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Effects of Si, Sn, Sr, Zn, and Zr on microstructure and properties of magnesium alloys for biomedical applications: a review

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ABSTRACT
This review article critically examines the influence of alloying elements, namely silicon (Si), tin (Sn), strontium (Sr), zinc (Zn), and zirconium (Zr), on the microstructures, mechanical properties, and corrosion resistance of magnesium alloys, with the primary focus being on biomedical applications. Magnesium alloys have garnered significant attention owing to their lightweight nature and potential for enhancing product performance. This review systematically explores how these alloying elements impact mechanical properties, microstructural configurations, and corrosion resistance, shedding light on the intricate mechanisms governing these changes. Emphasis is placed on their role in improving tensile strength, hardness, and ductility while balancing corrosion resistance to meet industrial demands. Additionally, considering the growing interest in magnesium alloys for biomedical applications, this review briefly highlights their potential for biodegradable implants, where tailored alloy compositions can optimize biocompatibility and degradation rates. A comprehensive synthesis of existing research findings offers valuable insights for researchers, engineers, and practitioners in optimizing magnesium alloys for biomedical applications.

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KEYWORDS
Magnesium alloys; alloying elements; microstructures; corrosion resistance; biomedical application

1. Introduction

Magnesium, symbolized as Mg with an atomic number of 12, is a widely available element, recognized as the lightest structural metal with a density of 1.7 g/cm^3. Typically appearing as a shiny grey solid, magnesium is abundant in Earth's oceans. Its hexagonal

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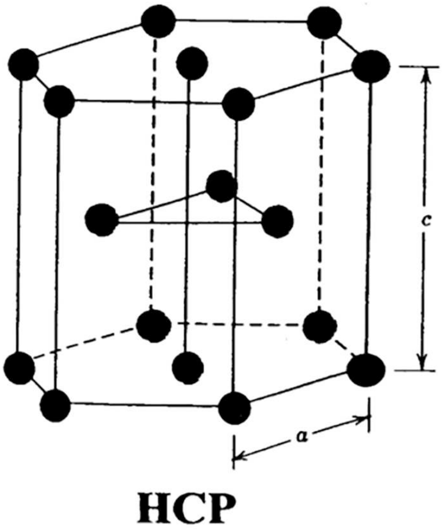

Figure 1. Crystalline structure of HCP Magnesium [1].

close-packed (hcp) crystal structure (Figure 1) presents a challenge for deformation at room temperature because this structure provides fewer slip systems at lower temperatures, which limits its plasticity. This characteristic makes magnesium and its alloys more difficult to work with under normal conditions. Despite its relatively low melting point, which simplifies casting processes, magnesium is chemically unstable and prone to rapid corrosion, particularly in marine environments. This rapid corrosion is primarily due to impurities rather than the metal's inherent properties [1]. Consequently, pure magnesium is seldom used in manufacturing, especially in the biomedical, where biocompatibility, durability and resistance to environmental factors are crucial. To enhance its properties for biomedical applications, magnesium is commonly alloyed with other metals. These alloying elements include aluminium, zinc, cerium, silver, thorium, yttrium, and zirconium, each contributing specific benefits. For instance, aluminium and zinc improve the strength and corrosion resistance of the alloy which is suitable for bone fixation and scaffolds, while elements like thorium and zirconium enhance high-temperature performance and stability, and reduce the corrosion rate, making the alloy more stable in biological environments. The alloy decomposes naturally in the body, eliminating the need for secondary surgery. Cerium and yttrium can also add to the overall performance by refining the grain structure and improving ductility. The alloys are safe for use in the human body, with minimal toxicity from yttrium. These alloys degrade at a controlled rate, reducing the need for surgical removal. Therefore, magnesium alloys, with their superior characteristics compared to pure magnesium, are more frequently utilized in biomedical industries. These alloys offer a combination of light weight, enhanced strength, and better corrosion resistance, making them suitable for applications where performance and durability are critical.

The American Society for Testing and Materials (ASTM) has developed a comprehensive system for classifying magnesium alloys, making their identification and categorization more straightforward and standardized. This classification system assigns specific names to different magnesium alloys based on their unique compositions. The naming convention starts with two letters, which represent the primary alloying elements present in the alloy. These letters are followed by one or two additional letters that provide further specification. The final part of the name consists of numbers that indicate the weight percentages of these alloying elements, rounded to the nearest whole number. For instance, when an alloy is designated as AZ91, it signifies that the alloy comprises magnesium (Mg) as the base element with 9% aluminium (Al) and 1% zinc (Zn) by weight. This systematic approach ensures that each magnesium alloy can be easily and accurately identified based on its composition, facilitating better communication, and understanding among manufacturers, engineers, and users. The system also helps in standardizing the properties and performance expectations of various magnesium alloys used in different industrial applications, ensuring consistency and reliability across the board [2].

Magnesium can form alloys with rare-earth elements, which significantly enhance its high-temperature strength and overall performance. This lightweight metal is approximately 33% lighter than aluminium, 60% lighter than titanium, and a remarkable 75% lighter than steel [3–5]. Owing to its strong reducing properties, magnesium is vital in the extraction of other metals from their compounds, including titanium, zirconium, and hafnium. The unique combination of high strength, ductility, and creep resistance makes magnesium alloys exceptionally valuable in various engineering applications. Compared to engineered plastics, magnesium alloys offer a similar density but provide superior strength, recyclability, and cost-effectiveness. This has led to magnesium alloys replacing plastics in numerous areas. Additionally, their lightweight and robust characteristics make magnesium alloys highly sought after in biomedical applications, where reducing weight without compromising strength is crucial. The advantageous properties of magnesium, such as its ability to form strong alloys with rare-earth elements, contribute to its widespread use in advanced engineering and industrial sectors. Whether in biomedical, or other high-performance fields, magnesium and its alloys continue to play a pivotal role in modern material science and engineering due to their unique combination of lightness, strength, biocompatibility, and versatility.

Magnesium alloys are used in the biomedical field for different products such as orthopaedic implants [6], cardiovascular stents [7], bioresorbable medical devices [8], bone fixation [9], and scaffolds [10]. They also offer several notable advantages in casting processes. Firstly, they enable the production of thinner wall castings compared to aluminium, with wall thicknesses of 1–1.5 mm as opposed to 2–2.5 mm [1]. Secondly, castings made from magnesium alloys cool more rapidly because of their lower latent heat of fusion per unit volume [1]. Thirdly, thier low density allows for high entry pressures with moderate applied pressure during casting. Lastly, the limited solubility of iron in magnesium alloys reduces the incidence of die soldering, which occurs when iron from the casting dies dissolves into the molten metal, causing defects [1]. These characteristics make magnesium alloys highly advantageous in various manufacturing processes. The ability to create thinner and lighter components without compromising strength or durability is particularly beneficial in industries where weight reduction is crucial. The faster cooling times and lower incidence of die soldering further enhance the efficiency and quality of the casting process. As a result, magnesium continues to be a valuable material in the production of advanced, lightweight, and durable components across multiple sectors.

2. Magnesium and its alloys: processing

Magnesium alloys are manufactured using various techniques, with casting processes being especially common. Key casting methods include high-pressure die casting and gravity casting, such as sand and permanent mould casting. Additionally, other significant methods include squeeze casting, thixocasting, and thixomolding [11–13]. These techniques offer various advantages in terms of the properties and applications of the alloys produced. Furthermore, magnesium alloys can also be created using a carbon process at around 2300 °C. This process involves reduction of MgO (magnesium oxide) with carbon, resulting in the formation of magnesium (Mg), which can then be alloyed with other elements. These diverse manufacturing techniques enable the production of magnesium alloys for use in a broad spectrum of industrial applications.

The International Magnesium Association (IMA) has noted a significant yearly rise in the utilization of -cast magnesium alloys for automotive parts, suggesting that high-pressure die casting offers substantial potential for the further development of magnesium alloys [14,15]. Though die casting is a frequently employed method, magnesium alloys present distinctive advantages, such as their low density, making them especially suitable for aerospace applications when utilized through sand casting. For components that must endure prolonged exposure to temperatures ranging from 250°C to 300°C, specialized casting alloys containing zirconium, rare-earth elements, yttrium, silver, and zinc are utilized [12,16].

While cast alloys are more prevalent than wrought materials like extrusions, forgings, sheets, and plates, the latter are also utilized across diverse applications. In recent times, the biomedical sector has exhibited a renewed inclination towards wrought alloys as a prospective avenue for magnesium utilization [15]. Magnesium alloys boast a substantially lower annual consumption, comprising less than one million tonnes, in stark contrast to the staggering 50 million tonnes of aluminium alloys consumed annually. This substantial variance predominantly stems from the inherent challenges associated with magnesium alloys, including their susceptibility to corrosion, tendency to creep at elevated temperatures, and flammability. To mitigate these challenges, magnesium is alloyed with an array of metals, yielding alloys endowed with enhanced properties when compared to pure magnesium [2]. Through alloying, magnesium alloys can exhibit improved corrosion resistance, biocompatibility, elevated temperature creep resistance, and reduced flammability, thereby broadening their applicability across various industries, including biomedical. Thus, while magnesium alloys face inherent hurdles, strategic alloying practices hold promise in unlocking their full potential and fostering their widespread adoption in diverse industrial applications.

3. Magnesium (Mg) interaction with different alloying elements

By adding extra elements to magnesium, its characteristics can be altered, and additional enhancements can be achieved through compositional adjustments. This study seeks to evaluate the effects of different materials when it is combined with Mg in alloys.

3.1. Pure magnesium (Mg)

Magnesium and its alloying elements exhibit significant chemical reactivity, making them prone to galvanic corrosion in their pure forms. In such cases, the Mg matrix often functions as the positive charge within micro-galvanic cells, leading to its accelerated dissolution [17]. Research conducted by Song [18] and Ren et al. [19] suggests that specific purification processes can substantially reduce the corrosion rate of pure magnesium. The corrosion resistance of pure magnesium is intrinsically linked to the levels of impurities present. When these impurities exceed certain thresholds, the corrosion rate escalates rapidly. Iron (Fe), copper (Cu), and nickel (Ni) are especially harmful contaminants for pure magnesium, with acceptable limits set at 170 parts per million (ppm), 1000 ppm, and 5 ppm, respectively [20]. These limits are not fixed and can be influenced by the manufacturing techniques used, as well as the presence of other elements. For instance, the corrosion resistance behaviour of pure Mg is not solely evaluated by the absolute values of impurity contents but rather by the ratio of these impurities. As proposed by Lee et al., [21] the ratio of iron to manganese (Fe/Mn) plays a crucial role in defining the corrosion characteristics. This implies that managing the proportion of impurities can be as important as controlling their absolute amounts. Understanding these intricate factors is essential for enhancing the corrosion resistance of magnesium. By doing so, we can ensure its effective utilization in various industrial and technological applications where durability and longevity are paramount. Consequently, ongoing research and advancements in purification techniques are vital for optimizing the performance and lifespan of magnesium and its alloys in diverse settings.

3.2. Mg–Si alloys

Magnesium–silicon (Mg–Si) alloys, with their unique composition and properties, offer an intriguing proposition in terms of economic viability. This stems from the relatively lower cost associated with silicon when compared to rare-earth metals, making Mg–Si alloys a cost-effective choice. In their comprehensive study, Beer et al. [22] meticulously examined the intricate thermophysical and mechanical attributes inherent in cast Mg–Si alloys. Through their research, they shed light on the manifold characteristics that define these alloys. Notably, Mg–Si alloys exhibit a compelling array of features, making them particularly suited for various applications. Among these attributes are their exceptional heat resistance, lightweight nature, and impressive mechanical strength. These qualities are largely attributed to the distinctive properties of Mg2Si, a pivotal constituent found within these alloys. Mg2Si, with its biocompatibility, high melting temperature, low density, elevated hardness, and reduced thermal expansion coefficient, significantly enhances the performance and reliability of Mg–Si alloys [22,23]. These properties contribute to the alloys' strength, biocompatibility, and durability, making them ideal for non-toxic and supportive of cell adhesion and bone growth. As such, Mg–Si alloys exemplify the ingenuity and potential of materials science in developing advanced materials that meet the demanding needs of modern engineering, showcasing the field's capacity to innovate and solve complex industrial challenges.

Mabuchi et al. [24] conducted an in-depth exploration into the material's tensile properties, percentage of elongation, and fracture behaviour of magnesium-silicon (Mg–Si) alloys, marking a pivotal advancement in material science. Illustrated in Figure 2 are the intricate microstructures of a diverse array of cast Mg–Si alloys, spanning compositions such as magnesium-2 wt. percent of silicon, magnesium-6 wt. percent of silicon, magnesium-10 wt. percent of silicon, magnesium-18 wt. percent of silicon, and magnesium-21 wt. percent of silicon. The micrographs revealed a notable observation: the Mg2Si particles exhibited a coarse dendritic structure, a departure from the anticipated granular morphology. Moreover, upon closer examination, the cast materials exhibited discernible pores, whose volume fraction appeared to escalate with the higher silicon content. These findings show the complex interplay between alloy composition, microstructural features, and mechanical properties, offering valuable insights for further advancements in alloy design and fabrication techniques.

Figure 3 visually represents the relationship between silicon concentration and the fluctuation in the Vickers hardness values observed at room temperature in cast Mg–Si alloys. Based on data averaged from approximately 10 measurements, it is evident that, within the studied range, an increase in silicon concentration correlates with enhanced hardness. Specifically, the hardness values exhibited a notable increase, ranging from 37 to 139 HV. This correlation highlights the significant impact of silicon content on the mechanical properties of Mg–Si alloys.

Figure 4 illustrates the intricate relationship between the silicon content and the maximum tensile strength exhibited by cast Mg–Si alloys. This correlation unveils intriguing insights, particularly regarding alloys with varying silicon concentrations. Notably, alloys boasting higher silicon contents (> 10 wt.%) demonstrate a discernible trend of lower values of ultimate tensile strength values within the temperature range of 293–373 K, in stark contrast to their counterparts with lower silicon content (less than 10 weight percent). For instance, the Mg-6 wt. percent of Si alloy exhibits a commendable ultimate tensile strength (UTS) of 110 MPa at the room temperature. In contrast, the Mg-21 wt. percent of Si alloy exhibits a notably lower ultimate tensile strength of merely 88 MPa under identical conditions. Nevertheless, it is crucial to highlight a noteworthy observation: the ultimate tensile strength at 573 K exhibits a consistent upsurge with the progressive increase in silicon content across the examined range. This intriguing finding explains the complex interplay between silicon concentration, temperature,

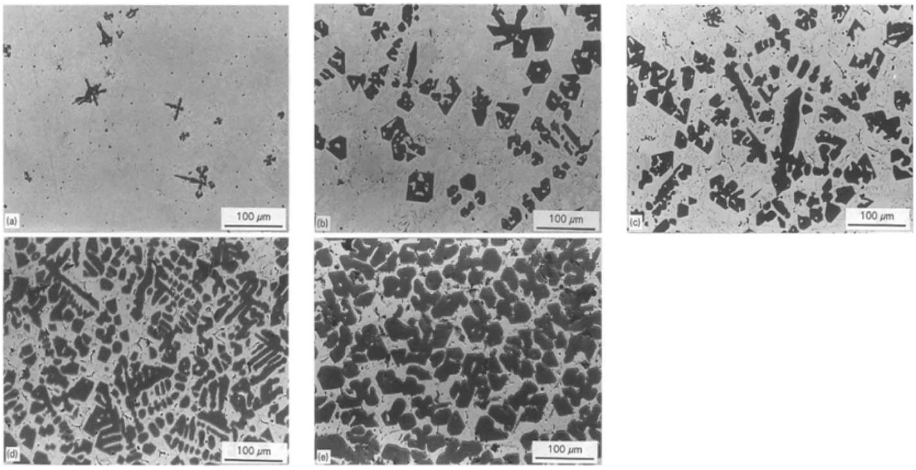

Figure 2. Microstructures of magnesium alloys from Mabuchi et al. [24]: (a) 2% Si, (b) 6% Si, (c) 10% Si, (d) 18% Si, and (e) 21% Si.

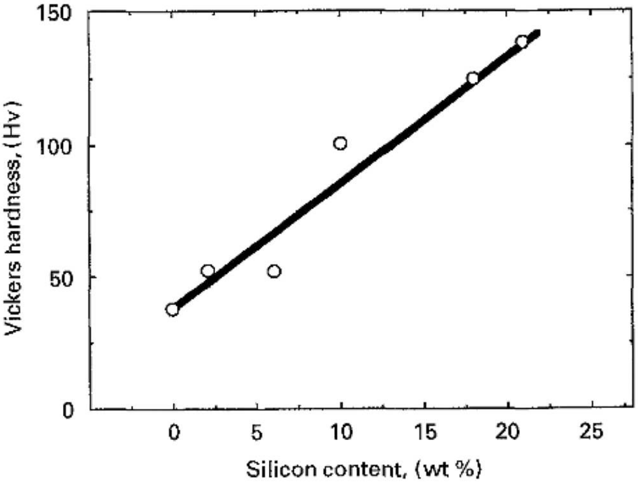

Figure 3. Vickers hardness of Mg–Si alloyfrom Mabuchi et al. [24].

and mechanical properties, offering valuable insights for material engineers and researchers alike as they endeavour to optimize the performance of Mg–Si alloys across diverse operating conditions and applications.

Figure 5 portrays the intricate relationship between silicon concentration and elongation to failure observed in cast Mg–Si alloys. This depiction shows a clear trend: as the silicon concentration increases, the elongation to failure diminishes, regardless of the temperature within the explored range. Notably, the Mg-21 wt. percent Si alloy stands out, showcasing significantly reduced elongations of less than 1% across temperatures ranging from 293 to 573 K. This finding highlights the crucial role of silicon content

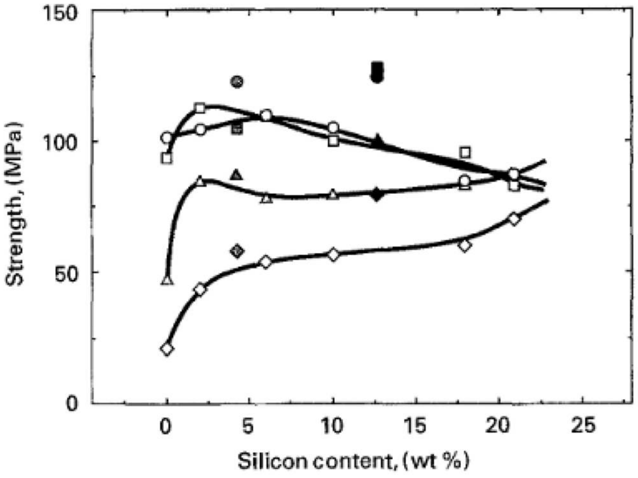

Figure 4. The variation in maximum tensile strength concerning the silicon content for the cast specimens from Mabuchi et al. [24]: (a) Mg–Si alloy at (o) room temperature, (□) 373 K, (Δ) 473 K, and (◇) 573 K; (b) Mg–Si–Zn alloy at (o) room temperature (□) 373 K, (Δ) 473 K, and (◇) 573 K; and (c) Mg–Si–Al alloy at (●) room temperature, (■)373 K, (▲) 473 K, and (◆) 573 K.

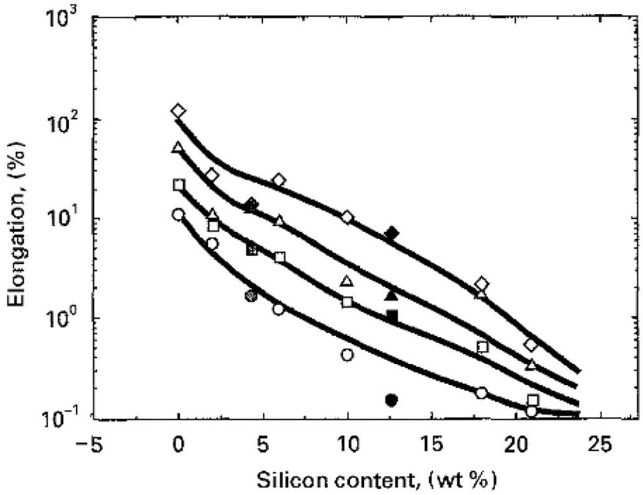

Figure 5. The variation in elongation to failure concerning the silicon content for the cast specimens from Mabuchi et al. [24]: (a) Mg–Si alloy at (o) room temperature, (□) 373 K, (Δ) 473 K, and (◇) 573 K; (b) Mg–Si–Zn alloy at (o) room temperature (□) 373 K, (Δ) 473 K, and (◇) 573 K; and (c) Mg–Si–Al alloy at (●) room temperature, (■) 373 K, (▲) 473 K, and (◆) 573 K.

in influencing the ductility and mechanical behaviour of Mg–Si alloys, emphasizing the importance of carefully optimizing alloy compositions to meet specific performance requirements across various operating conditions.

Figure 6 presents a comprehensive visualization of the stress (σ) vs strain (ε) curves recorded at room temperature for three different alloy compositions: (a) cast pure magnesium, (b) cast magnesium-6 wt. percent of silicon, and (c) cast magnesium-21 wt. percent of silicon. Analysing these curves reveals a clear trend: the alloy with a high silicon content, specifically Mg-21 wt. percent Si, shows a reduced strength owing to its poor ductility. This issue stems from the high concentration of Mg2Si within the Mg–Si alloys, causing embrittlement and resulting in unfavourable tensile properties in alloys with high silicon content. Consequently, it is apparent that there is a critical need to address the inadequate ductility of Mg–Si alloys. By improving their ductility, the overall performance and applicability of these alloys can be significantly enhanced, making them more suitable for a broad range of biomedical fields. This insight explains the importance of continued research and development in this area of materials science.

Figure 7 presents a detailed examination of the fractured surfaces (fractography) of specimens that failed at room temperature, showcasing three distinct alloy compositions: (a) cast pure magnesium (b) cast magnesium-6 wt. percent of silicon, and (c) cast magnesium-21 wt. percent of silicon. Upon meticulous inspection of these fracture surfaces, the presence of Mg2Si becomes unmistakable. Numerous Mg2Si particles are prominently distributed across the fracture surface, with a particularly notable concentration observed in the case of the cast Mg-21 wt. percent Si alloy. Intriguingly, the fracture surface of this alloy appears relatively flat, suggesting a unique fracture behaviour influenced by the high concentration of Mg2Si. It is postulated that these Mg2Si particles serve as initiation points for fracture propagation, highlighting their significant role in

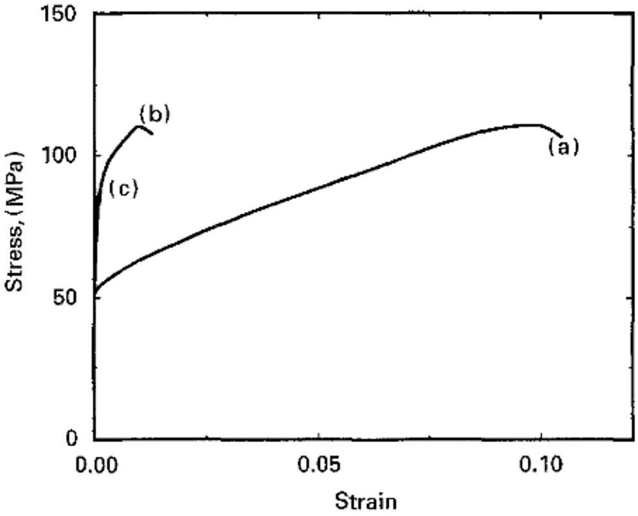

Figure 6. The stress–strain curves for cast from Mabuchi et al. [24]: (a) pure Mg, (b) 6% Si, and (c) 21% Si at room temperature.

dictating the mechanical behaviour and fracture characteristics of magnesium-silicon alloys. This observation affirms the importance of understanding the microstructural features and their effects on fracture mechanisms to optimize the design and performance of Mg–Si alloys in various biomedical applications.

Figure 8 illustrates the deformation-induced fracture of relatively large Mg2Si particles, shedding light on their fracture mechanisms. These fractures stem from stress–strain concentrations around the particles, consistent with previous research from Davidson [25]. The progression of fractures from these sites leads to diminished ductility in the alloys. The notably restricted ductility observed in high Si alloys is attributed to the early onset and spread of fractures induced by the proximity between particles. This close proximity heightens the susceptibility to fracture, accentuating the importance of understanding fracture mechanisms for optimizing the mechanical properties of Mg–Si alloys.

The integration of alloying elements has emerged as a pivotal strategy to significantly bolster the mechanical properties of cast materials. This enhancement owes itself to the meticulous refinement of the grain structure and the precise dispersion of Mg2Si particles throughout the material matrix. These crucial factors synergistically contribute to the

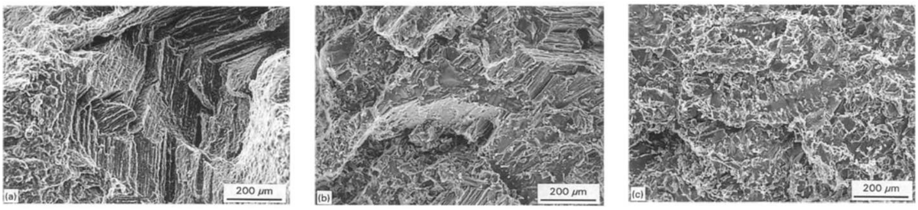

Figure 7. Fractured surfaces of specimens which failed at room temperature, include cast from Mabuchi et al. [24]: (a) pure Mg, (b) 6% Si, and (c) 21% Si.

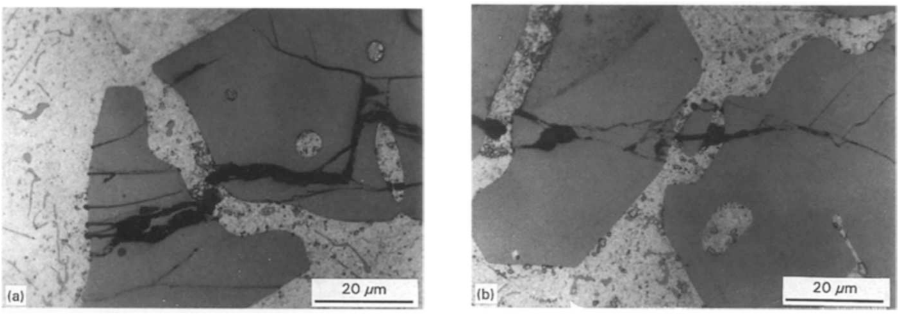

Figure 8. Micrographs depicting specimens deformed to failure at ambient temperature in Mg- from Mabuchi et al. [24]: (a) 18% Si and (b) 21% Si, illustrating the fracture of the Mg_2Si particles.

substantial augmentation of strength and various other desirable mechanical attributes exhibited by the alloys.

3.3. Mg–Sn alloys

In the early 1930s, there was a notable surge in interest surrounding magnesium–tin (Mg–Sn) alloys [26]. In recent times, these alloys have attracted increasing attention owing to their potential applications in high-temperature environments [27–29]. A critical insight gleaned from the binary phase diagram [30] is the maximum solidification temperature range for Mg–Sn binary alloys, which hovers around 67°C. This range starkly contrasts with those of magnesium-aluminium (Mg–Al) and magnesium-zinc (Mg–Zn) binary alloys, which boast values of 136°C and 283°C, respectively. Consequently, this disparity has significant implications for the casting process. Casting flaws, such as distributed shrinkage and hot tearing – common challenges encountered during solidification – are markedly less severe in Mg–Sn alloys when compared to their Mg–Al and Mg–Zn counterparts. The narrower solidification temperature range of Mg–Sn alloys allows for more controlled and uniform solidification behaviour, minimizing the occurrence of casting defects and improving the overall quality of cast components. This advantage positions Mg–Sn alloys as promising candidates for various industrial applications, particularly in scenarios where high-temperature stability and superior casting performance are paramount considerations. Thus, the continued exploration and development of Mg–Sn alloys hold immense potential for advancing the frontier of materials science and engineering in diverse sectors.

The solubility of tin (Sn) in the α-magnesium (Mg) solid solution undergoes a significant and notable decrease, dropping from 14.85 wt. percent at the eutectic transition temperature of 561°C to just 0.45 wt. percent at 200°C. This substantial change provides a valuable opportunity to enhance the mechanical properties of Mg–Sn alloys through effective aging processes. One of the key features of Mg–Sn alloys is the intermetallic phase Mg–2Sn, which has a significantly higher melting point of 770°C. This is in stark contrast to Mg–Al alloys, where the intermetallic phase Mg17Al12 has a much lower melting point of 462°C [31]. The higher melting point of Mg2Sn highlights the potential of Mg–Sn alloys to withstand elevated temperatures, making them highly suitable for applications that require superior thermal stability and mechanical performance. Therefore, it is evident that Mg–Sn alloys hold considerable promise for various industrial applications. Further research and development efforts focused on harnessing the unique properties of Mg–Sn alloys are crucial. Such advancements could drive significant progress in materials science and engineering, enabling the development of advanced materials that meet the demanding requirements of biomedical industrial applications. By addressing the challenges and exploring the opportunities presented by Mg–Sn alloys, researchers can contribute to the creation of materials with exceptional performance characteristics.

Liu et al. [32] conducted a study on the microstructure, tensile properties, and creep behaviour of as-cast Mg-(1–10)%Sn alloys. Figure 9 illustrates the optical metallographic microstructure of Mg–Sn binary alloys, revealing that the primary α-Mg phases exhibit a dendritic structure. The addition of tin significantly refines the secondary dendritic arm spacing of the original α-Mg phase. This refinement highlights the impact of tin on the microstructural characteristics of Mg–Sn alloys and suggests potential improvements in mechanical properties. The research highlights the complex relationship between alloy composition, microstructure, and mechanical behaviour, offering valuable insights for the development and optimization of Mg–Sn alloys for diverse engineering applications. This study provides a foundation for understanding how tin influences the microstructure and performance of Mg–Sn alloys, emphasizing the importance of alloying elements in enhancing the properties of magnesium alloys for various industrial uses.

X-ray diffraction (XRD) analysis was meticulously conducted on the as-cast alloys [32]. The comprehensive findings are vividly depicted in Figure 10, offering invaluable insights into their structural composition. The diffraction patterns unequivocally reveal the presence of the anticipated α-magnesium (Mg) and Mg2Sn phases, each exhibiting distinct diffraction peaks. Notably, as the tin (Sn) concentration increases, there is a discernible enhancement in the intensity of the Mg2Sn phase peak, indicating a proportional augmentation in its abundance within the alloy matrix. Furthermore, the

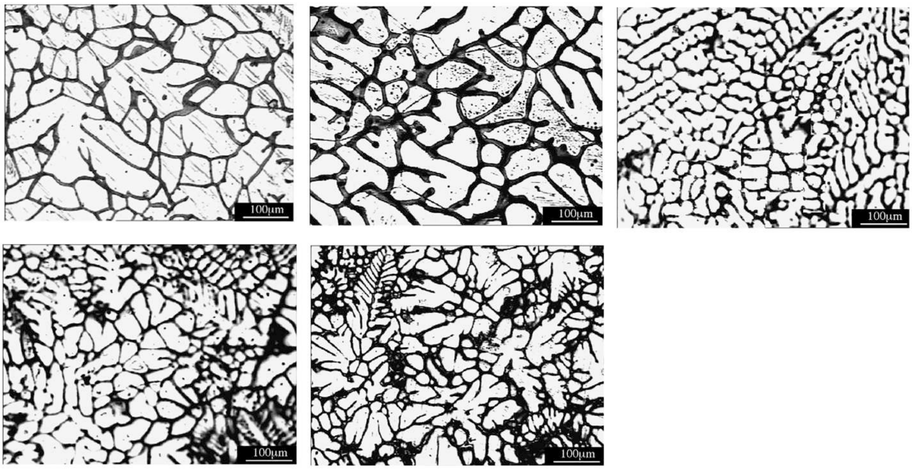

Figure 9. Microstructures of Mg–Sn alloys observed through optical microscopy include from Liu et al. [32]: (a) 1% Sn, (b) 3% Sn, (c) 5% Sn, (d) 7% Sn, and (e) 10% Sn.

investigation delved deeper through scanning electron microscopy (SEM), presenting detailed microstructures of Mg-5 wt. percent of Sn and Mg-10 percent wt. of Sn alloys as shown in Figure 11. These high-resolution images offer a comprehensive glimpse into the intricate microstructural characteristics of the alloys. Within the micrographs, distinct features emerge: a primary α-Mg matrix, distinguished by its dark coloration, forms the structural backbone of the alloys. Interspersed within this matrix is a eutectic mixture comprising α-Mg and Mg2Sn phases, evident from the alternating black and white regions, signifying the coexistence of these phases at specific compositional ratios. Additionally, the micrographs unveil the presence of segregated Mg2Sn phases, denoted by their white coloration, distributed throughout the alloy matrix. These segregated phases represent localized accumulations of Mg2Sn, suggesting a non-uniform distribution within the alloy microstructure. Furthermore, smaller particles of the secondary component Mg2Sn phase, depicted as tiny white colour particles, are observed which is dispersed within the α-magnesium matrix and eutectic mixture. A notable observation arises when comparing the Mg-10 percent Sn alloy to its Mg-5 percent Sn counterpart. The micrographs distinctly showcase a higher quantity and larger size of Mg2Sn phases within the Mg-10 percent Sn alloy, indicative of the significant influence of tin (Sn) content on the microstructural evolution of magnesium-tin alloys. This disparity demonstrates the importance of alloy composition in dictating microstructural features, highlighting the potential for tailoring alloy compositions to achieve desired microstructural characteristics and, consequently, tailored material properties.

The mechanical characteristics of the as-cast alloys underwent meticulous evaluation, and the detailed findings are illustrated in Figure 12. It is evident that with tin additions below 5 wt. percent, both the UTS and percentage of elongation of the alloys undergo gradual increments as shown in Figure 12a. The optimal mechanical properties are achieved at a 5% Sn addition, exhibiting a remarkable 40.7% increase in UTS and a substantial 39.3% increase in elongation compared to pure magnesium. However, both the

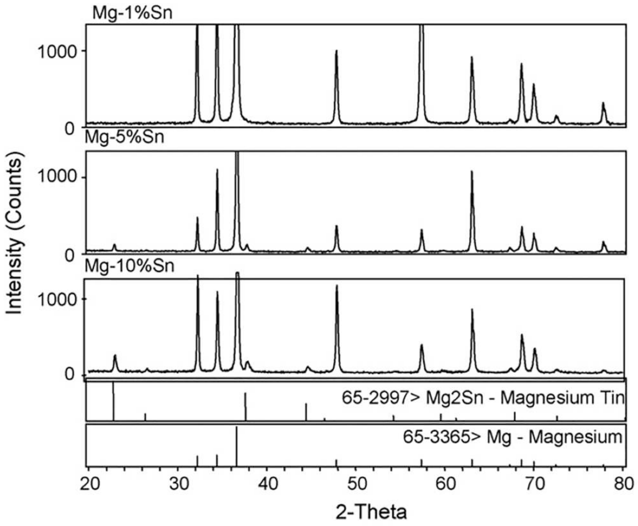

Figure 10. X-ray diffraction (XRD) patterns of Mg–Sn alloys from Liu et al. [32].

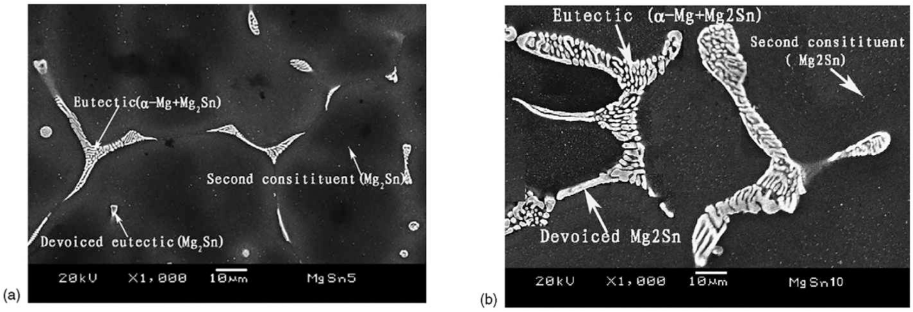

Figure 11. Scanning electron microscope micrographs of Mg alloys from Liu et al. [32]: (a) 5% Sn and (b) 10% Sn.

values of tensile properties and the percentage of elongation decrease when the tin addition exceeds 5%, particularly the elongation, which experiences a notable decline by 57.7% with a 10% Sn addition compared to the Mg-5% Sn alloy. Additionally, the microhardness of the material steadily increases with the addition of tin (Sn) (Figure 12b). Among the alloys examined, the Mg-5 wt. percent of Sn alloy showcases the most favourable mechanical characteristics at room temperature, highlighting the importance of precise alloy composition in tailoring mechanical properties to meet specific engineering requirements. These findings offer valuable insights for the optimization of Mg–Sn alloys for a wide range of biomedical applications, where superior mechanical performance is paramount.

3.4. Strontium (Sr) influence

The introduction of strontium (Sr) into magnesium (Mg) alloys is widely recognized for its notable refinement of grain structure, a phenomenon extensively documented in previous research [33,34]. In a comprehensive study by Brar et al. [34], the mechanical and degradative properties of Mg–Sr and Mg–Zn–Sr alloys were examined to assess their potential as biodegradable implant materials. Optical microstructure of the binary magnesium-x wt. percent of Sr alloys ($x = 0.5$ wt. percent, 1.0 wt. percent, 1.5 wt. percent,

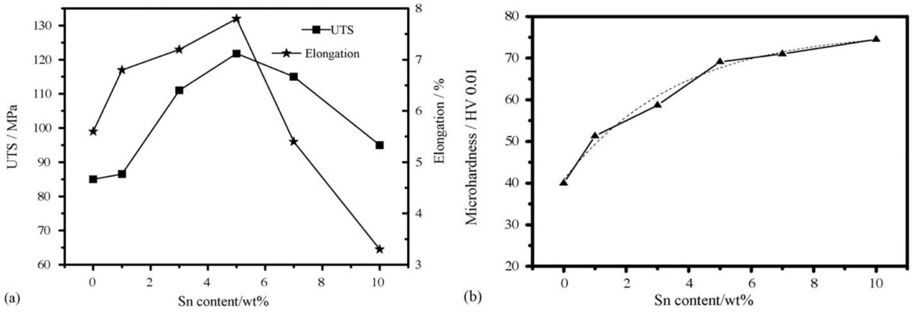

Figure 12. The mechanical properties of Mg–Sn alloys from Liu et al. [32]: (a) UTS and (b) Microhardness.

(solution-treated)) are prominently displayed in Figure 13a–c. Microstructural analysis reveals the predominant presence of both Mg and Mg17Sr2 phases in Figure 14. Further, Figure 15 demonstrates that Sr primarily resides within the Mg17Sr2 phase, while the matrix itself contains minimal Sr, owing to the limited solubility of strontium (Sr) in magnesium (Mg), only small amounts of Sr can dissolve in Mg before forming separate phases. This is because their atomic sizes and structures differ significantly. This detailed investigation highlights the potential of Mg–Sr alloys for biodegradable implants, offering valuable insights for ongoing research and development in this area of materials science. This study's findings show the importance of Sr in improving the properties of Mg alloys, enhancing their performance and viability for biomedical applications. As such, it provides a foundational understanding that can drive future innovations and improvements in the field of biodegradable materials.

The grain refining effect induced by solute additions is intricately influenced by several factors, including the growth restriction factor (Q), nucleation potency, and availability [35–37]. Specifically, in the context of pure magnesium (Mg), the introduction of strontium (Sr) has demonstrated a remarkable ability to refine the grain structure. This phenomenon can be attributed to Sr's limited solid solubility in Mg, which stands at a mere 0.10 wt.%, coupled with the effects of the non-equilibrium solidification process. Throughout the process of casting, Sr atoms are compelled towards the solid/liquid boundary on account of non-equilibrium solidification dynamics, thereby causing a significant growth restriction effect [38]. This intricate interplay of factors highlight the significant role of solute additions, particularly Sr, in modulating the microstructural evolution of magnesium alloys, thereby offering valuable insights for enhancing their mechanical properties and performance in diverse industrial applications.

The presence of a liquid phase enriched in strontium (Sr) tends to aggregate at grain boundaries and solidify through a eutectic process, as documented by Lee et al. [38]. These authors have highlighted the size of grains which is around 500bμm for a magnesium–0.3 wt. percent of strontium alloy. In our study, we observed an average size of grain approximately 379 μm for magnesium–0.5 wt. percent strontium alloys and 390 μm for magnesium–1.0 wt. percent strontium alloys. Interestingly, the magnesium–1.5 wt. percent strontium alloy exhibited a smaller size of grain of around 145 μm. X-ray diffraction (XRD) analysis of these alloys confirmed the presence of the secondary phase, Mg17Sr2, as shown in Figure 14. A similar trend in grain size variation with increasing alloying concentration has been noted in magnesium–aluminium alloys, as reported by Lee et al. [38]. As the concentration of the alloying element Sr increases,

Figure 13. The optical microstructure of the solution treated magnesium alloys from Brar et al. [34]: (a) 0.5% Sr, (b) 1.0% Sr, and (c) 1.5% Sr.

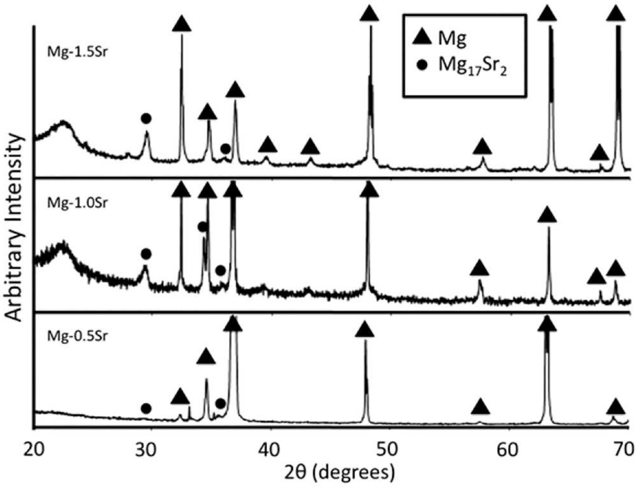

Figure 14. X-ray diffraction (XRD) graphs of binary Mg–Sr alloys homogenized for 18 h at 450°C from Brar et al. [34].

the number of secondary phase precipitates also rises. This rise in secondary-phase precipitates results in greater growth restriction, which promotes the formation of finer grains. The formation of finer grains is directly related to the higher concentration of the alloying element Sr and the increased number of secondary phase precipitates. This relationship between Sr concentration, secondary phase precipitates, and growth restriction ultimately leads to finer grain formation. This highlights the complex relationship between alloy composition, phase distribution, and grain refinement, which is key factors that influence the mechanical characteristics and its performance of the

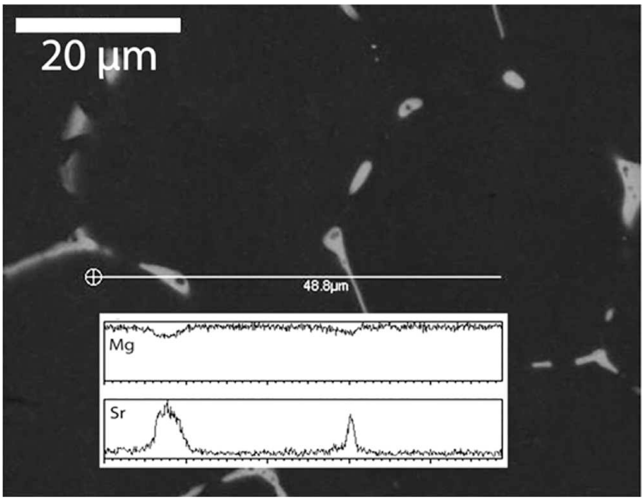

Figure 15. Scanning electron microscope (SEM) micrograph of the homogenized Mg-1% Sr alloys is accompanied by a line scan indication of the relative concentration of Mg and Sr, where line scan demonstrates that the precipitate exhibits a higher concentration of Sr from Brar et al. [34].

magnesium–strontium alloys. Understanding these mechanisms is crucial for optimizing Mg–Sr alloys for various applications, including biomedical application. The findings suggest that adjusting the Sr content can significantly refine grain size, thereby enhancing the alloy's mechanical properties. Further research into these mechanisms will help advance the development and optimization of Mg–Sr alloys, improving their performance for a wide range of applications. This intricate interplay between the alloy composition and phase distribution shows the importance of precise control in alloying processes to achieve desired material properties, paving the way for future innovations in materials science and engineering.

The impact of strontium (Sr) concentration on the strength characteristics of Mg–Sr alloys is presented in Table 1. Interestingly, it is observed that the incremental rise in Sr concentration does not exert a significant influence on the alloy's strength. Both the ductility and yield strengths properties of the magnesium-strontium alloys exhibit enhancement up to a Sr concentration of 2 wt. percent, after which a decline in strength is noted [33,39]. This initial strengthening effect is attributed to the presence of second-phase precipitates [40]. However, despite the increase in strength up to a certain threshold, the elongation of the alloys demonstrates a contrasting trend, diminishing with higher Sr concentrations [40,41]. Consequently, as the Sr content increases, the elongation of the Mg–Sr alloys decreases, resulting in diminished ductility compared to alloys with lower Sr content. This nuanced relationship between Sr concentration and mechanical properties shows the complexity involved in optimizing the composition of Mg–Sr alloys for specific applications, necessitating careful consideration of both strength and ductility requirements in material design and engineering endeavours.

As observed in Table 1, it is evident that increasing the Sr concentration in Mg–Sr alloys is associated with higher hardness. This indicates that adding Sr enhances the alloy's resistance to deformation, resulting in elevated hardness values. For detailed numerical values and a visual representation of the trend showing the increase in hardness with rising Sr concentration, readers should refer to the specific data provided in Figure 16.

When magnesium (Mg) combines with strontium (Sr) in alloys, research investigations reveal a notable enhancement in corrosion resistance [40–43]. This improvement typically reaches its peak around 1.5–2 wt. percent Sr. However, exceeding this optimal concentration range with an excess of Sr may lead to a reduction in corrosion resistance. Hence, it is crucial to maintain the Sr concentration within the specified range to achieve optimal corrosion resistance in Mg–Sr alloys, as demonstrated by extensive experimental evidence and observations.

Researchers have extensively explored the correlation between corrosion rate and microstructure in magnesium (Mg) and its alloys. RE TO HERE Factors such as grain size and precipitates wield significant influence over corrosion rate dynamics. It has

Table 1. The mechanical properties of homogenized Mg–Sr alloys from Brar et al. [34].

Alloy	0.2% YS (MPa)	UTS (MPa)	% Elongation
Mg–0.5 Sr	37	74	2.6
Mg–1.0 Sr	33	73	3.3
Mg–1.5 Sr	40	81	2.6

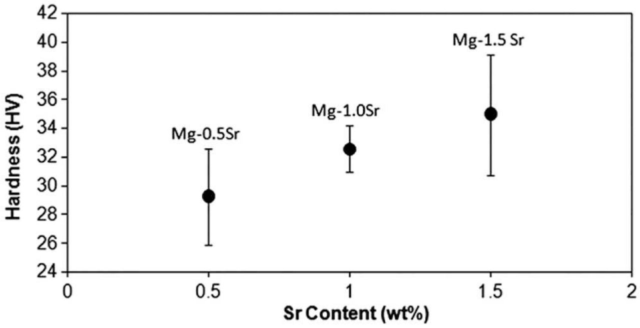

Figure 16. The Vickers' hardness of homogenized binary Mg–Sr alloys from Brar et al. [34].

been observed that smaller Mg grain sizes tend to bolster corrosion resistance, potentially attributed to the formation of a protective passive layer on the surface [44,45]. Conversely, heightened precipitate concentration in the alloy has been correlated with decreased corrosion resistance. The corrosion resistance of Mg–Sr alloys is intricately linked to the interaction between Sr concentration, grain size, and precipitate content. Through meticulous optimization of these factors, it is conceivable that the corrosion resistance of Mg–Sr alloys can be enhanced, paving the way for improved durability and longevity in diverse applications.

Comparing the data depicted in Figure 17, a clear trend emerges: as the Sr concentration increases in Mg–Sr alloys, there is a corresponding reduction in grain size. However, it is crucial to note that this decreased size of grain is accompanied by a decline in corrosion resistance as the Sr concentration rises, ultimately resulting in accelerated deterioration. This phenomenon may be attributed to the heightened presence of second-phase precipitates, which could potentially exacerbate micro galvanic corrosion mechanisms and consequently diminish the overall corrosion resistance of Mg–Sr alloys.

Gu et al.'s findings [41] support this observation. Their in-vitro investigation, conducted using Hank's solution at 37°C, unveiled a noteworthy trend: the corrosion resistance of Mg–Sr alloys exhibited enhancement up to 2 wt. percent Sr, beyond which a decline ensued. This affirms the critical importance of achieving a delicate equilibrium between grain refinement and sustaining corrosion resistance in the utilization of Mg–

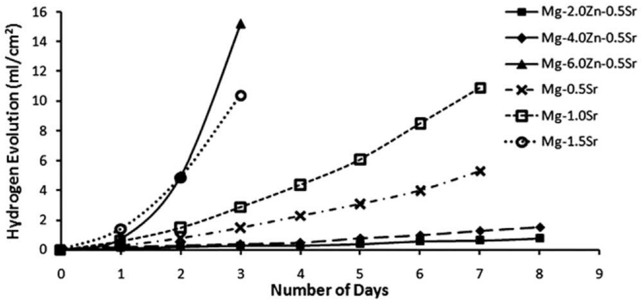

Figure 17. Hydrogen evolution plot to compare the degradation rates of binary Mg–Sr and ternary Mg–Zn–Sr alloys in solution from Brar et al. [34].

Sr alloys. While the addition of Sr for grain-size refinement holds promise for augmenting certain mechanical properties, prudent consideration of the inherent trade-off with corrosion resistance is indispensable for maximizing the efficacy of Mg–Sr alloys in practical applications. Such insights offer valuable guidance for researchers and engineers alike in navigating the complexities of alloy design and performance optimization.

3.5. Mg–Zn alloys

Incorporating zinc (Zn) into magnesium (Mg) has emerged as a highly effective strategy for simultaneously enhancing both corrosion resistance and mechanical properties [46]. This alloying process initiates solid-state and precipitation strengthening mechanisms, profoundly augmenting the alloy's mechanical characteristics. Solid-state strengthening is achieved as Zn atoms integrate into the Mg matrix, inducing lattice distortions that impede dislocation movement, and thereby significantly enhancing the alloy's strength and hardness. Furthermore, precipitation strengthening occurs when solute atoms, such as Zn, precipitate within the Mg matrix. These precipitates act as formidable barriers, further fortifying the alloy's strength and hardness. The formation of these precipitates can occur through either appropriate heat treatments or during the cooling process of the alloy. Notably, the inclusion of Zn in magnesium alloys not only bolsters mechanical characteristics but also enhances the corrosion resistance property. Zn functions as a sacrificial anode, preferentially corroding in corrosive environments, thus shielding the Mg matrix from corrosion attacks. This sacrificial corrosion mechanism serves to extend the lifespan of the Mg–Zn alloy in harsh environments, making it particularly suitable for applications requiring robust corrosion resistance. The synergistic effects of solid-state and precipitation strengthening, coupled with the sacrificial corrosion protection provided by Zn, render Mg–Zn alloys highly promising for a diverse array of applications. These applications span industries where a harmonious blend of mechanical strength and corrosion resistance is paramount. The integration of zinc into magnesium alloys represents a multifaceted approach to engineering materials with superior performance characteristics. By harnessing the dual mechanisms of solid-state and precipitation strengthening, alongside the sacrificial corrosion protection afforded by zinc, Mg–Zn alloys offer unparalleled mechanical strength and corrosion resistance. As such, they stand poised to revolutionize a wide spectrum of biomedical applications, catering to the ever-evolving demands of modern technology and engineering.

Cai et al. [47] undertook a comprehensive study investigating the influence of zinc (Zn) on the microstructure, mechanical properties, and corrosion behaviour of magnesium-zinc (Mg–Zn) alloys. Their investigation unveiled substantial grain size refinement and an augmented volume percentage of intermetallic compounds in Mg–Zn alloys with incremental Zn element addition. Optical metallographic images, presented in Figure 18, offer a comparative analysis between pure magnesium and as-cast Mg–Zn alloys featuring varying Zn concentrations. These images provide valuable insights into the microstructural evolution and highlight the pronounced changes induced by Zn incorporation in Mg–Zn alloys. Through meticulous examination and analysis, Cai et al. elucidated the intricate interplay between Zn content, microstructure, and mechanical properties, shedding light on the underlying mechanisms governing the behaviour of Mg–Zn alloys in biomedical applications.

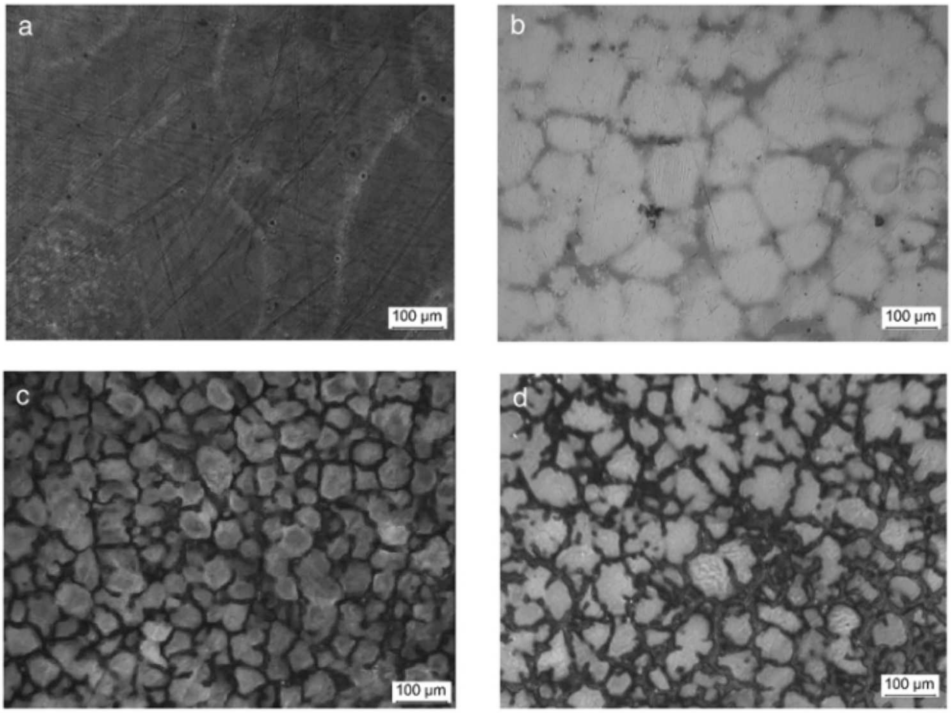

Figure 18. Optical microstructures from Cai et al. [47]: (a) pure Mg, (b) 1% Zn, (c) 5% Zn, and (d) 7% Zn alloys.

The microstructure of as-cast Mg–Zn alloys is characterized by a primary α-Mg matrix intricately interlaced with a secondary phase, primarily distributed along the grain boundaries. This dual-phase structure plays a pivotal role in determining the mechanical and physical properties of the alloys. A notable trend observed in these alloys is the correlation between increasing Zn content and a reduction in grain size. For instance, as depicted in Figure 18a, the pure Mg sample showcases a relatively coarse grain size of 350 μm, whereas the average grain sizes in Mg-1Zn, Mg-5Zn, and Mg-7Zn alloys are approximately 100, 55, and 56 μm, respectively (Figure 18b–d). These findings highlight the significant refinement in grain size with the addition of up to 5% Zn by weight. However, beyond the 7% Zn threshold, there is no further significant refinement observed in the grain size, indicating a saturation point in this relationship. Moreover, at a Zn concentration of 7 wt.%, the secondary phase undergoes a notable transformation, adopting a dendritic network structure that is prominently distributed along the grain boundaries, as illustrated in Figure 18d. This transition signifies a distinct shift in the microstructural evolution of Mg–Zn alloys, suggesting a phase transformation influenced by the higher Zn content. The intricate interplay between Zn concentration and microstructural characteristics demonstrates the complex nature of phase transformations in Mg–Zn alloys. Understanding these relationships is crucial for tailoring the microstructural properties of Mg–Zn alloys to meet specific engineering requirements. By precisely controlling the alloy composition, engineers and materials scientists can optimize the mechanical strength, ductility, and other performance parameters of these alloys for diverse industrial applications. Therefore, further research aimed at elucidating the underlying mechanisms governing the microstructural evolution of Mg–Zn alloys holds significant promise for advancing materials science and engineering, driving innovation, and enabling the development of next-generation alloys with enhanced properties and performance.

At temperatures below 325°C, the Mg7Zn3 alloy can undergo a eutectic reaction, resulting in the formation of α-Mg and Mg–Zn intermetallic phases during the cooling process, as indicated by binary alloy phase diagrams [30]. Additionally, Zn demonstrates relatively high solubility in Mg, with a solubility limit of up to 1.6 wt.%. Under normal temperature conditions, Zn can fully dissolve in the α-Mg matrix [30]. Consequently, when the addition of Zn remains within the solubility limit, it tends to seamlessly integrate into the α-Mg matrix, contributing to the alloy's overall structural integrity and mechanical properties. This integration enhances the alloy's performance across various applications, ensuring optimal functionality and durability in diverse operational environments.

The microstructure analysis conducted on the as-cast Mg–Zn alloys in this study provides clear insights into the impact of Zn incorporation on the grain size of the Mg matrix, corroborating findings from prior research [48–51]. Similar trends have been observed in binary Mg-Y alloys, where an increase in Y content resulted in a significant reduction in grain size [52]. This phenomenon of grain refinement is commonly attributed to the segregation of zinc at the grain front, inducing pronounced constitutional undercooling in the diffusion layer ahead of the solid/liquid interface. This undercooling mechanism effectively impedes grain growth and facilitates the nucleation of primary Mg, consequently leading to a refinement in the grain size [53]. By elucidating the microstructural evolution in Mg–Zn alloys, this study contributes to a more profound understanding of the mechanisms underlying grain refinement in magnesium-based alloys. By exploring these mechanisms, the research provides valuable insights into how grain refinement occurs. The study's findings are essential for developing better magnesium alloys with improved grain refinement, which is crucial for their performance in various applications. The observed enhancement in grain size due to Zn incorporation shows the potential for tailored microstructural control in Mg alloys, with implications for various industrial applications including biomedical sectors. Furthermore, the parallels drawn with Mg-Y alloys highlight the universality of the grain-refinement mechanism, offering valuable insights for alloy design and optimization strategies.

Evaluating the growth restriction factor (GRE) proves to be a valuable method for assessing the refining effectiveness of alloying elements [21]. Among these elements, zinc (Zn) stands out with a notably higher GRE value of 5.31 compared to aluminium (Al) at 4.32 and yttrium (Y) at 1.70, indicating Zn's superior growth restriction capability and refining efficiency. This highlights the potential of Zn as a key alloying element for enhancing the microstructural enhancement of magnesium (Mg) based alloys.

Additionally, the mechanical properties and corrosion resistance of magnesium-zinc alloys are substantially affected by the presence and volume fraction of secondary phases [47]. These secondary phases play a crucial role in determining the overall performance and suitability of Mg–Zn alloys for various applications, particularly in biomedical fields where both mechanical strength and corrosion resistance are paramount. Understanding the composition and distribution of these phases is essential for tailoring Mg–Zn alloys to meet specific requirements in industries such as aerospace, automotive, and medical devices, where reliability and durability are critical factors. In Table 2, a comprehensive comparison of the mechanical characteristics between as-cast Mg–Zn alloys and natural bone is provided, offering valuable insights into the potential suitability of Mg–Zn alloys for biomedical applications, such as orthopaedic implants and prosthetics. Further research and optimization efforts in Mg–Zn alloy development hold promise for advancing their performance and expanding their practical applications in diverse biomedical industries.

The addition of zinc to pure magnesium has emerged as a promising avenue for enhancing a wide array of mechanical properties in Mg–Zn alloys. These properties include hardness, yield strength, tensile strength, and compressive strength, with notable improvements observed, particularly up to a Zn content of 5% by weight. This incorporation of zinc imparts a strengthening effect on the alloy, leading to enhanced mechanical performance across various load conditions. However, it is crucial to highlight that the mechanical behaviour of Mg–7Zn alloy tends to deviate from this trend, displaying inferior performance compared to alloys with lower zinc content. This deviation shows the intricate interplay between alloy composition and mechanical properties, suggesting potential limitations associated with higher zinc concentrations. Of particular interest is the observation that the maximum elongation is achieved in Mg–1Zn alloy, reaching an impressive 13.77%. However, this elongation decreases as the zinc concentration increases to 5% by weight, diminishing to 8.5%. Furthermore, a subsequent increase in the zinc content to 7% by weight results in a significant reduction in elongation to 6.0%, a value even lower than that of pure magnesium. These findings highlight the importance of carefully balancing alloy composition to attain the intended mechanical characteristics. In Mg–Zn alloys, emphasizing the need for a nuanced understanding of the relationship between alloy constituents and mechanical performance. Such insights can inform the design and optimization of Mg–Zn alloys for various engineering applications, ranging from automotive components to biomedical implants.

Research findings have thoroughly examined the elongation values of Mg–4.4Zn and extruded Mg–6Zn alloys, revealing distinct mechanical behaviours among various magnesium-zinc (Mg–Zn) compositions. These studies illuminate the diverse range of mechanical properties exhibited by different alloy compositions. Specifically, elongation values of 8.4% and 18.8% have been documented for Mg–4.4Zn and extruded Mg–6Zn alloys, respectively. Notably, there is a noticeable enhancement in both tensile and yield strength in Mg–Zn alloys containing up to 5% Zn by weight. The increase in strength can be attributed to the Hall–Patch connection, a phenomenon widely supported by numerous research findings in the field. The correlation between Zn content and mechanical

Table 2. The mechanical properties of three Mg–Zn alloys in their as-cast state from Cai et al. [47].

Alloy	Youngs Modulus (GPa)	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Compression strength (MPa)	Hardness (HB)
Natural bone	5–23	–	35–283	1.07–2.10	164–240	–
Pure Mg	1.86	29.88	100.47	7.43	183.09	37.10
Mg–1Zn	24.23	60.62	187.73	13.77	329.60	47.33
Mg–5Zn	36.47	75.60	194.59	8.50	334.12	53.80
Mg–7Zn	39.60	67.28	135.53	6.00	353.11	56.26

properties affirms the importance of precise alloy composition control in tailoring magnesium-zinc alloys for specific biomedical applications. Moreover, according to the Mg–Zn binary phase diagram, the maximum solubility of Zn in magnesium at room temperature under equilibrium conditions is 1.6 wt. percent, indicating the primary mode of Zn dissolution into the primary Mg phase, consequently facilitating solid solution strengthening. Furthermore, the introduction of Zn at 5% by weight triggers the precipitation of MgZn phases along grain boundaries, effectively contributing to dispersion strengthening mechanisms and thereby augmenting the overall enhancement of strength in Mg–Zn alloys. These comprehensive insights h the intricate highlight interplay between alloy composition, microstructure, and mechanical properties in Mg–Zn systems, providing invaluable knowledge for the optimization and design of magnesium-based alloys for various biomedical applications.

The improved mechanical characteristics evident in Mg–Zn alloys, which continues up to 5% Zn by weight, arise from a multitude of reinforcing mechanisms. These encompass fine-grain strengthening, solid-solution strengthening, and second-phase strengthening. Investigations spanning various studies consistently demonstrate that the emergence of precipitated second phases plays a pivotal role in augmenting the alloys' strength. However, this strengthening effect often comes at the expense of reduced plasticity. Despite this trade-off, the presence of these reinforcing mechanisms highlights the complex interplay of factors influencing the mechanical behaviour of magnesium-zinc alloys. Understanding these mechanisms is crucial for optimizing alloy design and tailoring their properties to reach the specific requirements of diverse engineering applications. These findings show the importance of understanding and optimizing the microstructural characteristics of magnesium-zinc alloys to tailor their mechanical properties for biomedical applications. By leveraging these reinforcing mechanisms, engineers can develop alloys with improved performance and versatility, addressing diverse industrial needs with greater efficiency and efficacy.

In their exploration of Mg–Zn–Ca alloy as a biodegradable biomaterial, Zhang et al. [54] observed that increasing the Zn concentration in Mg leads to improved yield strength up to a specific threshold, identified as 6 wt. percent Zn. Similarly, both the ultimate tensile strength and elongation exhibit an upward trajectory up to 4 wt. percent Zn; however, beyond this concentration, there is a decline in both parameters. This suggests a critical balance in alloy composition, where optimizing Zn concentration within defined limits is essential for maximizing mechanical properties and ensuring the suitability of Mg–Zn–Ca alloy as a biodegradable biomaterial.

Gu et al. [55] conducted a comprehensive exploration into the binary Mg-1Zn alloy, shedding light on the favourable influence of zinc (Zn) as an alloying element on both mechanical properties and corrosion resistance. Noteworthy findings emerged, particularly regarding the Mg–6Zn composition, which exhibited commendable tensile strength and elongation properties suitable for implant applications. Moreover, this composition demonstrated a low degradation rate in vitro and showcased high biocompatibility in vivo [46,56]. Additionally, Liu et al. [57] conducted a comprehensive examination of heat treatments' effects on themagnesium-3zinc alloy. They found that while solution treatment improved corrosion resistance, aging treatment had the opposite effect, reducing it. This shows the nuanced impact of heat treatments on alloy properties. Meanwhile, Boehlert et al. [58] evaluated Mg–Zn alloys with Zn concentrations ranging from 0 to 4.4 wt. percent. The research highlighted zinc's dual role as a grain refiner and strengthener for magnesium, with an optimal concentration identified at 4 wt. percent. These findings emphasize zinc's versatility in enhancing mechanical properties, corrosion resistance, and biocompatibility in Mg-based materials. Such insights are crucial for advancing Mg-based materials, particularly in biomedical engineering and implantology, where tailored properties are essential for success.

In comparison to pure magnesium (Mg), the introduction of zinc (Zn) to magnesium (Mg) alloys has consistently demonstrated enhanced corrosion resistance [46,47,55,56]. Electrochemical assessments, conducted on 3, magnesium-zinc alloys (magnesium-1zinc, magnesium-5zinc, and magnesium-7zinc) in simulated body fluid (SBF) as conducted by Cai et al. [47], demonstrated enhanced corrosion resistance compared to the pure magnesium [59–62]. Notably, Mg-5Zn exhibited the highest resistance among them (as depicted in Figure 19). Furthermore, when contrasted with pure Mg, the Mg-5Zn alloy displayed the least alteration in pH. Throughout a 70-hour immersion period in SBF, all three Mg–Zn alloys demonstrated minimal pH variations, highlighting their potential suitability for biomedical applications [47]. Overall, zinc (Zn) exhibits significant potential as an alloying component, highlighting the critical importance of meticulous control over its quantity when enhancing the mechanical properties of magnesium (Mg) alloys.

3.6. Mg–Zr alloys

Zirconium (Zr) is frequently utilized as a grain modification element in magnesium (Mg) alloys, a practice well-documented in various studies [63–65]. Its addition to Mg outcomes in the formation of finely refined equiaxed grains, contributing to enhanced mechanical properties. Despite Zr's solubility limit in Mg being relatively low at 3.8 wt.%, it remains a viable choice for alloying with Mg owing to its exceptional grain refinement

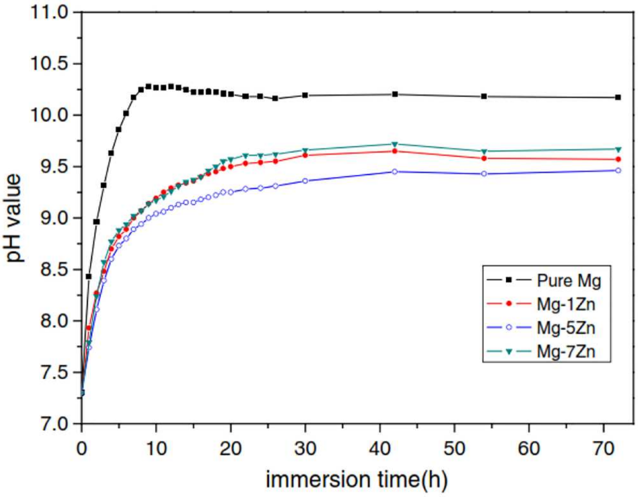

Figure 19. The pH of simulated body fluid (SBF) varies with immersion duration for both pure Mg and Mg–Zn alloys from Cai et al. [47].

capabilities and superior corrosion resistance [66–69]. Notably, Zr exhibits remarkable resistance to corrosion across diverse aggressive environments, including acids and alkalis, further enhancing the durability and longevity of Mg–Zr alloys. This exceptional resistance to corrosion is particularly advantageous in applications where the alloy is subjected to harsh operating conditions, ensuring prolonged service life and reliability [70–72]. Therefore, the utilization of Zr as a grain refiner in Mg alloys represents a judicious choice, offering a compelling combination of mechanical strength and corrosion resistance across a spectrum of biomedical applications [33].

The study conducted by Fan et al. [73] delved into the nuanced impact of Zr addition on both the microstructure and mechanical properties of a magnesium alloy. Initially, in the absence of Zr, the Mg-3.5Y-0.8Ca alloy exhibited a coarse grain size, typically ranging from 50–100 µm, with grain boundaries measuring approximately 5 µm (see Figure 20a). However, upon the introduction of 0.10 wt.% zirconium into the magnesium-3.5yittrium-0.8calcium-0.1zirconium alloy, minimal changes were discernible in the microstructural characteristics (see Figure 20b). Subsequently, with the higher Zr content of 0.4 wt.%, notable alterations manifested within the microstructure [74–76]. The dendritic grain structure underwent a profound transition, evolving into uniformly distributed polygon shaped equiaxed grains with an average grain size of 50 µm, as vividly illustrated in Figure 20c. Furthermore, significant enhancements were illustrated in the grain boundaries, contributing to the overall structural integrity of the alloy [55,73,77,78]. As the Zr content was further increased, as depicted in Figure 20d, a trend towards more granular grains and refined grain boundaries emerged, albeit with a marginal

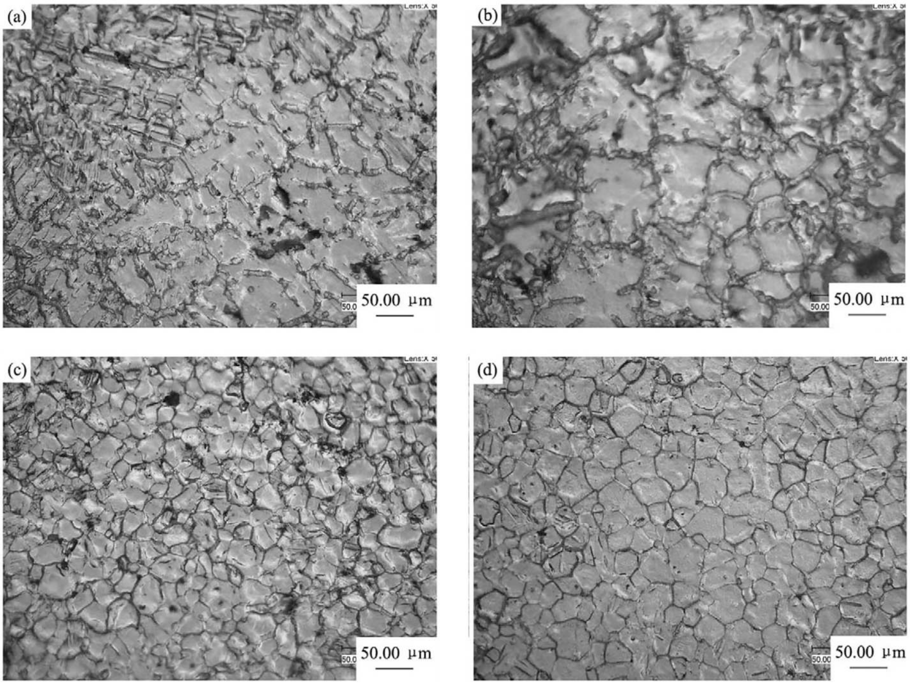

Figure 20. The optical microstructures of Mg-3.5% Y-0.8% Ca-x% Zr alloy from Fan et al. [73]: (a) 0% Zr, (b) 0.1% Zr, (c) 0.4% Zr, and (d) 0.5% Zr.

increase in grain diameter. This comprehensive investigation sheds light on the intricate interplay between Zr content and microstructural evolution in magnesium alloys, showing the pivotal role of Zr in tailoring the material properties to meet specific biomedical requirements and applications.

Figure 21 provides a detailed insight into the tensile mechanical behaviours observed in as-cast magnesium-3.5% yitrium-0.8% calcium-x zirconium alloys at room temperature. A discernible trend emerges as the Zr content varies there is a noticeable improvement in the values of yield, ultimate tensilestrength, and the percentage of elongation of the alloy. Particularly remarkable is the performance of the magnesium-3.5% yittrium-0.8% calcium-0.4% zirconium alloy, which demonstrates favourable overall characteristics. With the tensile properties of 190 MPa and the percentage of elongation of 11%, this alloy exhibits impressive mechanical properties. Its elongation value is notably comparable to those of conventional wrought magnesium alloys listed in Table 3. These findings show the significant potential of Zr alloying to enhance the mechanical properties of magnesium-based alloys, thereby offering promising opportunities for a wide array of biomedical applications.

In borate buffer solutions, the integration of zirconium (Zr) into Mg–Zr alloys serves to enhance corrosion resistance by facilitating the formation of Zr-Mg double oxyhydroxide compounds. Among the array of binary alloys scrutinized, Mg-1Zr emerges as a standout performer, showcasing exceptional mechanical properties. Notably, Mg-1Zr exhibits elevated values for yield strength, ultimate tensile strength, and elongation compared to its counterparts. Furthermore, extensive exposure tests reveal the remarkable corrosion resistance of Mg-1Zr. Following a rigorous 300-hour immersion period, Mg-1Zr demonstrates significantly lower levels of hydrogen evolution in both simulated body fluid (SBF) and Hank's solutions when contrasted with pure Mg. Similarly, when subjected to immersion in Dulbecco's Modified Eagle Medium (DMEM) [79–81], Mg-1Zr exhibits minimal alterations in pH levels (8.58 ± 0.05), a stark contrast to the substantial pH shift observed in pure Mg (9.18 ± 0.14). These findings show the efficacy of zirconium integration in magnesium-zirconium alloys, not only in augmenting

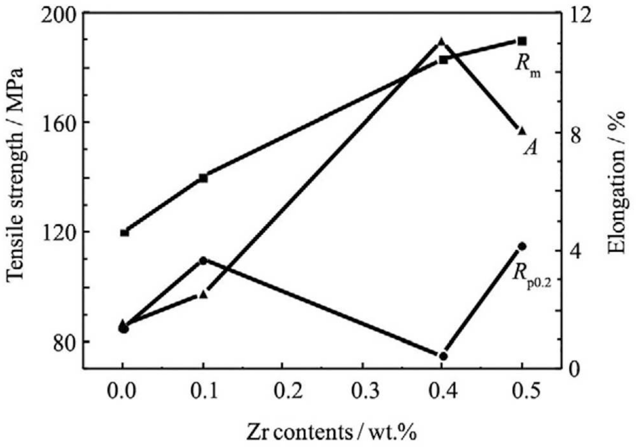

Figure 21. The tensile properties of Mg-%Y-%Ca-%Zr alloys from Fan et al. [73].

Table 3. The mechanical properties of newly developed alloys differ from traditional pure magnesium: from Fan et al. [73].

Alloys	Tensile strength (MPa)	Elongation %
Mg-3Y-0.5Ca	120	1.5
Mg-3Y-0.5Ca-0.1Zr	140	4
Mg-3Y-0.5Ca-0.4Zr	183	11

mechanical attributes but also in enhancing corrosion resistance and maintaining chemical stability in various environmental conditions.

4. Conclusions

The influence and effects of alloying elements, including Si, Sn, Sr, Zn, and Zr, on the microstructures, mechanical characteristics, corrosion resistance, biocompatibility of magnesium alloys are extensively discussed and analysed within the scope of this article. Each of these alloying elements, when present in compositional values of up to 2% along with pure magnesium, consistently demonstrates superior mechanical qualities, biocompatible, and corrosion resistance, which is promising for biomedical applications. It is evident that the incorporation of these alloying elements significantly impacts the microstructure of magnesium alloys, resulting in notable enhancements in mechanical properties, biocompatibility and corrosion resistance relative to pure magnesium alone.

Statement of originality

The authors declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. The authors confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. The authors further confirm that the order of authors listed in the manuscript has been approved by all of us. The authors understand that the Corresponding Author is the sole contact for the Editorial process. The corresponding author is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

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Author Contributions

The authors have significantly contributed to the development and the writing of this article.

Credit Statement

Rajadurai Murugesan: Funding acquisition, Formal analysis, Investigation, and Writing – original draft. **Siva Marimuthu:** Formal analysis, Software, Visualization, and Writing

– review & editing. **Manikandan Natarajan:** Data curation, Formal analysis, Investigation, and Writing – review & editing. **Srikanth Holalu Venkataramana:** Conceptualization, Investigation, Methodology, and Writing – review & editing. **Praveena Bindiganavile Anand:** Methodology, Resources, Supervision, and Writing – review & editing. **Muhammad Imam Ammarullah:** Conceptualization, Project administration, Validation, and Writing – review & editing.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Declaration of AI use

The authors declare the use of generative artificial intelligence (AI) and AI-assisted technologies in the preparation of this manuscript. Specifically, ChatGPT (version GPT-4, OpenAI) was used to improve the readability and language of the article. The AI tool was not used for data analysis, interpretation of results, or drawing scientific conclusions. All content has been reviewed and verified by the authors to ensure accuracy and integrity.

Transparency statement

The authors affirm that this manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant, registered) have been explained.

Data availability statement

The necessary data used in the manuscript are already present in the manuscript.

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