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The Influence of Casting Technology on the Mechanical Properties and Microstructure of the WE43 Alloy for Medical Applications

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Abstract

Melting and casting technologies were developed for the aluminum-free magnesium alloy WE43, which is a promising candidate for biomedical applications due to its high biocompatibility. The alloy was melted in a steel crucible under a protective high-purity argon atmosphere at approximately 710°C to prevent oxidation. To evaluate the influence of the casting method on the final properties of the material, samples were prepared using three different technologies: from ingots, from castings produced by gravity casting into a steel mold, and from components obtained by high-pressure die-casting using a horizontal cold-chamber machine. The prepared samples were subjected to chemical composition analysis, non-destructive testing, mechanical characterization (hardness and tensile strength), and detailed microstructural evaluation using optical and electron microscopy. The results demonstrated that the alloy exhibited tensile strengths in the range of 100–200 MPa and porosity between 1.0–2.6%, while the microstructure was refined as a result of the applied casting techniques. The aim of this study was to identify the optimal production route to ensure the alloy's highest possible quality and performance of the alloy for biomedical use. Based on a comparative analysis of all the test results, the most suitable form and processing conditions of the WE43 alloy were determined for further development as the matrix material in an innovative, biodegradable magnesium-based biomaterial.

Keywords: Mechanical properties, Non-destructive testing, WE43 magnesium alloy, Microstructure, Biomaterial

1. Introduction

Engineering materials are increasingly being used as biomaterials in medicine. Thanks to advances in science and technology, they are being used more widely in the manufacture of a wide range of medical devices, such as equipment, tools, and implants. Although only implants are implanted into the human body, selecting appropriate materials remains a key factor in designing this group of medical devices. Materials used in medicine must meet a few specific requirements related to the nature of their application. The main requirements include: biocompatibility, bioactivity, biofunctionality, appropriate physical and mechanical properties, corrosion and abrasion resistance, sterilizability, biodegradability or bioresorption, as well as thermostability. Currently, the most used alloys in reconstructive medicine are titanium (e.g., Ti-6Al-4V) [1], cobalt (e.g., Co-Cr-Mo) [2], and stainless steel (e.g., 316L) [3]. While they have excellent mechanical properties and corrosion resistance, they have disadvantages, such as stress shielding and the release of toxic metal ions [4]. Therefore, there is a justified need to replace the currently used implants based on titanium, cobalt, or stainless steel.

Magnesium and its alloys are a promising alternative. They are fully bioresorbable, biocompatible, and biodegradable, as indicated in the literature [5-10].

Based on a literature review, the magnesium alloy WE43 was selected for testing. Due to its excellent mechanical properties, WE43 is often used in the automotive, aviation, and aerospace industries. Its use in the medical industry has been the focus of many studies over the past few years, with some of these studies looking at its use in implants [11-15].

The WE43 alloy does not contain aluminum in its chemical composition, so it is non-toxic and fully biocompatible, making it a great alternative to biomaterials used in orthopedics. Biomaterials intended for bone implants should have mechanical and structural properties similar to those of natural bone. The material should have a strength of at least 100 MPa and a Young's modulus in the range of 10–30 GPa to minimise the stress shielding effect. The microstructure should be homogeneous and fine-grained, contain stable and biocompatible phases, and be free of large defects to ensure high strength, fatigue resistance, and effective biological integration with bone.

2. Materials and methodology

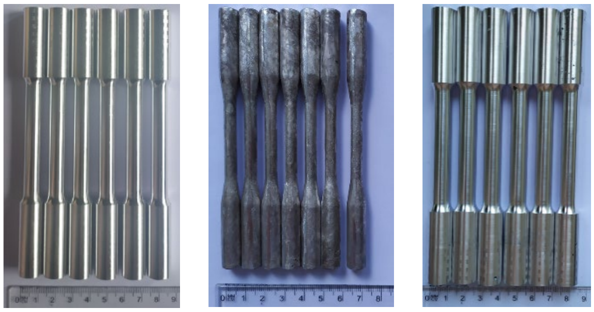
2.1. Materials

The material tested was a WE43 magnesium casting alloy. The alloy was purchased from Hilbo Magnesium Alloy Material Co., Limited (China) in the form of ingots. As part of the project, a melting and pouring technology for WE43 alloy was developed. The melting process was carried out in a CZYLOK electric resistance furnace with an approximate capacity of 15 kg. Before being loaded into the furnace, the metal charge was heated to a temperature in the range of 100-150°C for approx. 1 hour. Once the crucible reached the set temperature, the tested alloy was loaded into a steel crucible. During smelting, the temperature of the metal charge and then the liquid alloy was continuously monitored. During smelting, the furnace was covered with a special lid to prevent additional gasification and reduce the risk of the alloy igniting. Due to its intended use in medicine, no anti-flaming salts were used. After melting, the temperature of the liquid metal was maintained at approx. 700-715°C. The crucible was also covered between individual pours.

One type of casting was prepared using high-pressure die-casting technology. Castings in the form of strength test bars (in the so-called "ready-made" mode) and samples for determining hardness were cast on a cold-chamber horizontal high-pressure die-castings machine from the Swiss company BÜHLER with a clamping force of 1600 kN. The research station for melting experimental alloys and casting on the high pressure die-casting machine is in the laboratory hall of the Łukasiewicz Research Network - Krakow Institute of Technology. To conduct the research, ten HPDC castings were made, producing 20 samples in total.

The second type of castings was obtained using gravity casting technology into a metal (steel) mold. For the tests, eight die castings were cast for strength testing and three so-called cube castings for other tests.

The HPDC and mold castings obtained were further machined (cutting, turning) to prepare the samples (see Fig. 1) for further testing.



a) b) c)

Fig. 1. Samples of the WE43 alloy: a) ingots, b) HPDC castings, c) mold (steel mold) castings

The samples were then subjected to chemical, mechanical, non-destructive, and microstructural testing. These tests were performed at the Łukasiewicz Research Network – Krakow Institute of Technology in Krakow, Poland. To ensure the reliability of the results, the tests were carried out on at least three samples of the same type of material. The results obtained were compared with literature data and normative requirements to assess their compliance.

2.2. Chemical composition and microstructure

Chemical composition tests were performed using a GNR S3 Minilab spark spectrometer. Samples prepared from ingots and experimental castings were tested.

Microstructures were observed using an AxioObserver Z1m light microscope and a FEI SCIOS scanning electron microscope with the following parameters: accelerating voltage of 20 kV and a BSE detector. The elemental composition in selected microareas was determined by EDS X-ray microanalysis using an EDAX microanalyser with the TEAM v.4.4 system.

The phase composition of the WE43 alloy was analysed by X-ray diffraction (XRD) using a PANalytical Empyrean device, a PiXcel3D detector with an ICDD PDF-4+2023 database, using the following parameters: measurement time: 1h, measurement range: 10-100, copper lamp: 45kV/40mA. Samples in the form of 30x30x10mm cubes were used for the analysis. The measurements were performed in step scan mode with recording of the intensity of the reflected beam as a function of the 2θ angle. For each sample, one scan was performed over the full angle range.

2.3. Mechanical properties

The mechanical testing included a static tensile test and a Brinell hardness test. The static tensile test was performed on an EU-20 device. Cylindrical samples were prepared in accordance with PN-EN ISO 6892-1:2020-5. The test was performed at ambient temperature. The purpose of the test was to obtain data on the mechanical properties of the material, such as yield strength, tensile strength, and relative elongation. The tensile test consisted of uniformly stretching the sample in the direction of its length until it broke. During the test, two basic variables were recorded: the force acting on the sample and its elongation, which were recorded using a measuring system. The behavior of the material was observed, the characteristic points on the force-elongation curve, including the yield strength and the maximum tensile strength.

Hardness testing was performed using the BH025.HZHU.3000.00 hardness tester, in the Brinell hardness test. Tests were conducted under a load of 612 N and a penetrator core diameter of 2.5 mm. The samples were prepared in accordance with the requirements of PN-EN ISO 6506-1:2014-12. The samples were machined to obtain the appropriate surface smoothness and cleaned prior to testing to remove any surface contamination and impurities. The samples were placed on the hardness tester's worktable so that the measurement area was parallel to the working surface of the device. Then, the carbide ball was lowered onto the sample surface, exerting a force in accordance with the test assumptions. The loading process lasted 10 seconds, after which the force was relieved, and an impression of the ball remained on the sample surface.

2.4. Non-destructive testing

Computed tomography (CT) scans were performed using a GE V|TOMEX|L-450 X-ray computed tomography scanner with the following exposure parameters: voltage 90 kV, current 100 µA, exposure time 500 ms, voxel size: 29.3 µm/vox. The analysis was performed using VGStudioMax 2022 software.

Radiographic (RT) examinations were performed on a YXLON MU2000 device using the following examination parameters: voltage: 80 kV, current: 5.6 mA, and detector sensitivity: 6%.

Porosity (P) was measured by weighing the samples in air and in water, calculating their density, and then converting the porosity according to the following formula:

$$P = \frac{\rho_t - \rho_p}{\rho_p} \times 100\% \quad (1)$$

where:
P – porosity,
ρ_t – theoretical density,
ρ_p – real density.

Cylindrical WE43 alloy samples were subjected to non-destructive testing. The presence of discontinuities such as pores, eutectic phases, cracks, and inhomogeneities was assessed. RT testing provided a rapid, non-destructive evaluation of the material's internal condition, identifying potential defects such as cracks, pores, and undercuts. CT testing, on the other hand, allowed for a detailed, three-dimensional analysis of the structure, enabling quantitative determination of the parameters of internal defects and their distribution within the sample volume.

3. Results

3.1. Chemical composition and microstructure

Table 1 shows the chemical composition of the WE43 alloy as defined by the standard, alongside the results of the tests conducted on the samples.

Table 1.
Chemical composition WE43 alloy, wt. %

	Y	RE	Zr	Mg
Standard Range	3.7-4.3	2.4-4.4	0.4-1.0	rest
Actual Composition	4.0	3.5	0.5	rest

Observation of the microstructure revealed the presence of segregations at the boundaries of grains. Both casting technologies resulted in grain refinement of the observed microstructures. Figure 2 shows the microstructure selected for the tested samples.

a)
b
)
c)

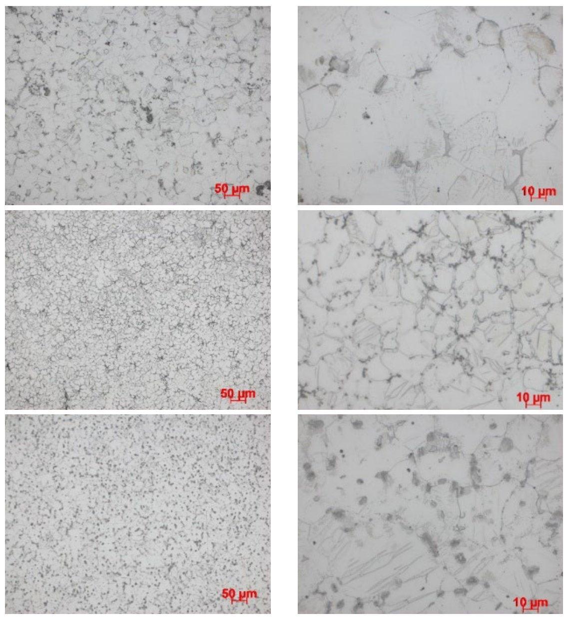


Fig. 2. The microstructure of the WE43: a) ingots, b) HPDC castings, c) mold (steel mold) castings

HPDC is characterized by its fine grain and evenly distributed intermetallic phase precipitates. This is the result of the alloy solidifying rapidly under high pressure. Compared to HPDC, mold casting has an intermediate grain size, with slightly larger precipitates indicating the slower cooling rate typical of gravity casting. Ingots have the largest grain size, with visible, elongated precipitates along the grain boundaries resulting from the slowest solidification process.

The aim of the XRD study was to identify the phases present in the WE43 alloy samples using X-ray diffraction. Fig. 3 shows the obtained diffractograms, on which the analyzed phases are indicated: α-Mg, $Mg_{41}Nd_5$, $Mg_{12}Nd$ and $Mg_{24}Y_5$. Analysis of the

XRD spectrum of the WE43 alloy showed that the dominant phase is the hexagonal α-Mg phase. Its intense peaks were located in the vicinity of 32°, 34°, 36° and 47° 2θ, among others. Additionally, characteristic peaks of intermetallic phases containing rare earth elements, which are typical of Mg–Y–Nd alloys, were identified. Additional visible reflections in the range of 25–40° and 55–75° suggest the presence of the $Mg_{12}Nd$ and $Mg_{24}Y_5$ phases. The absence of Zr-rich phases is consistent with their very low content and typical invisibility in standard X-ray diffraction.

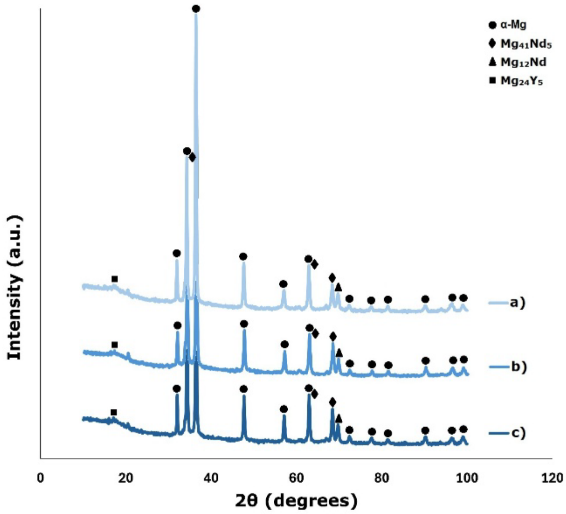


Fig. 3. XRD pattern of the WE43 alloy: a) ingots, b) HPDC castings, c) mold (steel mold) castings

SEM testing enabled the microstructure and morphology of the samples to be evaluated. EDS analysis revealed the presence of elements (e.g. Mg, Y and Nd) in the tested microareas, as well as their relative weight and atomic content. This indicates the presence of eutectic phases. These two methods complemented each other by providing information on the structure and chemical composition of the tested material. Selected results are presented in Figure 4.

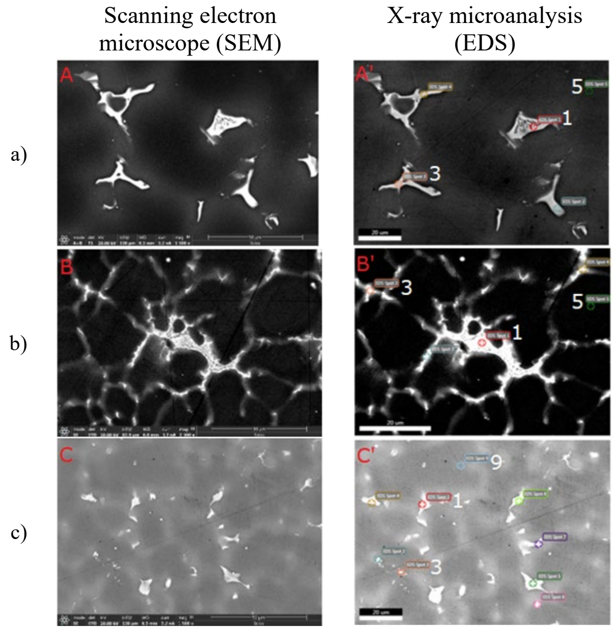


Fig. 4. SEM and EDS analysis of the WE43: a) ingots, b) HPDC castings, c) mold (steel mold) castings

Table 2 presents the table of chemical composition for selected microareas.

Table 2.
EDS results of the experimental castings, wt. %

Locations	Elements					Σ
	Mg	Y	Nd	Gd	Zr/Si*	
Fig. 4A', spot 1	58.97	8.20	25.24	7.59	-	100
Fig. 4A', spot 3	59.11	7.82	24.84	7.34	0.9*	100
Fig. 4A', spot 5	100	-	-	-	-	100
Fig. 4B', spot 1	68.61	8.99	15.81	6.59	-	100
Fig. 4B', spot 3	74.48	7.39	12.63	5.50	-	100
Fig. 4B', spot 5	100	-	-	-	-	100
Fig. 4C', spot 1	60.49	7.65	24.94	5.92	-	100
Fig. 4C', spot 3	81.26	11.74	2.14	-	4.86	100
Fig. 4C', spot 9	100	-	-	-	-	100

3.2. Mechanical properties

Main material properties such as tensile strength, yield strength and elongation were determined and presented graphically in Figure 5 based on the analysis of the tensile test results. Samples prepared using casting technologies exhibit lower strength properties than samples prepared from ingots. Samples made using high-pressure die-casting exhibit higher properties than those made using gravity casting. However, the strength properties of the material were considered suitable for medical applications for both technologies. The lower mechanical properties of the cast samples should be interpreted with caution, as they are strongly influenced by specimen geometry and preparation method.

Based on the HBW hardness test results (Fig. 6), it was determined that the WE43 alloy billet material has an average hardness of 69. Cast samples show a slight decrease in value (HPDC - 68 and mold - 65) compared to billet samples. The hardness of the material is considered suitable for temporary, biodegradable, orthopedic applications (cortical bone ~15-40 HBW).

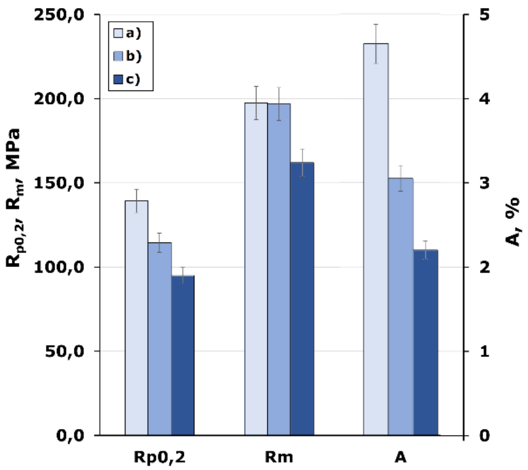


Fig. 5. Strength properties results of the WE43 alloy: a) ingots, b) HPDC castings, c) mold (steel mold) castings

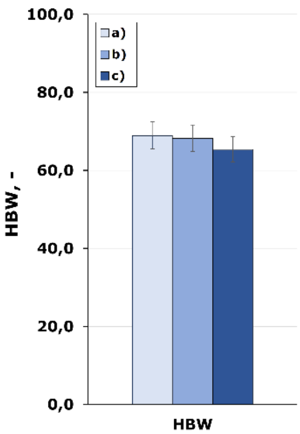


Fig. 6. Hardness results of the WE43 alloy: a) ingots, b) HPDC castings, c) mold (steel mold) castings

3.3. Non-destructive testing

The aim of the research was to non-invasively image the internal structure and identify possible material discontinuities in the tested samples using industrial radiography (RT) and computed tomography (CT) methods.

Porosity testing using the Archimedes method showed the presence of porosity in the tested samples at a level of 1.0-2.6% (Fig. 7). Casting technologies significantly reduced the porosity of the samples. HPDC is a casting method that is susceptible to gas porosity (air bubbles). Typical values can range from 0.5% to 3% by volume, depending on process optimisation and mold geometry. Although gravity casting processes often have lower gas porosity, shrinkage porosity may be present in the feed areas of the casting. Radiographic testing (RT) confirmed the presence of porosity in the tested samples. The surface of the samples was free from cracks, other continuity defects, and casting defects. Computed tomography (CT) revealed a homogeneous material structure with few pores. The pores are irregular in shape and distributed irregularly throughout the sample volume. The presence of porosity is typical for casting technology. The absence of visible cracks and foreign eutectic phases indicates good material homogeneity.

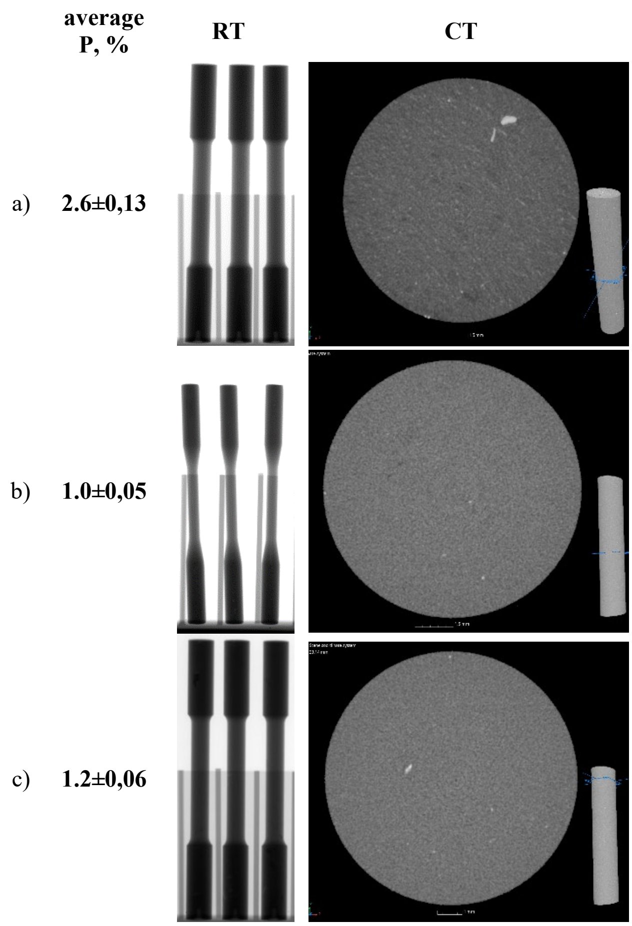


Fig. 7. Non-Destructive Testing results of the WE43 alloy: a) ingots, b) HPDC castings, c) mold (steel mold) castings

Non-destructive testing using RT and CT methods provided complementary information on the internal quality of the tested samples. RT radiography enabled a quick assessment of homogeneity and detection of defects. CT, on the other hand, provided detailed, three-dimensional information on the distribution and shape of defects. Although small, the porosity found may affect the strength and fatigue resistance properties of the material. Both methods confirmed the high quality of the material in terms of the absence of cracks and large inclusions.

4. Conclusions

The analysis of the research results obtained allows for the following conclusions:

(1) Properly developed melting and pouring technology for the WE43 alloy did not show any changes in the chemical composition of the cast samples.
(2) The cast samples had a refined microstructure due to the casting technologies used.
(3) The microstructure of the WE43 alloy consists of the following phases: α-Mg, $Mg_{41}Nd_5$, $Mg_{12}Nd$ and $Mg_{24}Y_5$.
(4) The mechanical properties of the cast samples are lower than those of the ingot samples. However, for both technologies, the mechanical properties of the material were considered suitable for medical applications (temporary, biodegradable, orthopedic implants).
(5) Cast samples are characterised by lower porosity than samples from ingots. Non-destructive testing ruled out the presence of other discontinuities and casting defects.

The present results do not allow any direct biological conclusions to be drawn. This assessment is limited to a preliminary mechanical evaluation and requires further studies to address degradation behaviour and the biological response (future work).

Based on the comparative analysis performed in this study, the cast WE43 alloy produced using the developed melting and pouring technology was identified as the most suitable material form for further development toward biomedical applications. This processing route ensures chemical stability of the alloy, a refined microstructure, low porosity, and mechanical properties considered adequate for temporary biodegradable orthopedic implants. Therefore, within the scope of the present work, casting under controlled melting and pouring conditions can be regarded as the optimal production route for the WE43 alloy intended for further biomaterial-oriented investigations.

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