Material State and Heat Treatment Effects on the Corrosion of Mg-Zn Alloys for Biomedical Use

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***Abstract*—This study investigates the corrosion behavior of a magnesium-zinc (Mg-Zn) alloy in a simulated physiological environment, with the aim of optimizing its degradation rate for biodegradable medical implant applications. Magnesium alloys are promising for such applications due to lightweight properties, biocompatibility, and ability to corrode naturally in the body, eliminating the need for surgical removal. Despite these advantages, their rapid corrosion rate often exceeds the bone healing period, limiting their clinical use.**

To address this issue, different heat treatments and material states are analyzed to understand their effect on corrosion rates. A medium-concentration Mg-Zn alloy was immersed in Hank's Balanced Salt Solution (HBSS) at 37°C to mimic physiological conditions. Corrosion kinetics was monitored over seven days using an isothermal calorimeter. This is a specialized instrument developed at Lund University that combines heat and pressure measurements to analyze material degradation over time. Specimens were suspended in HBSS within sealed containers that were placed in the calorimeter, and corrosion was monitored continuously over a seven-day period

Obtained results demonstrate that specimens in homogenized state have the lowest corrosion rate, whereas those heat-treated at 180°C for peak-aged condition show the highest corrosion rate. These findings contribute to a better understanding of how processing conditions affect corrosion behavior and support the development of optimized biodegradable implants.

I. Introduction

MAGNESIUM is one of the lightest metals used in engineering, with a density of around 1.74 g/cm³. It has attracted growing attention in biomedical fields due to its mechanical properties being similar to natural bone, making it a strong candidate for temporary implants. Unlike titanium or steel, which often require surgical removal after implantation and completion of bone healing, magnesium can degrade safely in the body, reducing the need for secondary procedures. Its biocompatibility and favorable mechanical characteristics make it especially suitable for orthopedic applications such as screws and plates. However, its relatively low hardness and wear resistance remain challenges for long-term performance [1].

One of the main challenges in using magnesium for biomedical implants is its high degradation rate in aqueous environments such as body fluids. Magnesium has a high electronegativity, which enables it to corrode even in the absence of oxygen. In atmospheric conditions, magnesium reacts with oxygen to form a thin oxide layer:

$$\mathrm{Mg}(s) + \frac{1}{2}\mathrm{O_2}(g) \rightarrow \mathrm{MgO}(s) \quad \Delta H = -601.6\,\mathrm{kJ/mol}$$

However, in physiological environments, magnesium corrodes more rapidly due to its direct reaction with water, forming magnesium hydroxide and hydrogen gas:

$$\mathrm{Mg}(s) + 2\mathrm{H_2O}(l) \rightarrow \mathrm{Mg(OH)_2}(s) + \mathrm{H_2}(g) \quad \Delta H = -353.01\,\mathrm{kJ/mol}$$

Although MgO and $\mathrm{Mg(OH)_2}$ form on the surface, they offer limited protection. Their low mechanical integrity and high solubility in aqueous environments mean that they cannot effectively prevent further corrosion. As a result, magnesium continues to degrade rapidly in physiological conditions, which limits its long-term use in biomedical applications [2].

To improve magnesium's corrosion resistance while maintaining its biocompatibility, alloying with other elements has become a common strategy. Zinc is a widely used alloying element in magnesium-based materials due to its ability to enhance both strength and ductility, which are critical for biodegradable implants intended to bear mechanical load. The addition of zinc contributes to improved mechanical performance by influencing dislocation structures and promoting hardening mechanisms. Furthermore, zinc reduces the negative impact of common impurities such as iron, nickel, and copper, which are known to accelerate corrosion in magnesium. As an essential trace element naturally present in the human body, zinc also supports bone healing and cellular activity, making Mg–Zn alloys especially suitable for biomedical applications [3].

However, understanding the corrosion behavior of magnesium alloys is challenging due to the complex and dynamic nature of the degradation process, especially under physiological conditions where local thermal and chemical variations influence the outcome. Traditional methods like immersion testing with hydrogen gas collection have long been used to estimate corrosion rates, but they offer limited insight into the underlying thermodynamic processes.

To address this, a new approach combining isothermal calorimetry and pressure measurements has been developed. Calorimetry enables direct monitoring of the heat released during corrosion, allowing for real-time evaluation of the enthalpy change associated with material degradation. When combined with pressure sensors that track hydrogen evolution, this method provides a more complete picture of the reaction kinetics and thermodynamics. This kind of combined method is especially helpful for biomedical alloys because it gives a

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clearer and more reliable way to understand how they break down in changing conditions [4].

In addition to alloy composition, heat treatment plays a key role in modifying microstructure and corrosion performance. Heat treatment of magnesium-zinc alloys significantly improves their mechanical strength, hardness, and resistance to corrosion. To ensure uniform heating and precise temperature control during the process, an oil bath is commonly used. As the alloy is heated, atomic diffusion leads to the formation of fine, uniformly distributed secondary phases such as $\mathrm{MgZn_2}$, which strengthen the material by hindering dislocation motion. These effects make heat-treated magnesium-zinc alloys particularly well-suited for demanding applications, such as biomedical implants, where both mechanical performance and controlled degradation are essential [1].

Mg-Zn alloys with different zinc concentrations (low, medium and high) are available for testing. The medium-zinc (Med-Zn) alloy was selected for this study based on previous findings that highlight its improved corrosion resistance and mechanical performance. Previous studies have shown that magnesium alloys with medium zinc content (Med-Zn) exhibit a favorable combination of microstructural, mechanical, and corrosion-related properties. Med-Zn specimens have been reported to contain the highest density of secondary phase precipitates, contributing to enhanced structural stability and mechanical strength. Furthermore, these specimens demonstrate the most stable hardness values and the lowest corrosion rates, regardless of the manufacturing method. These characteristics make Med-Zn a promising composition for applications where both durability and corrosion resistance are critical [5]. In biomedical applications, the balance between mechanical strength and corrosion rate is crucial to ensure that the material degrades at a controlled rate while still providing sufficient support during the healing process. Accordingly, the alloy selected in the present study reflects these earlier findings.

Studies on heat treatment conducted under identical conditions to this experiment, using the same equipment and electrolyte solution, have shown that heat treatment at $180\,^{\circ}\mathrm{C}$ results in a slower corrosion rate for homogenized medium-zinc alloys, whereas it produces almost no change in corrosion behavior for extruded medium-zinc alloys [6].

The aim of this study is to evaluate how different material states and heat treatments influence the corrosion behavior of magnesium alloys containing a medium concentration of zinc. The study aims to contribute to a better understanding of how different material conditions affect the degradation of magnesium-zinc alloys for potential biomedical applications.

It is hypothesized that heat-treated and homogenized magnesium-zinc alloys will exhibit lower corrosion rates compared to extruded alloy under physiological conditions.

The report begins with a description of the materials and methods, including sample preparation, electrolyte composition, and calorimetric measurements. This is followed by the presentation of results, focusing on how corrosion rate, heat evolution, and hydrogen gas development are influenced by material condition and heat treatment. The results are then analyzed and discussed in relation to previous research to draw conclusions about how different processing methods affect the degradation of magnesium-zinc alloys under physiological conditions.

II. Materials and method

A. Sample Preparation

Four different types of magnesium alloys, all containing a medium concentration of zinc, were analyzed. The alloys varied in their structural state and heat treatment. The tested magnesium-zinc alloys included one extruded sample and three homogeneous samples, of which two were heat-treated for peak ageing at $150\,^{\circ}\mathrm{C}$ and $180\,^{\circ}\mathrm{C}$.

From each sample, five disc-shaped specimens (approximately $\varnothing 10\,\mathrm{mm} \times 1\,\mathrm{mm}$) were cut using a Struers Accutom-5 precision saw with a 10S15 SiC-based cut-off wheel. Four specimens per sample were used in the calorimeter, while one was saved as a reference.

After cutting, each specimen was ground using silicon carbide (SiC) paper in multiple steps (500, 1200, 2000 and 4000 grit) with a PENTA-5000 hand grinder by Pace Technologies. Grinding was performed on both the top and bottom surfaces to achieve a smooth, homogeneous surface free from deformation and visible scratches. Between the first three grinding steps, the specimens were rinsed with water and dried with clean air. After the final step, the specimens were washed with ethanol and dried with clean air.

The mass, thickness, and diameter of each specimen were then measured using a balance and a micrometer. To compensate for potential uneven grinding, five measurements were taken per dimension. The average values were used in the isothermal calorimetry software to ensure accurate analysis and to generate a report including multiple graphs.

After the measurements, the specimens were placed in ethanol-filled beakers and cleaned in an ultrasonic bath for five minutes.

All preparation and analysis steps described in this method section were repeated for four individual specimens from each of the four sample types, resulting in a total of sixteen experimental specimens.

B. Preparation of HBSS Solution

Hanks' Balanced Salt Solution (HBSS) was used to simulate the physiological environment. To prepare the solution, 0.265 g of calcium chloride dihydrate was first added to 1 liter of pre-mixed HBSS (Sigma H6648) while stirring. Then, 1.250 g of sodium bicarbonate was added, and the solution was stirred using a magnetic stirrer until all components were fully dissolved.

C. Isothermal Calorimeter Setup

All measurements were conducted using a TAM Air isothermal calorimeter from TA Instruments, equipped with eight

channels. In each run, four channels were used, with each channel containing both a sample vial and a reference vial. The calorimeter is equipped with a pressure sensor and a temperature regulator that maintains a constant temperature of $37\,^{\circ}\mathrm{C}$ to simulate physiological conditions.

The temperature regulator ensures a stable thermal environment, allowing the calorimeter to detect changes in heat flow. This enables measurement of the heat released during the corrosion reaction between the magnesium alloys and HBSS. At the same time, the pressure sensor detects the buildup of hydrogen gas, which is produced as a byproduct of the reaction, providing additional information on the corrosion process.

Reference vials were prepared by weighing four 20 mL glass vials and filling each with 17 mL of HBSS using a glass pipette. The vials were then placed in their respective channels. Sample vials were prepared in the same way but initially left empty.

Before inserting the samples, a 24-hour baseline measurement was conducted with only the HBSS-filled vials in place. This step ensured thermal stabilization of the system and provided a stable reference point for both heat flow and pressure measurements during the actual experiment.

After the baseline, the alloy specimens were carefully placed into the sample vials and fully immersed in the solution. A small amount of vacuum oil was applied to the vial stoppers to ensure proper sealing. The actual measurements were then conducted over a period of 7 days.

After seven days, the measurement was stopped, and the specimens were gently removed, rinsed with HBSS and double-distilled water, dried, and stored for later cleaning.

D. Cleaning of Corrosion Products

To remove corrosion products from the specimens, Chromium oxide based solution according to ASTM G1 solution C.5.2 was used. A small amount of the solution was poured into a beaker, enough to fully submerge the specimen. The specimen was held with tweezers and gently placed into the solution, where it was lightly shaken to help loosen the corrosion products. The specimen was then transferred to a first beaker filled with ethanol, shaken again, and finally cleaned in a second ethanol beaker using the same method. After cleaning, the specimen was placed on sterile tissue and left to dry for two minutes.

The first cleaning cycle consisted of 90 seconds in the cleaning solution, followed by 30 seconds in the first ethanol beaker and 30 seconds in the second. Subsequent cycles included 20 seconds in cleaning solution, 30 seconds in ethanol 1, and 30 seconds in ethanol 2. After each cycle, the specimen was carefully weighed, and the cleaning process was repeated until no further change in mass was observed.

E. Data Processing and Corrosion Rate Calculation

To calculate the corrosion rate based on the observed mass change, the mass of each specimen measured before and after the calorimeter experiment was used, together with the dimensional measurements taken prior to the experiment. The volume V of each cylindrical specimen was calculated using the formula:

$$V = \frac{\pi \cdot l \cdot d^2}{4} \tag{1}$$

where l is the length and d is the diameter of the specimen (both in cm). The density D of the specimen was then determined as:

$$D = \frac{\text{weight (g)}}{\text{volume (cm}^3\text{)}} \tag{2}$$

The surface area A of the specimen was calculated using:

$$A = \pi \cdot d \cdot l + \frac{\pi \cdot d^2}{2} \tag{3}$$

Finally, the corrosion rate C_r in mm/year was calculated according to:

$$C_r = \frac{8.76 \times 10^4 \cdot W}{A \cdot T \cdot D} \tag{4}$$

where W is the mass loss in grams, A is the surface area in cm², T is the exposure time in hours, and D is the density in g/cm³.

Additionally, a Python script was used to process the calorimeter data, including pressure changes from hydrogen gas evolution and the heat released during the reactions. This script generated diagrams showing the development of the corrosion rate and thermal power over time. For each experiment, an average corrosion rate was calculated based on four individual specimens per sample, resulting in four distinct average values corresponding to the four different alloy conditions.

III. Results

Figure 1 shows the development of corrosion rates over time for representative specimens from each sample, as measured using isothermal calorimetry. To reduce noise and highlight general trends, the curves were smoothed using a wider moving average filter. Negative values that appeared at the beginning of the measurements and did not reflect real corrosion behavior were removed from the data.

In most cases, the corrosion rate increased initially and then decreased to a stable level. This trend was observed for the extruded, homogenized, and $150\,^{\circ}\mathrm{C}$ heat-treated magnesium-zinc alloys, where the decline began approximately 15 hours into the measurement. In contrast, the alloy heat-treated at $180\,^{\circ}\mathrm{C}$ displayed a different pattern: the corrosion rate continued to rise for about 94 hours before starting to decrease, without reaching a clear steady state.

Two technical issues affected the data collection:

- **Sensor connection problems:** One sensor exhibited intermittent connection failures. As a result, all measurements from that channel were excluded in all experiments.
- **System leakage:** Detected leakage events led to the exclusion of data from affected channels.

Due to these limitations, the final analysis was performed using 2 specimens per sample instead of the full set of 4.

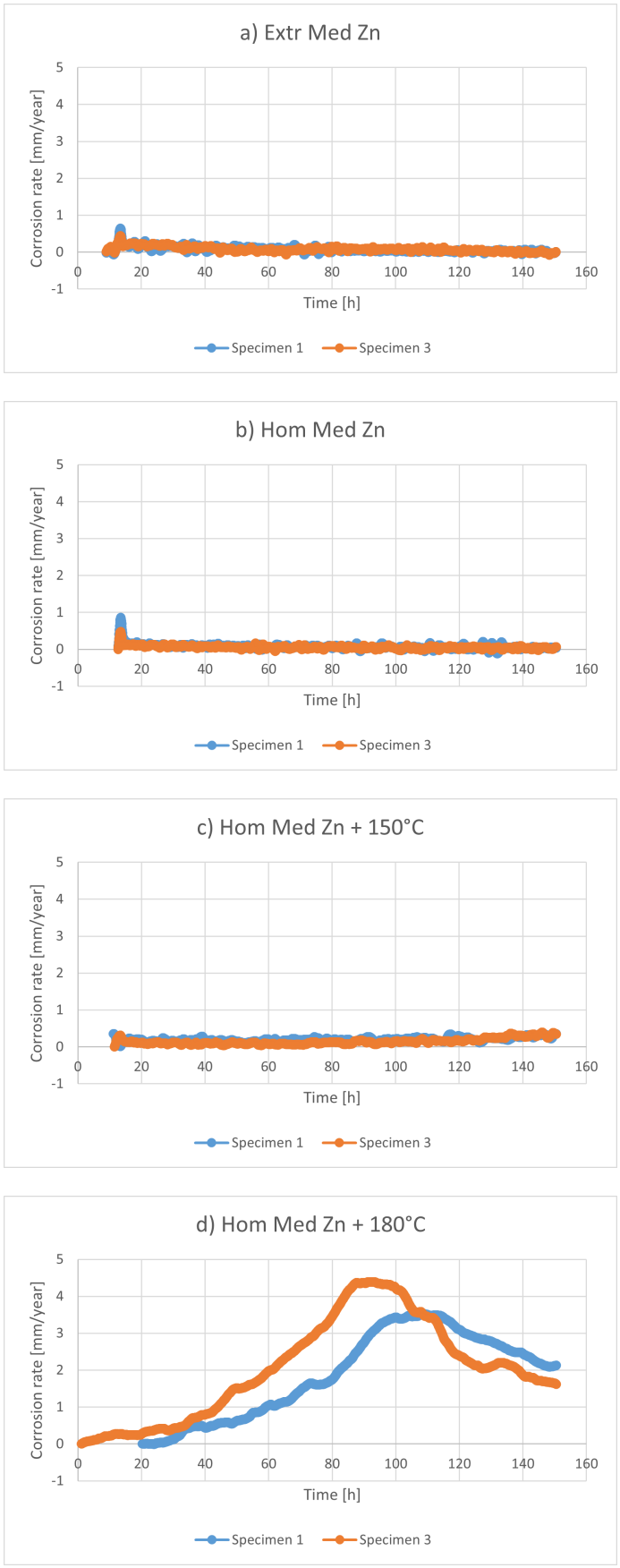

Figure 1: Development of corrosion rates during calorimetric measurements for magnesium-zinc alloys in four different material conditions: (a) extruded, (b) homogenized, (c) homogenized and heat-treated at 150 °C, and (d) homogenized and heat-treated at 180 °C.

To determine the corrosion rates from the calorimetric graphs, the point at which the curves reached a steady state was identified, and an average corrosion rate was calculated for the period from this point until the end of the test. In the case of the fourth experiment, involving homogenized medium zinc heat-treated at 180 °C, no clear steady state was reached; instead, the average corrosion rate was calculated across the entire measurement period.

The results obtained using the mass loss calculations and those derived from the diagrams in the script exhibit similar trends, although the specific corrosion rate values differ for the various calculation methods. Figure 2 presents the average corrosion rates for each sample, calculated using two methods: mass loss (orange) and hydrogen evolution (blue).

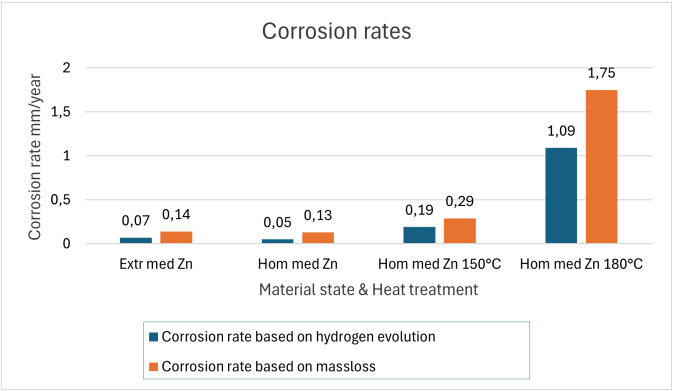

Figure 2: Average corrosion rates for magnesium-zinc alloys in four different states, calculated using two methods: mass loss (orange) and hydrogen evolution (blue).

According to the results, the homogenized medium-zinc alloy shows the lowest corrosion rate. This is followed by extruded alloy, then the homogenized alloy heat-treated at 150 °C, and finally the homogenized alloy heat-treated at 180 °C, which exhibits the highest corrosion rate.

In addition to the corrosion rate measurements, thermal power curves were recorded for each experimental group to analyze the heat released during corrosion. These curves provide complementary information about the reaction kinetics and heat output over time.

Figure 3 shows the thermal power data from the calorimeter for the extruded, homogenized, and heat-treated magnesium-zinc alloys. As with the corrosion rate curves, a similar pattern was generally observed, consisting of an initial increase followed by a stabilization phase. However, differences in intensity and timing were seen between samples.

For the extruded magnesium-zinc alloy, the thermal power curves stabilized at a low but steady level of around 0.05 mW after approximately 25 hours. One of the specimens exhibited a stable negative thermal power throughout the experiment and was therefore excluded from the diagram as it did not reflect actual reaction behavior.

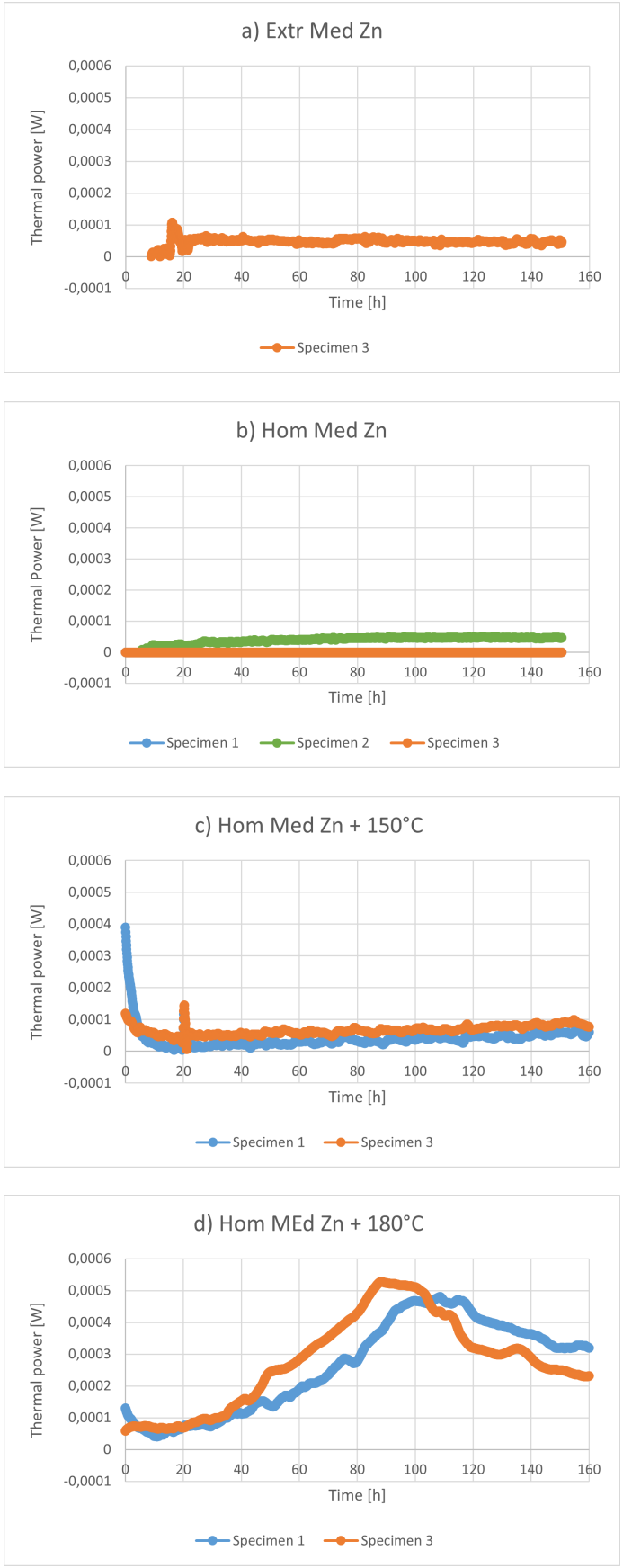

Figure 3: Thermal power curves for the four magnesium-zinc alloy conditions during isothermal calorimetry measurements: (a) Extruded, (b) Homogenized, (c) Homogenized + 150°C heat treatment, and (d) Homogenized + 180°C heat treatment. Each curve represents the heat released during corrosion over time.

For the homogenized alloy, no measurable thermal power was detected in the channels corresponding to the corrosion rate samples, as the signal remained at 0 mW throughout the experiment. However, a third specimen from the same sample, excluded from corrosion rate evaluation due to pressure curve deviation, showed measurable thermal activity. Its thermal power curve followed a similar general pattern to the other samples, stabilizing at approximately 0.03–0.04 mW, indicating that corrosion did occur in this material condition.

In the case of the homogenized alloy heat-treated at 150 °C, the thermal power curves showed a small peak around 20 hours into the experiment and then stabilized at approximately 0.05 mW, indicating the onset of a steady corrosion phase with relatively low thermal activity.

The 180 °C heat-treated alloy displayed the highest thermal power levels among all experimental groups. A continuous increase in thermal power was observed over approximately 100 hours, reaching a peak of around 0.5 mW, followed by a gradual decrease. No clear thermal stabilization was observed within the measurement period.

IV. Discussion

The aim of this study was to evaluate how different material conditions—extruded, homogenized, and heat-treated at 150 °C and 180 °C—affect the corrosion behavior of magnesium-zinc alloys with medium zinc concentration. The results, obtained through both mass loss and hydrogen evolution measurements, indicate that the corrosion behavior varied significantly between the different material conditions, both in terms of how fast the corrosion occurred and how it progressed over time.

Among the tested conditions, the homogenized alloy (without heat treatment) demonstrated the lowest and most stable corrosion rate, as reflected in its corrosion curve. This was followed by the extruded condition, then the alloy heat-treated at 150 °C, and finally the alloy heat-treated at 180 °C, which exhibited the highest corrosion rate and the most delayed stabilization.

Corrosion rates were calculated using two approaches: mass loss and hydrogen evolution based on calorimetric measurements. While both methods exhibited similar trends, the calorimetry-based values were given primary analytical focus. This decision is supported by Esmaily et al. (2017) [7] , who highlight that mass loss methods provide only an average corrosion rate over the entire immersion period, whereas calorimetric techniques offer time-resolved data that better reflect the progression and dynamics of the corrosion process. Consequently, the mass loss values in this study were used mainly for validation and supported the same ranking of alloy behavior observed in the calorimetry data.

The corrosion rates derived from mass loss were consistently higher than those obtained from calorimetric measurements. This difference is likely due to the nature of the methods. A significant source of error in the mass loss method may be related to the post-exposure cleaning process. According to the methodology, a chemical solution is used to remove corrosion products from the sample surface, ideally leaving

only the intact metal behind. However, in practice, there is a risk that the cleaning process becomes too aggressive, especially if the acid solution is concentrated or if the sample is agitated too vigorously. This can result in the removal of not only corrosion products but also intact, non-corroded metal. In such cases, the recorded mass loss is overestimated, leading directly to an inflated calculated corrosion rate. The mass loss then reflects not only actual corrosion but also mechanical or chemical removal of non-corroded material, leading to an overestimated corrosion rate. In contrast, the calorimetric approach measures heat and hydrogen evolution directly from the chemical reaction, offering a more specific estimate of corrosion activity. But in some cases, the calorimetric method also presents potential sources of error, particularly in the measurement of hydrogen gas evolution. Even though hydrogen is produced during the anodic corrosion reaction, the experimental setup imposes certain limitations. Part of the hydrogen gas may dissolve in the electrolyte, especially during extended exposure times. Hydrogen may also diffuse into the sample material or escape from the system despite sealing efforts, such as the use of vacuum grease. These mechanisms lead to an underestimation of the actual hydrogen produced. As a result, the corrosion rate measured calorimetrically may be underestimated, since hydrogen evolution is one of the primary indicators of material degradation in this system. Together, these causes may explain why the mass loss method in some cases shows a higher corrosion rate than what is measured through calorimetry, despite the opposite trend often being reported in the literature.

In addition to hydrogen evolution, thermal power measurements provided valuable insights into the time-resolved corrosion behavior of the different alloy conditions. These curves reflect the heat released during the corrosion process and thereby offer information about reaction intensity and progression over time. For most specimens, the thermal power curves followed a similar pattern as the corrosion rate, with a relatively rapid decline to a steady state. This consistency between thermal power and corrosion rate confirms the reliability of the calorimetric data.

Thermal power data also revealed clear differences between the tested material conditions. For the extruded and homogenized alloys, the curves stabilized early at low thermal power levels, suggesting a rapid transition into a more controlled and less aggressive corrosion process. This stabilization could be associated with the formation of a protective passive film composed of degradation products, such as magnesium hydroxide or other corrosion by-products, which limits further attack on the underlying metal. In contrast, the heat-treated samples at $150\,^{\circ}\mathrm{C}$ and $180\,^{\circ}\mathrm{C}$ displayed more complex profiles. The $150\,^{\circ}\mathrm{C}$ condition exhibited a small peak before reaching a steady level, possibly indicating repeated breakdown and regeneration of surface films. The $180\,^{\circ}\mathrm{C}$ condition showed a continuous increase in thermal power without achieving clear stabilization, pointing to sustained corrosion activity over a longer period. These differences suggest that heat treatment, influences not only the corrosion rate but also the kinetics of degradation.

Some technical deviations were also observed. One specimen in the extruded sample displayed a stable negative thermal power value, likely due to baseline offset or calibration drift, but since the corresponding corrosion rate followed the expected trend, this did not affect the interpretation. In the homogenized sample, no measurable thermal signal was detected for the specimens with reliable pressure data, likely due to signal levels falling below the detection threshold. However, another specimen from the same sample, excluded from hydrogen analysis due to pressure curve deviation caused by leakage, showed a measurable thermal signal consistent with ongoing corrosion, further supporting the presence of active degradation in that condition.

Although the total enthalpy was not calculated, thermal power served as a valuable complement to hydrogen evolution and mass loss measurements. It provided a more detailed picture of how corrosion evolved over time and helped distinguish kinetic differences between the alloy conditions that may not be fully captured through mass-based measurements alone.

These findings were then compared with previous studies to assess consistency and potential deviations. The corrosion rates observed in this study show both agreement and deviation from earlier findings. Dimakopoulou (2024) [6] conducted a comparable study using the same electrolyte solution (HBSS) and experimental setup, but with a shorter immersion period of 3 days. In contrast, the present study extended the exposure time to 7 days, which may explain the variations in reported corrosion rates.

For extruded medium-zinc alloys, Dimakopoulou [6] reported a corrosion rate of approximately 0.5 mm/year, while a lower rate of 0.14 mm/year measured here. In the homogenized condition, this study also showed a considerably reduced rate of 0.13 mm/year compared to 4.09 mm/year in her results. For the alloy heat-treated at $180\,^{\circ}\mathrm{C}$, the corrosion rate was higher in this study, at 1.75 mm/year, compared to 0.71 mm/year reported by Dimakopoulou. No data were presented in her work for the $150\,^{\circ}\mathrm{C}$ condition, which in this study exhibited a rate of 0.29 mm/year.

According to Esmaily et al. (2017) [7], the corrosion behavior of magnesium alloys is highly time-dependent. Longer immersion can reveal additional degradation mechanisms, such as surface passivation or breakdown of protective layers, which may not be captured during shorter tests. This highlights the importance of considering test duration when comparing corrosion data between studies.

The extended measurement period in the present study may therefore explain the lower rates observed for the extruded and homogenized conditions, which appear to stabilize over time. In contrast, the elevated corrosion rate of the $180\,^{\circ}\mathrm{C}$ heat-treated alloy may reflect a progressive increase in reactivity during prolonged exposure, although the possibility of experimental error cannot be excluded.

Heat treatment at $180\,^{\circ}\mathrm{C}$ was found to increase the corrosion rate, in contrast to previous studies that reported improved corrosion resistance through heat treatment and a reduction in the corrosion rate. This may indicate that the deviating result is most likely due to individual sources of error during the experiment, such as contamination, but our method has otherwise been the same throughout all our experiments.

The difference may also be explained by changes in the alloy's microstructure according to Viklund (2020) [2]. In such cases some parts of the metal may act as the anode and the surrounding material as the cathode, thereby accelerating localized corrosion. This suggests that heat treatment, despite its general benefits, may also induce microstructural changes that increase the risk of localized corrosion in certain regions of the material. However, these results are not conclusive, as only four experiments were conducted due to time constraints in the project. Therefore, further studies are needed, and to achieve statistically significant and reliable results, the experiment should be repeated and conducted multiple times.

Thus, these findings do not support the original hypothesis that heat-treated alloys would show lower corrosion rates than extruded ones. Instead, the results suggest that while homogenization had a positive effect, additional heat treatment, had the opposite outcome. This shows that heat treatment needs to be carefully considered, as it can lead to microstructural changes that may increase corrosion in certain areas of the material. For biomedical applications, where controlled degradation is important, these changes could affect how long an implant lasts and how safely it degrades in the body.

Future studies could focus on increasing the number of specimens to improve the reliability of the results and reduce the effect of individual variations. Extending the duration of the experiments could also help capture longer-term corrosion trends and possible late-stage stabilization effects. It would also be valuable to investigate how different zinc concentrations influence corrosion behavior, as this study focused only on a medium level. In addition, surface analysis methods such as microscopy or spectroscopy could help clarify the microstructural changes caused by heat treatment. These steps would contribute to a more complete understanding of how processing affects both the performance and degradability of magnesium-based materials.

A. Ethics and Sustainability

This research on biodegradable magnesium implants represents an exciting opportunity to simultaneously improve patient care today and promote a sustainable future. By combining medical innovation with strong ethical and environmental principles, it could potentially create a solution that is both effective and socially responsible.

According to medical technology ethics, medical research requires careful consideration of benefits versus risks. The project addresses a clear clinical challenge; current metal implants require additional removal surgery causing unnecessary suffering This not only leads to prolonged patient pain, particularly problematic for children, but also increases healthcare costs and places additional strain on the medical system. Magnesium-based solutions offer a promising alternative, designed to safely degrade in the body after fulfilling their function. This ensures that patient focus is maintained throughout the entire development process. By combining a patient-centered approach with sustainable material use, these innovations have the potential to result in both improved implants and a more sustainable healthcare system.

Magnesium implants offer several sustainability advantages. They reduce resource consumption by eliminating the need for additional surgical materials, and they help decrease medical waste as the implants naturally degrade within the body. Moreover, the energy required for their production is lower compared to the manufacturing and recycling processes associated with traditional implants. In addition, avoiding implant removal reduces strain on healthcare systems and contributes to more sustainable care delivery. Altogether, magnesium implants represent a step toward greener, patient-centered innovation in medical technology.

V. Conclusions

The corrosion behavior of medium-zinc magnesium alloys was clearly influenced by material condition. The homogenized alloy (without heat treatment) showed the lowest and most stable corrosion rate, while the $180\,^{\circ}\mathrm{C}$ heat-treated alloy exhibited the highest rate without stabilization. Heat treatment at $150\,^{\circ}\mathrm{C}$ also led to increased corrosion, though to a lesser extent.

Both mass loss and calorimetry confirmed the same trend, with calorimetry offering more detailed, time-resolved data. Thermal power curves further supported the findings by reflecting differences in corrosion intensity over time.

Overall, homogenization improved corrosion resistance, while higher-temperature heat treatment reduced it, likely due to microstructural changes that promote localized corrosion.

VI. Acknowledgements

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