



ZINC ALLOYS AS TEMPORARY BIOMEDICAL IMPLANTS: A REVIEW

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ABSTRACT

Absorbable metals, designed for temporary biomedical implants, degrade in physiological environments, with three primary families being magnesium, iron, and zinc alloys. Magnesium degrades rapidly, often losing structural integrity before bone healing completes, whereas iron degrades very slowly, maintaining excellent mechanical properties but with prolonged persistence in the body. Zinc, emerging as a promising biodegradable metal, offers an intermediate degradation rate and good biocompatibility. However, pure zinc has limitations like low strength, poor hardness, and limited plasticity, making it unsuitable for direct clinical use. Additionally, zinc's low melting point (419.5 °C) raises concerns about creep resistance, susceptibility to aging, and recrystallization, potentially causing device failures during storage and use. This research explores strategies to improve zinc's properties, focusing on alloying for enhanced strength and surface modification to improve biocompatibility, blood compatibility, and corrosion resistance. Future studies should aim to develop zinc alloys with optimal mechanical properties and predictable degradation suitable for medical applications.

KEYWORDS

Biomaterials, temporary medical implants, bone tissue, heals, Zinc alloy and biocompatibility.



1. INTRODUCTION

Recently, clinical problems associated with stress shielding and secondary surgery can be addressed by utilizing biodegradable materials which have the ability of providing an alternative choice to permanent materials in orthopedics (Shi et al., 2023). Many properties like good mechanical strength, wear resistance, toughness, ductility, and formability should be present in these materials to be attracted to use (Al-Khafaji et al., 2024; Dargusch, 2019). Additionally, to address the minimal host response and toxicity of corrosion products that released from many metallic elements (Al-Khafaji et al., 2024; Haleem et al., 2024; Hussein et al., 2024; Radhi et al., 2023; Radhi, Kareem, et al., 2022; Radhi, Sahi, et al., 2022; D. Zhu et al., 2019).

As a result, the biodegradable metals are the candidate to have a bulk composition composed to an essential metallic elements. These assembled materials should metabolize easily in the alive body by absorption or excretion and degrade at desirable time (Gu et al., 2009). Essential biodegradable metals involve iron (Fe), zinc (Zn), and magnesium (Mg). In the previous few years, the focus was on (Fe) and (Mg) biodegradable materials, although the success of such metals remains restricted. For example, when magnesium-based alloys implant touch with plenty of chloride ion in the human body environment, are corrode in the physiological medium and losing strength before the bone tissue fully heals. Conversely, Fe-based alloys have very slow deterioration rates and excellent mechanical characteristics in clinical applications (Bowen et al., 2012).

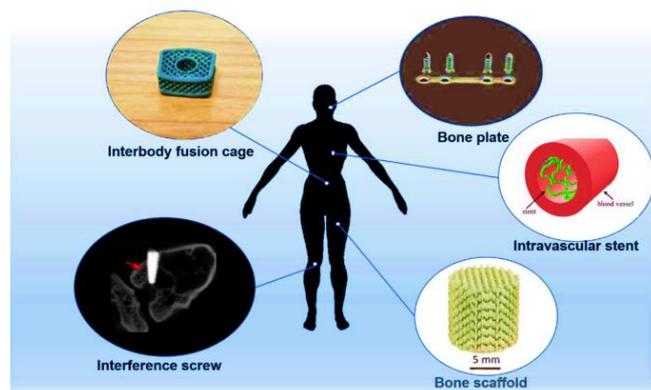
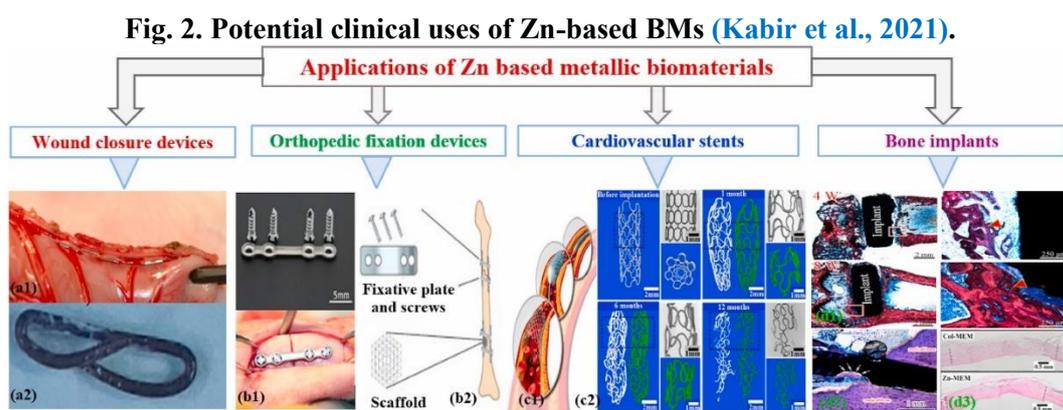


Fig.1. The biodegradable applications for Zinc alloys (Shi et al., 2023).

Zinc is a novel kind of biodegradable metal, after magnesium and iron, due to its high decomposition rate and biocompatibility. And because of the standard corrosion potential of Zinc is ($-0.762 V_{SCE}$), Zinc exhibits a lower corrosion rate than the Mg ($-2.372 V_{SCE}$) and Fe ($-0.440 V_{SCE}$) (Li et al., 2018). In the human body 90% of zinc is stored in bone tissue, therefore Zinc is a necessary element for human health since it affects how proteins and enzymes operate. When zinc ions disintegrate from the implant, they can still integrate into the body's metabolic

functions without causing harmful effects (Ghani Fahmi et al., 2020). Furthermore, considering bio-safety, the recommended limits for elemental zinc are approximated at 15 mg daily (Zheng et al., 2014). Zn-based alloy biomaterials degrade at an appropriate rate because they have a passive layer with moderate stability, and they are easy to cast because of their low melting temperature and chemical reactivity. Because of these characteristics, Zn-based alloys are intriguing candidates for a new generation of BMs, particularly for usage as osteosynthesis materials and cardiovascular stents (Bowen et al., 2015; Salih et al., 2024). Zn-based BMs are the next generation of bone-tissue engineering materials. Fig.2 illustrates many in vivo investigations using Zn-based compounds for possible clinical applications (Kabir et al., 2021). However, pure zinc has insufficient mechanical properties such as low strength, hardness and poor plasticity. Research has been conducted on σ_{UTS} (20-30 MPa), ϵ (0.25%), and H (37 HV) (Kubásek et al., 2011). Furthermore, creep resistance, the relatively limited fatigue strength, high susceptibility, and low-temperature recrystallization to the aging process of Zinc and Zinc alloys can lead to failure of surgical instruments when keeping at room temperature as well as during use in the human body, all them makes it unsuitable for clinical applications (Kubásek et al., 2011; Li et al., 2018). Therefore, these challenges can be controlled by alloying pure zinc with some appropriate elements such as silver (Ag), lithium (Li), copper (Cu), zirconium (Zr), manganese (Mn), calcium (Ca), aluminum (Al) and other elements to produce Zn alloys divided into binary alloy, ternary alloy and quaternary alloy. Selecting appropriate alloying elements is essential for achieving the sufficient mechanical strength, biocompatibility and degradation behavior (Chen et al., 2024).



2. THE AIM OF THIS REVIEW

The aim of this review is to present a comprehensive analysis of zinc-based biomaterials (BM) for potential biomedical applications, with a particular focus on biodegradable zinc alloys. In order to meet the requirements of biomedical applications, this paper examines different manufacturing processes for producing these alloys as well as methods to improve their

mechanical qualities by alloying with appropriate elements. It also investigates surface modification methods to enhance zinc-based BMs' corrosion resistance, blood compatibility, and biocompatibility.

3. THE EFFECT OF ALLOYING ELEMENTS ON ZINC ALLOYS

3.1. The Zn-Mg alloy system

One alloying method that has been extensively studied for biodegradable zinc alloys is the Zn-Mg system. Magnesium has a solubility of less than 0.1wt % in zinc at 364°C . Zn-Mg alloys are composed of Zn primary the dendrites and a lamellar eutectic combination of Zn and Mg_2Zn_{11} (Mostaed et al., 2016). The homogenization decreases lamellar characteristics in the eutectic phase, which leads to uniformity. Hot extrusion caused the process of dynamic recrystallization (DRX), creating a microstructure with recrystallized Zn grains and Mg_2Zn_{11} precipitates scattered along the extrusion direction. Mg_2Zn_{11} enhanced grain structure by creating stress concentration and particle-stimulated nucleation, which eventually saturated as the Mg quantity increased (Robson et al., 2009). As Mg concentration increased, most Zn-Mg alloys demonstrated lower ductility and a shift in fracture mode from ductile to cleavage due to the increased volume of Mg_2Zn_{11} . The hard Mg_2Zn_{11} phase created a mechanical mismatch with the Zn matrix phase, leading to crack initiation at phase boundaries. Wang et al. used multi-pass drawing to produce the highest tensile strength for the Zn-Mg system to date (455 ± 2) MPa (L. Wang et al., 2018).

3.2. The Zn-Ca and Zn-Sr alloys systems

The Ca and Sr are insoluble in zinc, leading to the production of $CaZn_{13}$ and $SrZn_{13}$ in low-alloyed zinc. Li et al. created binary Zn-Ca, Zn-Sr, and ternary Zn-Ca-Sr alloys as new biodegradable metals. These alloys were developed to carry out certain biological functions throughout the bone fixation process by simultaneously release the essential nutrients Ca, Sr, and Zn. The rolling process and extrusion improved the mechanical properties of the Zn-Ca binary alloy to 250 MPa and 11% (UTS, elongation) and the Zn-Sr binary alloy to 260 MPa and 20% (UTS, elongation), which were excellent to pure zinc but require improvement (G. Li et al., 2019). The addition of Mg to binary Zn-Ca and Zn-Sr alloys did not change the phase composition, but it reduced their ductility and strength (H. Li et al., 2015).

3.3. The Zn-Mn alloy system

At 400 °C, the alloying ingredient Mn is approximately 1% soluble in zinc (Yue et al., 2017). Sun et al. investigated Zn-Mn binary alloys and detected the $MnZn_{13}$ phase when the amount of Mn was greater than 0.4 wt%. At 0.2 wt% Mn, a single phase structure was noticed (Sun et al., 2017). In contrast to Mg, Mn has a significant influence on the mechanical properties

of extruded Zn-based alloys. Adding a small amount of Mn improved UTS and elongation in Zn-Mn alloys. Increasing concentration of Mn led to reduced UTS and improved elongation by more than 70%. The twinning process may improve strength in zinc alloys with low Mn levels but reduces as Mn amount increases (Sun et al., 2017).

3.4. The Zn-Ge alloy system

A novel zinc alloy, Zn-Ge, was created in 2018 for biodegradable uses (Tong et al., 2018). The addition of Ge produced a gray, short rod-like eutectic phase along the grain boundaries of zinc. Ge considerably enhanced grain refinement in zinc alloy, which strengthened the matrix. Hot rolling the Zn-5 wt% Ge alloy produced better mechanical properties and a more homogeneous microstructure (Tong et al., 2018).

3.5. The Zn-Li alloy system

Li's solubility in Zn is around 0.1 wt%, which is equivalent to 1 at%. At 403 °C, a eutectic reaction occurs, producing in β -LiZn₄, which then forms to α -LiZn₄ at 65 °C. The majority of research indicates that Zn-Li alloys that have a low Li concentration are formed of α -LiZn₄ and Zinc at room temperature. Zhao et al. identified missing diffraction peaks for Zn-2, 4, and 6% Li in the present database, as well as differences between experimental and recorded LiZn₄ lattice characteristics (Zhao et al., 2017). Zn-Li alloy had exceptional mechanical features, with yield strengths exceeding (200) MPa. According to Dai et al. (2019), this is due to the pinning action of nano-LiZn₄ precipitates. The Zn-0.5 wt% Li formulation demonstrated exceptional UTS (364.9)MPa and 22% elongation (Dai et al., 2019).



Fig. 2. The most common Zn alloying elements include Mg, Al, Cu, Li, Mn, Ag, Fe, Sr, V, Cr, Zr, and Ge. They may create a binary alloy, ternary alloy as well as quaternary alloy with zinc (Chen et al., 2024).

In present review, the Authors try to illustrate most the surface modifications that carried out for zinc alloys in order to enhance its biocompatibility and improve mechanical and biodegradation properties for usage it in the medical applications.

Research in biodegradable zinc-based materials (BMs) for biomedical applications has

expanded significantly due to their potential to address issues associated with traditional, permanent implants. Unlike implants that require removal, biodegradable materials gradually dissolve, reducing the need for secondary surgeries and allowing the body to heal naturally over time. Zinc-based materials, in particular, offer an ideal balance of degradation rate and biocompatibility compared to magnesium- and iron-based BMs, making them promising candidates for biomedical devices such as cardiovascular stents.

Numerous investigations have examined the features and alterations of zinc alloys to improve their corrosion resistance, mechanical qualities, and biocompatibility. For example, (Kubásek et al., 2011) examined Zn-Mg alloys of up to 3 weight percent magnesium and compared their properties to those of Zn-Al-Cu and Mg alloys. Zn-Mg alloys with a magnesium concentration of around 1 weight percent were found by the investigation using techniques including scanning electron microscopy (SEM) and tensile testing had a maximum elongation and strength of 150 MPa and 2%, respectively, and a reduced rate of corrosion in comparison to magnesium-based alloys. Likewise, when Gong et al. (2015) used a hot extrusion technique on a Zn-1Mg alloy, they discovered that the process decreased both corrosion rates and grain size, with the latter dropping by 57%. This alloy demonstrated improved biodegradation uniformity and biocompatibility, making it suitable for load-bearing applications.

To improve the qualities of zinc-based alloys, it has been shown that adding different alloying components is essential. (Liu et al., 2015) used hot-rolling and hot-extrusion techniques to improve the biocompatibility of Zn-based alloys that contained vital nutrient elements as Mg, Ca, and Sr. According to their findings, these components greatly enhanced cytocompatibility and hemocompatibility, satisfying the biosafety standards for clinical applications. Another study (Dambatta et al., 2015) looked at Zn-3Mg alloys and discovered that the alloy's mechanical integrity and corrosion resistance were enhanced by homogenization heat treatment at 360°C for 15 hours. The tensile strength was somewhat reduced and the fracture elongation rose from 2.3% to 8.8% as a result of the microstructure improvement. Zn-3Mg alloys are suitable for biodegradable bone implants due to their strength and corrosion resistance.

The utility of zinc alloys can be further increased by surface modification and the addition of metals like copper and aluminum. (Mostaed et al., 2016) investigated Zn-Mg and Zn-Al alloys and showed that extrusion caused uniform deterioration instead of localized pitting, which is beneficial for the controlled degradation required in medical applications. The most promising alloy was determined to be Zn-0.5Mg due to its optimum strength-ductility ratio and strain-hardening properties. (Tang et al., 2017) used hot extrusion to create a Zn-4Cu alloy and found that it had superior antibacterial properties and delayed degradation. This alloy is particularly

well-suited for applications such as vascular prosthesis because to its exceptional strength and biocompatibility.

By adding components like manganese and silver, zinc alloys' corrosion resistance and biocompatibility are further enhanced. In their investigation of Zn-Mn alloys, (Bagha et al., 2017) showed that manganese additions improve corrosion resistance and compressive strength. Zn-4Mn alloys shown notable enhancements in cell adhesion and vitality, highlighting its potential as a new biodegradable substance. A Zn-4Ag alloy was created in a different study by (Li et al., 2018), demonstrating that silver enhanced corrosion rate and offered antibacterial qualities. Zn-4Ag alloys may be helpful in reducing implant-related infections due to their mechanical strength, biocompatibility, and antibacterial properties.

Multi-element alloys have also been the subject of recent developments to improve the characteristics of zinc-based BMs. In their investigation of Zn-Ag-Zr alloys, (Wątroba et al., 2019) discovered that the simultaneous addition of Ag and Zr significantly improved the alloy's yield strength, tensile strength, and elongation to failure. Since electrochemical studies demonstrated consistent corrosion rates and antibacterial tests confirmed efficacy against common bacterial strains including *Staphylococcus aureus* and *Escherichia coli*, Zn-Ag-Zr is a good option for biodegradable medical implants. Similarly, (Jia et al., 2020) examined Zn alloys containing several elements, including Ca, Li, Sr and Mg. It was discovered that while Ca and Sr improve biocompatibility and osteogenesis, which are critical for bone healing applications, Mg and Li alloying elements improve the alloy's mechanical integrity.

Extrusion and hydrostatic extrusion are two mechanical processing methods that are crucial for enhancing the microstructure and characteristics of zinc alloys. The mechanical properties of Zn-Mg alloys with varying Mg concentrations were examined by (Pachla et al., 2021), who demonstrated that hydrostatic extrusion and equal-channel angular pressing improved grain size, strength, and elongation. This process also increased the corrosion resistance of the Zn-1Mg and Zn-1.5Mg alloys, making them suitable for use in vascular stents.

In vivo studies further confirm the biocompatibility of zinc alloys. (Xiao et al., 2021) examined Zn-0.05Mg-Ag alloys implanted in rabbits over a 24-week period, keeping an eye on biochemical indicators and implant integrity. The findings supported the alloys' potential as biodegradable implants by showing that serum zinc and magnesium levels gradually returned to normal and that histology investigation demonstrated strong bone adherence and integration. Additionally, cutting-edge alloying methods like laser additive manufacturing are being investigated. Cerium (Ce) was added to zinc (Zn) via laser alloying (Yang et al., 2021), which improved creep resistance, grain refinement, and tensile strength. The Zn-Ce alloy

demonstrated its promise for bone mending applications by demonstrating strong hemocompatibility and cytocompatibility.

The role of minor alloying elements like manganese in refining the grain structure and enhancing mechanical properties has also been demonstrated. Manganese was introduced to a Zn-0.2Mg alloy by (Mollaei et al., 2022), who discovered that Mn enhanced the yield and tensile strengths as a result of grain refinement and a rise in particle volume fraction. The alloy may be suitable for vascular stents notwithstanding the minor acceleration of corrosion caused by the inclusion of Mn.

Surface treatments can further enhance the antibacterial properties of zinc alloys. (Xiang et al., 2023) showed that etching zinc with nitric acid increased surface roughness, which improved Zn ion release and inhibited the formation of biofilms. This straightforward, efficient surface modification technology offers a special way to enhance the antibacterial qualities of materials based on zinc for use in medicine.

Finally, in their discussion of the potential of zinc-based materials for bone regeneration and repair, (P. Li et al., 2024) emphasized the need to close the gap between bioactivity and biological performance. Their research highlighted the areas that require more research for Zn-based biomaterials in regenerative medicine by demonstrating the function of zinc ions in bone regeneration and repair.

4. METHODS OF MANUFACTURING BIODEGRADABLE ZINC ALLOYS

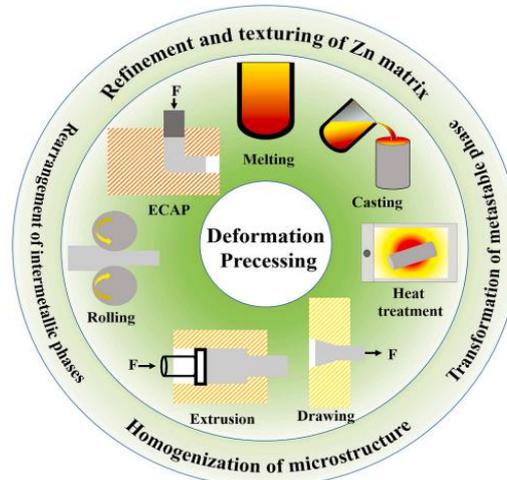
Casting, Conventional wrought methods, traditional powder metallurgy (PM) are the production methods used to create Zn-based alloys.

4.1. Casting

Casting is the conventional manufacturing process of Zn alloys because it makes easy customization of the alloy composition. Zinc alloys were produced by melting metal zinc with addition elements. After that pouring liquid alloys into the mold cavity (like steel or graphite) then allow them to solidify (Kabir et al., 2021). Following casting heat treatments including homogenization, annealing, and quenching may be used to get rid defects such as shrinkages, cracks and residual stresses (Chen et al., 2024). More over plastic deformation processes such as drawing, extrusion, forging and rolling also can be used after heat treatments. To prevent oxidation reactions and to limit porosity a controlled atmosphere must be maintained during the casting process, gas dissolution must also be controlled. Three subgroups of the casting process can be distinguished: sand casting, gravity casting, and squeeze casting (also known as die casting). The most popular method of processing used to create zinc alloys is squeeze casting. Melted metal is pushed under high pressure into the mold cavity during this

process (Ghomashchi & Vikhrov, 2000). The process of gravity casting entails pouring molten metal straight into the mold from the crucible (Kurnaz, 2005). Sand casting is a process that uses disposable sand molds to make intricately shaped metal pieces.

Fig. 3. The manufacturing method of Zn alloys by casting process (Chen et al., 2024).



Mostaed E. et. al., (2016) Four new Zn-Mg and two Zn-Al binary alloys are examined in this study as potentially useful biodegradable substances for implant usage. The alloys were made using the process of casting, the homogenization process and hot extrusion processes, which were followed by 48 hours of heating to 350°C. The extruded alloys showed a slower rate of degradation and slightly perfect corrosion resistance compared to the casting alloys, However, all corrosion rates were around half that of a normal purity magnesium control. Zn-0.5Mg is the most promising material for stent uses because it possesses a good combination of ductility, strength, strain hardening exponent, and a suitable rate of mechanical integrity lost through deterioration. Finally this research indicates that Zn alloys may be suitable for stent usage (Mostaed et al., 2016).

4.2. Conventional wrought methods

Wrought techniques in metal working are methods that employ mechanical force to plastically bend metal into the required shape. The word wrought meaning to worked that refers to mechanical nature of the technique. Wrought techniques can be carried out by using either hot or cold working, depending on how the working temperature and recrystallization temperature of the metal interact with one another. Hot working occurs when the metal is plastically molded above its recrystallization temperature. Other than that, it's cold working. The most often used wrought processes are drawing, rolling, forging, and extrusion (J. Niu et al., 2016; Shen et al., 2016; Tang et al., 2017; Mostaed et al., 2016) . Hot rolling is the main technique used in the majority of research on biodegradable zinc to produce a flat profile. To minimize thickness, a heated metal stock is passed through two rolls during the hot rolling process. To achieve a

homogeneous composition in the pre-formed Zn, the metal is typically heated at 250-350°C for 30-180 minutes before rolling process. The thickness of the rolled product might vary from a few millimeters to around 300 μm . Drawing or extrusion can be used to create the long, cylindrical profile that is characteristic of a tube (Liu et al., 2015; C. Wang et al., 2016). Extrusion is the process of pushing the metal through a die having a specific form opening. Extrusion can be either direct or indirect.

Wang Ch. et. al., (2015) The purpose of this research was to create a new method for producing zinc alloy micro-tube that function well for use in biodegradable vascular stent application. Where the new Zn-0.05Mg-0.01Fe (wt%) alloy micro-tubes were manufactured in suggestion a processing procedure by combining drilling, cold rolling, and optimal drawing. With their dimension errors are approximately 10 μm , this process was used to produce a micro-tube with an outer diameter of 2.5 mm and a thickness of 130 μm . The ultimate tensile strength and ductility of the micro-tube are greater than 220 MPa and 20% respectively, and it has a fine and homogenous microstructure. Moreover, Zn alloy micro-tube and stents perform excellent in vitro when it relates to corrosion and expansion. It might be feasible to arrive at the conclusion that the new Zn alloy micro-tube produced by the method mentioned above could make an excellent biodegradable stent candidate (C. Wang et al., 2016).

4.3. Powder metallurgy

Powder metallurgy (PM) is a method that can be used to process of metal powders, with the easy achievement of superior surface polish (Radhi et al., 2024). Additionally, metal powders need to be handled and treated in an inert atmosphere due to their susceptibility to oxidation during manufacturing. It necessitates refining the metal particles and handling them inertly. This method of processing usually includes three phases (i) Metal powders are combined or milled using an operations controlling agents at different speeds and times. (ii) Compressing metal particles with green compaction technique. (iii) sintering to create solid materials that are either completely dense or semi-dense (Kryst et al., n.d.)(Akhtar et al., 2018). The metal powders are sintered at a temperature that is (0.6–0.8) times their melting temperature in a regulated setting. It is also possible to fabricate biodegradable Zn-based alloys using this method (Guleryuz et al., 2017). Mg-5wt.%Zn alloys were chosen by Yan Y. et. al., (2021) In the present investigation, Mg-5wt.%Zn alloys were fabricated by powder metallurgy and used a study. They were influenced by the usage of hot extrusion and aging processes to create microstructures with various properties. Through in vitro degradation, cytocompatibility and electrochemical corrosion were used to examine their self-forming corrosion result layer in Ringer's solution, biodegradable behavior, and corrosion process in detail. After 96 hours of

aging, the extruded Mg-5wt.%Zn alloy exhibited superior corrosion resistance, excellent biocompatibility for L929, and great sample integrity during immersion. The alloy's fine-grain microstructure and consistent distribution of nano-sized second phases led to production of a homogeneous and smooth corrosion layer at the beginning of immersion. These features helped to facilitate the production of a smooth and uniform corrosion product layer at the start of immersion. In chloride-containing aqueous solutions, the corrosion product layer was more stable and easily created and repaired, protecting the matrix from additional corrosion (Hou et al., 2019).

4.4. Spark plasma sintering technique

Spark plasma sintering (SPS), often called pulsed electric current sintering (PECS), is a relatively new sintering process. This new technology usage for fabricating materials that use direct electrical current (DEC) to consolidate powders quickly in a very short period and at high sintering pressures (Sharma et al., 2019). Because of the impacts of PEC and spark plasma, the technique (SPS) successfully applies extreme pressure while rapidly heating and cooling the powder sample in a single step that comprises compaction and sintering. Čapek J.et. al., (2017) This work used spark plasma sintering to manufacture porous zinc for implantation into trabecular bone. The materials were characterized for their microstructure, mechanical properties, and corrosion resistance. The prepared porous samples have a porosity of roughly 20%. The mechanical characteristics were based on pore size, initial powder particle size and distribution. In porous Zn, corrosion rates varied from (0.6 - 0.8) mm/a according to the distribution, pore size, and starting size of the powder particles. After the porous Zn had been pre-incubated in simulated bodily fluid, biological extracts were obtained that had Zn concentrations lower than the dangerous threshold for L929 cells. The results of the study show that porous biodegradable orthopedic implants may be created with materials manufactured from finer zinc powder (Lipov & Lipov, 2017).

5. MODIFICATION STRATEGIES SURFACE

This process enhance the biocompatibility and degradation behavior of Zn alloys by creating a layer or many layers that differ from the matrix zinc in terms of chemical composition, microstructure, and other characteristics. There are two types of surface modification ,first type involves modify the material's surface properties by changing structural and chemical composition in a close proximity to the surface and second type involves adding a coating of substance to the raw material's surface to change its properties (Chen et al., 2024; Fahad et al., 2023; Hussein et al., 2024). Surface modification techniques include plasma electrolytic, anodic oxidation, chemical deposition and magnetron sputtering:

5.1 Plasma electrolytic (PEO) or micro-arc oxidation(MAO) are a quickly surface treatment method can provide bioactive coatings on the metallic surface (Du et al., 2019)(B. Niu et al., 2016). PEO method created at high voltage and are made up of species that come from the substrate and electrolyte in amounts determined by the discharge state. The PEO coating's surface contains a lot of micropores, which encourages the formation of bone tissue (Kim et al., 2019).

Sheng Y. et. al., (2019) during this work can be prepared effectively the Zn-1Mg alloy by a porous ceramic coating by using a plasma electrolytic oxidation (PEO). Evaluations were conducted to determine how the PEO coating affected on the corrosion resistance the Zn-1Mg alloy and in vitro cyto-compatibility. By extending the oxidation duration from 30 to 120 seconds, it was shown that the PEO coatings' thickness could be changed from 6.7 ± 0.5 microns to 28.6 ± 2 microns. The surface of ZnO and Zn_2SiO_4 became hydrophobic and rougher with longer oxidation times. The protective oxide layer improved the corrosion resistance for the Zn-1Mg alloy. The Zn-1Mg coated with PEO showed improved cyto- and blood-compatibility. The little amounts of Si^{2+} and Mg^{2+} released during early of the degradation of the PEO coating are primarily responsible for the improved cyto-biocompatibility (Sheng et al., 2019).

5.2 Anodic oxidation is an electrolytic method using metal or alloy components as the anode to create an oxide coating on their surface. Anodizing does not require high voltage discharge, in contrast to PEO.

Gilani Sh. et. al. (2016) In this study, an anodizing of zinc foil NaOH and oxalic acid electrolytes were examined under the influence of varying electrolyte concentrations, maintaining constant voltage and temperature. X-ray diffraction (XRD) analysis, UV–V is diffuse reflectance spectroscopy (DRS UV–V) and Scanning electron microscopy (SEM) were used for assessing anodized zinc plates. SEM analysis of anodized zinc plates demonstrated that the kind and concentration of anodizing electrolyte had a major impact on the morphology of the plates. The ZnO thin films had hexagonal wurtzite structures, as demonstrated by XRD tests. Measurements of contact angle has indicated that the anodized film has a higher contact angle than pure zinc foil. Based on the antibacterial studies, the parent zinc foil did not exhibit any antibiotic action, however anodized zinc oxide is efficient against both Gram-positive and Gram-negative bacteria (Gilani et al., 2016).

5.3 Chemical deposition is a practical successful and economical technique for creating a bioactive layer on metallic biomaterials.

Zhu M. et. al., (2019) To enhance the pure zinc corrosion rate and cytocompatibility, a magnesium-based coating was created on pure zinc in this study by using the simple chemical

deposition for the first time. By using the SEM and XPS, the coating microstructure and the composition were investigated respectively. The immersion and electrochemical tests were used for examining the corrosion behavior. The substrate was covered in crystal particles, as the SEM indicated. The readings of the pH and electrochemical test indicated that the magnesium-based coating can be lower the rate of corrosion of pure zinc. An in vitro cell adhesion test showed that the magnesium-based coating greatly improve the BMSC cells that adhered to the samples surface. It was demonstrated that the coating made of magnesium was thought to be a good option for coating the medical implants (M. Zhu et al., 2019).

5.4 Magnetron sputtering is a kind of physical vapor deposition (PVD) that has main advantages such as powerful adhesion, wide coating area, flexible control, and inexpensive equipment.

Peng F. et. al., (2021) In the present study, magnetron sputtering is utilized to deposit diamond-like carbon (DLC) coats on zinc (Zn). Zn's hydrophobic characteristics are changed by the DLC films at a contact angle of roughly 90°, but the surface shape of zinc remains unchanged. Examining the DLC-coated Zn in vitro immersion and electrochemically revealed an unexpected decrease in corrosion resistances. This could be because of galvanic corrosion between the Zn substrate and DLC coating. Moreover, the coated and uncoated zinc samples exhibit hemolysis ratios that are less than 1%. Since the cells cultivated in the zinc extract have more vitality than those produced in the extract of the zinc coated with DLC, it is evident that the DLC films decrease the cytocompatibility of zinc. The hemolysis ratio is not significantly affected by the reduced corrosion resistance, indicating that hemolysis is not a hindrance to the development of biological materials based on zinc. The findings show that the conventional preventative method with DLC-coated films may not be effective everywhere and that DLC-coated zinc actually has more little corrosion resistance and cytocompatibility (Peng et al., 2021).

6. CONCLUSIONS AND RECOMMENDED

Biodegradable material implants are increasingly important for reducing the need for painful, secondary surgeries required to remove or replace implants. Zinc-based biomaterials (BMs), in particular, offer an ideal degradation rate compared to magnesium- and iron-based alternatives, making them promising candidates for applications like biodegradable cardiovascular stents. However, improving the mechanical properties of zinc remains a key challenge. This review explores primary methods to enhance zinc's characteristics, specifically alloying and surface modification. Alloying is widely regarded as an effective and straightforward approach for

enhancing mechanical strength, while surface modification is crucial for improving biocompatibility, corrosion resistance, and biological activity of zinc alloys.

Recent research has focused on manufacturing techniques, degradation processes, and composition design to enhance the mechanical properties, biocompatibility, and degradation rate of zinc alloys. Moving forward, studies should aim to further improve zinc alloys' mechanical integrity, degradation performance, and biocompatibility. Important research avenues include establishing a comprehensive database for zinc alloy compositions and manufacturing processes, which would assist in the design and development of optimized zinc alloys. Additionally, structural design considerations are essential for implant functionality, particularly for vascular stents, where finite element analysis can address stress concentrations during expansion, mitigating accelerated localized degradation.

Finally, the long-term mechanical stability of biodegradable zinc stents remains a critical factor. Future research should focus on maintaining mechanical integrity during degradation and investigate stress corrosion cracking and fatigue performance. Addressing these factors will be essential for advancing zinc-based biomaterials as reliable, biodegradable options for medical implants.

7. REFERENCES

- Akhtar, S., Saad, M., Rasikh, M., & Chandra, M. (2018). ScienceDirect Recent Advancements in Powder Metallurgy: A Review. *Materials Today: Proceedings*, 5(9), 18649–18655. <https://doi.org/10.1016/j.matpr.2018.06.210>
- Al-Khafaji, Z., Kazem, M. A., Radhi, N. S., Falah, M., & Hadi, Z. M. (2024). Reducing the Issues of Implements in the Human Body by Applying HAp: Review. *Material and Mechanical Engineering Technology*, 64(2). <https://doi.org/10.52209/2706-977X>
- Bagha, P. S., Khaleghpanah, S., Sheibani, S., Khakbiz, M., & Zakeri, A. (2017). *AC SC. Journal of Alloys and Compounds*. <https://doi.org/10.1016/j.jallcom.2017.11.155>
- Bowen, P. K., Gelbaugh, J. A., Mercier, P. J., Goldman, J., & Drelich, J. (2012). Tensile testing as a novel method for quantitatively evaluating bioabsorbable material degradation. 1–13. <https://doi.org/10.1002/jbm.b.32775>
- Bowen, P. K., Guillory, R. J., Shearier, E. R., Seitz, J. M., Drelich, J., Bocks, M., Zhao, F., & Goldman, J. (2015). Metallic zinc exhibits optimal biocompatibility for bioabsorbable endovascular stents. *Materials Science and Engineering C*, 56, 467–472. <https://doi.org/10.1016/j.msec.2015.07.022>

- Chen, S., Du, T., Zhang, H., Qi, J., Zhang, Y., Mu, Y., & Qiao, A. (2024). Biomaterials Advances Methods for improving the properties of zinc for the application of biodegradable vascular stents. *Biomaterials Advances*, 156(November 2023), 213693. <https://doi.org/10.1016/j.bioadv.2023.213693>
- Dambatta, M. S., Izman, S., Kurniawan, D., Farahany, S., Yahaya, B., & Hermawan, H. (2015). Influence of thermal treatment on microstructure, mechanical and degradation properties of Zn – 3Mg alloy as potential biodegradable implant material. *JMADE*, 85, 431–437. <https://doi.org/10.1016/j.matdes.2015.06.181>
- Dargusch, M. S. (2019). The Influence of Alloying and Fabrication Techniques on the Mechanical Properties, Biodegradability and Biocompatibility of Zinc: A Comprehensive Review Statement of Significance: *Acta Biomaterialia*. <https://doi.org/10.1016/j.actbio.2019.01.035>
- Du, Q., Wei, D., Wang, S., Cheng, S., Wang, Y., & Li, B. (2019). Applied Surface Science Rapidly formation of the highly bioactive surface with hydroxyapatite crystals on the titania micro arc oxidation coating by microwave hydrothermal treatment. *Applied Surface Science*, 487(April), 708–718. <https://doi.org/10.1016/j.apsusc.2019.05.165>
- Fahad, N. D., Radhi, N. S., Al-Khafaji, Z. S., & Diwan, A. A. (2023). Surface modification of hybrid composite multilayers spin cold spraying for biomedical duplex stainless steel. *Heliyon*. <https://doi.org/10.1016/j.heliyon.2023.e14103>
- Ghani Fahmi, M. W., Trinanda, A. F., Pratiwi, R. Y., Astutiningtyas, S., & Zakiyuddin, A. (2020). The Effect of Zr Addition on Microstructures and Hardness Properties of Zn-Zr Alloys for Biodegradable Orthopaedic Implant Applications. *IOP Conference Series: Materials Science and Engineering*, 833(1). <https://doi.org/10.1088/1757-899X/833/1/012065>
- Ghomashchi, M. R., & Vikhrov, A. (2000). Squeeze casting: an overview. 101(May 1998), 1–9.
- Gilani, S., Ghorbanpour, M., & Parchehbaf, A. (2016). Antibacterial activity of ZnO films prepared by anodizing. *Journal of Nanostructure in Chemistry*, 6(2), 183–189. <https://doi.org/10.1007/s40097-016-0194-1>
- Gong, H., Wang, K., Strich, R., & Zhou, J. G. (2015). In vitro biodegradation behavior, mechanical properties, and cytotoxicity of biodegradable Zn – Mg alloy. 1632–1640. <https://doi.org/10.1002/jbm.b.33341>

- Gu, X., Zheng, Y., Cheng, Y., Zhong, S., & Xi, T. (2009). Biomaterials In vitro corrosion and biocompatibility of binary magnesium alloys. *Biomaterials*, 30(4), 484–498. <https://doi.org/10.1016/j.biomaterials.2008.10.021>
- Guleryuz, L. F., Ipek, R., Aritman, I., & Karaoglu, S. (2017). Microstructure and Mechanical Properties of Zn-Mg Alloys as Implant Materials Manufactured by Powder Metallurgy Method. 020020. <https://doi.org/10.1063/1.4975435>
- Haleem, A. H., Radhi, N. S., Jaber, N. T., & Al-Khafaji, Z. (2024). Preparation and Exploration of Nano-Multi-Layers on 316l Stainless Steel for Surgical Tools. *Jordan Journal of Mechanical and Industrial Engineering (JJMIE)*, 18(2), 339–350.
- Hou, W., Lu, S., Liu, G., Li, M., & Ma, J. (2019). Long-term in vivo study of biodegradable Zn-Cu stent: A 2-year implantation evaluation in porcine coronary artery. *Acta Biomaterialia*. <https://doi.org/10.1016/j.actbio.2019.08.012>
- Hussein, E. Y., Al-murshdy, J. M. S., Radhi, N. S., & Al-khafaji, Z. (2024). Surface Modification of Titanium Alloy by Titania / Silver Multilayers Coating for Biomedical Application. 1(1), 66–79.
- Jia, B., Zhang, Z., Qu, X., & Lin, W. (2020). Alloying design of biodegradable zinc as promising bone implants for load-bearing applications. *Nature Communications*, 1–16. <https://doi.org/10.1038/s41467-019-14153-7>
- Kabir, H., Munir, K., Wen, C., & Li, Y. (2021). Bioactive Materials Recent research and progress of biodegradable zinc alloys and composites for biomedical applications : Biomechanical and biocorrosion perspectives. *Bioactive Materials*, 6(3), 836–879. <https://doi.org/10.1016/j.bioactmat.2020.09.013>
- Kim, Y., Jang, Y., Kim, S., & Lee, M. (2019). Applied Surface Science Functions achieved by the hyaluronic acid derivatives coating and hydroxide film on bio-absorbed Mg. *Applied Surface Science*, 473(December 2018), 31–39. <https://doi.org/10.1016/j.apsusc.2018.12.139>
- Kryst, M., Doležal, P., & Fintov, S. (n.d.). Preparation and Characterization of Zinc Materials Prepared by Powder Metallurgy. <https://doi.org/10.3390/met7100396>
- Kubásek, J., Šerák, J., Novák, P., & Vojte, D. (2011). *Acta Biomaterialia* Mechanical and corrosion properties of newly developed biodegradable Zn-based alloys for bone fixation. 7, 3515–3522. <https://doi.org/10.1016/j.actbio.2011.05.008>

- Kurnaz, S. C. (2005). Materials & Design Hot tensile and fatigue behaviour of zinc – aluminum alloys produced by gravity and squeeze casting. 26, 479–485. <https://doi.org/10.1016/j.matdes.2004.07.023>
- Li, G., Yang, H., Zheng, Y., Chen, X. H., Yang, J. A., Zhu, D., Ruan, L., & Takashima, K. (2019). Challenges in the use of zinc and its alloys as biodegradable metals: Perspective from biomechanical compatibility. *Acta Biomaterialia*, 97(5), 23–45. <https://doi.org/10.1016/j.actbio.2019.07.038>
- Li, H., Yang, H., Zheng, Y., Zhou, F., Qiu, K., & Wang, X. (2015). Materials & Design Design and characterizations of novel biodegradable ternary Zn-based alloys with IIA nutrient alloying elements Mg , Ca and Sr. *JOURNAL OF MATERIALS&DESIGN*, 83, 95–102. <https://doi.org/10.1016/j.matdes.2015.05.089>
- Li, P., Dai, J., Li, Y., Alexander, D., Capek, J., Wan, G., Han, J., Yu, Z., & Li, A. (2024). Materials Today Bio Zinc based biodegradable metals for bone repair and regeneration : Bioactivity and molecular mechanisms. 25(December 2023). <https://doi.org/10.1016/j.mtbio.2023.100932>
- Li, P., Schille, C., Schweizer, E., Rupp, F., Heiss, A., Legner, C., Klotz, U. E., Gerstorfer, J. G., & Scheideler, L. (2018). Mechanical characteristics, in vitro degradation, cytotoxicity, and antibacterial evaluation of Zn-4.0Ag alloy as a biodegradable material. *International Journal of Molecular Sciences*, 19(3). <https://doi.org/10.3390/ijms19030755>
- Lipov, J., & Lipov, J. (2017). Accepted Manuscript. <https://doi.org/10.1016/j.matchemphys.2017.10.008>
- Liu, X., Sun, J., Yang, Y., & Zheng, Y. (2015). Author ' s Accepted Manuscript Reference : To appear in : Materials Letters. *Materials Letters*. <https://doi.org/10.1016/j.matlet.2015.06.107>
- Mollaei, N., Razavi, S. H., Aboutalebi, M. R., & Fatemi, S. M. (2022). Effect of Mn addition on the microstructure , mechanical , and corrosion properties of an extruded biodegradable Zn-0 . 2Mg alloy. *Journal of Materials Research and Technology*, 22, 1983–1998. <https://doi.org/10.1016/j.jmrt.2022.12.049>
- Mostaed, E., Sikora-jasinska, M., Mostaed, A., Loffredo, S., & Demir, A. G. (2016). Novel Zn-based alloys for biodegradable stent applications : Design , development and in vitro degradation. *Journal of the Mechanical Behavior of Biomedical Materials*, 60, 581–602. <https://doi.org/10.1016/j.jmbbm.2016.03.018>

- Niu, B., Shi, P., Wei, D., Li, Q., & Chen, Y. (2016). Surface & Coatings Technology Preparation and characterization of HA sol – gel coating on MAO coated AZ31 alloy. 286, 42–48. <https://doi.org/10.1016/j.surfcoat.2015.11.056>
- Niu, J., Tang, Z., Huang, H., Pei, J., Zhang, H., Yuan, G., & Ding, W. (2016). Research on a Zn-Cu alloy as a biodegradable material for potential vascular stents application. *Materials Science & Engineering C*, 69, 407–413. <https://doi.org/10.1016/j.msec.2016.06.082>
- Pachla, W., Przybysz, S., Jarz, A., Bieda, M., Sztwiertnia, K., Kulczyk, M., & Skiba, J. (2021). Bioactive Materials Structural and mechanical aspects of hypoeutectic Zn – Mg binary alloys for biodegradable vascular stent applications. 6(May 2020), 26–44. <https://doi.org/10.1016/j.bioactmat.2020.07.004>
- Peng, F., Lin, Y., Zhang, D., Ruan, Q., Tang, K., Li, M., Liu, X., Chu, P. K., & Zhang, Y. (2021). Corrosion Behavior and Biocompatibility of Diamond-like Carbon- Coated Zinc : An In Vitro Study. <https://doi.org/10.1021/acsomega.1c00531>
- Radhi, N. S., Jamal Al-deen, H. H., Safaa Hadi, R., Al-Ghaban, nada, & Al-Khafaji, Z. S. (2023). Preparation And Investigation A Hydroxyapatite Layer Coating On Titanium Substrate For Surgical Implants. *Journal of Nanostructures*. https://jns.kashanu.ac.ir/article_113861.html
- Radhi, N. S., Kareem, N. E., Al-Khafaji, Z. S., Sahig, N. M., & Falah, M. W. (2022). Investigation Biological and Mechanical Characteristics of Hybrid PMMA Composite Materials as Prosthesis Complete Denture.
- Radhi, N. S., Nattah, A. M., & Al-Khafaji, Z. S. (2024). Identify the effect of Fe₂O₃ nanoparticles on mechanical and microstructural characteristics of aluminum matrix composite produced by powder metallurgy technique. *Open Engineering*, 14(1), 20220519.
- Radhi, N. S., Sahi, N. M., & Al-Khafaji, Z. (2022). Investigation Mechanical and Biological Properties of Hybrid PMMA Composite Materials as Prosthesis Complete Denture. *Egyptian Journal of Chemistry*. <https://doi.org/10.21608/EJCHEM.2022.110545.5034>
- Robson, J. D., Henry, D. T., & Davis, B. (2009). Particle effects on recrystallization in magnesium-manganese alloys: Particle-stimulated nucleation. *Acta Materialia*, 57(9), 2739–2747. <https://doi.org/10.1016/j.actamat.2009.02.032>
- Salih, E. M., Karim, H. J., Al-Sultani, K. F., & Al-Khafaji, Z. (2024). Effect of Ge on oxidation behavior of 60% Cu–40% Zn Muntz metal. *Engineering Review: Međunarodni Časopis Namijenjen Publiciranju Originalnih Istraživanja s Aspekta Analize Konstrukcija, Materijala i*

Novih Tehnologija u Području Strojarsva, Brodogradnje, Temeljnih Tehničkih Znanosti, Elektrotehnike, Računarstva i Građe, 44(1), 25–37.

Sharma, N., Alam, S. N., & Ray, B. C. (2019). Fundamentals of Spark Plasma Sintering (SPS): An Ideal Processing Technique for Fabrication of Metal Matrix Nanocomposites.

Shen, C., Liu, X., Fan, B., Lan, P., Zhou, F., & Li, X. (2016). RSC Advances Mechanical properties, in vitro degradation behavior, hemocompatibility and cytotoxicity. 86410–86419. <https://doi.org/10.1039/C6RA14300H>

Sheng, Y., Zhou, H., Li, Z., Chen, L., Wang, X., Zhao, X., & Li, W. (2019). PT US CR. Materialia, 100244. <https://doi.org/10.1016/j.mtla.2019.100244>

Shi, Y., Xue, Z., Li, P., Yang, S., Zhang, D., Zhou, S., Guan, Z., & Li, Y. (2023). Surface modification on biodegradable zinc alloys. *Journal of Materials Research and Technology*, 25, 3670–3687. <https://doi.org/10.1016/j.jmrt.2023.06.149>

Sun, S., Ren, Y., Wang, L., Yang, B., Li, H., & Qin, G. (2017). Abnormal effect of Mn addition on the mechanical properties of as-extruded Zn alloys. *Materials Science and Engineering: A*, 701, 129–133. <https://doi.org/10.1016/j.msea.2017.06.037>

Tang, Z., Niu, J., Huang, H., Zhang, H., Pei, J., Ou, J., & Yuan, G. (2017). Potential biodegradable Zn-Cu binary alloys developed for cardiovascular implant applications. *Journal of the Mechanical Behavior of Biomedical Materials*, 72(March), 182–191. <https://doi.org/10.1016/j.jmbbm.2017.05.013>

Tong, X., Zhang, D., Zhang, X., Su, Y., Shi, Z., Wang, K., Lin, J., Li, Y., Lin, J., & Wen, C. (2018). Microstructure, mechanical properties, biocompatibility, and in vitro corrosion and degradation behavior of a new Zn–5Ge alloy for biodegradable implant materials. *Acta Biomaterialia*, 82, 197–204. <https://doi.org/10.1016/j.actbio.2018.10.015>

Wang, C., Yu, Z., Cui, Y., Zhang, Y., Yu, S., Qu, G., & Gong, H. (2016). Processing of a Novel Zn Alloy Micro-tube for Biodegradable Vascular Stent Application. *Journal of Materials Science & Technology*. <https://doi.org/10.1016/j.jmst.2016.08.008>

Wang, L., He, Y., Zhao, H., Xie, H., Li, S., Ren, Y., & Qin, G. (2018). Effect of cumulative strain on the microstructural and mechanical properties of Zn-0.02wt.%Mg alloy wires during room-temperature drawing process. *Journal of Alloys and Compounds*. <https://doi.org/10.1016/j.jallcom.2018.01.059>

- Wątroba, M., Bednarczyk, W., Kawałko, J., Marciszko, M., Boelter, G., Banzhaf, M., & Bała, P. (2019). *Journal of Materials & Design*, 108154. <https://doi.org/10.1016/j.matdes.2019.108154>
- Xiang, E., Moran, C. S., & Ivanovski, S. (2023). Nanosurface Texturing for Enhancing the Antibacterial Effect of Biodegradable Metal Zinc : Surface Modifications.
- Xiao, C., Shi, X. Y., Yu, W. T., Wei, X. W., Cheng, L. L., Qiu, X., Li, B. R., Fan, D. C., Li, J. L., Zhang, X. Z., & Zhao, D. W. (2021). Materials Science & Engineering C in New Zealand rabbits. *Materials Science & Engineering C*, 119(March 2020), 111435. <https://doi.org/10.1016/j.msec.2020.111435>
- Yang, Y., Yang, M., He, C., Qi, F., Wang, D., Peng, S., & Shuai, C. (2021). Rare earth improves strength and creep resistance of additively manufactured Zn implants. *Composites Part B*, 216(February), 108882. <https://doi.org/10.1016/j.compositesb.2021.108882>
- Zhao, S., McNamara, C. T., Bowen, P. K., Verhun, N., Braykovich, J. P., Goldman, J., & Drelich, J. W. (2017). Structural Characteristics and In Vitro Biodegradation of a Novel Zn-Li Alloy Prepared by Induction Melting and Hot Rolling. *Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science*, 48(3), 1204–1215. <https://doi.org/10.1007/s11661-016-3901-0>
- Zheng, Y. F., Gu, X. N., & Witte, F. (2014). Biodegradable metals. 77, 1–34. <https://doi.org/10.1016/j.mser.2014.01.001>
- Zhu, D., Cockerill, I., Su, Y., Zhang, Z., Fu, J., Lee, K., Ma, J., Okpokwasili, C., Tang, L., Zheng, Y., Qin, Y., & Wang, Y. (2019). Biological and Medical Applications of Materials and Interfaces Mechanical Strength , Biodegradation , and In Vitro and In Vivo Biocompatibility of Zn Biomaterials. <https://doi.org/10.1021/acsami.8b20634>
- Zhu, M., Lu, Y., Zhang, C., Li, L., Xie, M., & Tang, K. (2019). *PT NU SC. Surface & Coatings Technology*. <https://doi.org/10.1016/j.surfcoat.2019.05.034>.