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Design and Performance Testing of Vacuum Induction Furnaces for the Development of Magnesium-Based Biodegradable Implant Materials

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Abstract: Magnesium (Mg) has emerged as a promising biomaterial for implants due to its similarity in physical and mechanical properties to human bone, as well as its ability to degrade safely in the body. However, the main challenges with magnesium are its relatively low mechanical strength and its high tendency to oxidize during the casting process. The use of the Vacuum Induction Casting (VIC) method is crucial to overcome oxidation and porosity issues, resulting in cast products with better integrity. This study aims to design and test the performance of a laboratory-scale vacuum induction furnace for the development of magnesium-based biodegradable implant materials. The furnace was designed using Autodesk Inventor, using a 3.000 W induction module, a water-cooled copper coil, an HA-1 refractory chamber, and a graphite crucible (±52 mL/90 g Mg). Tests showed that the furnace was able to reach an operating temperature of approximately 1.020°C in 2 minutes and 15 seconds, and successfully melted 60 grams of Mg–Gd alloy while the lowest vacuum pressure achieved by the equipment was 0.473 Atm. Rockwell A scale hardness tests yielded average values of 67.1 HRA for Mg–3%Gd and 74.9 HRA for Mg–4%Gd, indicating an increase in hardness with increasing gadolinium content.

Keywords: Biodegradable Implants; Magnesium; Melting; Performance Testing; Vacuum Induction Furnace

Introduction

Bone fractures are one of the most common health problems in Indonesia. Based on data from the 2018 Basic Health Survey (Riskesdas) conducted by the Health Research and Development Agency, bone fractures rank fourth among the most common injuries with an incidence of 5.5%, with 67.9% of cases occurring in the lower extremities (Riskesdas, 2018). In the medical field, biomaterial implants materials inserted into the body to support damaged tissue during recovery are the primary solution. Among options such as titanium, stainless steel, and magnesium, magnesium (Mg) is now attracting significant attention due to its biodegradable properties that allow it to dissolve and be absorbed naturally by the body, thereby supporting bone regeneration without the need for implant removal surgery(Amin et al., 2025; Lestari et al., 2022; Amukarimi & Mozafari, 2021; Zhang et al., 2022; J. Wang et al., 2020; Dachasa et al., 2024)

However, magnesium cannot be used directly in its pure form for material engineering applications, especially bone implants. Magnesium has a relatively high corrosion rate in the body (Sunil Kumar et al., 2022; Pradhana et al., 2022). To overcome this shortcoming, magnesium is combined with other elements such as aluminum (Al), zinc (Zn), and chromium (Cr) to reduce the corrosion rate while improving its mechanical properties (Pogorielov et al., 2017; Azni, 2023; L. Wang et al., 2022; Cha et al., 2013; Uddin et al., 2015). Currently,

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Mg alloys with rare earth elements such as lanthanum (La), cerium (Ce), yttrium (Y), neodymium (Nd), and especially gadolinium (Gd) are being developed, which have been proven to slow down the corrosion rate and improve the mechanical properties of magnesium (Mg).

The process of manufacturing magnesium alloys, including Mg-Gd, is generally carried out using the melting alloying method, which involves combining the two metals in a liquid phase using a special melting furnace with a vacuum or protective gas system to prevent oxidation of the liquid Mg-Gd (Sophia Fan, Xu Wang, 2023; Cha et al., 2013; Uddin et al., 2015; Kumar et al., 2018; Xu et al., 2019; You et al., 2017; Prasad et al., 2022). On an industrial scale, the process is carried out using induction furnaces with a capacity of hundreds of kilograms or electric resistance furnaces equipped with an inert gas protection system, as well as molding equipment such as High Pressure Die Casting Machines, Tilting Furnaces, and Holding Furnaces (Hirai & Higashi, 2003). Although very effective on an industrial scale, the capacity of this equipment is too large and unsuitable for laboratory-scale research needs.

Currently, vacuum induction furnaces are not available at Andalas University, especially in metallurgy laboratories. Although research on biodegradable magnesium implants in Indonesia is growing rapidly, it is hampered by a lack of adequate laboratory facilities. This equipment is crucial for the development of magnesium alloys as a base material for biodegradable bone implants. Therefore, the development and manufacture of vacuum casting furnaces is a strategic step to support biomaterial research, enabling the production of high-quality alloys that can be applied as a solution for treating bone fractures in Indonesia.

Method

Figure 1 shows the research flowchart, which begins with a literature review to collect all references related to vacuum induction furnaces. This is followed by the design of a vacuum induction furnace according to the required parameters. The parameters used here are atm. Next, the vacuum melting furnace is built. After that, functional testing of the device is carried out to observe the performance of the vacuum induction furnace. If the parameters are not achieved, the design process is repeated. Finally, the melting results are analyzed and conclusions are drawn. The furnace specifications are designed with a maximum melting capacity of 60 mL, a maximum working temperature of 1020°C, and an electromagnetic induction heating system.

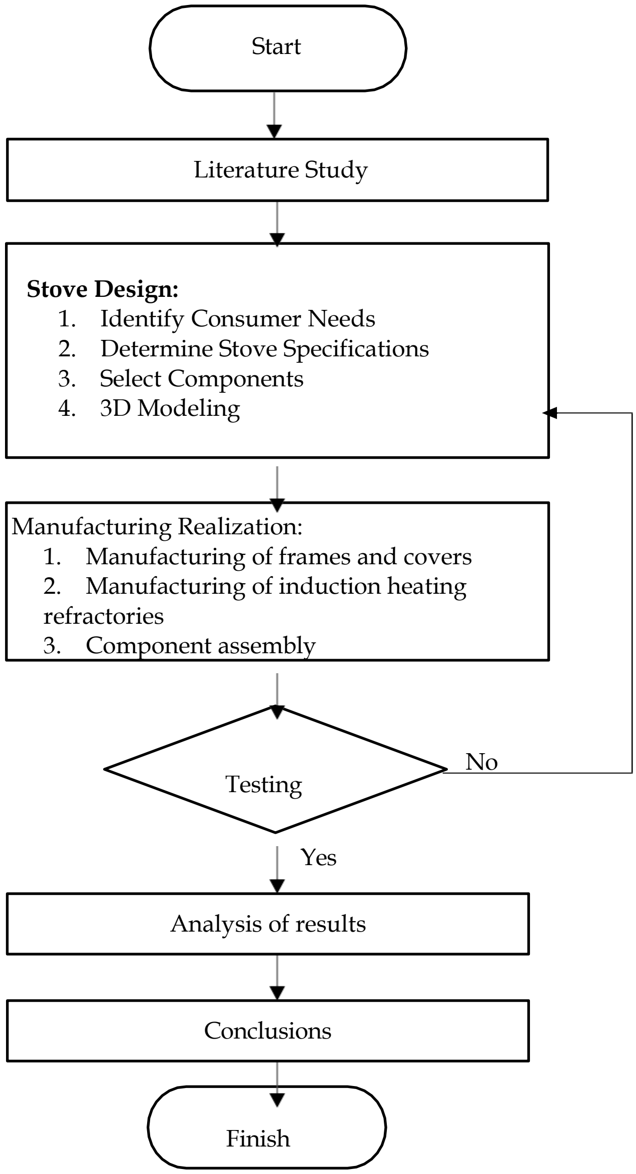

Figure 1. Diagram Alir

Literature Study

Literature study is the activity of collecting all references and materials for this research. The materials for this research were obtained from previous final projects, books, the internet, and scientific journals.

Furnace Design

The design process was carried out by considering the parameters required in the design of a vacuum induction furnace. The furnace design was created in such a way as to meet the required parameters. The design process included:

Identification of Consumer Needs

Information on consumer needs was obtained from discussions with the final project supervisor. Consumer needs include The casting material is magnesium, The casting product is a test specimen with dimensions of 10 cm x 1 cm x 1 cm for 1 mold cavity, and Up to 3 molds can be cast in one melting process.

The vacuum induction furnace uses relatively low 1-phase electrical power, making it easy to use on a laboratory scale. With this vacuum induction furnace, it is hoped that it can be the beginning of the development of easily soluble implant materials.

Determination of Furnace Specifications

Furnace specifications are determined based on consumer needs, and the specifications determined consist of melting capacity and maximum temperature that can be achieved.

Melting Capacity

Based on the identification of consumer needs, the furnace specifications are determined. The material to be melted is magnesium. This melting capacity will later be related to the selection of crucible components to be used. The volume of material to be melted is calculated as follows:

Vproduct = p x l x t (1)

Vproduct = 10 x 1 x 1

Vproduct = 10 cm^3

During the casting process, the material will shrink. For magnesium, the shrinkage is 1%. (Jorstad, 2008)

VTotal = [Vproduct x shrinkage x tolerance] x number of pours (2)

VTotal = [(10 cm^3x 1.01%) x 1.10%] x 3

VTotal = 22.2 cm^3

VTotal = 33.3 mL

With a density of magnesium of 1.74 g/cm^3, the mass of material in a single melting is calculated using the equation:

m = ρ x v (3)

m = 1.74 x 33.3

m = 57.94 grams

Maximum Temperature

Magnesium has a melting point of 650°C. In the casting process, the temperature is generally set higher, around 100°C above the melting point of the material. This is so that the material can melt completely and facilitate the pouring process(Campbell, 2015). Since the induction furnace is designed for the development of easily soluble implant materials, the maximum temperature of the furnace is adjusted to meet the research variables. Therefore, the furnace is designed to reach a maximum temperature of 1020°C.

Result and Discussion

The main frame of the furnace is made of 2 mm thick carbon steel to ensure structural strength and heat resistance. The melting chamber uses a graphite crucible that has high thermal conductivity and is resistant to the chemical reactions of molten magnesium. The heating system consists of water-cooled copper coils connected to a 3 kW ZVS module with a working voltage of 60 V DC. The vacuum system is made of a steel chamber with a rotary vane pump and heat-resistant silicone seals to maintain low pressure during melting. Temperature monitoring is performed using a type K thermocouple sensor connected to an Omron CP1E-N30DR-A PLC as an automatic control system. Temperature monitoring using a K-type thermocouple sensor connected to an Omron CP1E-N30DR-A PLC provides precise, automatic temperature measurement and control in vacuum induction equipment. This system utilizes the Seebeck effect principle of a K-type thermocouple, which generates a voltage signal proportional to the temperature difference, which is then processed by the PLC to control the vacuum and induction processes. The K-type thermocouple sensor consists of chromel and alumel, suitable for temperature ranges up to 1200°C in melting or vacuum induction heating processes. The Omron CP1E-N30DR-A PLC serves as a control center with analog inputs to read thermocouple signals (via a converter if necessary) and digital/relay outputs to control the induction heating element or vacuum pump.

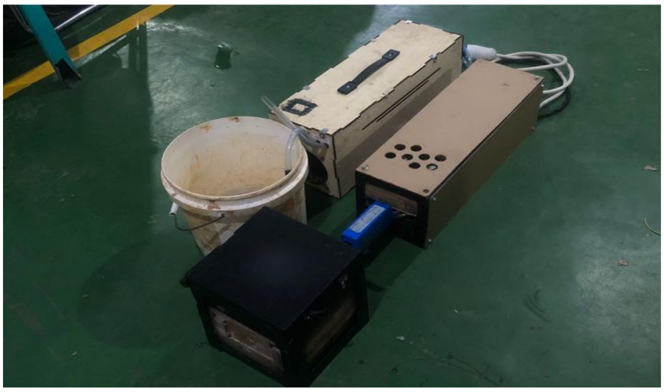

Figure 2. Results of Induction Furnace Manufacture

The test was conducted to determine the furnace's ability to reach high temperatures and thermal stability. The results of temperature measurements over time are shown in Table 1.

Table 1. Increase in vacuum induction furnace temperature over time

Time(minutes)	Temperature(°C)	Heating rate (^{0}C/minutes)
0.00	28.00	-
0.50	322.60	589.20
1.00	564.80	484.40
1.50	743.10	356.60
2.00	855.60	225.00
2.50	940.20	169.20
3.00	1020.00	159.20

From the test results, the furnace was able to reach a temperature of 1020.00°C in 3 minutes with a stability of ±5°C and an average heating rate of 330.67°C/min. This rapid heating is due to the effect of electromagnetic induction, which transfers energy directly to the metal. Although the melting chamber was under vacuum, mild oxidation was detected on the surface of the molten magnesium due to traces of residual oxygen, so a protective flux was still used to minimize inclusions and ensure alloy purity. This result is much more efficient than conventional resistive furnaces, which take up to 20 minutes to reach 900°C with an average heating rate of <50°C/min. The achieved thermal efficiency shows a significant increase in device performance, with a reduction in operating time of up to 85%. These results are in line with research by (Susanti et al., 2020) and (Sulistyawan et al., 2017) who reported improved performance in induction heating systems, particularly in mitigating partial oxidation under partial vacuum conditions for reactive metals such as magnesium. The use of additional flux is recommended for bioimplant applications to prevent biocompatibility degradation.

Hardness testing

Hardness testing was conducted using the Rockwell A scale (HRA) method to determine the hardness and homogeneity of the material produced by melting magnesium (Mg) using an induction furnace. Testing was performed at 12 test points spread across the four long sides of the specimen, with three test points on each side. The average hardness results for each side are shown in Figure 3.

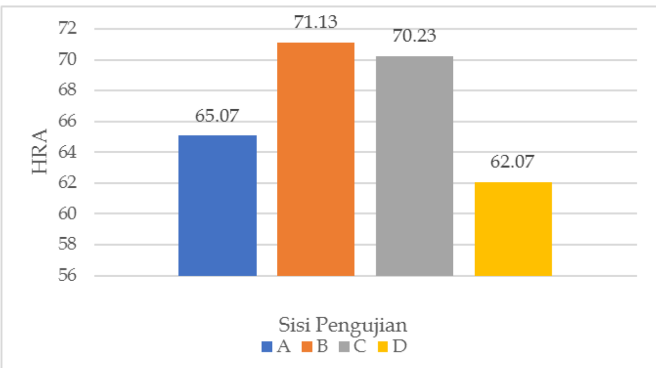

Figure 3. Graph of Average Hardness Values for Each Side (Mg-3%Gd)

From Figure 3, the hardness values of the Mg-3%Gd alloy specimens are shown. It can be seen that the average hardness values on all four sides of the specimen range from 62.06 to 71.13 HRA. The highest value is found on side B (71.13 HRA), while the lowest value is found on side D (62.06 HRA).

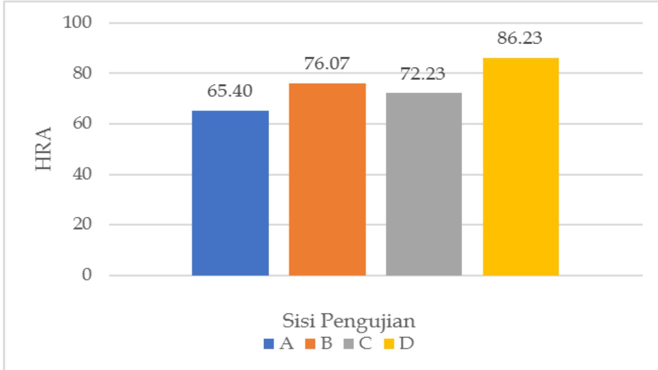

Figure 4. Graph of Average Hardness Values for Each Side (Mg-4%Gd)

From Figure 4. showing the hardness value of the Mg+4Gd alloy specimen, it can be seen that the average hardness value on all four sides of the specimen ranges from 77.3 to 78.23HRA. The highest value is on side D (86.23 HRA), while the lowest value is on side A (65.4 HRA).

Conclusion

The device achieved excellent performance, proven through superior operational parameters. It is capable of reaching a maximum temperature of 1020.00°C in just 3.00 minutes while maintaining a tight temperature stability of ±5.00°C, with a vacuum pressure as low as 0.473 Atm, dramatically minimizing metal oxidation for homogeneous, high-quality magnesium smelting. Without optimal vacuum, smelting previously produced inhomogeneous metal with significant oxidation impurities, but the current vacuum conditions limit oxidation to minimal, manageable levels. Rockwell A hardness testing revealed measurable variations with a strong average of 67.125 HRA for Mg-3%Gd and 74.98 HRA for Mg-4%Gd, demonstrating significantly improved material performance due to improved oxidation control.

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Author Contributions

Conceptualization, M.A.A. and O.S.; methodology, M.A.A.; instrument development, M.A.A.; data analysis, M.A.A.; review and editing, O.S, R, F.I.; supervision, O.S. All authors have read and approved the final version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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