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Development of biomechanical behaviour of magnesium alloys for biomedical context

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ABSTRACT

Magnesium alloys, which belong to the category of biodegradable metals, have a significant amount of potential to be utilized as implant materials, and as a result, they draw a lot of attention. This article is a review that summarizes the mechanical properties of magnesium alloys that are used in medical applications. This article illustrates the mechanical behaviors of magnesium alloys that are used in biomedical applications as well as the ways that may be used to improve the mechanical characteristics of biodegradable magnesium alloys. In conclusion, the difficulties that will need to be overcome in the creation of biodegradable magnesium alloys are discussed.

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1. INTRODUCTION

The emergence of biodegradable metals has disrupted the conventional paradigm in the biomaterials domain, resulting in the production of metals that are resistant to corrosion. The purpose of biodegradable implants is to facilitate tissue regeneration, accelerate wound healing, and ultimately degrade in their native surroundings [1], [2]. Magnesium (Mg) and its alloys have become a subject of significant interest in contemporary times as a potentially advantageous new category of materials, owing to their biodegradability, anti-inflammatory, anti-tumor, antibacterial, osteogenesis inductivity, and other bio functional characteristics. Furthermore, Mg and its alloys have the capability of undergoing decomposition into less complex materials [3]–[5].

According to reports, the initial medical utilizations of Mg involved its application as ligatures in 1878. Magnesium wires were employed by Edward C. Huse to perform cauterization of the arteries in three patients who were experiencing severe hemorrhaging. Each of the patients had been in a critical condition. According to Huse’s findings in 1878, there is a correlation between the size of the Mg wire and the rate of corrosion it experiences in the body, with larger wires exhibiting slower corrosion [5], [6]. The pure Mg wire exhibited brittleness which hindered its knotting ability; hence it was blended with other metals to enhance its pliability. Erwin Payr, a physician, proposed in 1900 the concept of inserting magnesium plates and sheets into animal joints as a means of preserving or reinstating joint mobility. The magnesium sheets that were introduced into the knee joints of canines and lagomorphs underwent complete corrosion within a span of 18 days or a few weeks, contingent on the thickness of the sheets [5], [7], [8].

The onset of the 21st century initiated a fresh wave of research on magnesium and its analogous alloys as prospective biodegradable materials. Significant advancements have been achieved in this field of study since the turn of the 21st century. The year 2013 marked the achievement of Biotronic, a German corporation, in obtaining the CE mark for a coronary stent composed of a biodegradable magnesium alloy. The CE mark was granted to Syntellix, a German corporation, in 2013 for a screw composed of a biodegradable magnesium alloy. The aforementioned acknowledgement was granted in light of the corporation's efficacious clinical investigation pertaining to surgical intervention for hallux valgus. In 2015, the South Korean Ministry of Food and drug safety granted approval for the utilisation of biodegradable K-MET metallic screws, produced by the U&I Corporation, in the process of osteosynthesis, which pertains to the mending of fractured bones. Furthermore, a total of 53 instances of hand and wrist fractures that underwent treatment with MgCaZn alloy screws were documented in China. Furthermore, in that particular country, over 100 instances of clinical trials utilizing pure magnesium screws for hip-preserving surgery accompanied by vascularized bone graft implantation have been executed with favorable outcomes. Magnesium alloy screws have been historically and currently utilized in clinical settings for the fixation of non-weight-bearing structures, including hallux valgus, hand and wrist fractures, and femoral head bone transplants. The reason for this is that these fractures and grafts are non-weight bearing. Studies have shown that biodegradable implants made of magnesium are equally efficacious as titanium screws in the management of mild hallux valgus conditions.

The significant impact of MAGNEZIX® was evidenced by its commercial success, as demonstrated by the distribution of 25000 MAGNEZIX® implants in December 2016. As a result of this accomplishment, the quantity of implants that were distributed during the previous two and a half years has been exceeded within a solitary year. The MAGNEZIX® CBS, with a circumference of 3.5 mm, has demonstrated efficacy in the treatment of patients across various age groups. The MAGNEZIX® implants are weight-bearing devices utilized for bone fixation, often implemented on a temporary basis. Seitz *et al.* [9] conducted research indicating that MAGNEZIX® compression screws are manufactured in various sizes, with each size being designated for a specific treatment purpose. The aforementioned values denote measurements of 2.0, 2.7, 3.2, and 4.8 millimeters, respectively. Furthermore, it is noteworthy to mention that the Magmaris stent, [10] created by Biotronik AG located in Bulach, Switzerland, received the CE mark in 2016. The Magmaris stent is composed of a magnesium scaffold that is both bioresorbable and eluted with sirolimus. Several properties can be observed, such as superior deliverability, radial reinforcement, and swift absorption [11], [12].

The task is achieved by inducing a tensile stress along the entire length of the screw, which emanates from the torsional moment that will be imparted onto the screw during the implantation procedure. The objective of a surgical bone screw is to securely fasten bone fragments or a bone plate by means of clamping. Although Mg alloy screws are currently predominantly used in non-load-bearing positions, they are still necessary for certain mechanical applications. Despite the in vivo degradation of Mg alloy screws caused by the shear strength of the bone, mechanical fixation remains necessary post-implantation to facilitate the bone healing process. Preservation of the mechanical property and mechanical integrity of Mg alloy implants in the physiological environment is imperative for effective treatment of fractures and execution of procedures pertaining to the cardiovascular system [5], [13], [14].

The elevated Young's modulus exhibited by metals utilized in enduring human implants, such as titanium alloy, stainless steel, and cobalt-chromium alloy, may result in stress shielding. The suboptimal mechanical properties of polymer materials, such as poly-L-lactic acid, limit their clinical applications. Table 1 presents a comparative analysis of the mechanical properties of magnesium alloys and several frequently employed medical materials in clinical settings. However, the strength of Mg alloy is inferior to that of bio-inert metals, yet superior to that of biodegradable polymers. Currently, Mg alloy implants are restricted to non-load bearing positions, and to expand their applicability, it is imperative to improve the mechanical properties of Mg alloys. The mechanical properties and potential medical uses of various biodegradable magnesium alloys, including Mg-Ca based alloys, Mg-Zn based alloys, and Mg-Sr based alloys are reviewed [15]–[17].

Table 1. Mechanical properties and applications of medical metals

Materials	Young's modulus (GPa)	Yield strength (MPa)	Ultimate strength (MPa)	Density (g/cm^3)	Elongation (%)	Applications
Magnesium-based alloys	44	170	220	1.84	2	Biodegradable fixation plates and other medical devices.
Stainless steel	193	190	490	8	40	Surgical instruments, partial stents, and temporary fixation materials.
Titanium-based alloys	185	138	207	16.6	30	Total arthroplasty, fracture fixator.
Cobalt-based alloys	210	310	860	9.2	20	Knee and hip replacement prostheses.

2. DEVELOPMENT OF BIOMECHANICAL PROPERTIES OF MAGNESIUM ALLOYS

Magnesium has been the subject of considerable research on alloys due to its status as one of the lightest metals. Magnesium alloys possessing elevated specific strengths, ductility, and creep resistance are deemed advantageous in the field of engineering. Conversely, it is expected that magnesium alloys possess biocompatibility; exhibit elevated initial mechanical strength and demonstrate gradual degradation post in vivo implantation. Hence, it is imperative to consider biocompatibility and degrading attributes while endeavoring to enhance the mechanical properties of biodegradable Mg alloys [5], [13], [17]. This review centers on three critical domains, namely alloy development, heat treatment, and plastic deformation, which are essential in achieving the desired characteristics. The domains of interest encompass alloy development, heat treatment, and plastic deformation Figure 1.

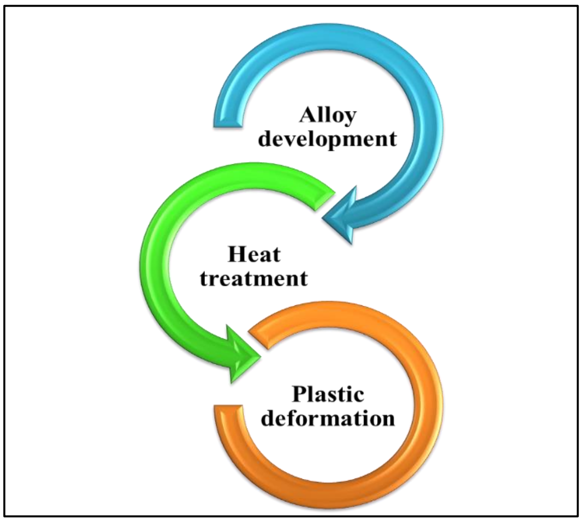

Figure 1. Techniques for enhancing the mechanical characteristics of biodegradable magnesium alloys, magnesium alloys

3. ALLOYING REMEDIATION

Alloying is considered to be one of the most effective methods for improving the mechanical characteristics of metals. Solid solution strengthening and second phase strengthening are widely recognized as the two primary techniques for improving the mechanical properties of magnesium alloys. The development of biocompatible magnesium alloys with enhanced strength characteristics represents a departure from conventional magnesium alloys engineered for other purposes. To achieve optimal biocompatibility, certain nutrient elements have been identified as the preferred alloying agents. Moreover, the appropriate processing significantly affects the mechanical characteristics of magnesium alloys [18], [19]. Two examples of such nature are the utilisation of thermal energy and the process of altering the shape of a material through plastic deformation. The breakdown products have metabolic and tissue-related implications. The study conducted by Waizy *et al.* [20] involved a histopathological examination of tissue samples from various organs including the lung, liver, colon, kidney, pancreatic, and spleen. The results of the investigation revealed no evidence of abnormalities in the aforementioned organs [20]. Furthermore, Witte *et al.* [21] suggested that corrosion products may have the potential to expedite the process of bone repair [21].

Calcium's role in bone health and repair has been established by several studies [5]. The mechanical properties of Mg-Ca alloys are significantly influenced by the distribution of Mg2Ca along the grain boundaries, as highlighted by Seong and Kim [22]. The impact of Ca on the grain refinement of Mg has been observed to enhance the strength and elongation rate of the material, as reported by Du *et al.* [23]. The addition of excessive amounts of calcium to magnesium can lead to a reduction in its corrosion resistance. According to Ding *et al.* [24] it is recommended that Ca should not exceed 1% in Mg alloys. According to Seong and Kim [25], the presence of a significant volume fraction of Mg2Ca particles, despite their fine refinement and even distribution, can negatively impact the ductility. The occurrence of cavities and micro-cracks at interfaces is a common phenomenon during plastic deformation. This can be attributed to the lack of coherence at the interface between Mg and Mg2Ca, resulting in weak interfacial bonding. The Mg-0.4Ca alloy exhibited the highest tensile ductility, measuring at 21.9%. The study conducted by Zeng *et al.* [26] revealed that the

Mg-0.79Ca alloy exhibited the highest level of hardness (58.3 HV) and ultimate tensile strength (200 MPa) when compared to the Mg-0.54Ca and Mg-1.35Ca alloys [26].

Zinc (Zn) is a crucial and biocompatible trace element in the human body due to its role as a cofactor for several enzymes in bone and cartilage [27]–[29]. According to Istrate *et al.* [30], the incorporation of Zn with magnesium results in a significant increase in solubility (6.2% wt%) and enhances the strength of both solid solution and precipitation. Zinc's utility as an additive stem from its ability to produce intermetallic compounds and refine grain, as well as enhance the age hardening response [31]. The microstructure of the as-cast Mg-Zn alloy is characterized by the distribution of a primary Mg matrix and MgZn intermetallic phase along the grain boundary [32]. The augmentation of Zn content up to 5% resulted in an enhancement of strength in Mg-Zn alloys. There existed an inverse relationship between the concentration of Zn and elongation. When the concentration of zinc in the alloy exceeds 5%, numerous MgZn phases will precipitate from the Mg matrix along the grain boundaries, leading to an increase in the alloy's strength through dispersion [33].

Researchers in the field of structural materials have directed significant efforts towards investigating the impact of incorporating aluminium into magnesium alloys with the aim of enhancing their mechanical characteristics and resistance to corrosion [34]. At aluminium concentrations exceeding 2%, the prevalent secondary phases are Mg17Al12 and Mg4Al3. The presence of Mg17Al12 along the grain boundaries of the Mg alloy results in a continuous network that enhances its mechanical properties and corrosion resistance [35], [36]. Nevertheless, the presence of Al in Mg alloys can result in nerve toxicity, and an association has been established between elevated levels of Al3+ in the brain and Alzheimer's disease [37]. Therefore, additional investigation is warranted to evaluate the potential toxicity of Mg alloys that incorporate Al. The aforementioned constitutes a constraint of Mg-Al alloys in their capacity as biodegradable Mg alloys.

The addition of alloying elements can lead to an improvement in the mechanical properties of magnesium alloys. The incorporation of alloying elements is believed to enhance the corrosion resistance of biodegradable magnesium alloys. This, in turn, is expected to prolong the mechanical durability of the alloys within the in vivo environment.

4. THERMAL REMEDIATION

The utilisation of heat treatment is a common practice in improving the mechanical properties of Mg alloys due to the temperature-dependent solubility of certain alloying elements. Heat treatment is a thermal processing technique that modifies the microstructural properties of materials while preserving their macroscopic appearance and chemical composition. The enhancement of mechanical properties in Mg alloys can be achieved by means of strengthening through fine grain and second phase mechanisms [38], [39]. The majority of magnesium alloys are subjected to T4, T5, or T6 heat treatments. These treatments include solid solution treatment, ageing, and solid solution plus ageing [40], [41].

The mechanical properties of Mg-Zn alloys were commonly improved through heat treatment, owing to the considerable solubility of Zn in magnesium [42], [43]. The study conducted by Lotfabadi *et al.* [44] revealed that subjecting Mg-9Zn alloy to T4 treatment at 340°C for 6 hours resulted in a significant enhancement in both strength and elongation. This improvement can be attributed to the existence of residual Mg51Zn20 and Mg12Zn13 second phases at grain boundaries.

Rare earth (RE) metal-containing magnesium alloys were subjected to heat treatment within the temperature range of 500 to 530 degrees Celsius, resulting in the formation of an oversaturated solution. Upon subjecting the alloys to the T5 ageing treatment within the temperature range of 150 to 250°C, a significant strengthening effect is observed. Magnesium alloys that contain REexhibit the capacity to attain their utmost strength at the stage of intermediate ageing. Upon subjecting the extruded Mg-3Nd-0.2Zn-0.4Zr alloy to an ageing process at a temperature of 200 degrees celsius for a duration of ten hours [5].

The T6 treatment of Mg-Y-Nd alloy may enhance its mechanical properties through precipitation hardening, as suggested by Maier *et al.* [40] research findings. After undergoing the treatment, the alloy exhibited a yield strength of 133.3 MPa, an ultimate tensile strength of 235.5 MPa, and an elongation of 15.4%. The utilisation of heat treatment is an effective method for enhancing the mechanical properties and biodegradability of magnesium alloys. Upon undergoing heat treatment, modifications to the microstructure and second phase distribution of magnesium alloys occur, which exhibit a significant correlation with their mechanical properties [5], [40].

5. PLASTIC DEFORMATION IMPROVEMENT

Plastic deformation techniques, such as extrusion, rolling, drawing, and forging, have been found to significantly enhance the mechanical properties of magnesium and its alloys. The observed phenomenon can be attributed to the rise in dislocation density of Mg alloys that occurs during plastic deformation. This process is also known to have a discernible impact on grain refinement. As a consequence, the resistance to which Mg alloys are subjected leads to an enhancement in their strength [45], [46].

The plastic deformation technique of extrusion is widely employed to enhance the mechanical properties of magnesium alloys. The impact of extrusion ratio on the mechanical properties of Mg-Nd-Zn-Zr alloy [47]. The findings of the study indicate that a decrease in extrusion ratio led to the formation of finer grains and an increase in strength, as evidenced by the ultimate tensile strength of 312 MPa. However, this was accompanied by a reduction in elongation, which was measured at 2.2%. Conversely, an increase in extrusion ratio resulted in the formation of coarser grains and a decrease in strength, with the ultimate tensile strength measuring at 233 Mpa [47]. However, this was accompanied by an increase in elongation, which was measured at 25.9% and significant enhancements in the mechanical properties of ZK series magnesium alloys were observed subsequent to the extrusion process [48].

Grain refinement through rolling is a commonly employed technique for enhancing the mechanical characteristics of magnesium alloys. The as-cast Mg-1Ca alloy exhibited an ultimate tensile strength of 71 MPa and elongation of 1.9%. However, after undergoing hot rolling and hot extrusion, the alloy's ultimate tensile strength and elongation were significantly enhanced, measuring at 167 MPa and 3%, and 239.63 MPa and 10.63%, respectively. These improvements were attributed to the refinement of the microstructure [49]. Additionally, the study found that hot extrusion had a greater impact on the mechanical enhancement of Mg-1Ca compared to hot rolling. Furthermore, the fatigue properties of AZ31 alloy could be improved through the process of rolling. The AZ31 alloy, which underwent squeeze casting (SC), demonstrated notably low fatigue strength, as evidenced by an endurance limit of approximately 40 MPa at 107 cycles. However, the fatigue strength of the SC AZ31 alloy was enhanced through hot rolling (HR), resulting in an endurance limit of 95 MPa for the HR AZ31 alloy. This value was more than twice as high as that of the SC alloy and even surpassed that of the ECAP alloy [50].

6. MEDICAL APPLICATION OF BIODEGRADABLE MAGNESIUM ALLOY

In recent years, there has been significant research and development focused on magnesium-zinc alloys due to the advantageous degradation properties of zinc and the essential role of magnesium as a vital nutrient [51]. The aforementioned phenomenon involves the manifestation of cellular processes, specifically the coordination of various organic ligand interactions and the induction of apoptosis [52]. Regarding corrosion, the corrosion rate of zinc (Zn) in simulated body fluids can be classified as moderate, in contrast to magnesium which exhibits a faster corrosion rate. Additionally, the corrosion of pure zinc is characterized as mild. Previous research conducted on animal models has demonstrated that MgeZn implants exhibit remarkable biocompatibility in both bone and vascular tissue [53]. Therefore, the addition of magnesium as an alloying element to zinc results in enhanced mechanical properties and a significant reduction in corrosion degradation rate. The zinc content in magnesium-zinc alloy exhibits similar effects on the mechanical properties and corrosion performance of the alloy as magnesium-calcium alloy [53].

According to Xiao *et al.* [54], the extruded Mg-4Zn-0.2Ca alloy exhibited a peak strength of 297 MPa, a yield strength of 240 MPa, an elongation of 21.3%, and an elastic modulus of 45 GPa. However, after being immersed in a simulated body fluid (SBF) solution for a period of 30 days, these values decreased to 220 MPa, 160 MPa, 8.5%, and 40 GPa, respectively. The utilization of indirect contact for the extraction of ZK30 and ZK60 alloys has demonstrated the ability to promote cell proliferation in cell culture [54].

Ma *et al.* [55] conducted in vitro and in vivo experiments to compare the Zn-0.05wt%Mg alloy (referred to as Zn-0.05Mg alloy) with pure Zn. The Zn-0.05Mg alloy is characterized by the presence of a small amount of Mg2Zn11 phase, which is embedded within the refined Zn matrix. The average grain size of this phase is measured to be 20 μm. Uniform deterioration occurs within a span of six months, without eliciting an inflammatory response or promoting the formation of new bone at the interface between the bone and the implant.

Zhu *et al.* [56] conducted a study to examine the immediate impact of extracellular Zn(2+) on human smooth muscle cells (SMCs) over a period of 24 hours. Their findings revealed a noteworthy biphasic effect of Zn(2+). The presence of Zn(2+)ions at a concentration of 80 M did not have any negative effects on the viability of cells. However, it did promote various cellular processes such as adhesion, spreading, proliferation, migration, as well as the production of F-actin and vinculin. The cellular morphology of the specimens exposed to low concentrations of Zn(2+) exhibited a distinct elongation when compared to the untreated control group. When cells were subjected to elevated concentrations of Zn(2+) (ranging from 80 to 120 M), they exhibited a contrasting response and exhibited divergent behavior [56].

The study conducted by Zhi *et al.* [57] investigated the cellular signaling pathways and biological responses of human bone marrow mesenchymal stem cells (hMSC) to Zn. The commonly used magnesium alloy AZ31 was employed as the control standard in this study. Superior cell adhesion, proliferation, and motility were observed on Zn compared to AZ31 following direct cell culture. The presence of Zn or AZ31 resulted in observable alterations in the structure of the cytoskeleton. The results of the Alizarin red staining and alkaline phosphatase (ALP) activity assays revealed that the osteogenic differentiation of hMSCs was significantly enhanced under the influence of Zn or AZ31 culture conditions. The impact of zinc on hMSCs exhibited significant enhancements across various aspects, such as increased proliferation, enhanced differentiation into osteoblasts, improved extracellular matrix formation, and augmented mineral deposition [57].

The magnesium-calcium alloy has been identified as the most suitable alloy system for the formation of the mineral phase in bone [58], given that calcium is the predominant constituent of human bone. Calcium is a cost-effective and advantageous alloying element for magnesium alloys. The addition of calcium to magnesium alloy results in the formation of a stable compound. This addition enhances the biocompatibility of the material and simultaneously leads to significant refinement of the grain structure of the magnesium alloy. Consequently, the mechanical properties of the alloy are greatly improved [59].

Based on the findings of Erdmann *et al.* [60], study, it was observed that MgCa1.6 exhibited superior performance in both tensile and hardness tests when compared to other Mg-xCa alloys in close proximity to cortical bone. Notably, the maximum hardness achieved by the Mg-1.6Ca alloy was measured at 79 HV. Further investigation is required in order to ascertain whether MgCa1represents the optimal magnesium-calcium alloy in terms of its mechanical properties [60].

The biomechanical behavior and degradation of MgCa0.8 alloy screws implanted in the hind legs of rabbits has been investigated by using a series of uniaxial pull-out tests that were conducted at different time intervals following implantation. After a period of two weeks post-surgery, there was no observable disparity in the pull-out forces exhibited by MgCa0.8 and S316L. The pull-out force of the MgCa0.8 material exhibited a slight decrease six weeks following the surgical procedure. On the contrary, the magnitude of power necessary to induce the fracture of S316L exhibited an increasing trend as time progressed. Additionally, it was discovered that the components of the screws in close proximity to the blood arteries and bodily fluid exhibited a higher rate of degradation compared to those within the cortical bone. The degradation behavior of the MgCa0.8 alloy was observed to facilitate bone growth and promote tissue integration [61].

Different calcium concentrations of 0.6, 0.8, 1.0, were used and calcium concentrations of 0.6, 0.8, 1.0, and 1.2 weight percent in order to explore the effects of degradable magnesium-calcium alloys on the function of dendritic cells. According to the findings, the magnesium-calcium alloy has good biocompatibility, and the magnesium and calcium ions produced by in vitro degradation do not significantly interfere with the function of dendritic cells. This suggests that the magnesium-calcium alloy could be used in medical applications. The fact that the alloy was examined by scientists lends credence to this assertion [62].

The findings indicate that the utilization of Mg-0.5Ca alloy as a temporary biodegradable implant material for clinical applications is promising, owing to its controlled in vivo degradation, minimal inflammatory response, and favorable bone-forming properties. Consequently, the Mg-0.5Ca alloy exhibits superior corrosion resistance when compared to alloys with similar compositions. Based on in vivo experiments, it has been observed that the Mg-0.5Ca alloy demonstrates superior biocompatibility and promotes bone growth compared to the Mg-5.0Ca alloy after a period of 4 weeks post-implantation. The initial rates of corrosion, inflammation, and deterioration in magnesium-calcium (Mg-Ca) alloys with a calcium content of 5.0% are observed to be greater compared to Mg-Ca alloys with a calcium content of 0.5%. This statement corroborates the previous assertion regarding the beneficial effect of fine grain size on corrosion resistance. Additionally, it highlights the role of calcium in the degradation layer, which accelerates the formation of biogenic calcium phosphate on the surface. Consequently, this process enhances both osteoinduction and osteoconductivity [63], [64].

Aluminum is employed in numerous alloys owing to its comparatively low density, notable strength-to-weight ratio, and moderate resistance to corrosion. Research findings have indicated that the incorporation of aluminum (Al) elements within the concentration range of 1% to 5% significantly enhances the microstructure of the material. As a result, the application of this technique is commonly observed in the context of magnesium alloy, with the aim of improving its mechanical properties and resistance to corrosion [65], [66]. The corrosion resistance of magnesium alloy can be enhanced by augmenting its aluminum content. The presence of aluminum (Al) has been observed to have a diminishing effect on the grain size. This can be attributed to the partial dissolution of Al within the magnesium solid solution, followed by precipitation as b-phase (Mg17Al12) along the boundaries of the grains [67], [68].

The acceleration of corrosion can occur when there is microelectric interaction between the a-phase matrix and coarse, isolated b-phase particles. Therefore, a consensus regarding the influence of aluminum content on the corrosion performance of magnesium-aluminum (Mg-Al) alloys has not been reached. In order to examine the individual influence of aluminum on corrosion behavior, Michael Grimm employed the metal type casting technique to fabricate magnesium-aluminum binary model alloys. These alloys encompassed a range of aluminum compositions, spanning from 1% to 30% [68]–[70]. The measurement of the degree of cross-linking or continuity (Cb) of the b-phase was conducted under as-cast (F) conditions, and subsequent to a solid solution thermal treatment. The corrosion rates of different tissues were investigated through the utilization of immersion corrosion experiments and weight loss tests Strontium (Sr) exhibits strong chemical and physical similarities to calcium. It possesses the inherent ability to selectively target and accumulate within the skeletal system, particularly in newly formed trabecular bone [71].

Binary magnesium-strontium alloys exhibit promising potential for utilization in skeletal applications. The most favorable Sr content was determined to be 2 wt%. The addition of Sr concentrations below 2 wt% to Mg alloys has been found to enhance their strength and corrosion resistance. However, excessive Sr addition has been observed to negatively impact the mechanical properties of the as-rolled Mg-Sr alloys. Additionally, it has been found that higher Sr concentrations increase the corrosion rate of these alloys. In vivo tests conducted on mice femurs have demonstrated that the as-rolled Mg-2 Sr alloy promotes bone mineralization and the formation of new bone around the implant site, without causing any significant adverse effects [72], [73]. Table 2 presents the mechanical properties, biocompatibility, and prospective biomedical uses of various magnesium alloys.

Table 2. The mechanical behavior biocompatibility and potential biomedical application of some representative magnesium alloys

Alloys	Impact on mechanical properties	Possibility of use in medical	Biocompatibility	References
Magnesium-zinc	Increased tensile strength; strengthened in both solid solution and with age; decreased elongation at a Zn concentration of 5 wt%.	Orthopaedic application; screw	An integral part of the human body, they aid in the recovery of broken bones.	[53]–[57]
Magnesium-calcium	Ca content should be less than 1 wt% to maximize strength and elongation rate while minimizing degradation of corrosion resistance.	Use in orthopaedics, suture materials, mending the intestines and bile tubes.	The human body contains significant trace elements that serve as essential co-factors for enzymes involved in bone and cartilage metabolism.	[58]–[64]
Magnesium-aluminium	Concentrations below 6% show a marked improvement in both final yield strength and ductility.	Orthopaedic application; screw	Increases Al3+ concentration and toxicity to nerves.	[65]–[70]
Magnesium-strontium	Sr concentrations below 2 wt% resulted in increased strength and corrosion resistance, while Sr concentrations above 2 wt% resulted in diminished mechanical.	Use in orthopedics; procedures involving the skeleton	Allows osteoblasts to mature, which benefits bone creation.	[72], [73]

7. CONCLUSIONS AND FUTURE TRENDS

Magnesium alloys, which belong to the category of biodegradable metals, have a significant amount of potential to be employed as implant materials, and as a result, they garner a lot of interest. Magnesium and its alloys have found diverse applications in clinical practice thus far. The entirety of the data presented indicates the feasibility of effectively treating disorders through the utilization of magnesium screws within a clinical context. Nevertheless, in the clinical context, magnesium and its alloys are commonly employed as implants that do not bear loads. Moreover, due to the intricate nature of the stress conditions, the evaluation of plate and screw systems has been limited to animal testing exclusively. Consequently, the application of magnesium plates and screws in conjunction has not yet been implemented in clinical environments. The limited solubility of alloying elements in magnesium, coupled with the need to consider biocompatibility and biodegradability in the development of new biodegradable materials, significantly restricts the potential for enhancing the mechanical properties of the material. A recent development involves the integration of nanocrystallinity and amorphization to create a dual-phase material that demonstrates exceptional strength of 3.3 GPa at room temperature, while also eliminating the influence of sample size. This advancement holds promise for enhancing the mechanical properties of magnesium alloys. The anticipated outcome can be realized through a heightened emphasis on the integration of novel alloy composition, heat treatment methodologies, and plastic deformation strategies. In recent times, a novel approach has been introduced that amalgamates the advantageous properties of nanocrystalline materials. The mechanical properties of magnesium alloys used in medical implants should not only prioritize strength, but also consider factors such as ductility, corrosion fatigue, stress corrosion cracking, and others. This emphasis will contribute to the expansion of research in this field. Furthermore, the exploration of various potential products has been prompted by the advancement of magnesium alloys in the field of medicine. Furthermore, a wide range of potential products is presently under investigation.

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