ACTA METALLURGICA SLOVACA
2024, VOL. 30, NO. 1, 5-14

RESEARCH PAPER

BIORESORBABLE MAGNESIUM-BASED ALLOYS FOR OSTEOSYNTHESIS

Viktor Greshta[1], Vadim Shalomeev[1], Daria Tkach[1], Dmytro Pavlenko[2], Mykhaylo Brykov[3], Yevhen Yastsun[4], Nataliia Zhukova[5]

[1] Department of Materials Science, Faculty of Engineering and Physics, Zaporizhzhia Polytechnic National University, Zhukovsky Str. 64, Zaporizhzhia 69063, Ukraine
[2] Department of Aviation Engine Technology, Faculty of Mechanical Engineering, Zaporizhzhia Polytechnic National University, Zhukovsky Str. 64, Zaporizhzhia 69063, Ukraine
[3] Department of integrated technologies of welding and modeling of structures, Faculty of Engineering and Physics, Zaporizhzhia Polytechnic National University, Zhukovsky Str. 64, Zaporizhzhia 69063, Ukraine
[4] Department of Traumatology and Orthopedics, The first medical faculty, Zaporizhzhia State Medical and Pharmaceutical University, Mayakovsky Av. 26, Zaporizhzhia 69035, Ukraine
[5] Department of Foreign Philology and Translation, Faculty of Humanities, Zaporizhzhia Polytechnic National University, Zhukovsky Str. 64, Zaporizhzhia 69063, Ukraine

*Corresponding author: dvt@dvt.zp.edu.ua, tel.: +380963682986, Faculty of Engineering and Physics, Zaporizhzhia Polytechnic National University, 69063, Zaporizhzhia, Ukraine

Received: 08.12.2023
Accepted: 24.02.2024

ABSTRACT

The impact of micro-alloying of AZ91 and NZ30K magnesium alloys with silver and scandium to produce bioresorbable implants for osteosynthesis is studied in the paper. The application of these alloys is limited due to the significant reduction of the mechanical properties of magnesium during the regeneration of fractures. It was found that the higher the concentration of the above-mentioned elements, the bigger the amount of intermetalloids that appear and the smaller they become. There were different mechanical properties observed at the sample cross-section, but the difference was successfully eliminated by thermal treatment. It reduced the chemical heterogeneity of the workpiece at the cross-section and, respectively, the value of micro-hardness. It is shown that microalloying these alloys with 0.05…0.1 % of silver and scandium ensures the grinding of the structural elements of the metal and a significant increase of the set of their properties. The research of the developed alloys showed that NZ30K alloy, which additionally contains 0,05 ... 0,1% of silver, after a three-month treatment with gelofusine saves its mechanical properties like those of the bone tissue. Pre-clinical research revealed that they are non-toxic, have an antibacterial effect and preserve the whole set of properties till the complete fracture consolidation.

Keywords: magnesium alloy, microalloying, corrosion resistance, ultimate strength, intermetallides

INTRODUCTION

One of the modern methods for the treatment of bone fractures is osteosynthesis with metallic implants. The most common materials for manufacturing such implants are stainless steel, titanium or cobalt alloys, etc. Structures with the given alloys have high mechanical properties, but their constituent elements often have a negative effect on both the bone tissue and the human body overall [1]. Furthermore, when such materials are used, there can be a ‘stress-screening’ effect, which is related to their high mechanical properties [2]. Moreover, stainless steels, cobalt alloys, and, to some extent, titanium alloys contain highly toxic alloying elements (chromium, molybdenum, and nickel). However, the abovementioned materials permanently block the bone against mechanical exposure, making it more complicated to stabilise the bone tissue, which is necessary in case of mechanical stress. To avoid such negative effects, there are operations carried out to remove the implants. These operations are very expensive and cannot exclude the risk of repeated fractures, and they require extra time for re-treatment.
The solution to this problem is the application of bioresorbable materials able to dissolve in the human body. The most common materials of this kind are bioresorbable polymers (PLA, PDLLA, PLLA, etc.) [3] and polymer-based composites (POC-HA and PLA-HA) [4, 5]. These materials are not strong or ductile enough, which makes it difficult to use them as implants. What is more, their biodegradation products are not always absorbed by the body [6].
Magnesium-based alloys can be a promising material for manufacturing bioresorbable implants for osteosynthesis [7]. Magnesium best matches the properties of the skeleton, ensures proper fusion of the bone fragments and its quick regeneration in the fracture point. The body of an adult contains approximately 140 g of magnesium (0.2% of the body mass), with 2/3 of this amount being in the bone tissue, and the body daily needs 400 g to 500 g of magnesium. That is why using magnesium-alloy implants for osteosynthesis is better compared to implants made of other materials. Moreover, magnesium alloys can biodegrade in the human body creating products which the body can absorb without being intoxicated [8]. In particular, the authors of the paper [9] have developed a bioresorbable magnesium-based alloy which contains zirconium, neodymium and zinc. It is characterised by a satisfactory level of mechanical properties and is non-toxic, which was experimentally confirmed.

Intensive ductile deformation is a promising method to enhance the operational properties of metals and low-alloyed alloys. It enables to significant increase the mechanical properties without extra alloying elements [10]. The suggested technology gives the possibility to get work pieces of powder materials ensuring the hardness matches that of compact alloys [11]. Thanks to intensive ductile deformation, one can get non-standard alloys out of powder materials. Such alloys could be used for the purpose of the implant or another medical product. The advantage of this approach is both the possibility to produce workpieces with the given composition for a specific purpose and provide equal distribution of alloying elements at their cross-section [12], which is required for the long-term service of the implants. As low-alloyed magnesium-based alloys often have inadequate mechanical properties, it is proposed to use the technology of intensive ductile deformation [13], which enables to exclusion of the usage of toxic elements and additionally reduces the speed of implant degradation.

The main methods for achieving high strength of cast alloys with sufficient viscosity are the following: creation of compound alloyed solid solutions, strengthening with dispersed particles and creation of the optimal structure by thermal treatment [14]. To ensure a favourable combination of strength and ductile properties of cast magnesium alloys, it is necessary to use all three methods.

When selecting alloying elements for magnesium alloys, their ability to create solid solutions with magnesium is an important factor. The solubility of the elements in magnesium is determined by the proximity of their atomic radii, which, according to W. Hume-Rothery, should differ by not more than 15% [15]. When this ratio is disrupted, the atom binding energy of the solvent and alloying elements is reduced. As a result of the distortion of the crystalline lattice, the solubility reduces. Another important condition for the solubility of the element in the metal base, according to the research by various authors [16], is the difference in the electronegativity of the elements, which should be lower than 0.2…0.4 [17,18,19].

Out of all the variety of the elements in D. Mendeleev's periodic system, there is a small number of elements that have a favourable ratio of the atom diameter (≤ 15 %) to electronegativity (≤ 0,4), can create solid soluble substitutions with magnesium, slightly distorting its crystalline lattice and strengthening it. It is interesting to study their impact on the structure and the properties of the magnesium alloys.

Strengthening with dispersed fractions of magnesium alloys is another important factor in improving their properties. By interacting with several elements, magnesium creates intermetallides that strengthen the alloy [20]. The creation of intermetallides and their properties are predetermined by the electronic structure of the interacting elements in the alloy.

Thus, the selection of alloying elements for magnesium alloys when producing implants for osteosynthesis requires extra restrictions due to their toxicity. Application of the rare-earth elements for alloying magnesium alloys, including the production of implants, enables to enhancement of their mechanical, corrosion and technological properties, although the physiological impact has not been studied well enough [21]. However, available findings indicate the prospects for the use of such rare-earth elements as Y, Ce, Pr, Gd, Dy, Yb, Sm, and Eu, with scandium being noted as the most promising element in terms of physiological effects. It was shown in the paper [22] that modification of NZ30K alloy with around 0.05% scandium improves the structure and mechanical properties of the alloy. It is proposed to use Mg-1Sc alloy in orthopaedic implants. When tested, this alloy demonstrated satisfactory mechanical properties and degradation rate [23].

Since, in addition to satisfactory mechanical properties and required corrosion rate, it is necessary to reduce possible complications, the Mg-Ag-Y alloy was studied. Research on rats has confirmed that this alloy does not cause any complications and that bone tissue restoration occurs at a satisfactory rate [24]. What is more, silver has additional anti-bacterial properties, which reduce the risk of infection in the area of surgery. However, when developing bioresorbable magnesium alloys, one should take into account that silver can affect the corrosion rate [13]. Silver promotes the formation of a galvanic reaction with the magnesium matrix, which accelerates degradation, and in turn, the formation of an oxide texture reduces the degradation rate [25]. Thus, the biodegradation rate of magnesium alloys can be controlled by changing the silver content. Since the corrosion rate is the key indicator for bioresorbable magnesium alloys, it must be sufficient to allow the location of the implant to be gradually replaced by bone tissue, but too rapid corrosion should not lead to the recurrent destruction of the bone. Rare-earth metals are also applied to regulate the corrosion rate, and by changing their content, the newly received implants can be used for various types of bones. For example, the Mg-3Sc-3Y alloy under consideration did not show a significant degradation rate for 23 days, which makes possible the restoration of cells [26, 27]. Taking this into account, silver and scandium were selected as promising elements for alloying magnesium alloys in order not only to improve their mechanical properties but also to eliminate toxic effects on the human body.

MATERIAL AND METHODS

The structure and mechanical properties of pure magnesium and AZ91 and NZ30K alloys were studied in comparison with the properties of the human bone. The chemical composition and mechanical properties of these metals are presented in **Table 1**.

Table 1 Chemical composition and mechanical properties of pure magnesium and magnesium alloys

Material	**Chemical composition, mass percentage**						**Mechanical properties**	
	Al	***Mn***	***Zn***	***Zr***	***Nd***	***Mg***	***σ_u, MPa***	***δ, %***
Magnesium	-	-	-	-	-	99.9	113	1.4
AZ91	8.5	0.32	0.7	-	-	base	232 ± 5	2,8 ± 0.6
NZ30K	-	-	0.2	0.4	3.0	base	235 ± 7	3.7± 0.5

These elements have limited solubility in their solid state and can form many intermetalloides with magnesium. The influence of silver and scandium (0.05%, 0.1%, and 1.0%) on the structure and properties of AZ91 and NZ30K magnesium alloys was studied separately.

To determine the effect of the chemical composition on the mechanical properties of the alloy, standard samples were poured into a sand and clay mould for mechanical tests.

The study was carried out after heat treatment in a Bellevue-type thermal shaft furnace whose capacity is 112 kW and productivity reach 95 kg/h. ПАП-4М-type thermal furnace was also used. Its productivity is 50 kg/h. The following mode was used: heating at 540±5 °C, treatment for 8 hours, air cooling, and aging at 200±5 °C, treatment for 15 hours, air cooling.

The mechanical properties of the magnesium alloy samples were determined using INSTRON 2801 tensile tester on both standard magnesium alloy samples and samples that had been treated in an artificial blood substitute, gelofusine, for 1, 2, 3, and 6 months at 36 ± 1.0 °C. The stable temperature of the liquid was ensured by the УТ-15 ultra thermostat. Before placing the samples into blood substitutes, they were degreased with ethyl alcohol. After

a specified period, the samples were taken out of the solution, corrosion products were removed from their surface with chromic anhydride, in which the samples were treated at 18-25°C for 3 minutes. After the corrosion products were removed, the samples were washed in running and distilled water, dried and subjected to mechanical testing.
The macro- and microstructure of the samples after mechanical testing were studied using light microscopy methods. The samples were magnified by 100, 350, and 500 times with Neophot 32 and OLYMPUS IX 70.
Preclinical trials included a study of the toxic effects of biodegradation products of the experimental alloy on rats and a study of bone regeneration processes in rabbits.
The experimental animals were 20 white outbred male rats weighing 220-270 g. The animals were split into 2 groups: the experimental group which had a magnesium alloy implant inserted into the thigh muscle mass, and the control group, which did not undergo surgery. The number of animals in the experimental group was N = 14, in the control group there were N = 6. Manipulations were performed in accordance with the "Regulations for the Use of Animals in Biomedical Research". Animals of both groups were kept in standard vivarium conditions for 6 months.
Possible signs of intoxication were detected by regular weighing (twice a month), monitoring of locomotor and exploratory activity, food and water consumption, and the state of the hair and mucous membranes. Possible disorders of the urinary system were detected by examining urine samples by a standard biochemical method using a biuret reagent [28].

The effect of biodegradation products on bone tissue repair processes was studied in 12 sexually mature rabbits divided into experimental and control groups. All surgical interventions were performed in a district veterinary hospital.
The study of the toxic effects of biodegradation products of the experimental magnesium alloy of the Mg-Zr-Nd system was carried out on rats using the "open field" test [29], which allows the detection of minimal deviations in the animal body caused by toxic agents. The coefficients of horizontal and vertical locomotor activity, grooming (brushing of wool), examination of orifices, and defecation were used as control parameters.

RESULTS AND DISCUSSION

Having analysed the studies devoted to the mechanical properties of various human bones, we found out that the level of their properties range is as follows: σ_B = 130...150 MPa, δ = 1...2 % [30]. Given that the average bone growth rate in fractures is ~3 months, the mechanical properties of the alloys were studied in dynamics on samples after their treatment in gelofusine (an artificial blood substitute) for 1, 2, 3, and 6 months (**Table 2**).

Table 2 Mechanical properties of magnesium-based alloys after treatment in gelofusine*)

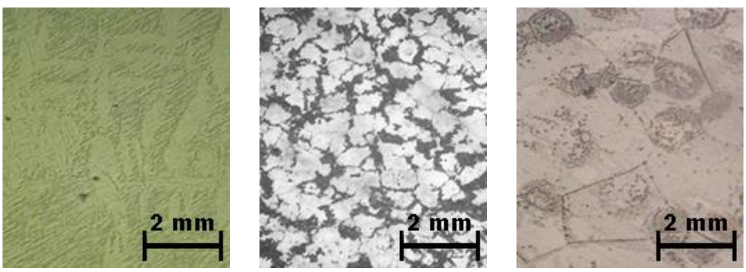
Material	Input		1 month		2 months		3 months		6 months	
	σ_u, MPa	δ, %	σ_u, MPa	δ, %	σ_u, MPa	δ, %	σ_u, MPa	δ, %	σ_u, MPa	δ, %
Mgpure	160	2.0	140	2.0	110	1.9	80	1.8	50	1.5
AZ91	230	3.2	170	3.1	135	3.1	100	3.0	70	1.8
NZ30K	235	4.0	180	3.8	145	3.5	110	3.2	80	2.3

Note: *) – average value

Fractographic examination of the fractures of the pure magnesium cast samples revealed the presence of a brittle coarse crystalline structure (**Fig. 1, a**). The fracture of the standard AZ91 alloy showed a more ground structure (**Fig. 1, b**), and NZ30K alloy had an increased proportion of the viscous component in the fracture and a matte fine-crystalline structure (**Fig. 1, c**).

a b c
a – 99.9% Mg; b – AZ91; c – NZ30K
Fig. 1 Macrostructure of sample fractures, x5

The microstructure of pure magnesium had a heterogeneous brittle structure (**Fig. 2, a**). The microstructure of AZ91 alloy of standard composition was a δ-solid solution with the $\delta+\gamma$ type eutectics located along the grain boundaries and individual inclusions of the γ-phase (**Fig. 2, b**). The microstructure of the heat-treated NZ30K alloy was a δ-solid solution with a spherical eutectic of compound composition containing Zr and Nd (**Fig. 2, c).**



a b c
a - 99,9% Mg; b – AZ91; c – NZ30K
Fig. 2 Microstructure of heat-treated samples, x100

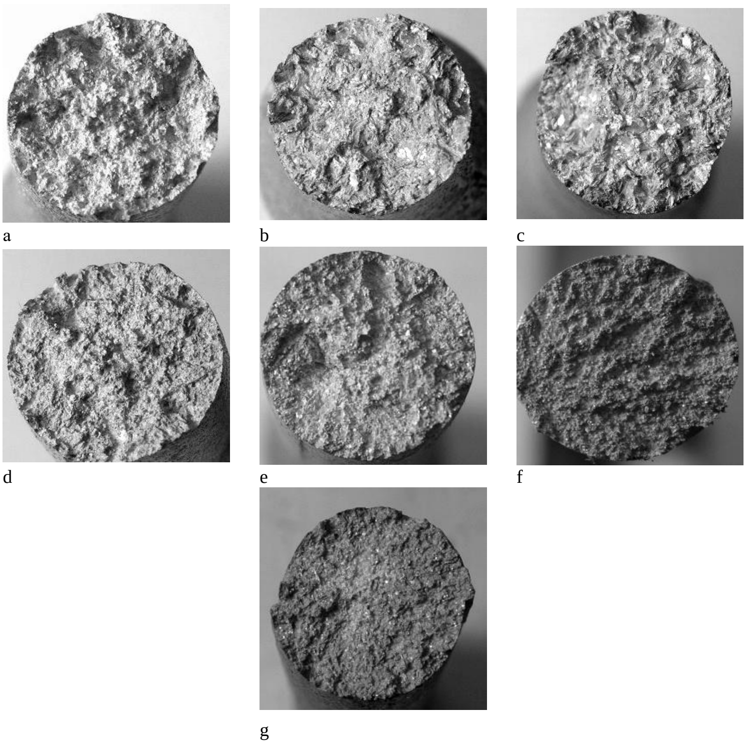
DOI: 10.36547/ams.30.1.1974

The analysis of the obtained data showed that the loss of ductile properties of the materials under consideration at different treatments in gelofusine solution is insignificant and corresponds to the ductility of the bone material up to almost 6 months of treatment of the samples. However, treating samples with gelofusine before testing leads to a significant loss of strength. For example, samples made of pure magnesium before their treatment in gelofusine have a strength level corresponding to the bone strength, which slightly decreases after 1 month of treatment. Increasing the sample treatment time to 3 months or longer makes the use of magnesium for implants unsuitable due to their low strength (less than the bone strength). Samples made of AZ91 and NZ30K alloys have higher strength indicators compared to pure magnesium. However, their strength level after 3 months of treatment with gelofusine is insufficient and does not correspond to the strength of the bone, which can lead to premature structural destruction when an external load is applied.

Thus, the studied magnesium-based materials cannot provide strength equal to that of the bone during its growth after a fracture ($\sigma_B \geq 150$ MPa and $\delta \geq 3\%$ within 3 months). It is possible to improve the mechanical properties of magnesium alloys by using metallurgical technologies, microalloying being one of the most promising areas of development.

The study of the influence of silver and scandium with 0.05, 0.10, 1.0 mass percentage on the structure and properties of AZ91 alloy showed that silver and scandium have a favorable factor regarding magnesium. These elements have limited solubility in the solid state and can form a large number of intermetallides with magnesium.

A fractographic study of fractures of cast samples from the standard AZ91 alloy revealed the presence of a coarse-crystalline structure. The introduction of silver and increased scandium content markedly refined the macrostructure and the fracture became matte fine-crystalline (**Fig. 3**).



a – standard alloy; b – 0,05 % Ag; c – 0,1 % Ag; d – 1,0 % Ag; e – 0,05 % Sc,
f – 0,1 % Sc, g – 1,0 % Sc

Fig. 3 Fractograms of fractures of cast samples from AZ91 alloy with silver and scandium, x5

The microstructure of AZ91 alloy with a standard composition was a δ-solid solution with δ+γ type eutectics along the grain boundaries and individual γ-phase intermetallides (**Fig. 4, a**).

The increased scandium and silver content favoured the decrease in the distance between the axes of the second-order dendrites and the size of the structural components (**Table 3**), as well as to the crushing of the eutectics.

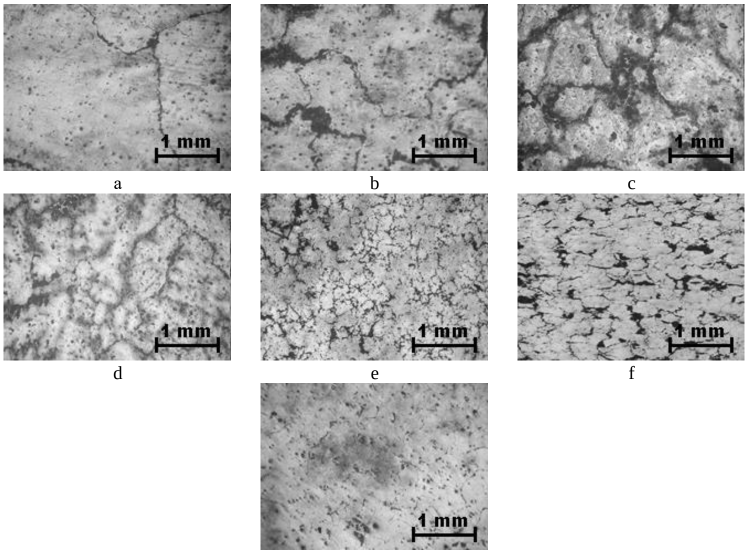
As the concentration of silver and scandium increased in the alloy, intermetallide clusters were observed, but the size of the intermetallides decreased. In the alloy containing 1.0% of silver and scandium, film formation was observed.

The average microhardness of the δ-solid solution of the standard alloy (before heat treatment) was 1115 MPa and that of the eutectic was 1227 MPa. After the heat treatment, the microhardness of the matrix and eutectic increased, with the microhardness of the eutectic in relation to the matrix becoming lower (**Fig. 5**).

In the standard AZ91 alloy, the intermetallide phase was of two types. It was spherical inside the grains and lamellar at the grain boundaries. The micro-X-ray spectral analysis of the spherical intermetallides showed that they contained ~ 15% Al, ~ 80% Mg

DOI: 10.36547/ams.30.1.1974

and additionally Si and Mn; the lamellar intermetallides had ~ 60% Mg and ~ 40% Al.
Spherical intermetallides located inside the grains serve as centers of crystallization, in contrast to lamellar intermetallides with a lower melting point and located, respectively, at the grain boundaries. Micro X-ray diffraction analysis of AZ91 alloy with silver and scandium showed that these elements are part of the intermetallides and change the structural characteristics of the alloy.



a – standard alloy; b – 0.05 % Ag; c – 0.1 % Ag; d – 1.0 % Ag; e – 0.05 % Sc; f– 0.1 % Sc; g – 1.0 % Sc
Fig. 4 Microstructure of AZ91 alloy with silver and scandium after heat treatment (x 200)

Table 3 Dimensions of structural components in samples made of AZ91 alloy with increased scandium and silver content

Element	Content of alloying elements, mass percentage	Distance between the axes of the 2nd order dendrites, µm	The size of the micrograin, µm
standard	-	23	140
	0.05	18	120
Sc	0.10	17	100
	1.0	16	90
	0.05	18	120
Ag	0.10	18	100
	1.0	17	90

Note: Average values are given

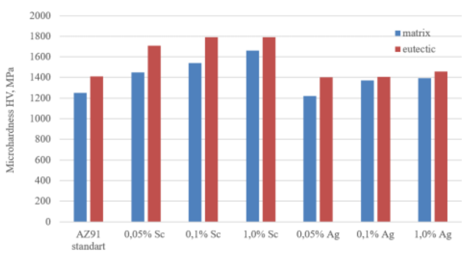


Fig. 5 Microhardness of the matrix and eutectics in AZ91 alloy samples containing silver and scandium after heat treatment

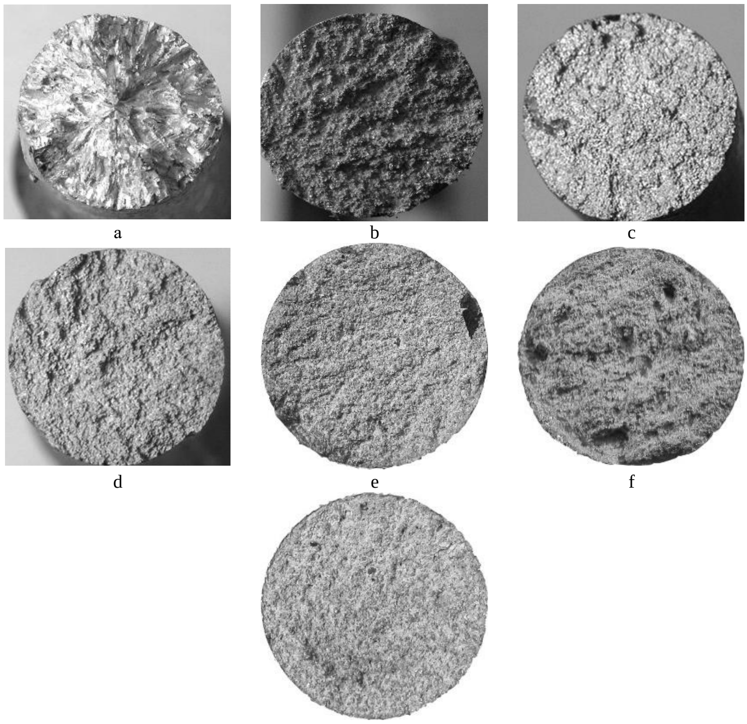
The mechanical properties obtained on the samples without heat treatment varied considerably. Thermal treatment reduced the chemical heterogeneity of the alloy, aligned the microhardness of the matrix and eutectics, which reduced structural stresses and provided higher mechanical characteristics (**Table 4**).

Table 4 Mechanical properties of AZ91 alloy with silver and scandium

Element	Content, mass percentage	Mechanical properties			
		before heat treatment		*after heat treatment*	
		σ_u, MPa	*δ, %*	*σ_u, MPa*	*δ, %*
Standard		160.8	2.3	232.7	2.8
Sc	0.05	165.6	3.8	246.8	4.4
	0.1	177.4	4.1	258.3	5.3
	1.0	180.2	3.8	272.0	5.0
Ag	0.05	164.5	3.6	235.6	4.0
	0.1	166.5	2.8	243.4	4.4
	1.0	169.8	2.5	258.0	4.2

Note: Average values are given in the table

Thus, silver and scandium improved the macro- and microstructure of AZ91 alloy and increased its mechanical strength and ductility, with the optimum content of these elements (0.05...0.1 %) ensuring the maximum level of its mechanical characteristics.
Analysis of macro fractures of cast samples of the standard NZ30K alloy and alloys additionally alloyed with silver and scandium showed their positive effect on the macrostructure of the metal. The introduction of silver and increased scandium content markedly refined the macrostructure and the fracture became matte fine-crystalline (**Fig. 6**).



a - standard alloy; b - 0.05% Ag; c - 0.1% Ag; d - 1.0% Ag; e - 0.05% Sc,
f - 0.1% Sc, g - 1.0% Sc

Fig. 6 Macrofractograms of fractures of cast samples made of NZ30K alloy with silver and scandium, x5

The microstructure of the standard heat-treated NZ30K alloy was a δ-solid solution with spherical eutectics. As the concentration of scandium and silver in the alloy increased, the size of this eutectic increased as well (**Fig. 7**).

The microhardness of the structural components of NZ30K alloy increased markedly when the scandium and silver content grew. There was also an insignificant growth of matrix microhardness and intensive increase of eutectic microhardness (**Fig. 8**).

The micro X-ray spectral analysis with JSM-6360LA electron microscope showed that the eutectic is enriched mainly with zirconium, neodymium, scandium, and silver. In alloys with silver and scandium in the spherical eutectic, there were ~ 1.5...2.0 times more of these elements than in the δ-solid solution.

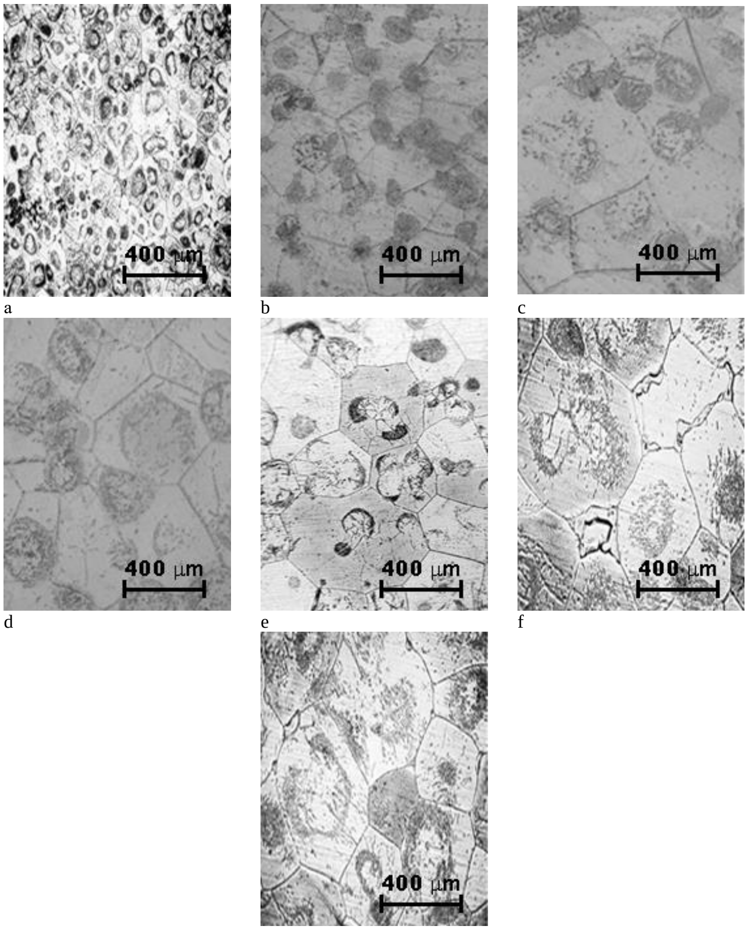
The alloying of NZ30K with scandium and silver improved the entire complex of its mechanical properties (**Table 5**).

Increasing the scandium and silver content in the NZ30K alloy within 0.05...0.1 % range contributed to improving both the strength and the ductile properties. Further increase in the concentration of these elements in the metal to 1.0% reduced the physical and mechanical characteristics of the material. In the structure of samples containing 1.0% scandium and silver, there were observed coarse precipitations of intermetallides at the grain boundaries, led to rapid fracture of the samples when they were tested.

Thus, adding 0.05...0.1 % of scandium and silver to NZ30K alloy is optimal, as it provides the highest level of mechanical properties.

Comparative studies of AZ91 and NZ30K alloys with silver and scandium in artificial blood substitutes have shown that their microalloying gives a positive result. In this case, the greatest improvement in the metal structure and increase in mechanical properties is provided by 0.05...0.1% of scandium and silver in the alloys.

DOI: 10.36547/ams.30.1.1974



a - standard alloy; b - 0.05 % Sc; c - 0.1 % Sc; d - 1.0 % Sc; e - 0.05 % Ag;
f - 0.1% Ag; g - 1.0 % Ag

Fig. 7 Microstructure of NZ30K alloy with silver and scandium after heat treatment (x 500)

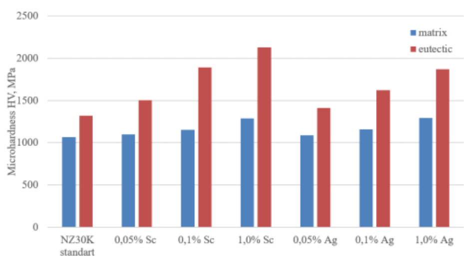


Fig. 8 Microhardness of the matrix and the eutectics in NZ30K alloy samples containing silver and scandium after heat treatment

Table 5 Mechanical properties of NZ30K alloy with silver and scandium after heat treatment

Element	Content, mass percentage	Mechanical properties	
		σ_u, *MPa*	δ, *%*
	Standard	235.7	3.6
Sc	0.05	273.8	4.4
	0.1	258.3	6.3
	1.0	202.0	4.0
Ag	0.05	245.6	4.0
	0.1	283.4	6.4
	1.0	258.0	4.2

Note: Average values are given in the table

The rate of biodegradation of AZ91 and NZ30K alloys with 0.05...0.1 % of scandium and silver after 3 months of treatment in gelofusine was studied (**Table 6**).

Table 6 Mechanical properties of alloys with different chemical compositions after treatment in gelofusine for 3 months

Alloy	Mechanical properties	
	σ**$_u$**, MPa	***δ, %***
AZ91	100.6	1.1
AZ91 + (0.05…0.1) % Sc	132.4	1.4
AZ91 + (0.05…0.1) % Ag	141.8	1.8
NZ30K	110.9	1.4
NZ30K + (0.05…0.1) % Sc	148.6	2.0
NZ30K + (0.05…0.1) % Ag	171.8	2.3

Note: Average values are given.

Studies have shown that NZ30K alloy has an increased corrosion resistance compared to AZ91 alloy. Additional microalloying of the studied alloys with 0.05...0.1 % of scandium and silver increased their mechanical properties after 3 months of treatment in gelofusine. NZ30K alloy, which additionally contains 0.05...0.1 % of Ag, had the highest level of mechanical properties after 3 months of treatment in gelofusine. It should be noted that its mechanical properties were higher than those of the bone tissue, which ensures its performance until complete fracture consolidation. What is more, silver in the magnesium alloy ensures its antibacterial effect. Taking this into account, NZ30K alloy additionally alloyed with 0.05...0.1 % of silver was recommended for further preclinical testing.

To determine the effect of the newly received magnesium alloys on a living organism, preclinical studies of the toxic effect of the newly received alloys on rats were conducted. Monitoring of weight dynamics in the study by the "open field" method showed a decrease in this indicator by 7% during the first 2 weeks after surgery (**Fig. 9**). Then there was a significant weight gain and a considerable improvement in the appetite of the animals from the experimental group, which suggests that the initial decrease was the result of the impact of surgical trauma and pain at the site of the intervention, rather than toxic effects. Moreover, regular monitoring of the condition of the hair and mucous membranes revealed no abnormalities. Urine tests of the experimental animals also showed no signs of toxic effects of implant biodegradation products.

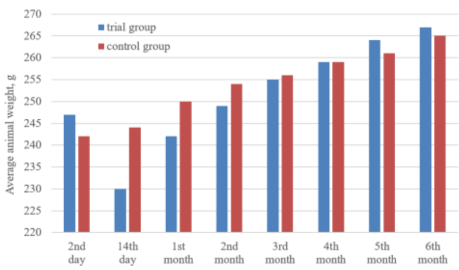


Fig. 9 Dynamics of the animal weight in the experimental and control groups after surgery

The study of the spatial and exploratory activity of animals in the "open field" (**Fig. 10**) showed a decrease in the total indicator by 60.6 % on the 2nd day after surgery. On the 14th day, the rate was 35.3% higher, but it did not exceed that of the control group. After the 1st month, the results did not differ significantly. The results from the 2nd to the 6th month, when the greatest toxic effect of biodegradation products is expected, are particularly indicative. Thus, the dynamics of locomotor and exploratory activity of animals revealed the absence of toxic effects of the implant, and the decrease of the indicator in the early stages of the study was caused by the effect of surgical trauma.

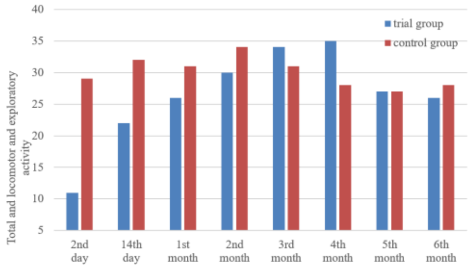


Fig. 10 Dynamics of total and locomotor and exploratory activity of experimental animals

The analysis of indicators of locomotor and exploratory activity of animals (**Table 10**) showed a positive trend for animals of the experimental group, which is due to a gradual increase in locomotor and exploratory activity of animals of the experimental group starting from the 2nd month after surgery. No significant differences were found between the control and experimental groups by almost all criteria. The high level of the general neurological status of the animals confirms the absence of neurotoxicity of the biodegradation products of the new magnesium alloy.

Morphological analysis of reparative osteogenesis was performed in experiments on rabbits. To determine the effectiveness of using the newly-received implants, fractures of the upper third part of both femurs were modeled in animals of the control and experimental groups. The animals of the experimental group were implanted with magnesium alloy fixators, and the control group had 12X18H10T stainless steel implants (**Fig. 11**).

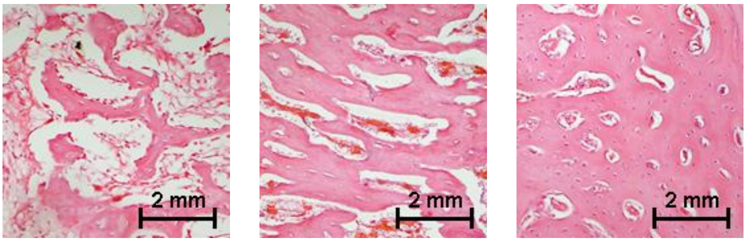
Fig. 11 X-ray of a rabbit after osteosynthesis with implants

The animals were withdrawn from the experiment at 2 weeks, 1, 4, and 6 months after surgery. Then the bone was sawn together with the implant through the fracture zone (**Fig. 12**).

The study showed that the use of implants made of a new magnesium alloy did not lead to disruption of the growth of femoral fractures in animals. The fracture consolidation time in the control and experimental groups did not differ significantly, and no pathological changes occurred. The use of implants made of a new magnesium alloy did not disrupt the formation of new blood vessels in the fracture areas. At all stages of observation, a widespread network of microvessels was found, whose density increased in direct proportion to the intensity and duration of the regeneration. In comparison, at these stages of treatment, implants made of stainless steel caused a disturbance in blood supply and led to bone cell death, followed by their dissolution and displacement by connective tissue fibers.

A - rabbit femur; B - working implant; C - view of the implant before surgery
Fig. 12 General view of the rabbit bone after surgery

Normal blood supply ensured a gradual and increasing process of regenerative changes with minimal deviations from the normal course of reparative osteogenesis (**Fig. 13**).



a b c

a - 2 weeks; b - 1 month; c - 4 months
Fig. 13 Dynamics of the reparative process after experimental trauma with the use of implants made of a new magnesium alloy, x100

At the later stages of treatment (6 months), the structure of the bone tissue area at the implantation location did not differ from the normal structure. Only some disorderly arrangement of bone crosspieces was noted (**Fig. 14**).

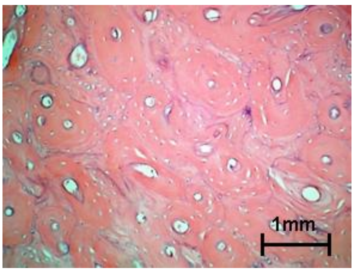


Fig. 14 Bone area in the implant location, x200

CONCLUSIONS

Thus, the existing materials for producing implants for osteosynthesis were analyzed. It is shown that magnesium alloys are a promising material for making bioresorbable implants, but they require some improvement.
As a result of the study, the alloying elements for the improvement of AZ91 and NZ30K magnesium alloys, providing the formation of compound alloyed solid solutions and strengthening the metal by dispersed particles, have been selected. It is shown that microalloying of these alloys with 0.05...0.1 % of silver and scandium provides refinement of structural components of the metal and a significant increase in the set of their properties.
The tests of the alloy compositions under consideration have shown that NZ30K alloy containing an additional 0.05…0.1% of silver retains its mechanical properties at the level of bone tissue properties after 3 months of treatment in gelofusin, which ensures the operability of the implant up to complete consolidation of the fracture with the following biodegradation.

Preclinical studies using the "open field" method revealed the absence of any significant deviations in physiological manifestations of experimental animals, and the biocorrosion products of the new magnesium alloy do not cause endogenous intoxication of body tissues and do not enhance cellular destruction. Moreover, neither any adverse effects on the general physical condition of the tested animals, nor any significant changes in their behavior were detected. The results indicate that the biodegradation products of the new alloy do not have a toxic effect on a living organism.
As a result of the experimental morphological study, it was found that the use of a new magnesium alloy of the Mg-Zr-Nd system for fracture osteosynthesis did not disrupt the processes of reparative regeneration of the bone tissue. The proposed alloy is recommended for further clinical tests.

REFERENCES

1. Q. Chen, G. A. Thouas: Materials Science and Engineering R: Reports, 87, 2015, 1-57. https://doi.org/10.1016/j.mser.2014.10.001.
2. M. I. Z. Ridzwan et al.: Journal of Medical Sciences, 7(3), 2007, 460-467.
https://doi.org/10.3923/jms.2007.460.467.
3. Y. Xia, W. Xu, H. Zhang, X. Wu, H. Dai: Journal of Applied Polymer Science, 139(46), 2022, pages or number of the paper. https://doi.org/10.1002/app.53147.
4. J. Ponkala, M. Rizwan, P. S. Shiakolas: On the design of a biodegradable POC-HA polymeric cardiovascular stent. In: *ASME International Mechanical Engineering Congress and Exposition*, Proceedings (IMECE), 2, 2012, 379-386. https://doi.org/10.1115/IMECE2012-88703.
5. S. Tanodekaew, S. Channasanon, P. Kaewkong: Physicochemical properties and biocompatibility of in situ-hardening polylactide/nano hydroxyapatite composite for bone substitute. International Journal of Polymeric Materials and Polymeric Biomaterials, 72(2), 2013, 108-118. https://doi.org/10.1080/00914037.2021.1990056.

6. S. Farah, D.G. Anderson, R. Langer: Physical and mechanical properties of PLA, and their functions in widespread applications — A comprehensive review. Advanced Drug Delivery Reviews, 107, 2016, 367-392. https://doi.org/10.1016/j.addr.2016.06.012.
7. Y. Sun, H. Helmholz, R. Willumeit-Römer: Preclinical in vivo research of magnesium-based implants for fracture treatment: A systematic review of animal model selection and study design. Journal of Magnesium and Alloys, 9(2), 2021, 351-361. https://doi.org/10.1016/j.jma.2020.09.011.
8. H. Tang, Q. Li, M. Li, X. Gu, C. Cheng, Y. Fan: In vitro and in vivo evaluation of micro-alloyed magnesium for potential application in alveolar bone fixation screws. Journal of Materials Science and Technology, 144, 2023, 62-69. https://doi.org/10.1016/j.jmst.2022.09.060.
9. V. Shalomeev, N. Aikin, V. Chorniy, V. Naumik: Design and examination of the new biosoluble casting alloy of the system mg-zr-nd for osteosynthesis. Eastern-European Journal of Enterprise Technologies, 1(12-97), 2019, 40-48. https://doi.org/10.15587/1729-4061.2019.157495.
10. V.E. Olshanetskii, L.P. Stepanova, V.L. Greshta, D.V. Pavlenko, D.V. Tkach: Deformation behavior of titanium VT1-0 with submicrocrystalline structure formed by the method of helical extrusion. Metal Science and Heat Treatment, 55(11-12), 2014, 603-607. https://doi.org/10.1007/s11041-014-9676-2.
11. Y.E. Beygelzimer, , Pavlenko, D.V., Synkov, O.S., & Davydenko, O.O. The efficiency of twist extrusion for compaction of powder materials. Powder Metallurgy and Metal Ceramics, 58(1-2), 2019, 7-12. https://doi.org/10.1007/s11106-019-00041-8.
12. D.V. Pavlenko, Y.E. Beygel'zimer: Theory and technology of forming process: Vortices in noncompact blanks during twist extrusion. Powder Metallurgy and Metal Ceramics, 54(9), 2016, 517-524. https://doi.org/10.1007/s11106-016-9744-9.
13. Z. Liu, R. Schade, B. Luthringer, N. Hort, H. Rothe, S. Müller, F. Feyerabend: Influence of the microstructure and silver content on degradation, cytocompatibility, and antibacterial properties of magnesium-silver alloys in vitro. Oxidative Medicine and Cellular Longevity, 2017, 2017. https://doi.org/10.1155/2017/8091265.
14. F. Czerwinski, W. Kasprzak: Heat Treatment of Magnesium Alloys – Current Capabilities. Materials Science Forum, 765, 2013, 466-470. https://doi.org/10.4028/www.scientific.net/MSF.765.466.
15. W. Hume-Rothery, G.V. Raynor: *The Structure of Metals and Alloys*, Institute of Metals, London, 1954.
16. N. Loukil: Alloying Elements of Magnesium Alloys: A Literature Review. In T. A. Tański & P. Jarka (Eds.), Magnesium Alloys Structure and Properties, 2021, 1-6, *IntechOpen*. https://doi.org/10.5772/intechopen.96232.
17. L.S. Darken: *Physical Chemistry Of Metals*, CBS Publishers & Distributors, Delhi, 2002.
18. K.A. Gschneidner, Jr. and LeRoy Eyring: *Handbook on the Physics and Chemistry of Rare Earths Metals. Volume 1*, Elsevier, Amsterdam, 1978.
19. J.H.L. Voncken: The rare earth elements: an introduction-A Special Group of Metals. In.: *Springer Briefs in Earth Sciences*. Springer, Heidelberg, 2016, p. 1-13. https://doi.org/10.1007/978-3-319-26809-5_1.
20. S. Belikov, V. Shalomeev, E. Tsivirko, N. Aikin, S. Sheyko: Microalloyed magnesium alloys with high complex of properties. *Materials Science and Technology Conference and Exhibition 2017*, Pittsburgh, David L. Lawrence Convention Center, 2017, 84-91. https://doi.org/10.7449/2017/MST_2017_84_91.
21. W. Weng, A. Biesiekierski, Y. Li, M. Dargusch, C. Wen: A review of the physiological impact of rare earth elements and their uses in biomedical mg alloys. Acta Biomaterialia, 130, 2021, 80-97. https://doi.org/10.1016/j.actbio.2021.06.004.
22. V.A. Shalomeev, E.I. Tsivirko, Y.N. Vnukov, D.A. Morozov: New magnesium alloy with promote properties for automobile construction. Metallurgical and Mining Industry, 3, 2013, 54-60. [03.12.2023], https://www.metaljournal.com.ua/assets/Journal/11-.pdf
23. Y. Lin, J. Liu, D. Bian, Z. Huang, Z. Lin, M. Wang, Y. Zheng: In vivo studies on Mg-1Sc alloy for orthopedic application: A 5-months evaluation in rabbits. Materials Letters, 2020, 262. https://doi.org/10.1016/j.matlet.2019.127130.
24. K. Yu, Y. Dai, Z. Luo, H. Long, M. Zeng, Z. Li, Y. Zhu: In vitro and in vivo evaluation of novel biodegradable mg-ag-Y alloys for use as resorbable bone fixation implant. Journal of Biomedical Materials Research - Part A, 106(7), 2018, 2059-2069. https://doi.org/10.1002/jbm.a.36397.
25. G. Liu, J. Han, X. Yu, S. Yuan, Z. Nie, T. Qiu, C. Guo: Influences of extrusion and silver content on the degradation of mg-ag alloys in vitro and in vivo. Bioinorganic Chemistry and Applications, 2022, 2022. https://doi.org/10.1155/2022/2557518.
26. H.S. Brar, J.P. Ball, I.S. Berglund, J.B. Allen, M.V. Manuel: A study of a biodegradable mg-3Sc-3Y alloy and the effect of self-passivation on the in vitro degradation. Acta Biomaterialia, 9(2), 2013, 5331-5340. https://doi.org/10.1016/j.actbio.2012.08.004.
27. K. Bryła, J. Horky, M. Krystian, L. Lityńska-Dobrzyńska, B. Mingler: Microstructure, mechanical properties, and degradation of Mg-Ag alloy after equal-channel angular pressing. Materials Science and Engineering C, 109, 2020. https://doi.org/10.1016/j.msec.2019.110543.
28. C.S. Hall: Emotional behavior in the rat. III. The relationship between emotionality and ambulatory activity. Journal of Comparative Psychology, 22(3), 1936, 345–352. https://doi.org/10.1037/h0059253.
29. R.N. Walsh, R.A. Cummins: The Open-Field Test: A Critical Review. Psychological Bulletin, 83(3), 1976, 482-504.
30. J. Currey: The structure and mechanical properties of bone. Bioceramics and Their Clinical Applications, 2008, 3–27. https://doi.org/10.1533/9781845694227.1.3.