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RESEARCH

Cavitational Erosion Behavior of a Biodegradable Alloy from the Zn-Mg System for Biomedical Applications

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A B S T R A C T

Zinc and magnesium are known to be biocompatible metals. For this reason, current technologies seek to build parts to be implanted in various places to help the human body. Among these are those in the blood circulatory system, such as the stars and valves at the heart, which aim to increase the life span of the hydrodynamic shocks of the blood circulatory system, in order to prevent heart attacks, respectively the bursting of various vessels that can be life-threatening. Studies in the field of flow show that even in the human body there are manifestations of cavitational type, as a result of pressure variations, with decrease below that of vaporization and then increase. Starting from these findings, the paper presents the results of the cavitation tests, carried out on the bicocompatiobil ZnMg alloy, created in Politehnica University of Bucharest laboratories. The objective is a new and future one that will lead to the realization of valves for the heart, or stars, that can withstand the shocks produced by the implosions of the cavitational bubbles in the blood. For this purpose, microstructural investigations are performed, mechanical properties are analysed and the behavior and resistance to erosion generated by vibrating cavitation are studied, according to the reference standard ASTM G32-2016. The results, compared to those of pure zinc, show that this alloy is a solution for building biocompatible components that can serve cardiac people, in order to reduce the harmful effects of the blood circulatory system.

1. INTRODUCTION

Biodegradable metals and alloys have been researched lately, considering that they can completely dissolve after fulfilling the mission of supporting or helping to heal tissues and organs, without the need for the expensive secondary surgical operation for revision [1]. Next to the previously developed Mg and Fe based biodegradable alloys, Zn based biodegradable alloys have aroused the researcher's wide interest and attention because they have

overcome the major concerns and disadvantage found in Mg and Fe-based biodegradable materials: the degradation rate too fast of Mg-based alloys [2] and too slow degradation rate of Har-based alloys [3]. Alloying Zn with different metallic materials can improve both mechanical properties and other important properties for the human body [4] . Zn-Mg binary alloys are a reasonable alternative to Mg alloys for implant applications. Previous research on biodegradable materials has focused mainly on Mg or Fe, as well as their alloys [5]. However, the very crucial feature of these materials is not optimal. Mg corrodes too quickly in the human body – it is resorbable before the damaged tissue heals. However, Fe has a low corrosion rate and, as a result, is in contact with the tissue much more than necessary. This creates a special opportunity for Zn with Mg, creating a improved corrosion resistance and high mechanical properties [6,7]. Therefore, for Zn-Mg binary alloys it becomes necessary to further increase the mechanical properties of Zn-Mg casting alloys, which has been attempted,with moderate results, in many publications by a combination of plastic deformation with heat treatment [5- 11]. Therefore, the authors of this paper proposed a more efficient way to increase the properties of Zn-Mg binary alloys by pre-forming the casting material combined with another severe plastic deformation (SPD) obtained by cold cumulative hydrostatic extrusion (HE). This approach is supported by widely confirmed facts that biodegradable metals, due to their mechanical properties, are more useful for highly loaded biodegradable implants than polymeric materials [12,13]. Vojtech et al. [14] studied the mechanical properties and in vitro biodegradation of cast Zn-Mg binary alloys in the Mg content range from 0.5 to 3 wt%. They found that the corrosion rate for binary Zn-Mg alloys, while not changing significantly the percentage of Mg, is much lower compared to Mg alloys. Their strength and elongation reached 190 MPa and 1.8% at 1% Mg and decreased above this value. This was due to an excessive amount of brittle eutectic phase. Such low elongation is insufficient for many applications of biodegradable implants. In addition, Zn-Mg castings are characterized by a natural tendency to create a heterogeneous microstructure, which favors heterogeneous corrosion in places that include rapidly corroded Mg. Therefore, considering the mechanical properties, homogeneity of biodegradation and typical cytotoxicity of most alloys binary Zn-Mg intended as initial material for biodegradable implants, in recent years a combination of cast material with the possibility of subsequent deformation has been looking [14-19].

Starting from the cavitation problems encountered with biodegradable vascular stents, in the present paper we propose a new composition for the Zn-Mg alloy, which we compare with pure Zn for cavitation filling.

2. METHODOLOGY AND RESERCH

In this work, two metallic materials were studied, respectively a pure zinc metal and an alloy with a specially designed composition from the Zn-Mg system.

The alloy was developed considering the Zn-Mg system, in a crucible flame furnace at 650°C using elements of advanced purity, respectively Zn 99.99%, magnesium 99.99% and calcium 99.99%. Casting was done in stainless steel ingot. The resulting chemical composition was Zn = 97.68%; Mg = 1.458%; Fe= 0.589%; Mn = 0.086%; Cu= 0.09%: Si= 0.065%; Al=0.032%. The dimensions of the experimental ingots were 20x20x200 mm. Microstructural investigations were carried out on the experimental samples to identify the phases and microstructural constituents .The mechanical hardness characteristics were determined. The metallographic analysis to determine the metallographic phases and constituents was carried out on an Olympus type metallographic microscope, and an Olympus SZX type stereomicroscope, equipped with QuickMicro Photo 2.2 software.

2.1 Cavitation test and method

The cavitation erosion test program was conducted on the piezoceramic crystal vibrator, fig.1, of the Cavitation Erosion Research Laboratory, within the Timișoara Polytechnic University, respecting the international requirements contained in ASTM G32-2016 [20]. The functional parameters of the device are standard, according to the provisions of ASTM G32-2016 (power of the

electronic ultrasound generator = 500 W, vibration amplitude = 50 μm, vibration frequency = 20 μm ± 0.1 kHz, sample diameter = 15.8 mm). The tests were carried out in distilled water at a temperature of 22 ± 1^{0}C, using the indirect method with a stationary sample (the distance between the vibrating surface of the sonotrode and that of the surface of the tested sample = 1.0 mm).

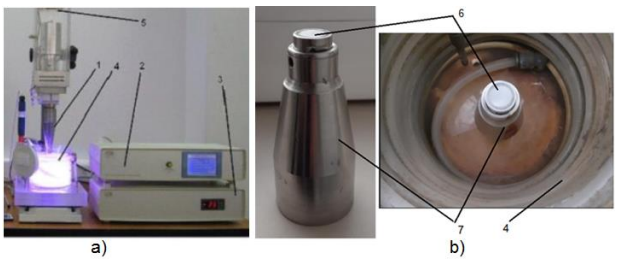


Fig. 1. The vibrating device with piezoceramic crystals: a) vibratory device; b) sample fixture for testing by the indirect method;1- sonotrode; 2- the electronic ultrasound generator; 3- electronic device for regulating the water temperature; 4- the container with liquid and the cooling coil; 5- the piezoceramic transducer of 20 KHz and 500 W; 6- sample for cavity testing (d= 15.8 mm, length = 18 mm); 7- sample fixing device for carrying out the experimental test.

The total duration of the cavitation application, according to laboratory custom [21-26], was 165 minutes, divided into 12 periods (each of 5 and 10 minutes and 10 of 15 minutes each). Before the start of the test and at the end of each intermediate period, the samples were washed in a stream of potable water from the network, in distilled water and acetone, dried in a stream of hot air, weighed with the Zatklady analytical balance, which has an accuracy of 10^{-5} g, and the cavitated surface was photographed with the Canon Power Shot A480 camera. Three samples were tested from each type of material.

The mass losses, determined at the end of the intermediate period, were used to determine the average erosion depth MDE and the related velocity MDER [21,27-30]. With the help of these values, the specific cavitation erosion diagrams in fig.4..7. For the accuracy of the results, the upper (S) and lower (I) limits of the dispersion band were defined for the experimental values of the MDE parameter (fig.4 and 6), which correspond to the tolerance intervals shown inside the diagrams. Also for the accuracy of the experiment, the diagrams in fig. 4 and 6 the standard deviation values .

The two limits S and I, the standard deviation and the degree of precision (tolerance) were determined with statistical relationships, according to [21,22,24,30].

As can be seen in the 4 diagrams, using statistical mathematics and the Matchad program, the averaging curves of the experimental values obtained for MDE and MDER are constructed. The relationships used have the forms established in the cavitation laboratory [28,29]:

- for the cumulative average depth of erosion penetration

$$MDE\ (t) = A\cdot t\cdot(1-e^{-B\cdot t}) \quad (1)$$

- for the average rate of erosion penetration

$$MDER(t) = A\cdot(1-e^{-B\cdot t}) + A\cdot B\cdot t\cdot e^{-B\cdot t} \quad (2)$$

where:

A - is the scale parameter;

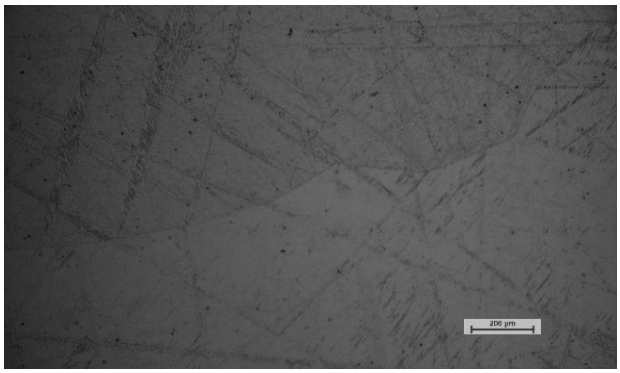
B - is the shape parameter of the curve.

3. EXPERIMENTAL RESULTS AND THEIR INTERPRETATION

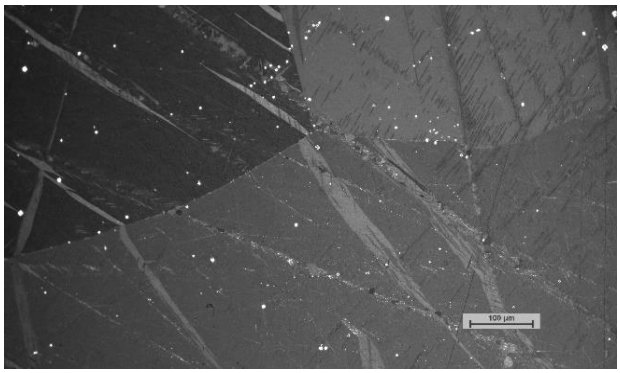
3.1 Structural analysis

The quantitative and qualitative metallographic analysis was carried out using an Olympus type metallographic microscope. The results of the metallographic analysis are shown in figure 2, for pure zinc and figure 3, for the Zn-Mg alloy. The microstructure of pure zinc, figure 2, indicates an aspect with large, mottled, differently colored grains. Thealloy in the Zn-Mg system is an alloy formed from a α solid solution based on inhomogeneous zinc and an intermetallic compound Mg_2Zn_{11}, as illustrated in figure 3. The cast structures are dendritic segregated, in which the dendritic arms are influenced by the solidification conditions . In the detailed image, fig. 3b, main dendritic arms of about 50-100 μm can be observed, with an in homogeneous aspect. The eutectic formed from solid solution and intermetallic compound has a lamellar, interdendritic appearance.

The results of determining the HB hardness characteristics are shown in table 1. It is noted that by alloying with magnesium the hardness of the pure metal can increase more than three times, respectively from 22 HB, reaching a value of 74 HB in Zn-Mg alloy.

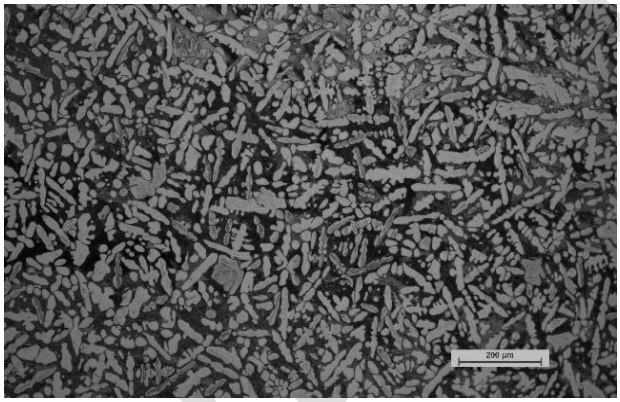


(a)

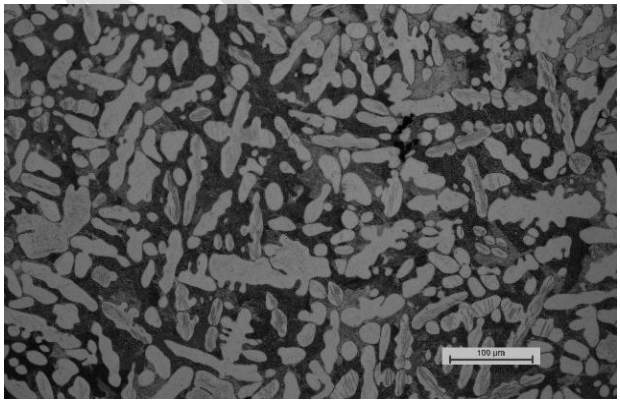


(b)

Fig. 2. Structural analysis of Zn samples , nital attack 2%: (a) - 8, (b) - detail of image a.



(a)



(b)

Fig. 3. Structural analysis of Zn-Mg alloy samples, 2% nital attack: (a) - 8, (b) - detail of image a.

Table 1. Brinell hardness values of the experimental samples.

Metallic material	State	Hardness HB
Zn	Cast	22
Zn-Mg	Cast	74

3.2 Curves and parameters specific to cavitation erosion

Fig. 4 and Fig. 5 represent the diagrams characterizing the behavior and resistance to vibrating cavitation of zinc, and fig.6 and 7 that of the ZnMg alloy.

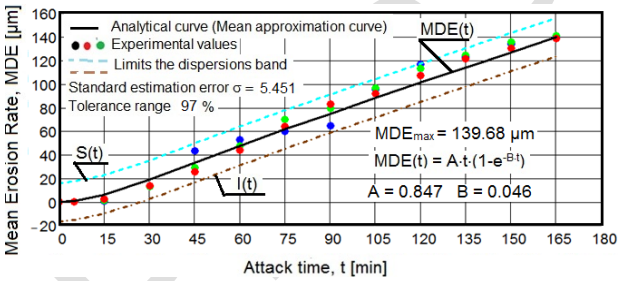


Fig. 4. Variation of the average cumulative depth with the duration of cavitation (control Zn).

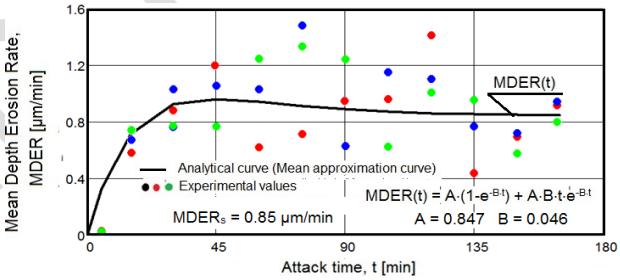


Fig. 5. Variation of the average erosion penetration speed with cavitation duration (Zn control).

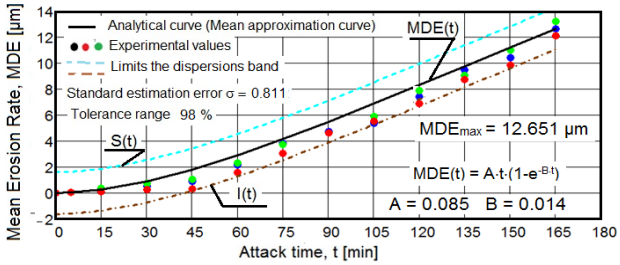


Fig. 6. Variation of the cumulative average depth with cavitation duration (ZnMg control).

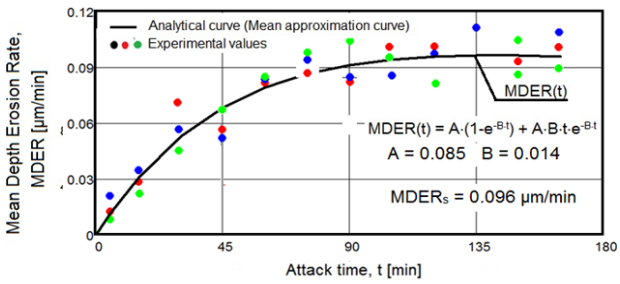


Fig. 7. Variation of the average erosion penetration speed with cavitation duration (ZnMg control).

The data in fig. 4-fig.7 show:

- the values of 97% and 98% of the tolerance intervals, as well as 5.451 and 0.811 of the mean standard deviation σ, confirm the rigorous control of the hydrodynamics of the cavitation, due to the fact that the entire process is followed by the computer through a software built in the cavitation laboratory [21,22,24,27,30]. The value of σ is 5,451 is natural due to the very high losses recorded throughout the cavitation period, respectively from the end of each intermediate period (see the photographic images in fig. 8 and the microscopic images in fig. 2-3.),
- a very weak behavior and resistance of zinc, given by the large differences between the experimental values of the three samples (see fig.5) and the very high values of the erosion depth (increasing with the increase in the duration of the cavitation attack) (fig.6). This mode of behavior is disadvantageous for the creation of stents and valves used in cardiac surgery, due to destruction in a short time (and assimilation by the body due to the biodegradable property), as a result of uncontrolled pressure variations in the blood circulatory system. Based on the experiences and results from the literature [22,24-28,30-32] we appreciate that the reason for the weak resistance of the zinc microstructure and the low values of the mechanical properties (see table 1) that do not provide resistance to the forces developed by the impact pressures of the surface with cavitational microjets,
- the Zn-Mg alloy (fig. 6 and 7) has a much more homogeneous dispersion of the values obtained on the three experimental samples compared to the averaging curves, with differences between them, much reduced, compared to those obtained on pure zinc (fig. 4 and 5). This aspect shows the importance of alloying zinc with magnesium for the manufacture of biodegradable devices, for protecting the cardiac system (veins and heart) against sudden pressure variations and for homogenizing the hydrodynamics of the blood flow, through the implantation of stents and valves. We attribute this behavior and increase in strength to the microstructure resulting from alloying (see the photographic images in fig. 8 and the microscopic ones in fig. 3) and to the increased values of the mechanical properties, especially for hardness (see the table 1).

In the table 2 the values of the parameters MDE_{max} and $MDER_s$ necessary for the comparative evaluation of the resistance to cavitation of the two metals are displayed. The data in table 2 show that the alloy between zinc and magnesium leads to a very high increase in the resistance to cavitation erosion, compared to that of pure zinc: about 11 times according to the ratio between the values of MDE_{max} and about 8.8 times, according to the ratio between the values of $MDER_s$. So these data show that, for devices used in cardiac cardiology, such as stents and valves, the use of an appropriate combination of biodegradable alloys, such as the one studied in this work, increases the lifetime of the device, with a beneficial effect on the patient's cardiac stability .

Tabel 2. Values of the characteristic parameters of resistance to cavitation erosion.

Parameter	Material	
	Zinc	ZnMg
MDE_{max} [μm]	139.68	12.651
$MDER_s$ [μm/min]	0.85	0.096

MDE_{max} – the value defined by the MDE(t) curve at the end of the cavitation duration (165 minutes); $MDER_s$ – the value defined by the MDER(t) curve at 165 minutes, known as cavitation erosion intensity stabilization [21,22,24,27,30]

3.3 Morphology of the eroded microstructure

Fig.8 shows images of the evolution of the erosion produced in the surfaces of two samples (randomly selected) of zinc and Zn-Mg alloy, at four durations of cavitation attack.

The statements made during the analysis made on the data from the diagrams in fig. 4...7 are confirmed by these photographic images and complemented by the microscopic ones in fig. 2 and fig. 3.

Are very well observed the deep and wide caverns produced in the zinc sample and the small size (fine pinches) produced in the Zn-Mg alloy. It is observed that as the duration of the cavitation attack increases, the cavities in the zinc samples widen and deepen, and those in the alloy multiply, but the dimensions do not increase excessively. From the point of view of the hydrodynamics of the flow in the circulatory system, the use of zinc stents is disadvantageous for two reasons: 1- because it degrades quickly, and 2- because these caverns change the configuration of the hydrodynamic field, generating strong turbulence and more pressure

variations [31,33,34], with effects that can become problematic (even destructive) for the cardiac stability of the patient.

The results of the stereomacrostructural analysis are shown suggestively in the images in fig 9 and 10 as well as in table 3. It is noted that the cavitation-attacked surface of the zinc samples indicates a massive cavitation attack, on a surface of 94%, and the area most affected by the cavitation attack is about 76%. In the Zn-Mg alloy, the surface affected by cavitation is slightly reduced, to about 81% and the surface most affected by cavitation attack is similar, respectively 74%. The aspects captured at 25 times magnification show a fragile, shiny crystalline aspect, with flattened caverns, extended in the case of pure zinc. In the case of the Zn-Mg alloy, the appearance is still shiny crystalline, but with the presence of some caverns with reduced dimensions.

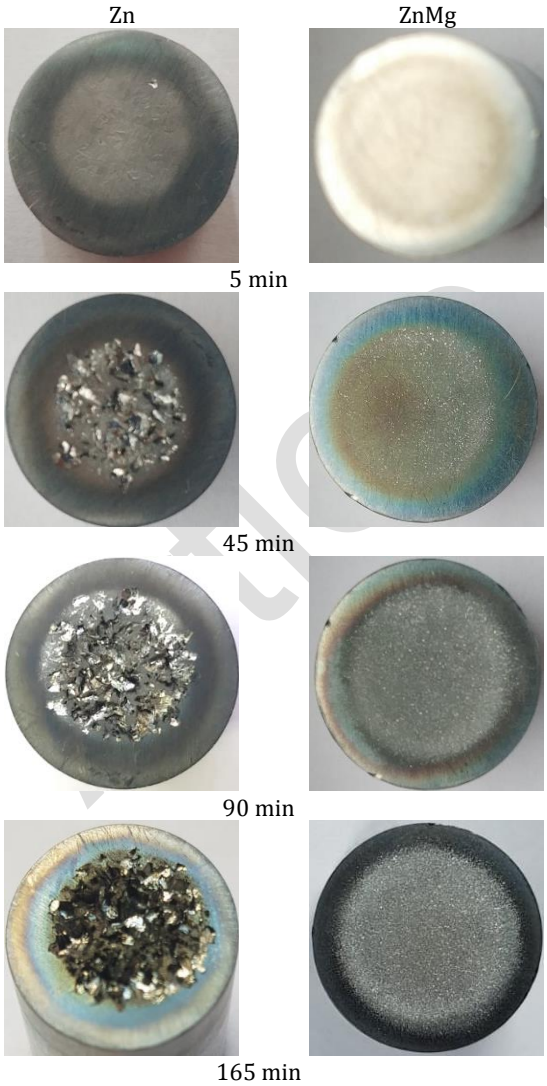
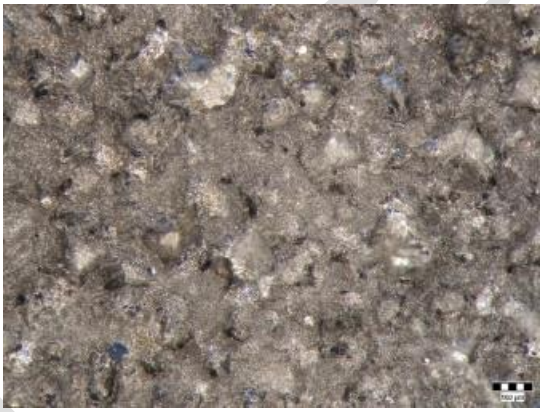


Fig. 8. Macrofractographic images of the experimental samples after different durations of cavitational attack.

(a)



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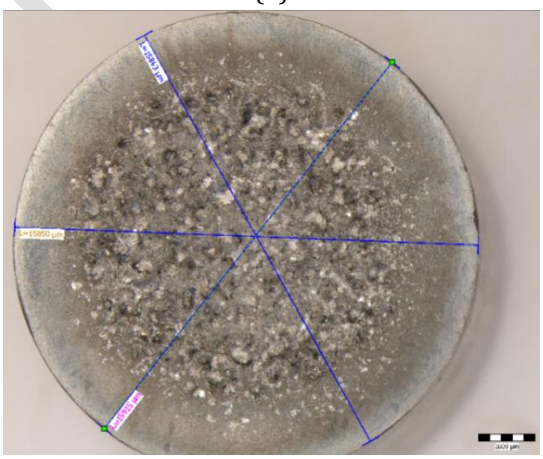

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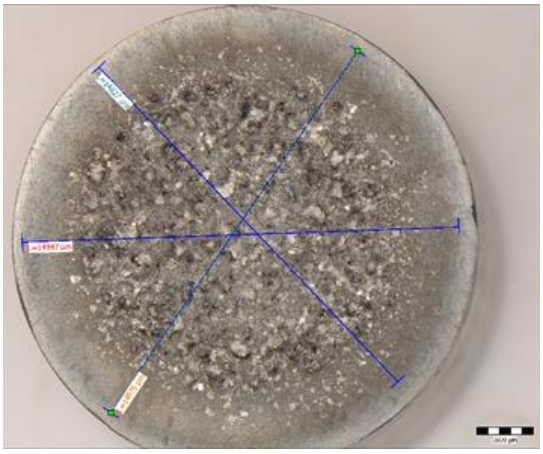
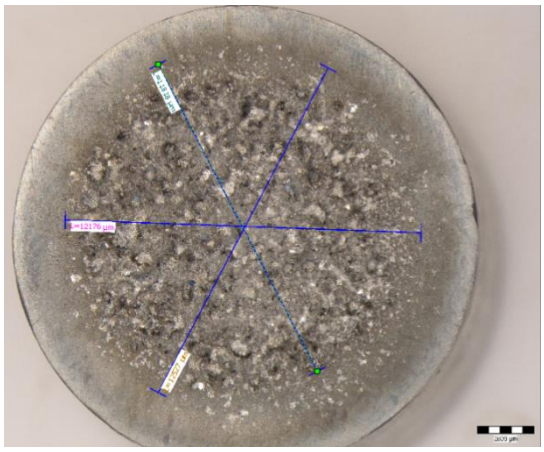


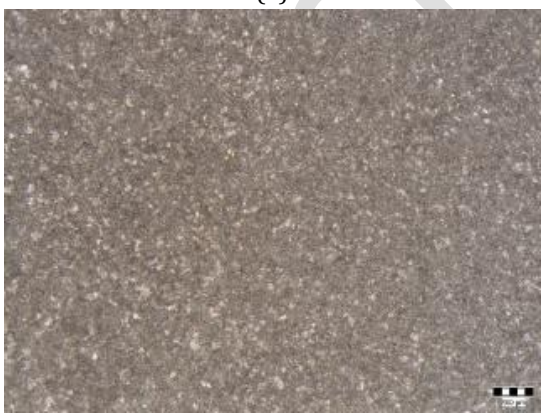
(d)



(e)

Fig. 9. The macrostructural aspect of the surfaces after cavitation erosion testing of pure zinc samples, as cast: (a) - x8; (b) - x25 (detail of image (a); (c) - measuring the diameter of the test specimen; (d) - measuring the diameter of the cavitationally eroded surface; (e) - measuring the diameter of the surface most affected by the cavitational attack.

(a)



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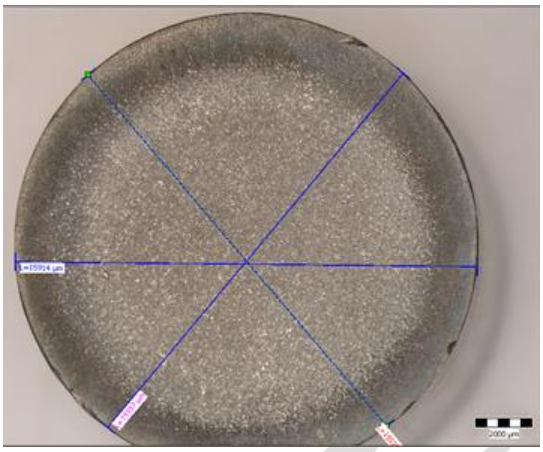

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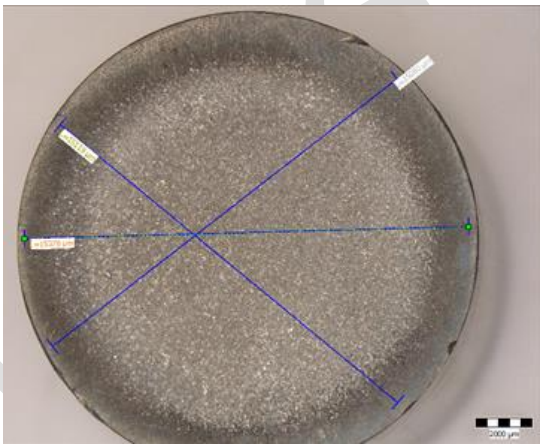

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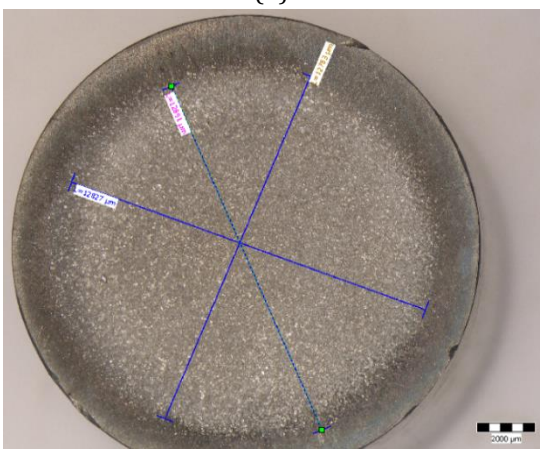

(e)

Fig. 10. The macrostructural appearance of the surfaces after cavitation erosion testing of Zn-Mg alloy samples, as cast: a- x8; b- x25 (detail of image a); c- measuring the diameter of the test specimen; d- measuring the diameter of the cavitationally eroded surface; e- measuring the diameter of the surface most affected by the cavitational attack.

Table 3. Measurement results regarding the dimensions of the areas affected by cavitation erosion of the experimental samples.

Alloy	Diameter of the sample, mm	Diameter of the area affected by the cavity, mm	The diameter of the most affected cavity area, mm	The proportion of the area affected by the cavity, %	The proportion of the most affected cavity area, %
Zn	15876	14916	12174	94	76
Zn-Mg	15925	15192	12834	81	74

4. CONCLUSIONS

The research results bring innovative elements for the use, by combination, of biodegradable metals in parts subject to hydrodynamic stresses, such as cavitation.

This paper shows the influence of alloying with magnesium on the mechanical behavior and cavity resistance of zinc. If a structure with large, cracked grains, such as that of zinc, does not confer resistance to cavitation erosion, a dentritic structure, consisting of a zinc-based solid solution and a lamellar eutectic of zinc and Mg_2Zn_{11}, shows both increased hardness and an increase of the cavity erosion resistance by more than 8 times.

The work opens new paths for the creation of biodegradable alloys needed to make devices, such as stents and valves, which regulate blood circulation and heart rhythms, by mitigating the effects of pressure variations and flow turbulence.

REFERENCES

[1] Y. Zheng, X. Gu, and F. Witte, "Biodegradable metals," *Materials Science and Engineering: R: Reports*, vol. 77, pp. 1–34, Mar. 2014, doi: 10.1016/j.mser.2014.01.001.

[2] Md. S. Uddin, C. Hall, and P. Murphy, "Surface treatments for controlling corrosion rate of biodegradable Mg and Mg-based alloy implants," *Science and Technology of Advanced Materials*, vol. 16, no. 5, p. 053501, Oct. 2015, doi: 10.1088/1468-6996/16/5/053501.

[3] T. Huang, Y.F. Zheng, Y. Han, Accelerating Degradation Rate of Pure Iron by Zinc Ion Implantation, Regen. Biomater, 3 pp. 205–215, 2016, doi: 10.1093/rb/rbw020.

[4] H. F. Li, Z. Shi, and L. N. Wang, "Opportunities and challenges of biodegradable Zn-based alloys," *Journal of Materials Science & Technology*, vol. 46, pp. 136–138, Jun. 2020, doi: 10.1016/j.jmst.2019.12.014.

[5] H. Li, Y. Zheng, L. Qin, *Progress of biodegradable metals*, Prog. Nat. Sci. Mater. vol. 24, issue 5, pp.414–422, 2014, doi: 10.1016/j.pnsc.2014.08.014.

[6] G. K. Levy, J. Goldman, and E. Aghion, "The Prospects of Zinc as a structural material for Biodegradable Implants—A Review paper," *Metals*, vol. 7, no. 10, p. 402, Oct. 2017, doi: 10.3390/met7100402.

[7] N. S. Murni, M. S. Dambatta, S. K. Yeap, G. R. A. Froemming, and H. Hermawan, "Cytotoxicity evaluation of biodegradable Zn–3Mg alloy toward normal human osteoblast cells," *Materials Science and Engineering: C*, vol. 49, pp. 560–566, Apr. 2015, doi: 10.1016/j.msec.2015.01.056.

[8] J. Kubasek, D. Vojtech. "Zn-based alloys as an alternative biodegradable materials," *Proc. Metal*, vol. 5, pp. 23–25, 2012.

[9] H. F. Li *et al.*, "Development of biodegradable Zn-1X binary alloys with nutrient alloying elements Mg, Ca and Sr," *Scientific Reports*, vol. 5, no. 1, May 2015, doi: 10.1038/srep10719.

[10] H. Li, H. Yang, Y. Zheng, F. Zhou, K. Qiu, and X. Wang, "Design and characterizations of novel biodegradable ternary Zn-based alloys with IIA nutrient alloying elements Mg, Ca and Sr," *Materials & Design*, vol. 83, pp. 95–102, Oct. 2015, doi: 10.1016/j.matdes.2015.05.089.

[11] E. Mostaed *et al.*, "Novel Zn-based alloys for biodegradable stent applications: Design, development and in vitro degradation," *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 60, pp. 581–602, Jul. 2016, doi: 10.1016/j.jmbbm.2016.03.018.

[12] M. P. Staiger, A. Pietak, J. Huadmai, and G. J. Dias, "Magnesium and its alloys as orthopedic biomaterials: A review," *Biomaterials*, vol. 27, no. 9, pp. 1728–1734, Mar. 2006, doi: 10.1016/j.biomaterials.2005.10.003.

[13] F. Witte *et al.*, "Degradable biomaterials based on magnesium corrosion," *Current Opinion in Solid State & Materials Science*, vol. 12, no. 5–6, pp. 63–72, Oct. 2008, doi: 10.1016/j.cossms.2009.04.001.

[14] D. Vojtěch, J. Kubásek, J. Šerák, and P. Novák, "Mechanical and corrosion properties of newly developed biodegradable Zn-based alloys for bone fixation," *Acta Biomaterialia*, vol. 7, no. 9, pp. 3515–3522, Sep. 2011, doi: 10.1016/j.actbio.2011.05.008.

[15] W. Pachla *et al.*, "Structural and mechanical aspects of hypoeutectic Zn–Mg binary alloys for biodegradable vascular stent applications," *Bioactive Materials*, vol. 6, no. 1, pp. 26–44, Jan. 2021, doi: 10.1016/j.bioactmat.2020.07.004.

[16] P. K. Bowen, J. Drelich, and J. Goldman, "Zinc exhibits ideal physiological corrosion behavior for bioabsorbable stents," *Advanced Materials*, vol. 25, no. 18, pp. 2577–2582, Mar. 2013, doi: 10.1002/adma.201300226.

[17] X. Wang, H.M. Lu, X.L. Li, L. Li, Y.F. Zheng, "Effect of cooling rate and compositionon microstructures and properties of Zn–Mg alloys," *Trans. Nonferrous Metals Soc. China,* vol. 17, pp, 122–125, 2007.

[18] S. Dobrita, B. Istrate, N. Cimpoeşu, S. Stanciu, V. Apostol, R. Cimpoeşu, I. Ioniţă,P. Paraschiv, "Preliminary results on the corrosion behaviour of a new biodegradablemetallic material based on zinc", *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 374, pp. 1–5, 2018, doi: 10.1088/1757-899X/374/1/012027.

[19] Z. Liu, "A New Approach Toward Designing and Synthesizing the Microalloying Zn Biodegradable Alloys with Improved Mechanical Properties," *Metallurgical and Materials Transactions*, vol. 50, no. 1, pp. 311–325, Oct. 2018, doi: 10.1007/s11661-018-4978-4.

[20] ASTM G 32-016, "Standard Test Method for Cavitation Erosion Using Vibratory Apparatus", ASTM International West Conshohocken, PA, USA, 2016

[21] I. Bordeasu, Monografia Laboratorului de Cercetare a Eroziunii prin Cavitatie al Universitatii Politehnica Timisoara (1960-2020) Editura Politehnica, Timişoara, Romania, 2020

[22] I. Mitelea, I. Bordeaşu, E. Riemschneider, I. D. Uţu, and C. M. Crăciunescu, "Cavitation erosion improvement following TIG surface-remelting of gray cast iron," *Wear*, vol. 496–497, p. 204282, May 2022, doi: 10.1016/j.wear.2022.204282.

[23] I. Bordeasu, M. O. Popoviciu, I. Mitelea, V. Balasoiu, B. Ghiban, D. Tucu, "Chemical and mechanical aspects of the cavitation phenomena," *Revista de Chimie*, vol. 58, no.12, 2007, pp. 1300–1304, 2007.

[24] V. O. Oanca, "Techniques for optimizing the resistance to cavitation erosion of some CuAlNiFeMn alloys intended for the execution of naval propellers", PhD thesis, Timisoara, Romania, 2014

[25] D. Istrate *et al.*, "Correlation between Mechanical Properties—Structural Characteristics and Cavitation Resistance of Cast Aluminum Alloy Type 5083," *Crystals*, vol. 12, no. 11, p. 1538, Oct. 2022, doi: 10.3390/cryst12111538.

[26] L.M. Micu, I. Bordeasu, M.O. Popoviciu, M. Popescu, D. Bordeasu, L.C.Salcianu, "Influence of volumic heat treatments upon cavitation erosion resistance of duplex X2CrNiMoN 22-5-3 stainless steels", *in International Conference on Applied Sciences 2014 (ICAS2014)*, 2-4 October 2014, vol. 85, art. number.012019, 2015

[27] I. Mitelea, I. Bordeaşu, D. Cosma, I. D. Uţu, and C. M. Crăciunescu, "Microstructure and cavitation damage characteristics of GX40CRNISI25-20 Cast stainless steel by TIG surface remelting," *Materials*, vol. 16, no. 4, p. 1423, Feb. 2023, doi: 10.3390/ma16041423.

[28] I. Bordeasu, C. Patrascoiu, R. Badarau, L. Sucitu, M. Popoviciu, V. Balasoiu, "New contributions in cavitation erosion curves modeling", FME Transactions, vol. 34, no. 1, pp. 39-44, 2006.

[29] L. M. Micu, I. Bordeaşu, and M. O. Popoviciu, "A new model for the equation describing the cavitation mean depth erosion rate curve," *Revista De Chimie*, vol. 68, no. 4, pp. 894–898, May 2017, doi: 10.37358/rc.17.4.5573.

[30] A.D. Jurchela, "Cercetări asupa eroziunii produse prin cavitaţie vibratorie la oţelurile inoxidabile cu conţinut constant în crom şi variabil de nichel", PhD thesis, Timisoara, Romania, 2012.

[31] J.-P. Franc and J.-M. Michel, *Fundamentals of cavitation*. 2005, doi: 10.1007/1-4020-2233-6.

[32] R. Garcia, Comprehensive Cavitation Damage Data for Water and Various Liquid Metals Including Correlation with Material and Fluid Properties, Technical Report No. 6, University of Michigan, 1966.

[33] I. Bordeasu, Eroziunea cavitationala a materialelor, Editura Politehnica Timisoara, 2006

[34] D. Bordeaşu, O. Proştean, I. Filip, F. Drăgan, and C. Vaşar, "Modelling, Simulation and Controlling of a Multi-Pump System with Water Storage Powered by a Fluctuating and Intermittent Power Source," *Mathematics*, vol. 10, no. 21, p. 4019, Oct. 2022, doi: 10.3390/math10214019.