].

### 3. Magnesium alloys for biomedical implants

Magnesium (Mg) alloys, which are generally biodegradable, have garnered considerable attention in the biomedical field in recent years. In addition to mechanical characteristics like human bone, Mg shows excellent biocompatibility. Mg is a vital supplement for keeping the human body healthy and promoting osteo-growth [58–60]. Additionally, during corrosion in the biological environment,  $Mg^{2+}$  is released, creating non-toxic magnesium hydroxide, hydroxyl ions, and hydrogen gas (as shown above), which are removed from the body via the kidneys [61–64]. On the other hand, the main disadvantages of using Mg alloys are the rapid degradation rates, and loss of mechanical properties, which may produce implant failure faster than the healing process [65]. Moreover, hydrogen gas emitted from corrosion may create gas pockets that cause the adjacent tissues to separate, and the  $OH^-$  ions cause surface alkalization and potential cell damage [66,67]. Additionally, the mechanical properties of Mg need improvement. Thus there are various challenges to tackle in developing Mg alloys. The advantages and disadvantages of Mg material are summarized in Table 3 and Table 4.

Even though Mg has many benefits as an implant material, pure Mg is not recommended for biomedical applications due to its higher corrosion rate and insufficient mechanical properties. Moreover, Mg shows low ductility because of the lack of slip characteristic in its hexagonal closest packed (HCP) structure. These problems are averted by alloying, which creates microstructural changes and adjust surface potential between phases, improving mechanical properties and corrosion resistance [70,71]. Common alloying elements for Mg are aluminum (Al) and zinc (Zn), as they contribute to hardness, strength, and castability [68]. Lithium provides low density and high solid solubility to Mg alloys. Moreover, Li can change the formability of Mg alloys by changing the crystal structure of Mg from HCP to the body-centered cube (BCC) [69]. Alloying elements refine grains and optimize the type, size, and distribution of the second phase, which reduces the corrosion rate of Mg alloys. Furthermore, alloying elements create passive films to prevent further corrosion. Presently, aluminum (Al), zinc (Zn), manganese (Mn), calcium (Ca), strontium (Sr), zirconium (Zr), and neodymium (Nd) are commonly used as alloying elements. The influence of these elements on the Mg alloys is shown in Table 5.

**Table 3.** Benefits of Mg alloys in medical implants [24].

<b>Advantages</b>	<b>Description</b>
Reduced density and elastic stiffness	Density and elastic stiffness are like human bone.
Higher specific strength	Strength to weight ratio is roughly 35-260 KNm/kg.
Machinability	Mg has good machining capability, achieving accurate dimensions and processing into complex shapes.
Stress shielding effect	The elastic stiffness of Mg is very close to bone.
Biocompatibility	Mg is shown to have osteogenic functions.
Degradability	Mg naturally degrades in the body, which is favorable to the patients.

**Table 4.** Limitations of Mg alloys in medical implants [24]

<b>Disadvantages</b>	<b>Description</b>
Low mechanical properties	Implants must be able to endure specific loads and deformation. It is difficult for Mg to meet medical demands in strength and plasticity.
High degradation rate	It leads to premature loss of mechanical integrity and implant supports.
Hydrogen generation	Hydrogen release creates air bubbles in the surrounding tissues.

Magnesium alloys have attracted substantial attention in the biomedical field owing to their impressive attributes, including remarkable strength, low density, and outstanding osteogenic biocompatibility, as highlighted in Table 3. Nonetheless, a notable challenge arises due to its considerable vulnerability to corrosion, originating from its remarkably low standard electrode potential of -2.37 V. Among the concerns in the domain of biomedical implants, the corrosion behavior of Mg implants plays a preeminent role. When Mg is immersed in an aqueous milieu, a pivotal electrochemical process occurs, as highlighted in equations (1) through (3) and underscores the significance of managing corrosion dynamics associated with Mg alloy implants for biomedical applications.

**Table 5.** Effect of alloying elements on Mg alloy performance [24].

<b>Alloying elements</b>	<b>Biocompatibility</b>	<b>Corrosion resistance</b>	<b>Mechanical performance</b>
Al	Al is neurotoxic. It can cause Alzheimer's disease and damage muscle fibers.	It is beneficial in providing corrosion resistance.	Increases strength and plasticity.
Zn	Non-cytotoxic and good biocompatibility.	Corrosion resistance decreases with higher Zn content.	Zn participates in solid solution strengthening, increasing strength with increasing Zn content.
Mn	Cytotoxic and neurotoxic	Provide good corrosion resistance.	It gives higher yield strength and reduces tensile strength and ductility.
Ca	An essential component of human bone	Corrosion resistance decreases with increasing Ca content	With increasing Ca content, strength increases, and plasticity decreases.

Sr	Sr is a vital component of human bone. It also aids in bone formation	Corrosion resistance of Mg alloy drops with increasing Sr content	The strength of the alloy increases with increasing Sr content
Zr	Good biocompatibility and bone-bonding ability	Corrosion resistance decreases with increasing Zr content	Grains undergo refinement, increasing strength and plasticity
Nd	Cytotoxic at high concentrations but has good biosafety at low concentrations.	Improves corrosion resistance	Forms new phases, grain refinement, and improvement in mechanical performance

Adding aluminum (Al) in commercial magnesium (Mg) alloys is the most prominent strategy, contributing to the overall corrosion resistance of Mg alloys. AE21, AZ32, and AZ91, are some examples of Al-enriched Mg alloys with remarkable mechanical and corrosion resistance properties that are used for biomedical applications. However, Al's potential in the development of Alzheimer's disease raises concerns and underscores the requirement of intricate equilibrium in biomedical applications. Zinc (Zn), on the other hand, is vital for the human body and enhances the material strength of Mg-Al alloys. Mg-Zn alloys are highly biocompatible. Moreover, it forms protective layers that effectively slow down degradation. Mn is an essential trace element for the human body with the potential to form a protective Mn-containing oxide film that inhibits Cl-ion infiltration, rendering it a commonly employed element in Mg alloys for biomedical applications. Mg-Ca alloys favor bone implantation, reducing potential differences and improving corrosion resistance. Furthermore, Strontium (Sr) also shares chemical properties with Mg and Ca; it is found in bones and promotes bone formation. Other elements found in Mg alloys for biomedical applications include Zirconium (Zr), Silicon (Si), and Lithium (Li), which foster bone bonding, and corrosion resistance and add ductility to vascular stents in biomedical applications, respectively.

#### 4. Surface modification used for Mg alloys

In addition to tweaking the bulk alloy chemistry to avoid toxicity and manipulate mechanical properties, the toxicity can be reduced by forming coatings on the surface, which impedes the release of toxic ions, so the local ion concentration can be kept low and the corrosion rate inhibited. Coatings allow the use of alloys with excellent mechanical properties, even if they contain some toxic ions. Such modifications may also enhance the bioactivity of these biodegradable materials [74,75]. Two types of surface modification are used for Mg alloys: (a) surface coating preparation and (b) surface microstructure modification.

- Surface coating preparation:

The oxide film formed on the Mg alloy surface is generally weak, which cannot chemically or mechanically protect the alloy for long exposures. Hence, there is a need to make a protective film on the surface utilizing chemical, physical, mechanical, and biological or biomimetic techniques [76].

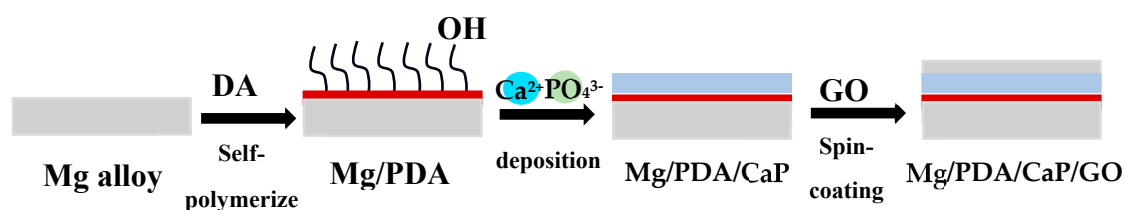
- Chemical conversion coatings:

These coatings are formed by electrochemical or chemical reactions of Mg-based alloys, within an electrochemical bath to form a layer that often contains fluoride, phosphates, carbonate, or chromate groups [77,78]. An insoluble compound film with reasonable adhesion formed on the Mg surface can protect the Mg alloy from light mechanical stress and harsh aqueous environments; these initial layers can improve the adhesion of further coatings. These methods are easy to execute and are often used in biomedical applications. Fluoride and phosphates coatings are used for biomedical Mg alloy surfaces [79–81]. Normally, fluoride coatings are produced in hydrofluoric acid (HF) by reaction with Mg alloys [82,83]. The main component of fluorine coating is magnesium fluoride (MgF<sub>2</sub>), which is water-insoluble and spontaneously deposited on the Mg surface. MgF<sub>2</sub> films increase corrosion resistance and improve cellular response and biocompatibility [84]. For phosphate

coatings, zinc phosphate and calcium phosphate are used for Mg alloys because of water insolubility, high-temperature resistance, corrosion resistance, and excellent biocompatibility [85,86].

- Biomimetic deposition

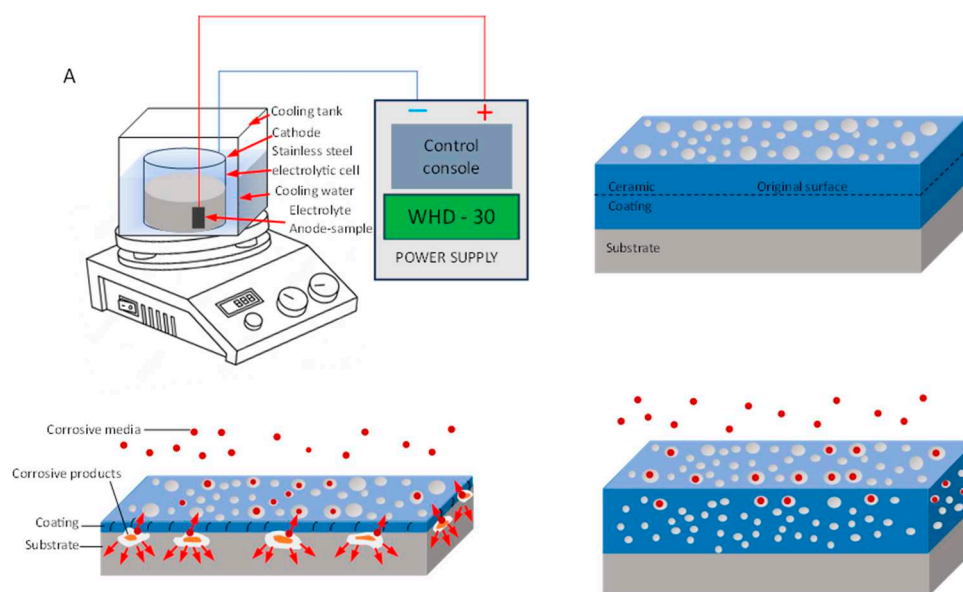
This process simulates physiological apatite mineralization in nature and deposits bio-ceramic membranes on the substrate surface, as shown in Figure 4. The benefits of this technique are (a) ease of adjusting coating composition, phase, and crystallinity, (b) capability of coating on porous or complex-shaped implants, and (c) having a simplified method of incorporating biologically active agents or drugs into apatite coatings through coprecipitation. Hence, the biomimetic method is widely used for metallic biomaterials [87]. Biomimetic deposition can effectively enhance corrosion resistance and biocompatibility. Dong et al. give an example of forming a biomimetic calcium phosphate film on a Mg alloy [88].



**Figure 4.** Biomimetic deposition of CaP on the surface of a poly(dopamine) (PDA) film in addition to subsequent graphene oxide coating [88].

- Micro-arc oxidation coating

Micro-arc oxidation (MAO), otherwise known as plasma electrolytic oxidation (PEO), is a high-voltage plasma-assisted anodic oxidation process developed from traditional anodizing to create ceramic-like coatings [89]. The details of MAO are summarized in Figure 5. MAO has been explored in a variety of fields due to its high efficiency, increased bonding strength between coating and substrate, and minimal restrictions on the surface shape of the workpiece [90,91]. The main limitation of MAO is its inability to provide long-term surface protection [89]. For biocompatibility and biological activity, MAO exhibits higher bonding strength with the substrate due to its dense interior; this porous outer layer is useful in protein adsorption, osteoblast adhesion, and bone tissue regeneration, which is often desirable for biological applications [24].



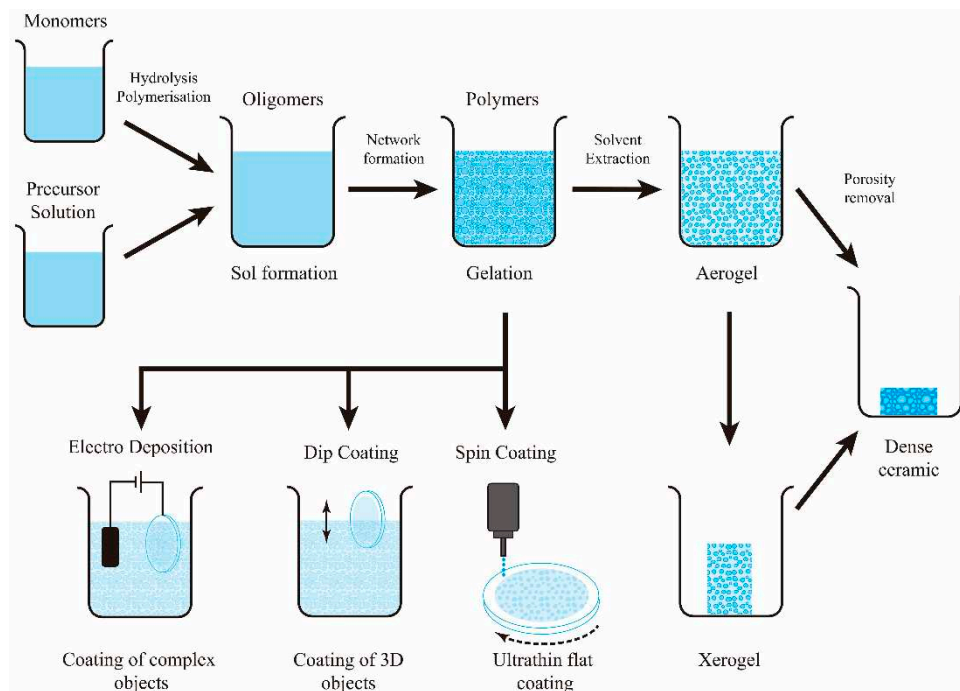
**Figure 5.** (A) MAO device, (B) growth model of MAO coating, (C) thin coating with through pores, (D) thicker coating with complex pores.

- Sol-gel coating

The sol-gel process, also known as chemical solution deposition, has been used widely in material science and ceramic engineering. This technique initially uses a chemical solution as a precursor to produce an integrated network of discrete particles or network polymers [92]. Generally, the sol-gel process involves four steps: (1) hydrolysis and polymerization of monomers for the formation of chains and particles, (2) condensation and polymerization of monomers for the formation of chains and particles, (3) growth of particles, and (4) accumulation of polymer structures followed by a continuous network formation in a liquid medium which increases viscosity for gel formation [93]. The schematics of preparation for sol-gel coatings are shown in Figure 6. The technique has the benefits of low cost, low processing temperature, and the ability to coat different materials that have complex shapes [94].

- Ion implantation:

It is a surface modification technique in which target materials are converted to an ion beam in a vacuum, which is later sputtered onto a modified material. Finally, a layer with a specific composition and structure is formed on the surface of the substrate [95]. Implanting specific ions onto the Mg substrate can increase the corrosion rate and improve mechanical performance and biocompatibility. For the biodegradable material (Mg alloy), metal ions from iron, cerium, zinc, zirconium, and strontium, and non-metallic ions, for instance, carbon, oxygen, and nitrogen are currently used for ion implantation [96–98]. The advantages of this technique include convenience, controllability, and flexibility. In addition to improving physical and chemical properties, ion implantation improves alloys' biological and antibacterial abilities [24].



**Figure 6.** Sol-gel coating process. For Mg alloy implants, the object would be subjected to dip coating or electro-deposition.

- Surface microstructural modification:

This technique involves the deformation of the metal surface through mechanical processing so that the surface acquires a microstructure and mechanical performance different from the bulk matrix material. The mechanical processing increases the mechanical characteristics, surface hardness, and corrosion resistance of Mg alloys by processes that lead to grain refinement and change in the distribution of second phases or intermetallic compounds [100]. The process usually does not involve

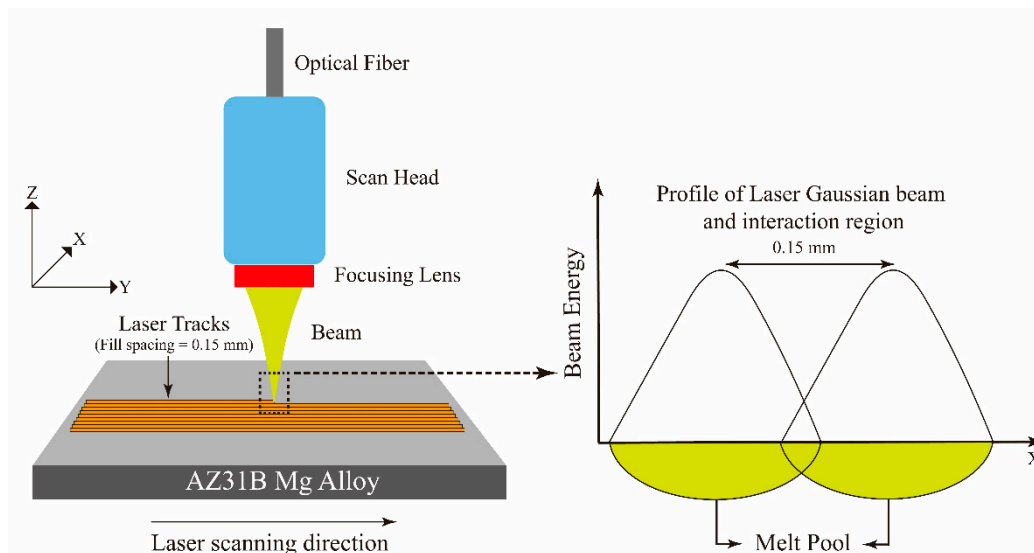
chemical reactions. Below are the details of microstructural modification techniques used for Mg alloys.

Surface mechanical grinding treatment, also known as surface mechanical attrition treatment (SMAT), is a surface nano-crystallization technique that refines grains in the nanoscale and forms gradient nanostructures without changing material composition. It has a noteworthy effect of improving the corrosion resistance of Mg alloys. After the SMAT process, the microstructure of Mg alloys is fine and uniform, the surface is comparatively smoother, and the corrosion rate is considerably lower [101]. The main problem of SMAT is reduced degradation resistance due to the crystal defect density caused by attrition balls [102,103]. So, SMAT is less effective in improving the biomedical Mg alloy performance [24].

Shot peening is a surface modification technique that introduces compressive residual stress on the Mg surface, like the SMAT technique. The shot peening process creates a plastically deformed zone with an extended and refined grain structure [104]. Mhaede et al. [105] discovered that microhardness and degradation resistance could be improved through shot peening by refining grains and increasing coating density. Peral et al. [106] proved that higher surface roughness developed from shot peening favors rapid degradation. Like SMAT, shot peening is limited in improving the biological function of Mg alloys.

- Laser surface modification

This technique is a productive method for modifying material surface by melting the surface by scanning with a high-intensity laser beam. The advantages are high treatment efficiency, no pollution, and low material consumption [107,108]. Currently, laser surface melting, laser cladding, and laser surface alloying are extensively used in surface engineering [109–111]. For the Mg alloys, laser surface melting is currently used to improve the alloys' mechanical performance and corrosion resistance [112]. In addition, laser modification increases the cytocompatibility and corrosion resistance of Mg alloys by modifying the substrate's surface microstructure [24].



**Figure 7.** Laser surface modification process.

- Friction stir processing

Friction stir processing (FSP) is a technique that is similar to friction stir welding, developed by Mishra [113], and is used for mechanical property improvement and surface composite fabrication of light alloys such as Mg alloys [114–116]. FSP uses a non-deformable tool that is forcibly inserted into the workpiece and revolved in a stirring motion as the device is pushed laterally to the alloy. FSP is a technique that can produce refined grains and uniform microstructures and enhance mechanical performances in base materials. FSP is also used to improve the corrosion resistance of Mg alloys by

optimizing surface microstructure or creating a composite layer on the metal surface in biomedical applications [117,118]. FSP creates severe plastic deformation, making grains refined and eliminating surface defects. Moreover, combining FSP with other technologies or reinforcement materials enhances mechanical and biological properties [24].

## 5. Summary

The field of biomedical materials and implants is a multifaceted domain that plays a pivotal role in improving the well-being of individuals with damaged or missing bone structures and addressing various other orthopedic health issues. Over the years, extensive research and development efforts have created a diverse array of materials, each with distinct properties and applications. One of the fundamental considerations in the design of biomedical implants is the necessity to balance mechanical performance, corrosion resistance, and tissue biocompatibility. These three core characteristics are vital for ensuring the long-term effectiveness of implants and minimizing adverse effects on the human body. Additionally, other attributes such as tribological properties, osseointegration, and non-toxicity further contribute to the success of these implants.

Understanding the complex interactions at the tissue-implant interface is crucial for assessing biocompatibility. Implants that release toxic elements are deemed unsuitable for medical use, underlining the importance of focusing on non-toxic, biocompatible materials with mechanical properties akin to those of human bone. While traditional metal-based implants have shown promise, they often produce stress-shielding, which can lead to bone deterioration and necessitate revision surgery. Innovative implant designs that consider material stiffness, geometry, and shape are required to mitigate these challenges.

The emergence of biodegradable materials, such as Mg alloys, presents an exciting avenue for metallic biomedical implants. These materials offer the advantage of controlled degradation, which allows them to temporarily support load-bearing requirements while facilitating the healing and regeneration of local tissues. Moreover, Mg alloys can corrode in a manner that is not harmful, and the resulting byproducts are naturally eliminated from the body. Nonetheless, Mg alloys face challenges related to their rapid degradation rates and the loss of mechanical properties over time. Alloying with elements like aluminum (Al), zinc (Zn), manganese (Mn), calcium (Ca), strontium (Sr), zirconium (Zr), and neodymium (Nd) can enhance both mechanical performance and corrosion resistance, making them suitable candidates for biomedical applications. Surface modification techniques, including chemical conversion coatings and biomimetic deposition, further improve the corrosion resistance and biocompatibility of Mg alloys. These techniques play a pivotal role in enhancing the longevity and effectiveness of Mg-based implants.

The development of biomedical implants is a dynamic and evolving field that continues to drive advancements in materials science and engineering. The pursuit of materials with superior mechanical properties, corrosion resistance, and biocompatibility, combined with innovative implant designs, holds the promise of improving the quality of life for individuals in need of orthopedic interventions. As research and technology progress, the future of biomedical implants will likely witness even more groundbreaking developments that will benefit patients and healthcare professionals alike.

**Author Contributions:** Original draft writing and visualization: K.K.T. and M.N.Z. Reviewing and editing: W.G.P. and G.A.H. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Dana Gas Endowed Chair for Chemical Engineering, American University of Sharjah Faculty Research Grants (FRG20-L-E48, FRG22-C-E08), Sheikh Hamdan Award for Medical Sciences MRG/18/2020, and Friends of Cancer Patients (FoCP).

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The authors would like to acknowledge the financial support of the American University of Sharjah Faculty Research Grants, the Al-Jalila Foundation (AJF 2015555), the Al Qasimi Foundation, the Patient's Friends Committee-Sharjah, the Biosciences and Bioengineering Research Institute (BBRI18-CEN-11), GCC Co-Fund Program (IRF17-003) the Takamul program (POC-00028-18), the Technology Innovation Pioneer

(TIP) Healthcare Awards, Sheikh Hamdan Award for Medical Sciences (MRG/18/2020, Friends of Cancer Patients (FoCP), and the Dana Gas Endowed Chair for Chemical Engineering. The work in this paper was supported, in part, by the Open Access Program from the American University of Sharjah and does not represent the position or opinions of the American University of Sharjah.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. M. Geetha, A. K. Singh, R. Asokamani, and A. K. Gogia, "Ti based biomaterials, the ultimate choice for orthopedic implants – A review," *Prog Mater Sci*, vol. 54, no. 3, pp. 397–425, 2009.
2. M. Abdel-Hady Gepreel and M. Niinomi, "Biocompatibility of Ti-alloys for long-term implantation," *J Mech Behav Biomed Mater*, vol. 20, pp. 407–415, 2013.
3. L. A. Dobrzański, A. D. Dobrzańska-Danikiewicz, and L. B. Dobrzański, "Effect of Biomedical Materials in the implementation of a long and healthy life policy," *Processes*, vol. 9, no. 5, p. 865, 2021.
4. D. Martinez-Marquez, Y. Delmar, S. Sun, and R. A. Stewart, "Exploring macroporosity of additively manufactured titanium metamaterials for bone regeneration with quality by design: A systematic literature review," *Materials*, vol. 13, no. 21, p. 4794, 2020.
5. B. Liao, R. F. Xia, W. Li, D. Lu, and Z. M. Jin, "3D-Printed Ti6Al4V Scaffolds with Graded Triply Periodic Minimal Surface Structure for Bone Tissue Engineering," *J Mater Eng Perform*, vol. 30, no. 7, pp. 4993–5004, 2021, doi: 10.1007/s11665-021-05580-z.
6. D. Barba, E. Alabort, and R. C. Reed, "Synthetic bone: Design by additive manufacturing," *Acta Biomater*, vol. 97, pp. 637–656, 2019.
7. L. C. Zhang, D. Klemm, J. Eckert, Y. L. Hao, and T. B. Sercombe, "Manufacture by selective laser melting and mechanical behavior of a biomedical Ti–24Nb–4Zr–8Sn alloy," *Scr Mater*, vol. 65, no. 1, pp. 21–24, 2011.
8. M. Navarro, A. Michiardi, O. Castano, and J. A. Planell, "Biomaterials in orthopaedics," *J R Soc Interface*, vol. 5, no. 27, pp. 1137–1158, 2008.
9. H. Singh, S. Singh, and C. Prakash, "Current trends in biomaterials and bio-manufacturing," in *Biomanufacturing*, Springer, 2019, pp. 1–34.
10. M. Long and H. J. Rack, "Titanium alloys in total joint replacement—a materials science perspective," *Biomaterials*, vol. 19, no. 18, pp. 1621–1639, 1998.
11. S. Jaiswal, A. Dubey, and D. Lahiri, "In Vitro Biodegradation and Biocompatibility of Mg–HA-Based Composites for Orthopaedic Applications: A Review," *J Indian Inst Sci*, vol. 99, no. 3, pp. 303–327, Sep. 2019.
12. L. Zhang and L. Chen, "A review on biomedical titanium alloys: recent progress and prospect," *Adv Eng Mater*, vol. 21, no. 4, p. 1801215, 2019.
13. M. Kaur and K. Singh, "Review on titanium and titanium-based alloys as biomaterials for orthopaedic applications," *Materials Science and Engineering: C*, vol. 102, pp. 844–862, 2019.
14. C.-W. Kang and F.-Z. Fang, "State of the art of bioimplants manufacturing: part I," *Adv Manuf*, vol. 6, no. 1, pp. 20–40, 2018.
15. M. Majeed, M. Vural, S. Raja, and M. B. N. Shaikh, "Finite element analysis of thermal behavior in maraging steel during SLM process," *Optik (Stuttg)*, vol. 208, p. 164128, 2020.
16. M. A. Alam et al., "Modelling and optimisation of hardness behaviour of sintered Al/SiC composites using RSM and ANN: A comparative study," *Journal of Materials Research and Technology*, vol. 9, no. 6, pp. 14036–14050, 2020.
17. N. Sezer, Z. Evis, S. M. Kayhan, A. Tahmasebifar, and M. Koç, "Review of magnesium-based biomaterials and their applications," *Journal of magnesium and alloys*, vol. 6, no. 1, pp. 23–43, 2018.
18. B. Yuan, M. Zhu, and C. Y. Chung, "Biomedical porous shape memory alloys for hard-tissue replacement materials," *Materials*, vol. 11, no. 9, p. 1716, 2018.
19. A. Warburton, S. J. Girdler, C. M. Mikhail, A. Ahn, and S. K. Cho, "Biomaterials in spinal implants: a review," *Neurospine*, vol. 17, no. 1, p. 101, 2020.
20. M. B. N. Shaikh, T. Aziz, S. Arif, A. H. Ansari, P. G. Karagiannidis, and M. Uddin, "Effect of sintering techniques on microstructural, mechanical and tribological properties of Al-SiC composites," *Surfaces and Interfaces*, vol. 20, p. 100598, 2020.
21. M. A. Alam et al., "Modeling, optimization and performance evaluation of TiC/graphite reinforced Al 7075 hybrid composites using response surface methodology," *Materials*, vol. 14, no. 16, p. 4703, 2021.

22. D. F. Williams, "Tissue-biomaterial interactions," *J Mater Sci*, vol. 22, no. 10, pp. 3421–3445, 1987.
23. M. Niinomi, "Mechanical properties of biomedical titanium alloys," *Materials Science and Engineering: A*, vol. 243, no. 1–2, pp. 231–236, 1998.
24. T. Zhang, W. Wang, J. Liu, L. Wang, Y. Tang, and K. Wang, "A review on magnesium alloys for biomedical applications," *Frontiers in Bioengineering and Biotechnology*, vol. 10. Frontiers Media S.A., Aug. 16, 2022.
25. O. Robertsson, "Knee arthroplasty registers," *J Bone Joint Surg Br*, vol. 89, no. 1, pp. 1–4, 2007.
26. D. F. Williams, "Titanium in medicine," *BIOMATERIALS-GUILDFORD-*, vol. 23, no. 18, pp. 3913–3914, 2002.
27. K. Varaprasad, K. Vimala, G. M. Raghavendra, T. Jayaramudu, E. R. Sadiku, and K. Ramam, "Nanotechnology Applications for Tissue Engineering." Elsevier Chennai, India.; 2015.
28. M. Takemoto, S. Fujibayashi, M. Neo, J. Suzuki, T. Kokubo, and T. Nakamura, "Mechanical properties and osteoconductivity of porous bioactive titanium," *Biomaterials*, vol. 26, no. 30, pp. 6014–6023, 2005.
29. M. Babić, O. Verić, Ž. Božić, and A. Sušić, "Fracture analysis of a total hip prosthesis based on reverse engineering," *Eng Fract Mech*, vol. 215, pp. 261–271, 2019.
30. J. Nagels, M. Stokdijk, and P. M. Rozing, "Stress shielding and bone resorption in shoulder arthroplasty," *J Shoulder Elbow Surg*, vol. 12, no. 1, pp. 35–39, 2003.
31. D. R. Sumner, "Long-term implant fixation and stress-shielding in total hip replacement," *J Biomech*, vol. 48, no. 5, pp. 797–800, 2015.
32. M. G. Joshi, S. G. Advani, F. Miller, and M. H. Santare, "Analysis of a femoral hip prosthesis designed to reduce stress shielding," *J Biomech*, vol. 33, no. 12, pp. 1655–1662, 2000.
33. D. Savio and A. Bagnò, "When the Total Hip Replacement Fails: A Review on the Stress-Shielding Effect," *Processes* 2022, Vol. 10, Page 612, vol. 10, no. 3, p. 612, Mar. 2022.
34. H. Hermawan, D. Dubé, and D. Mantovani, "Developments in metallic biodegradable stents," *Acta Biomater*, vol. 6, no. 5, pp. 1693–1697, 2010.
35. F. Witte, "The history of biodegradable magnesium implants: a review," *Acta Biomater*, vol. 6, no. 5, pp. 1680–1692, 2010.
36. Y. Xin, T. Hu, and P. K. Chu, "Influence of test solutions on in vitro studies of biomedical magnesium alloys," *J Electrochem Soc*, vol. 157, no. 7, p. C238, 2010.
37. S. Jaiswal, A. Dubey, and D. Lahiri, "In Vitro Biodegradation and Biocompatibility of Mg–HA-Based Composites for Orthopaedic Applications: A Review," *J Indian Inst Sci*, vol. 99, no. 3, pp. 303–327, Sep. 2019.
38. "Failure Mechanisms in Total-Joint and Dental Implants - Biomaterials for Osseointegration and Novel Engineering." <http://danieli.wikidot.com/2-failure-mechanisms-in-total-joint-and-dental-implants> (accessed Jan. 23, 2023).
39. G. Manivasagam, D. Dhinasekaran, and A. Rajamanickam, "Biomedical implants: corrosion and its prevention-a review," *Recent patents on corrosion science*, vol. 2, no. 1, 2010.
40. B. Aksakal, Ö. S. Yildirim, and H. Gul, "Metallurgical failure analysis of various implant materials used in orthopedic applications," *Journal of Failure Analysis and Prevention*, vol. 4, no. 3, pp. 17–23, 2004.
41. H. Amel-Farzad, M. T. Peivandi, and S. M. R. Yusof-Sani, "In-body corrosion fatigue failure of a stainless steel orthopaedic implant with a rare collection of different damage mechanisms," *Eng Fail Anal*, vol. 14, no. 7, pp. 1205–1217, 2007.
42. T. P. Chaturvedi, "An overview of the corrosion aspect of dental implants (titanium and its alloys)," *Indian Journal of Dental Research*, vol. 20, no. 1, p. 91, 2009.
43. H. Wu et al., "Crevice corrosion—A newly observed mechanism of degradation in biomedical magnesium," *Acta Biomater*, vol. 98, pp. 152–159, 2019.
44. B. D. Ratner, A. S. Hoffman, F. J. Schoen, and J. E. Lemons, "Biomaterials science: an introduction to materials in medicine," San Diego, California, pp. 162–164, 2004.
45. S. I. Landau, "International dictionary of medicine and biology (In three volumes)," 1986, Accessed: May 01, 2023. [Online].
46. J. M. Anderson, A. Rodriguez, and D. T. Chang, "Foreign body reaction to biomaterials," in *Seminars in immunology*, Elsevier, 2008, pp. 86–100.
47. B. D. Ratner, "Host response to biomaterials," Elsevier Inc, pp. 37–51, 2015.
48. Y. Oshida, E. B. Tuna, O. Aktören, and K. Gençay, "Dental implant systems," *Int J Mol Sci*, vol. 11, no. 4, pp. 1580–1678, 2010.

49. I. P. Van Rossen, L. H. Braak, C. De Putter, and K. De Groot, "Stress-absorbing elements in dental implants," *J Prosthet Dent*, vol. 64, no. 2, pp. 198–205, 1990.
50. M. A.-H. Gepreel and M. Niinomi, "Biocompatibility of Ti-alloys for long-term implantation," *J Mech Behav Biomed Mater*, vol. 20, pp. 407–415, 2013.
51. V. Orden, A. C. Fraker, and P. Sung, "The influence of small variations in composition on the corrosion of cobalt–chromium alloys," *Proceedings of the Society for Biomaterials*, vol. 5, pp. 108–112, 1982.
52. J. J. Ramsden et al., "The design and manufacture of biomedical surfaces," *CIRP annals*, vol. 56, no. 2, pp. 687–711, 2007.
53. I. Gotman, "Characteristics of metals used in implants," *J Endourol*, vol. 11, no. 6, pp. 383–389, 1997.
54. K. A. Pacheco, "Allergy to surgical implants," *Clin Rev Allergy Immunol*, vol. 56, no. 1, pp. 72–85, 2019.
55. N. J. Hallab, S. Anderson, M. Caicedo, A. Brasher, K. Mikecz, and J. J. Jacobs, "Effects of soluble metals on human peri-implant cells," *Journal of Biomedical Materials Research Part A: An Official Journal of The Society for Biomaterials, The Japanese Society for Biomaterials, and The Australian Society for Biomaterials and the Korean Society for Biomaterials*, vol. 74, no. 1, pp. 124–140, 2005.
56. S. Agarwal, J. Curtin, B. Duffy, and S. Jaiswal, "Biodegradable magnesium alloys for orthopaedic applications: A review on corrosion, biocompatibility and surface modifications," *Materials Science and Engineering: C*, vol. 68, pp. 948–963, Nov. 2016.
57. N. Tipan, A. Pandey, and P. Mishra, "MAGNESIUM BASED ALLOYS FOR BIODEGRADABLE IMPLANTS APPLICATIONS USING ADDITIVE MANUFACTURING TECHNIQUE: A REVIEW," vol. 22, no. 6, Jul. 2022.
58. J. Chen, L. Tan, X. Yu, I. P. Etim, M. Ibrahim, and K. Yang, "Mechanical properties of magnesium alloys for medical application: A review," *J Mech Behav Biomed Mater*, vol. 87, pp. 68–79, 2018.
59. J. Dong et al., "Advances in Degradation Behavior of Biomedical Magnesium Alloys: a Review," *J Alloys Compd*, p. 164600, 2022.
60. J. Zhang, B. Zhang, J. Zhang, W. Lin, and S. Zhang, "Magnesium Promotes the Regeneration of the Peripheral Nerve," *Front Cell Dev Biol*, p. 2169, 2021.
61. G. K. Schwalfenberg and S. J. Genuis, "The importance of magnesium in clinical healthcare," *Scientifica (Cairo)*, vol. 2017, 2017.
62. I. Johnson, D. Perchy, and H. Liu, "In vitro evaluation of the surface effects on magnesium-yttrium alloy degradation and mesenchymal stem cell adhesion," *J Biomed Mater Res A*, vol. 100, no. 2, pp. 477–485, 2012.
63. S. Agarwal, J. Curtin, B. Duffy, and S. Jaiswal, "Biodegradable magnesium alloys for orthopaedic applications: A review on corrosion, biocompatibility and surface modifications," *Materials Science and Engineering: C*, vol. 68, pp. 948–963, 2016.
64. J. Wang, J. Xu, C. Hopkins, D. H. Chow, and L. Qin, "Biodegradable magnesium-based implants in orthopedics—a general review and perspectives," *Advanced Science*, vol. 7, no. 8, p. 1902443, 2020.
65. P. Chakraborty Banerjee, S. Al-Saadi, L. Choudhary, S. E. Harandi, and R. Singh, "Magnesium implants: prospects and challenges," *Materials*, vol. 12, no. 1, p. 136, 2019.
66. O. Jung et al., "In vivo simulation of magnesium degradability using a new fluid dynamic bench testing approach," *Int J Mol Sci*, vol. 20, no. 19, p. 4859, 2019.
67. P. Yin Yee Chin, Q. Cheok, A. Glowacz, and W. Caesarendra, "A review of in-vivo and in-vitro real-time corrosion monitoring systems of biodegradable metal implants," *Applied Sciences*, vol. 10, no. 9, p. 3141, 2020.
68. S. Seetharaman, S. Jayalakshmi, R. Arvind Singh, and M. Gupta, "The Potential of Magnesium-Based Materials for Engineering and Biomedical Applications," *J Indian Inst Sci*, vol. 102, no. 1, pp. 421–437, 2022.
69. M. O. Pekguleryuz, K. Kainer, and A. Kaya, *Fundamentals of magnesium alloy metallurgy*. Elsevier, 2013.
70. K. Chen, J. Dai, and X. Zhang, "Improvement of corrosion resistance of magnesium alloys for biomedical applications," *Corrosion Reviews*, vol. 33, no. 3–4, pp. 101–117, 2015.
71. D. Wei et al., "Metalloid substitution elevates simultaneously the strength and ductility of face-centered-cubic high-entropy alloys," *Acta Mater*, vol. 225, p. 117571, 2022.
72. K. Munir, J. Lin, C. Wen, P. F. A. Wright, and Y. Li, "Mechanical, corrosion, and biocompatibility properties of Mg-Zr-Sr-Sc alloys for biodegradable implant applications," *Acta Biomater*, vol. 102, pp. 493–507, Jan. 2020

73. G. Mao et al., "Microalloying Design of Biodegradable Mg–2Zn–0.05Ca Promises Improved Bone-Implant Applications," *ACS Biomater Sci Eng*, vol. 7, no. 6, pp. 2755–2766, Jun. 2021
74. X. Yu, M. Ibrahim, Z. Liu, H. Yang, L. Tan, and K. Yang, "Biofunctional Mg coating on PEEK for improving bioactivity," *Bioact Mater*, vol. 3, no. 2, pp. 139–143, 2018.
75. S. Wu et al., "Microstructure, mechanical and corrosion properties of magnesium alloy bone plate treated by high-energy shot peening," *Transactions of Nonferrous Metals Society of China*, vol. 29, no. 8, pp. 1641–1652, 2019.
76. Z.-Z. Yin et al., "Advances in coatings on biodegradable magnesium alloys," *Journal of Magnesium and Alloys*, vol. 8, no. 1, pp. 42–65, 2020.
77. S. A. Rahim, M. A. Joseph, T. S. S. Kumar, and T. Hanas, "Recent progress in surface modification of Mg alloys for biodegradable orthopedic applications," *Front Mater*, 2022.
78. K. Wandelt, *Encyclopedia of interfacial chemistry: surface science and electrochemistry*. Elsevier, 2018.
79. M. D. Pereda, C. Alonso, M. Gamero, J. A. Del Valle, and M. F. L. De Mele, "Comparative study of fluoride conversion coatings formed on biodegradable powder metallurgy Mg: The effect of chlorides at physiological level," *Materials Science and Engineering: C*, vol. 31, no. 5, pp. 858–865, 2011.
80. X. B. Chen et al., "Controlling initial biodegradation of magnesium by a biocompatible strontium phosphate conversion coating," *Acta Biomater*, vol. 10, no. 3, pp. 1463–1474, 2014.
81. E. Willbold et al., "Effect of the addition of low rare earth elements (lanthanum, neodymium, cerium) on the biodegradation and biocompatibility of magnesium," *Acta Biomater*, vol. 11, pp. 554–562, 2015.
82. L. Mao, G. Yuan, J. Niu, Y. Zong, and W. Ding, "In vitro degradation behavior and biocompatibility of Mg–Nd–Zn–Zr alloy by hydrofluoric acid treatment," *Materials Science and Engineering: C*, vol. 33, no. 1, pp. 242–250, 2013.
83. T. Yan, L. Tan, B. Zhang, and K. Yang, "Fluoride conversion coating on biodegradable AZ31B magnesium alloy," *J Mater Sci Technol*, vol. 30, no. 7, pp. 666–674, 2014.
84. X. Liu et al., "Multifunctional MgF<sub>2</sub>/polydopamine coating on Mg alloy for vascular stent application," *J Mater Sci Technol*, vol. 31, no. 7, pp. 733–743, 2015.
85. R. Zeng, Z. Lan, L. Kong, Y. Huang, and H. Cui, "Characterization of calcium-modified zinc phosphate conversion coatings and their influences on corrosion resistance of AZ31 alloy," *Surf Coat Technol*, vol. 205, no. 11, pp. 3347–3355, 2011.
86. X.-B. Chen, H.-Y. Yang, T. B. Abbott, M. A. Easton, and N. Birbilis, "Corrosion protection of magnesium and its alloys by metal phosphate conversion coatings," *Surface engineering*, vol. 30, no. 12, pp. 871–879, 2014.
87. B. Lin et al., "Preparation and characterization of dopamine-induced biomimetic hydroxyapatite coatings on the AZ31 magnesium alloy," *Surf Coat Technol*, vol. 281, pp. 82–88, 2015.
88. Y. Dong, T. Wang, Y. Xu, Y. Guo, G. Li, and J. Lian, "A polydopamine-based calcium phosphate/graphene oxide composite coating on magnesium alloy to improve corrosion resistance and biocompatibility for biomedical applications," *Materialia (Oxf)*, vol. 21, Mar. 2022.
89. X. Lu et al., "Plasma electrolytic oxidation coatings with particle additions—A review," *Surf Coat Technol*, vol. 307, pp. 1165–1182, 2016.
90. E. Liu et al., "Micro-arc oxidation behavior of fly ash cenospheres/magnesium alloy degradable composite and corrosion resistance of coatings," *Surf Coat Technol*, vol. 391, p. 125693, 2020.
91. W. Liu, S. Liu, and L. Wang, "Surface modification of biomedical titanium alloy: micromorphology, microstructure evolution and biomedical applications," *Coatings*, vol. 9, no. 4, p. 249, 2019.
92. R. B. Figueira, I. R. Fontinha, C. J. R. Silva, and E. V Pereira, "Hybrid sol-gel coatings: Smart and green materials for corrosion mitigation," *Coatings*, vol. 6, no. 1, p. 12, 2016.
93. G. J. Owens et al., "Sol-gel based materials for biomedical applications," *Prog Mater Sci*, vol. 77, pp. 1–79, 2016.
94. R. B. Figueira, "Hybrid sol-gel coatings for corrosion mitigation: a critical review," *Polymers (Basel)*, vol. 12, no. 3, p. 689, 2020.
95. M. I. Jamesh et al., "Effects of zirconium and nitrogen plasma immersion ion implantation on the electrochemical corrosion behavior of Mg–Y–RE alloy in simulated body fluid and cell culture medium," *Corros Sci*, vol. 86, pp. 239–251, 2014.

96. H. Zhu et al., "Corrosion resistance improvement of Mg alloy AZ31 by combining bilayer amorphous DLC: H/SiNx film with N+ ions implantation," *J Alloys Compd*, vol. 762, pp. 171–183, 2018.
97. S. Somasundaram, M. Ionescu, and B. K. Mathan, "Ion implantation of calcium and zinc in magnesium for biodegradable implant applications," *Metals (Basel)*, vol. 8, no. 1, p. 30, 2018.
98. J. Liu, Y. Zheng, Y. Bi, Y. Li, and Y. Zheng, "Improved cytocompatibility of Mg-1Ca alloy modified by Zn ion implantation and deposition," *Mater Lett*, vol. 205, pp. 87–89, 2017.
99. Z. Y. Qiu, C. Chen, X. M. Wang, and I. S. Lee, "Advances in the surface modification techniques of bone-related implants for last 10 years," *Regen Biomater*, vol. 1, no. 1, pp. 67–79, Nov. 2014
100. Z.-Z. Yin et al., "Advances in coatings on biodegradable magnesium alloys," *Journal of Magnesium and Alloys*, vol. 8, no. 1, pp. 42–65, 2020.
101. S. Xia, Y. Liu, D. Fu, B. Jin, and J. Lu, "Effect of surface mechanical attrition treatment on tribological behavior of the AZ31 alloy," *J Mater Sci Technol*, vol. 32, no. 12, pp. 1245–1252, 2016.
102. K. Skowron et al., "Gradient microstructure induced by surface mechanical attrition treatment (SMAT) in magnesium studied using positron annihilation spectroscopy and complementary methods," *Materials*, vol. 13, no. 18, Sep. 2020
103. N. Li, Y. D. Li, Y. X. Li, Y. H. Wu, Y. F. Zheng, and Y. Han, "Effect of surface mechanical attrition treatment on biodegradable Mg–1Ca alloy," *Materials Science and Engineering: C*, vol. 35, pp. 314–321, 2014.
104. H. Kovacı, Y. B. Bozkurt, A. F. Yetim, M. Aslan, and A. Çelik, "The effect of surface plastic deformation produced by shot peening on corrosion behavior of a low-alloy steel," *Surf Coat Technol*, vol. 360, pp. 78–86, 2019
105. M. Mhaede, F. Pastorek, and B. Hadzima, "Influence of shot peening on corrosion properties of biocompatible magnesium alloy AZ31 coated by dicalcium phosphate dihydrate (DCPD)," *Materials Science and Engineering: C*, vol. 39, pp. 330–335, 2014.
106. L. B. Peral, A. Zafra, S. Bagherifard, M. Guagliano, and I. Fernández-Pariente, "Effect of warm shot peening treatments on surface properties and corrosion behavior of AZ31 magnesium alloy," *Surf Coat Technol*, vol. 401, p. 126285, 2020.
107. N. Hafeez et al., "Evolution of microstructural complex transitions in low-modulus  $\beta$ -type Ti-35Nb-2Ta-3Zr alloy manufactured by laser powder bed fusion," *Addit Manuf*, vol. 48, p. 102376, 2021.
108. S. Liu et al., "Strengthening mechanism and micropillar analysis of high-strength NiTi–Nb eutectic-type alloy prepared by laser powder bed fusion," *Compos B Eng*, vol. 200, p. 108358, 2020.
109. M. Gao et al., "Excellent thermal shock resistance of NiCrAlY coatings on copper substrate via laser cladding," *J Mater Sci Technol*, vol. 130, pp. 93–102, 2022.
110. U. Mistry and M. Vadali, "A steady-state semi-analytical approximation of melt pool evolution in pulsed laser surface melting," *J Manuf Process*, vol. 74, pp. 123–135, 2022.
111. Y. W. Yang, V. A. M. Cristino, L. M. Tam, K. H. Lo, and C. T. Kwok, "Laser surface alloying of copper with Cr/Ti/CNT for enhancing surface properties," *Journal of Materials Research and Technology*, vol. 17, pp. 560–573, 2022.
112. M. Afzal, A. N. Khan, T. Ben Mahmud, T. I. Khan, and M. Ajmal, "Effect of laser melting on plasma sprayed WC-12wt.%Co coatings," *Surf Coat Technol*, vol. 266, pp. 22–30, 2015.
113. R. S. Mishra and Z. Y. Ma, "Friction stir welding and processing," *Materials Science and Engineering: R: Reports*, vol. 50, no. 1, pp. 1–78, 2005.
114. X. Cao, Q. Shi, D. Liu, Z. Feng, Q. Liu, and G. Chen, "Fabrication of in situ carbon fiber/aluminum composites via friction stir processing: Evaluation of microstructural, mechanical and tribological behaviors," *Compos B Eng*, vol. 139, pp. 97–105, 2018.
115. L. Wang et al., "Tensile and superelastic behaviors of Ti-35Nb-2Ta-3Zr with gradient structure," *Mater Des*, vol. 194, p. 108961, 2020.
116. H. Gu et al., "Microstructure evolution and electrochemical properties of TiO<sub>2</sub>/Ti-35Nb-2Ta-3Zr micro/nano-composites fabricated by friction stir processing," *Mater Des*, vol. 169, p. 107680, 2019.

117. L. Wang et al., "Microstructure evolution and superelastic behavior in Ti-35Nb-2Ta-3Zr alloy processed by friction stir processing," *Acta Mater*, vol. 131, pp. 499–510, 2017.
118. L. Wang et al., "Investigation of Deformation Mechanisms in  $\beta$ -Type Ti-35Nb-2Ta-3Zr Alloy via FSP Leading to Surface Strengthening," *Metallurgical and Materials Transactions A*, vol. 46, no. 11, pp. 4813–4818, 2015.

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.