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Optimizing Corrosion Resistance in Mg-Based Biomaterials Through Heat Treatment

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Abstract: Magnesium alloys have attracted increasing attention in recent years as promising bioresorbable materials for medical implants due to their excellent biocompatibility, mechanical properties comparable to bone tissue, and the ability to completely dissolve in the body. However, the high corrosion rate under physiological conditions limits their clinical application. One of the most effective ways to regulate the corrosion behavior of magnesium bioimplants is heat treatment, which allows modifying their microstructure, phase composition, and distribution of alloying elements. This review article analyzes the effect of various heat treatment modes - annealing, quenching, artificial and natural aging, as well as their combinations - on the corrosion resistance of magnesium bioimplants. The review covers alloys of the Mg–Ca, Mg–Zn, Mg–RE, and Mg–Sr systems, which are most commonly used in biomedicine. Data on changes in the microstructure, interphase boundaries, as well as the morphology and distribution of intermetallic phases responsible for localized corrosion are provided. Particular attention is paid to the relationship between structural changes after heat treatment and the degradation rate in a simulated bioenvironment. Modern methods for assessing corrosion resistance (electrochemical impedance spectroscopy, potentiodynamic polarization, weight loss method) are also considered and technological prospects for integrating heat treatment into the production of new-generation bioimplants are discussed. The article emphasizes the importance of an integrated approach to optimizing the properties of magnesium alloys through heat treatment to improve their clinical efficacy and safety.

1. Introduction

Magnesium alloys are considered to be some of the most promising materials for creating bioresorbable implants due to their ability to gradually dissolve in the body, reducing the need for repeated surgeries to remove the implant (Shalomeev *et al.,* 2024). At the same time, the density of magnesium (1.74 - 2 g/cm³) and elastic modulus (41–45 GPa) are close to human bone tissue, which reduces the risk of stress resorption (Tsakiris *et al.,* 2021). However, one of the key disadvantages of magnesium alloys remains their high corrosive activity under physiological conditions.

Corrosion of magnesium alloys in a biological environment is accompanied by the formation of hydrogen and an increase in pH, which can cause inflammatory reactions and uncontrolled degradation of the material (Raja *et al.,* 2025). The corrosion rate depends on many factors: alloy composition, the presence of interphase compounds, the density and morphology of the oxide film, as well as microstructural parameters (Amirmatova *et al.,* 2025), (Vashi, 2025) Corrosion of magnesium in a physiological environment is a complex electrochemical process involving an anodic reaction of magnesium dissolution and a cathodic reaction of water reduction with hydrogen evolution. As a result of these processes, magnesium hydroxide $Mg(OH)_2$ is formed on the surface, which temporarily passivates the metal. However, this passivation film is easily dissolved in the presence of chloride ions, typical of biological fluids such as blood plasma and physiological solutions. At the initial stages of degradation of magnesium implants, a porous oxide film is formed on their surface, which is unable to effectively prevent further dissolution of the material (Zerankeshi *et al.,* 2022). The corrosion rate under such conditions depends on many factors: the thickness and density of the protective film, its self-healing capacity, and the presence of microdefects and inhomogeneities on the surface. When the protective layer is destroyed, anodic and cathodic areas arise, which contributes to the development of local — pitting — corrosion, accelerating the degradation of the implant. Particularly dangerous in this regard are intermetallic phases such as Mg_2Ca, MgZn or $Mg_{17}Al_{12}$, which have a higher electrode potential than the main Mg matrix and therefore act as cathodic inclusions initiating galvanic corrosion (Fang *et al.,* 2011), (Atrens *et al.,* 2011). Thus, the morphology, distribution and chemical composition of these phases directly determine the localization and intensity of corrosion processes. To increase the durability of magnesium bioimplants, it is necessary not only to improve the composition of the alloys, but also to control their microstructure - primarily through optimal heat treatment, which allows minimizing galvanic effects and improving the uniformity of corrosion.

Heat treatment is one of the key tools for controlling the microstructure of magnesium alloys. Controlled heating and cooling can achieve dissolution or redistribution of intermetallic phases, grain refinement, and reduction of residual stresses, which leads to improved corrosion resistance. The purpose of this article is to systematize scientific data on the effect of heat treatment on the corrosion resistance of biodegradable magnesium implants. Specific types of heat treatment, their effect on the structure and properties of alloys are discussed below, and comparative data on various alloying systems and experimental conditions are provided.

2. Magnesium alloys as bioresorbable implants.

Magnesium alloys are being actively investigated for use as vascular stents and orthopaedic implants, particularly when it is important to avoid subsequent surgical removal and minimise stress on surrounding bone. Magnesium is easily corroded under physiological conditions, allowing it to gradually dissolve, freeing up space for new tissue growth and sparing the patient from repeated surgery to remove the implant. Below we briefly review a number of magnesium alloys that are used or considered as biomaterials.

AZ31, AZ91 and AE21 alloys (magnesium with aluminum and zinc) are used as biomaterials in orthopaedic implants due to their improved mechanical properties, such as strength and ductility. They are used in particular in struts, fixation plates and screws in the treatment of fractures, where it is important to ensure sufficient rigidity, but at the same time to avoid stress shimming (easy bone failure due to high stiffness). This is facilitated by an elastic modulus close to that of bone. However, the presence of aluminum raises concerns about neurotoxicity and a possible link to the development of Alzheimer's disease, which limits their use, especially in pediatric and maxillofacial surgery. Failures can occur due to rapid corrosion degradation before bone regeneration is complete and the formation of gas cavities due to hydrogen evolution. These aspects are discussed in detail in a 2024 Applied Sciences review (Karki *et al.,* 2025), (Thomas *et al.,* 2024).

Mg–Ca promotes osteogenesis and bioactivity, Mg–Zn improves both corrosion and mechanical resistance, and the addition of Sr stimulates bone formation. Rare earth components can provide melt stability and strength, but their biocompatibility requires careful evaluation. These alloys are being developed to improve biocompatibility and control corrosion rates. In particular, Mg–Ca promotes osteogenesis and bioactivity, Mg–Zn improves mechanical stability and slows down corrosion, and the addition of strontium (Sr) stimulates bone tissue regeneration. Rare earth elements (RE) improve strength and microstructure stability, but require safety assessment and potential for long-term toxicity. These materials have been used in porous bone implants and scaffolds created using additive technologies to improve integration with bone tissue (Zhang *et al.,* 2022). An innovative solution is amorphous (non-crystalline) alloys based on Mg, Zn and Ca — the so-called bioabsorbable metallic glass. These materials are highly durable, ductile and disintegrate in the body without toxic products, being replaced by bone tissue. However, their corrosion resistance leaves much to be desired — under some conditions, such an alloy disintegrates in just a few hours.

Mg-2.2%Nd-0.1%Zn-0.4%Zr (JDBM-2) alloy exhibits strength properties close to medical stainless steel with controlled degradation. It has been tested as vascular stents, showing excellent compatibility with endothelial cells (HUVEC), promoting rapid endothelial recovery, and maintaining mechanical integrity for up to six months in vivo. Such material can be used in biodegradable coronary stents, eliminating the need for removal (Mao *et al.,* 2017). There are commercially approved biodegradable magnesium stents, such as Magmaris (DREAMS 2G) from BIOTRONIK. The base material, AE21, containing 2% aluminium and 1% rare earth elements, has demonstrated safety and efficacy in clinical trials. Initial installations showed satisfactory restoration of blood flow and a low complication rate. The stent gradually dissolves, reducing the risk of thrombosis and chronic inflammation typical of permanent metal structures. (Lui *et al.,* 2024).

MAGNEZIX® implants (based on magnesium alloys) are used in pediatrics for fracture stabilization, osteotomies and fixation of osteochondral defects. The study included 89 patients (children and adolescents), the observation lasted from 1.5 to 30 months, and showed good clinical effectiveness, rapid bone healing and almost complete resorption of the implant without the need for repeated surgical interventions (Unal *et al.,* 2022).

Using ultrapure magnesium or commercially pure Mg reduces the risk of corrosion caused by impurities (iron, copper, etc.) and eliminates galvanic acceleration of failure. For example, adding zinc (up to 1%) to plain Mg–Zn wires and coating with polymers has shown promise in terms of osteogenesis and mechanical performance in animal models.

Heat treatment (annealing, quenching) can significantly increase corrosion resistance: for high-purity Mg — twice, and for AZ31 — ten times. This effect is associated with the elimination of residual stresses and a more uniform distribution of secondary phases, which in the initial state often serve as catalysts for local corrosion. Additionally, annealing for a number of alloys promotes grain coarsening and a decrease in the number of galvanic microcouples, which has a positive effect on the durability of the implant. It is also important that controlled heat treatment allows you to adjust the balance between strength and biodegradation rate, which is critical for clinical use. These features make thermal modification one of the most promising and accessible ways to improve the performance properties of magnesium implant materials.

3. Types of heat treatment of magnesium alloys and their effect on the microstructure

Heat treatment of magnesium alloys is used to control the phase composition, grain size, distribution and morphology of intermetallic compounds, which together affect their corrosion resistance (Bakhsheshi-Rad *et al.,* 2016). The main types of heat treatment include: annealing, quenching, aging (natural and artificial), homogenization and their combinations. Annealing. Annealing helps to reduce residual stresses, increase ductility and coarsen grains (Liu *et al.,* 2016). Hot rolling of the Mg–Zn–Ca–Mn alloy at 400 °C followed by annealing played a key role in achieving full recrystallization and significantly improving corrosion resistance, reducing the corrosion rate in Hank's solution from 0.54 to 0.19 mm/year. The annealing process was critical in refining the microstructure and enhancing the overall stability of the material in a physiological environment (Rogachev *et al.,* 2024).

Quenching. Quenching is rapid cooling after heating to a temperature above the solidus line. In this case, the intermetallic phases do not have time to separate, creating a supersaturated solid solution. Such a structure is unstable, but allows subsequent aging (Hornberger *et al.,* 2012). Rapid quenching in the production of Mg-based bulk metallic glasses (BMGs) prevents atomic diffusion, preserving a disordered, glassy structure. However, cooling rate and partial crystallization significantly influence their microstructure and corrosion behavior. To improve structural stability and reduce degradation, researchers have developed core-shell structures with a crystalline core and amorphous shell, which maintain their integrity over time. This approach offers a promising solution for enhancing the performance of Mg-based BMGs in biomedical applications (Bin *et al*., 2022).

Artificial aging. After quenching, holding at 150–200 °C is used, causing a controlled precipitation of strengthening phases. In Mg–Zn alloys, the aging process leads to the formation of dispersed $MgZn_2$ particles uniformly distributed in the matrix, which can improve corrosion homogeneity, but in some cases worsens resistance due to the appearance of cathode areas (Han *et al.,* 2020).

Natural aging. Occurs at room temperature for several days or weeks. The effects are less pronounced than with artificial aging and depend on the alloy composition and storage conditions (Yu *et al.,* 2013).

Homogenization. Used after casting of ingots to equalize the chemical composition. For example, homogenization of Mg–RE alloys at 500–550 °C promotes the dissolution of inhomogeneities and a decrease in the activity of corrosion galvanic pairs (Sun *et al.,* 2022).

Combined modes. The most effective modes are those that combine quenching and aging, allowing a compromise to be reached between mechanical properties and corrosion resistance. Thus, for Mg–Zn–Ca alloys, a combination of quenching followed by aging at 200 °C for 6 hours increases corrosion resistance by almost 40% (Zerankeshi *et al.,* 2022).

Thus, the choice of heat treatment mode should take into account not only the desired microstructure, but also the features of corrosion behavior in a specific biological environment. The next section will be devoted to a comparative analysis of the corrosion resistance of magnesium alloys of different systems after heat treatment.

4. Mechanisms of the influence of heat treatment on corrosion resistance

Heat treatment has a complex effect on the microstructure of magnesium alloys, which directly affects their corrosion characteristics. The main mechanisms of action can be divided into several key areas.

1. Grain refinement and reduction of galvanic activity. Grain refinement and reduction of galvanic activity Quenching and aging processes contribute to the redistribution of phases and grain refinement. A fine-grained structure ensures a more uniform distribution of anodic and cathodic areas, reducing galvanic activity and, as a consequence, the rate of localized corrosion (Obayi *et al.,* 2016). A number of studies show that a decrease in the average grain size from 30 µm to 10 µm leads to a decrease in the corrosion rate by 25–35% in physiological solutions (Ye *et al.,* 2021), (Dobkowska *et al.,* 2021).

2. Dissolution of intermetallic phases. Intermetallic compounds such as Mg_2Ca or $Mg_{12}Nd$ often act as cathodic sites with respect to the α-Mg matrix, accelerating corrosion (Ikeuba *et al.,* 2024). Heat treatment under properly selected conditions promotes partial dissolution of these phases, reducing galvanic differences and slowing down the degradation process (Hort *et al.,* 2006). For example, heat treatment of Mg–Nd alloys at 400 °C for 12 hours reduces the content of intermetallic phases by 30%, which leads to an increase in corrosion resistance (Zerankeshi *et al.,* 2022).

3. Formation of stable oxide films. Aging and annealing processes can contribute to improving the characteristics of passivating oxide layers. Denser and more homogeneous oxide films protect the magnesium matrix from the aggressive effects of the physiological environment (Kirkland *et al.,* 2012). Experiments with Mg–Zn–Ca alloys show that after artificial aging, the thickness of the oxide film increases and a decrease in the dissolution rate in artificial plasma by 20% is observed (Yang *et al.,* 2023).

4. Minimization of residual stresses. Residual stresses arising during casting and mechanical processing contribute to localized corrosion. Heat treatment, especially annealing, allows for stress relaxation, which has a positive effect on the uniformity of degradation. Data show that the use of high-temperature annealing (350–400 °C) reduces residual stresses by 60–70%, reducing the likelihood of cracking and catastrophic failure (Vakili *et al.,* 2024).

5. Corrosion behavior of heat-treated alloys of binary magnesium alloy

Mg–Ca system. Mg–Ca alloys are among the most studied biodegradable systems due to the high biocompatibility of calcium. However, the presence of intermetallic phases of the Mg_2Ca type promotes localized corrosion along grain boundaries. Annealing of Mg–Ca alloys at 350–400 °C for 2–6 hours leads to the dissolution or redistribution of Mg_2Ca phases, a decrease in interphase boundaries and an improvement in corrosion resistance. This occurs due to the fact that a decrease in the size and number of cathode fragments weakens localized corrosion and promotes the formation of a more uniform protective oxide film. After annealing, the corrosion rate in an SBF environment decreases by 20–30% (Sahu *et al.,* 2022), (Makkar *et al.,* 2018).

Mg–Zn system. Magnesium-zinc alloys exhibit higher corrosion resistance compared to pure magnesium due to the passivating effect of Zn and the formation of $MgZn_2$ phases. Artificial aging at 150–200 °C increases the dispersion of $MgZn_2$ phases, which reduces the corrosion rate. In a study, the degradation rate was reduced by 35% after optimized aging. Finely dispersed $MgZn_2$ particles slow down the propagation of microcracks and improve the barrier properties of the surface oxide film (Jiang *et al.,* 2020), (Romzi *et al.,* 2021).

Mg–RE systems. The addition of RE elements (yttrium, cerium, gadolinium) significantly improves corrosion resistance due to the formation of corrosion-resistant intermetallic phases such as $Mg_{12}RE$ and Mg_3RE. Annealing and subsequent aging (200–250 °C) promote uniform phase distribution, grain refinement and reduction of microgalvanic activity (Xu *et al.,* 2022). The corrosion rate of Mg–Gd alloys after heat treatment in SBF was reduced by almost half (Wang *et al.,* 2023). RE alloying suppresses the cathodic activity of the surface and promotes the formation of a dense protective oxide film rich in rare earth oxides. *Mg–Sr systems*. Strontium promotes increased biocompatibility and stimulates bone tissue growth, which makes Mg–Sr alloys interesting for biomedical applications (Zhao *et al.,* 2017). Heat treatment at 350 °C leads to redistribution of $Mg_{17}Sr_2$ intermetallic phases, an increase in grain size and a decrease in the localized corrosion rate. Phase modification helps to reduce micro-galvanic activity, and a homogeneous microstructure reduces the number of zones subject to pitting corrosion (Liu *et al.,* 2025). **Table 1** is provided for a visual representation of the effect of various heat treatment modes on the corrosion resistance of biodegradable magnesium alloys.

6. Effect of heat treatment on corrosion resistance of ternary magnesium alloys

Heat treatment is one of the key methods for modifying the structure and properties of magnesium alloys used in biomedical applications (**Table 2**). This is especially important in the development of ternary systems Mg–Zn–X (where X = Ca, Sr, RE, etc.), since the correct selection of temperature conditions can significantly improve corrosion resistance and biocompatibility. **Table 2** presents a summary of experimental data on heat treatment of various ternary magnesium systems. Thus, in the case of the Mg–Zn–Ca alloy, quenching followed by aging promotes the formation of a dispersed phase $Ca_2Mg_6Zn_3$, which leads to a uniform distribution of the components and a decrease in microgalvanic effects. This provides improved corrosion resistance under physiological conditions (Cho *et al.,* 2025).

Table 1. Effect of heat treatment on the corrosion resistance of magnesium alloys

Alloy system	Type of heat treatment	Main effect	Change in corrosion resistance	Source
MgCa	Annealing at 350°C	Enlargement of grains, reduction of phase boundaries	Reducing the rate of corrosion	Deng *et al.*, 2023
	Artificial aging at 200°C	Precipitation of fine intermetallic particles $CaMg_2$	Increased localized corrosion	Nie *et al.*, 1997
MgZn	Quenching followed by aging	Increased homogeneity of structure, reduction of microgalvanic effects	Improving corrosion resistance	Nakanishi *et al.*, 2010
	Natural aging	Slow evolution of the $MgZn_2$ phase	Minor improvement in corrosion resistance	Buha *et al.*, 2008
Mg-RE	Annealing at 400°C	Dissolution of rare earth phases	Significant reduction in corrosion rate	Wei *et al.*, 2017
	Artificial aging at 250°C	Artificial aging at 250°C	Improving the barrier properties of the oxide film	Wu *et al.*, 2022, Sun et al., 2022
MgSr	Quenching followed by aging	Strengthening of the structure, redistribution of the $Mg_{17}Sr_2$ phase	Improving corrosion resistance in physiological environments	Nafikov *et al.*, 2023
	Annealing at 300°C	Partial dissolution of intermetallic phases	Reduction in the rate of hydrogen evolution	Bornapour *et al.*, 2015

Annealing, on the contrary, promotes grain coarsening and dissolution of unstable phases, which reduces internal stresses, but does not always have a clear effect on the corrosion rate. For the Mg–Zn–Sr system, heat treatment leads to the redistribution of Sr and Zn along the grain boundaries, which reduces the rate of hydrogen evolution and increases the stability of the protective oxide layer (Zerankeshi *et al.,* 2022).

Particular attention is paid to systems alloyed with rare earth elements (RE). In Mg–Zn–RE and Mg–Ca–RE alloys, annealing at 400°C promotes the dissolution of RE phases and alignment of the structure, which significantly reduces the intensity of corrosion processes. Aging at moderate temperatures (about 250°C) promotes the formation of thermodynamically stable phases that increase the barrier properties of the oxide coating (Tariq *et al.,* 2022), (Meng *et al.,* 2022).

Thus, optimization of temperature conditions and heat treatment parameters allows for targeted changes in the structure of ternary magnesium alloys, ensuring an increase in their resistance to an aggressive biological environment. This makes such alloys promising materials for the creation of biodegradable implants with predictable degradation periods and high biocompatibility.

Table 2. Effect of heat treatment on corrosion resistance of ternary magnesium alloys used in biomedicine

Alloy system	Type of heat treatment	Main effect	Change in corrosion resistance	Source
Mg–Zn–Ca	Quenching followed by aging	Formation of finely dispersed phase $Ca_2Mg_6Zn_3$, increasing homogeneity	Improving overall corrosion resistance	Cho *et al.,* 2025
	Annealing at 350°C	Coarsening of grains, partial dissolution of intermetallic phases	Moderate reduction in corrosion activity	Zerankeshi *et al.,* 2022
Mg–Zn–Sr	Artificial aging at 200°C	Formation of a thermostable phase $Mg_{17}Sr_2$, stabilization of the structure	Improving resistance to localized corrosion	Zerankeshi *et al.,* 2022
	Annealing at 300°C	Redistribution of Zn and Sr along grain boundaries	Reduction in the rate of hydrogen evolution	Wang *et al.,* 2023
Mg–Zn–RE	Annealing at 400°C	Dissolution of RE phases, alignment of structure	Significant reduction in corrosion rate	Tariq *et al.,* 2022
	Aging at 250°C	Formation of stable secondary phases, strengthening of the passivation layer	Improving barrier properties and stability in SBF	Xu *et al.,* 2013
Mg–Ca–Sr	Hardening + aging	Strengthening of the structure, formation of complex phosphides at grain boundaries	Moderate improvement in corrosion resistance	Nie *et al.,* 2012

7. Promising approaches to optimizing corrosion resistance through combined heat treatment and alloying methods

The development of biodegradable magnesium alloys requires increasingly fine-tuning their structure, chemical composition and surface properties. That is why traditional approaches to heat treatment, such as annealing, quenching and aging, are now being actively supplemented by multi-stage and hybrid methods. These methods allow for simultaneous impact on the phase composition, morphology of intermetallic compounds, residual stresses and characteristics of the protective oxide film. This section discusses modern optimization trends that have proven themselves to be effective means of increasing the corrosion resistance of magnesium implants (Mhedhbi *el al.,* 2017).

One of the most promising approaches is multi-stage heat treatment. For example, solution annealing at 400–420°C for 6 h, followed by artificial aging at 180–200°C for 8–10 h, allows for a more uniform distribution of intermetallic phases (e.g. $MgZn_2$ or $Ca_2Mg_6Zn_3$). This combination significantly reduces microgalvanic currents within the alloy, increasing its resistance to pitting corrosion in physiologically simulating solutions. For the Mg–Zn–Ca alloy, such treatment reduced the corrosion rate in SBF by 42% compared to the as-cast state (Du *et al.,* 2021), (Moussa *et al.,* 2024).

Particular attention is paid to combining heat treatment with severe plastic deformation (SPD) methods. The most widely studied method is equal channel angular pressing (ECAP), in which samples are subjected to repeated deformation at an angle of 90°, which allows for a radical reduction in grain size (to 1–2 µm) and a smooth distribution of alloying elements. Thus, ECAP followed by aging (150°C, 10 h) in the Mg–Gd system allowed not only to increase mechanical strength, but also to reduce the volume of hydrogen released during corrosion by more than 30% (Zhang *et al.,* 2023), (Yang *et al.,* 2023).

Localized heat treatment is another promising direction. Laser thermal modification, used, for example, for Mg–Zn–Sr alloys, promotes the formation of a dense, stable oxide film up to 1–1.5 µm thick, consisting of MgO and SrO. Such a film significantly reduces surface permeability and stabilizes the behavior of the material in SBF. Similarly, plasma electrolytic oxidation (PEO) allows to obtain multiphase coatings with nanostructured pores, reducing the rate of magnesium dissolution by 3-5 times compared to uncoated samples (Inoue *et al.,* 2024).

In next work was used a dip-coating technique, followed by drying the coating on AZ91 at room temperature for 24 hours and sintering at 400 °C for 6 hours. This process resulted in a uniform, crack-free coating with the desired thickness. The hydroxyapatite layer demonstrated the ability to reduce the release rate of magnesium ions and stabilize the pH of the surrounding environment, which positively influenced osteoblast activity and bone tissue regeneration. However, the bonding strength between the coating and the substrate remained limited (Rahman *et al.,* 2020), (Rojaee *et al.,* 2013). Integration of thermal and chemical-thermal treatment is also of interest.

Thus, the combination of heat treatment with surface fluorination promotes the formation of MgF_2-containing films with high adhesion and stability in chloride-containing solutions. This is especially effective for Mg–RE and Mg–Sr alloys, which are vulnerable to galvanic effects. Thus, the modern approach to modifying magnesium bioimplants does not consist in choosing one optimal method, but in their combination. Deep integration of heat treatment with mechanical, chemical and physical methods allows for targeted control of both the deep microstructure and surface properties of the material, which brings such alloys closer to the requirements of clinical practice. Research aimed at developing individualized processing modes for specific operating conditions, taking into account the patient's biochemistry and the anatomical zone of implantation, remains promising.

Conclusion

Biodegradable magnesium alloys open up new horizons for medicine — implants that do not need to be removed, materials that can dissolve in the body, leaving behind not scars, but restored tissue. However, for these hopes to become everyday practice, it is necessary to overcome one of the main obstacles — the high corrosive activity of magnesium under physiological conditions.

This review has shown that heat treatment is not just a technological technique, but a fine tool for adjusting the micro-world of the alloy. Skillfully selected temperature conditions allow not only to change the structure of the material, but also to significantly affect its behavior in the body: slow down corrosion, increase stability, reduce the risk of inflammation and accelerated destruction.

Particularly promising are ternary alloys such as Mg-Zn-RE and Mg-Zn-Ca, which combine high biocompatibility and controlled degradation. In combination with modern methods — intensive plastic deformation, localized heat treatment, application of bioactive coatings — the way opens to the creation of a new generation of implants: smart, safe, soluble and, importantly, humane. Thus, heat treatment is not just a stage of the technological process. It is a bridge between laboratory science and real care for the patient's health. We have an important task — to bring developments to the clinic, where they can change lives, reduce suffering and give a chance for recovery without unnecessary pain.

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References

Atrens A, Liu M, Zainal Abidin N. I. (2011) Corrosion mechanism applicable to biodegradable magnesium implants. *Mater Sci Eng B.* 176(20):1609–36. doi:10.1016/j.mseb.2010.12.017

Amirmatova K. V., Aliyev E. A. (2025) Review of degradation behaviour biodegradable magnesium MgZnCa alloys. *Mongolian Journal of Engineering and Applied Sciences*, 7(1). doi:10.22353/mjeas.v7i1.9284

Azzeddine H., Baudin T., Brisset F. (2023) Effect of long-term natural aging on the microstructural characteristics of an extruded WE54 alloy. *Current Applied Physics,* 54, 38-43. https://hal.science/hal-04245374/document

Bornapour M., Celikin M., Pekguleryuz M. (2015) Thermal exposure effects on the in vitro degradation and mechanical properties of Mg–Sr and Mg–Ca–Sr biodegradable implant alloys and the role of the microstructure. *Materials Science and Engineering C,* 46:16–24. 20215. doi:10.1016/j.msec.2014.10.008

Bin S. J. B., Fong K. S., Chua B. W., Gupta M. (2022,) Mg-based bulk metallic glasses: A review of recent developments. *Journal of Magnesium and Alloys*, 10(4) 899-914. https://doi.org/10.1016/j.jma.2021.10.010

Buha J., Ohkubo T. (2008) Natural Aging in Mg-Zn(-Cu) Alloys. *Metall Mater Trans A* 39, 2259–2273. https://doi.org/10.1007/s11661-008-9545-y

Cho D. H., Avey T., Kwon H., Dean D., Luo A. A. (2025) A phase-based approach to optimizing the mechanical and corrosion properties of biodegradable Mg-Zn-Ca alloys. *Journal of Alloys and Compounds*, 1031, 181127. https://doi.org/10.1016/j.jallcom.2025.181127

Deng M., Wang L., Snihirova D., Bohlen J., Kurz G., Lamaka S. V., Höche D.. Zheludkevich L. M. (2023) Micro-alloyed Mg-Ca: Corrosion susceptibility to heating history and a plain problem-solving approach. *Journal of Magnesium and Alloys*, 11(4) 1193-1205. https://doi.org/10.1016/j.jma.2022.12.014.

Du Y., Wei D., Zhang D., Ge Y. (2021) Enhancing mechanical properties of an Mg–Zn–Ca alloy via extrusion. *Materials Science and Technology* 37(2):1-8. doi:10.1080/02670836.2021.1938861.

Hort N., Huang Y., Kainer K. U.. (2006) Intermetallics in magnesium alloys. *Advanced Engineering Materials.* 8(4) . https://doi.org/10.1002/adem.200500202.

Hort N, Huang Y, Fechner D, Stormer M, Blawert C, Witte F. (2010) Magnesium alloys as implant materials – principles of property design for Mg–RE alloys. *Acta Biomater.* 6(5):1714–25. https://doi.org/10.1016/j.actbio.2009.09.010

Ikeuba, A. I., Njoku, C. N., Ekerenam, O. O., Njoku, D. I., Udoh, I. I., Daniel, E. F., Uzoma, P. C., Etim, I.-I. N., & Okonkwo, B. O. (2024). A review of the electrochemical and galvanic corrosion behavior of important intermetallic compounds in the context of aluminum alloys. *RSC Advances*, 14(43), 31921-31953. https://doi.org/10.1039/d4ra06070a

Inoue S., Iwanaga K., Kawamura Y. (2024) Oxidation behavior and improvement in nonflammability of LPSO-type Mg–Zn–Y–Sr alloy. *Journal of Magnesium and Alloys*, 12(2) 742-749. https://doi.org/10.1016/j.jma.2024.01.017

Jiang P., Blawert C., Zheludkevich M. L. (2020) The Corrosion performance and mechanical properties of Mg-Zn based alloys—a review. *Corros. Mater. Degrad.* 1(1), 92-158; https://doi.org/10.3390/cmd1010007

Karki B. S., Deepa, mohit and Misra A. (2025) Enhancing Mechanical and Microstructural Properties of metal Alloys through Deep Cryogenic Treatment: A Comprehensive Review, J. Mater. Environ. Sci., 16(5), 738-753.

Liu J., Yu W., Chen D., Wang S., Song H., Zhang S.(2025) A review of studies on the influence of rare-earth elements on the microstructures and properties of copper and copper alloys and relevant applications. *Metals*, 15(5), 536; https://doi.org/10.3390/met15050536.

Liu D., Yang K., Chen S., 2024, Development and Future Trends of protective Strategies for Magnesium Alloy Vascular Stents, Materials, 17(1), 68. https://doi.org/10.3390/ma17010068

Liu Y., Yin J., Zhu G. (2025) Advances in magnesium-based biomaterials: strategies for enhanced corrosion resistance, mechanical performance, and biocompatibility. *Crystals*, 15(3), 256; https://doi.org/10.3390/cryst15030256.

Liu C., Xin Y., Tang G., Chu P. K. (2007) Influence of heat treatment on degradation behavior of bio-degradable die-cast AZ63 magnesium alloy in simulated body fluid. *Mater Sci Eng A.* 456(1–2):350–7. http://dx.doi.org/10.1016/j.msea.2006.12.020

Makkar P., Kumar S. S., Padalhin A. R., Moon B., Lee Y. S., and Lee B. T. (2018) In vitro and in vivo assessment of biomedical Mg–Ca alloys for bone implant application. *Journal of Applied Biomaterials & Functional Materials.* 16(3):126-136. https://doi.org/10.1177/2280800017750359

Mao L., Shen L. 2017. A promising biodegradable magnesium alloy suitable for clinical vascular stent application. *Sci Rep.,* 7, 46343. https://doi.org/10.1038/srep46343

Meng M., Zhai Z., Lei G., Yan Z., Wu W., Wang Q., Zhang Z. (2025) Precipitation characteristics and short-time aging treatment of Mg-Gd-Y-Zn-Zr alloy. *Journal of Magnesium and Alloys.* https://doi.org/10.1016/j.jma.2025.05.004

Mhedhbi M., Khlif M., Bradai C., 2017 Investigations of microstructural and mechanical properties evolution of AA1050 alloy sheets deformed by cold-rolling process and heat treatment annealing. *JMES,* 8 (8), pp. 2967-2974.

Moussa, M.E., Salem, M.M.M., Hamid, M.A. (2024) Mechanical Integrity and In vitro Degradation Behavior of Mg–Zn–Ca Biodegradable Alloy Prepared by Different Casting Technologies. *Inter Metalcast* 18, 3062–3080 https://doi.org/10.1007/s40962-023-01229-w

Nie, J.F. (2012). Precipitation and Hardening in Magnesium Alloys. *Metall Mater Trans A,* 43, 3891–3939 https://doi.org/10.1007/s11661-012-1217-2

Nie J.F., Muddle B.C. (1997) Precipitation hardening of Mg-Ca(-Zn) alloys. *Scripta Materialia,* 37(10), 1475-1481. https://doi.org/10.1016/S1359-6462(97)00294-7

Nakanishi R., Kawabata T., Matsuda K., Ikeno S. (2010) Effect of Quenching on Aging Behavior of Binary Mg-Zn Alloys. *Materials Science Forum*, 654-656, 659-662. https://doi.org/10.4028/www.scientific.net/msf.654-656.659

Nafikov R. K., Kulyasova O. B., Khudododova G. D., Nariman A. Enikeev. (2023) Microstructural assessment, mechanical and corrosion properties of a Mg-Sr alloy processed by combined severe plastic deformation. *Materials*, 16(6), 2279; https://doi.org/10.3390/ma16062279

Obayi C. S., Tolouei R., Mostavan A., Paternoster C., Turgeon S., Okorie B. A., Obikwelu D. O., Mantovani D. (2016) Effect of grain sizes on mechanical properties and biodegradation behavior ofpure iron for cardiovascular stent application. *BIOMATTER*. 6(1) e959874. doi:10.4161/21592527.2014.959874

Rogachev S. O., Bazhenov V. E., Bautin V. A., Li A. V., Plegunova S. V., Ten D. V., Yushchuk V. V., Komissarov A. A., Shin K. S. (2024) Influence of hot rolling on microstructure, corrosion and mechanical properties of Mg–Zn–Mn–Ca Alloy. *Metals*, 14(11), 1249; https://doi.org/10.3390/met14111249

Romzi M.A.F., Alias J., Ramli M.I.M. (2021) Effect of zinc (Zn) on the microstructure and corrosion behaviour of magnesium (Mg). *Materials Today Proceedings*, 48(6) doi:10.1016/j.matpr.2021.09.261

Rahman M., Li Y., Wen C. (2020) HA coating on Mg alloys for biomedical applications: A review. *Journal of Magnesium and Alloys*, 8(3), 929-943. https://doi.org/10.1016/j.jma.2020.05.003

Rojaee R., Fathi M., Raeissi K. (2013) Controlling the degradation rate of AZ91 magnesium alloy via sol–gel derived nanostructured hydroxyapatite coating. *Materials Science and Engineering: C*, 33(7), 3817-3825. https://doi.org/10.1016/j.jma.2020.05.003

Raja C. P., Babu K. N. B., Balaji N. S., Saikiran A. (2025) Kannan R. A. Effect of nutrient-based alloying elements on biodegradable magnesium alloys: Evolution, challenges, and strategies for orthopaedic applications. *Biomedical Engineering Advances*, 9, 100161. https://doi.org/10.1016/j.bea.2025.100161

Sahu M.R., Kumar T.S.S. and Chakkingal U. (2022) A review on recent advancements in biodegradable Mg-Ca alloys. *Journal of Magnesium and Alloys*, 10 2094 – 2117. https://doi.org/10.1016/j.jma.2022.08.002

Sun J., Du W., Fu J., Liu K., Li S., Wang Z., Liang H. (2022) A review on magnesium alloys for application of degradable fracturing tools. *Journal of Magnesium and Alloys*, 10(10), 2649-2672. https://doi.org/10.1016/j.jma.2022.09.032

Shalomeev V. A., Greshta V. L., Papirov I. I., Shokurov V. S., Pikalov A. I., Mukhachev A. P., Yelatontsev D. O. (2024) Advances and prospects of high-purity magnesium and its alloys in medicine – A concise review. *Journal of Alloys and Compounds Communications*, 3, 100011. https://doi.org/10.1016/j.jacomc.2024.100011

Tariq H. M. R., Ishtiaq M., Kang H., Chaudry U. M., Jun T. (2025) A Critical Review on the Comparative Assessment of Rare-Earth and Non-Rare-Earth Alloying in Magnesium Alloys. *Metals*, 15(2), 128; https://doi.org/10.3390/met15020128

Tsakiris V., Tardei C., Clicinschi F. M. (2021) Biodegradable Mg alloys for orthopedic implants – A review. *Journal of Magnesium and Alloys*, 9(6), 1884-1905. https://doi.org/10.1016/j.jma.2021.06.024

Thomas K. K., Zafar M. N, Pitt W. G., Husseini G.A. 2024. Biodegradable Magnesium Alloys for Biomedical Implants: Properties, Challenges, and Surface Modifications with a Focus on Orthopedic Fixsation Repair. *Applied Sciences*. 14(1), 10. https://doi.org/10.3390/app14010010

Unal M., Demiyayak E., Ertan M., Kilicaslan O. F., Kose O. 2022. Bioabsorbable magnesium screw fixation for tibial tubercle osteotomy – a preminary study. Acta Biomed. 92(6). 2021263. doi:10.23750/abm.v92i6.11716

Vakili M., Koutník P., , Kohout J., Gholami Z. (2024) Analysis, Assessment, and Mitigation of Stress Corrosion Cracking in Austenitic Stainless Steels in the Oil and Gas Sector: A Review. *Surfaces*, 7(3), 589-642. https://doi.org/10.3390/surfaces7030040

Vashi R. T., (2025) Moringa oleifera as an Ecofriendly Corrosion Inhibitor for Protection of Metals and AlloysA Review, J. Mater. Environ. Sci., 16(6), 1008-1028.

Wang J., Meng L., Zhang Z., Sa B., Fu X., Sheng L., Xu D., Zheng Y. (2023) Investigation on the crystal structure and mechanical properties of the ternary compound Mg11-xZnxSr combined with experimental measurements and first-principles calculations. *Journal of Magnesium and Alloys*, 11(3), 1074-1082. https://doi.org/10.1016/j.jma.2021.07.011

Wang S., Du C., Shen X., Wu X., Sihui Ouyang, Jun Tan, Jia She , Aitao Tang, Xianhua Chen, Fusheng Pan. (2023) Rational design, synthesis and prospect of biodegradable magnesium alloy vascular stents. *Journal of Magnesium and Alloys*, 11(9), 3012-3037. https://doi.org/10.1016/j.jma.2023.07.020

Wei J., Huang G., Yin D., Li K., Wang Q. (2017) Zhou H. Effects of ecap and annealing treatment on the microstructure and mechanical properties of Mg-1Y (wt.%) Binary Alloy. *Metals*, 7(4), 119; https://doi.org/10.3390/met7040119.

Wu G.H., Tong X., Jiang R., Ding W.J. (2022) Grain Refinement of As-Cast Mg-RE Alloys: Research Progress and Future Prospect. *Acta Metall. Sin*., 58, 385–399, doi: 10.11900/0412.1961.2021.00519

Xu L, Yu G, Zhang E, Pan F, Yang K. (2007) In vivo corrosion behavior of Mg–Mn–Zn alloy for bone implant application. *J Biomed Mater Res A*. 83(3):703–11. doi: 10.1002/jbm.a.31273

Xu H., Li Y.,Wu L., Jiang F., Fu D., Teng J., Zhang H. (2022) Effect of Heat Treatments on the Corrosion Resistance of a High Strength Mg-Gd-Y-Zn-Zr Alloy. *Materials*, 15(8), 2813; https://doi.org/10.3390/ma15082813

Xu W. C., Han X. Z., Shan D. B. (2013) Precipitates formed in the as-forged Mg–Zn–RE alloy during ageing process at 250 °C. *Materials Characterization*, 75, 176-18. https://doi.org/10.1016/j.matchar.2012.09.009

Yang Y., Xiong X., Chen J., Peng X., Chen D., Pan F. (2023) Research advances of magnesium and magnesium alloys worldwide in 2022. *Journal of Magnesium and Alloys*, 11(8), 2611-2654. https://doi.org/10.1016/j.jma.2023.07.011

Ye L., Huang H., Sun C., Zhuo X., Dong Q., Liu H., Ju J., Xue F., Bai J., Jiang J. (2022) Effect of grain size and volume fraction of eutectic structure on mechanical properties and corrosion behavior of as-cast Zn–Mg binary alloys. *Journal of Materials Research and Technology*, 16, 1673-1685. https://doi.org/10.1016/j.jmrt.2021.12.101

Zerankeshi M. M., Alizadeh R., Gerashi E., Asadollahi M., Langdon T. G. (2022) Effects of heat treatment on the corrosion behavior and mechanical properties of biodegradable Mg alloys. *Journal of Magnesium and Alloys*, 10(7), 1737-1785. https://doi.org/10.1016/j.jma.2022.04.010

Zhaoqian S., Yongjun L., Kui Z., Xinggang L., Minglong M., Guoliang S., Jiawei Y. (2021) Research on Homogenization Treatment of Mg-8wt.% Sn-1.5 wt.% Al Alloy. *Journal of Physics: Conference, Series*.1907 012023. doi:10.1088/1742-6596/1907/1/012023

Zhang L., Mohammed E., Adriaens A. (2016) Synthesis and electrochemical behavior of a magnesium fluoride-polydopamine-stearic acid composite coating on AZ31 magnesium alloy. *Surface and Coatings Technology*, 307(Part A):56. doi:10.1016/j.surfcoat.2016.08.021

Zhang S., Zhu L., Song J., Liu Z., Chen M., Han J., Jiang Z. (2023) Effect of ECAP on corrosion behavior of innovative nano MgO/Mg-Zn-Ca composite as a biomedical material in simulated body environment. *Materials Today Communications*, 35, 106345. https://doi.org/10.1016/j.mtcomm.2023.106345

Zhang T., Wang W., Lui J., Wang L., Tang Y., Wang K., 2022. A review on magnesium alloys for biomedical applications. Frontiers in Bioengineering and Biotechnology. 16(10) 953344. doi:10.3389/fbioe.2022.953344

Zhao C., Pan F., Zhang L., Pan H., Song K., Tang A. (2017) Microstructure, mechanical properties, bio-corrosion properties and cytotoxicity of as-extruded Mg-Sr alloys. *Mater. Sci. Eng.*, 70(2), 1081-1088. http://dx.doi.org/10.1016/j.msec.2016.04.012

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