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SELECTIVE DEGRADATION CHARACTERISTICS OF SILVER-CLAD MAGNESIUM ALLOY BIODEGRADABLE IMPLANTS WITH FOR OSTEOSYNTHESIS APPLICATIONS

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Abstract. Biodegradable implants present significant challenges that hinder their widespread clinical application despite their potential benefits. Key issues include inconsistent degradation rates, insufficient mechanical strength, and the risk of inflammatory responses. These challenges must be addressed to enhance the efficacy and safety of biodegradable implants. This study focuses on the selective degradation behavior of a magnesium-zinc-zirconium-neodymium alloy coated with a silver layer of 200-300 and 500 nm in thickness. The material is proposed for manufacturing biodegradable implants intended for bone fracture treatment. According to the results of potential-dynamic studies of samples in the Ringer-Locke solution, it was found that its corrosion potential was -1.444 and -1.466 V, and the corrosion current density was 0.5012 and 0.3981 mA/cm², respectively. The observed corrosion behavior of the studied samples is attributed to the distinctive characteristics of selective degradation occurring in areas of localized corrosion damage. It was shown that the surface of the corrosion damage of a sample with a coating thickness of 500 nm was enriched with zinc. For the sample with a 200-300 nm coating, the localized corrosion area also became enriched in zinc, while the remaining elements dissolved in the following sequence: magnesium, zirconium, silver, and neodymium.

Keywords: selective degradation, biodegradable implant, corrosion, osteosynthesis, Ringer-Locke solution, magnesium alloys, silver coating.

1. Introduction

The development of biodegradable implants has gained considerable attention in modern orthopedics and traumatology due to their ability to provide temporary mechanical support during bone healing and subsequently degrade, eliminating the need for a second surgical removal. Despite the advantages, current biodegradable implant materials – especially those based on magnesium (Mg) – face critical limitations, including uncontrolled degradation rates, insufficient mechanical strength, and a lack of antibacterial properties, which may compromise long-term clinical outcomes [1, 2].

Conventional orthopedic implants made from titanium or stainless steel are mechanically robust but remain permanently in the body unless surgically removed, which introduces risks such as infection, stress shielding, and complications from secondary surgery. On the other hand, biodegradable polymers often lack the mechanical strength required for load-bearing applications. Thus, there is a strong demand for new-generation biodegradable materials that cannot only degrade in a controlled manner but also provide adequate mechanical support and prevent post-operative infections [3,4].

Magnesium alloys have emerged as promising candidates due to their biocompatibility, as Mg and its alloys are naturally present in the human body and play a vital role in various biological processes [3-9]. Unlike traditional implant materials, Mg alloys degrade over time within the body, negating the need for surgical removal as well as the degradation products are generally non-toxic and can be metabolized. Furthermore, the elastic modulus of Mg alloys is closer to that of natural bone compared to other metallic implant materials such as stainless steel and titanium alloys reducing the risk of stress shielding, a phenomenon where the implant bears too much of the load leading to bone resorption and weakening [3-9].

Nonetheless, one of the key challenges remains controlling the corrosion and degradation rate in physiological environments to ensure mechanical integrity during the healing period; rapid loss of strength or volume due to hydrogen evolution and premature degradation must be addressed through alloying, microstructure control and surface treatments. Extensive efforts have been made to enhance their corrosion resistance and mechanical performance through alloying, grain refinement via severe plastic deformation and the application of surface coatings [10-12]. For example, the work by Yousefpour et al. [13] demonstrated enhanced corrosion control and mechanical integrity in Mg-based implants via tailored microstructures and surface engineering. However, achieving both corrosion control and antibacterial functionality remains a challenge. To address these shortcomings, this study investigates a novel magnesium-zinc-zirconium-neodymium (NZ30K) alloy, further alloyed with silver (Ag) to form an NZ30K+Ag alloy, and modified with a silver cladding layer. Silver, well known for its broad spectrum of antibacterial activity, has gained attention as a functional addition to Mg-based alloys. The inclusion of Ag serves a dual purpose: enhancing mechanical properties and introducing antibacterial activity through the release of silver ions (Ag^+) ions during degradation [14-16]. Previous studies have demonstrated that Ag addition into biodegradable Mg-based alloys can provide antibacterial activity while also affecting their corrosion and degradation behaviour [17,18]. Furthermore, silver cladding not only boosts surface antimicrobial performance but also offers a means to influence the corrosion behaviour and degradation profile of the underlying alloy.

The NZ30K alloy was studied because the magnesium matrix ensures biodegradability, while zinc, zirconium, and neodymium contribute to microstructural stability and mechanical properties. The addition of silver is intended to provide an additional antibacterial effect and modify the corrosion behavior. Compared to conventional biodegradable Mg-Zn and Mg-Ca alloys, the studied system combines multicomponent alloying with a silver-containing surface layer. This allows for the evaluation of the influence of both bulk composition and surface modification on localized corrosion.

Understanding the selective degradation behavior of such a composite system is critical for tailoring degradation kinetics to match bone healing timelines. Therefore, this research focuses on the selective degradation characteristics of NZ30K+Ag alloy implants with silver cladding of varying thickness (200-300 nm and 500 nm) in Ringer-Locke solution. The results aim to guide the development of next generation biodegradable implants that address the current limitations in orthopedic applications by combining mechanical integrity, antibacterial protection and controlled biodegradability.

2. Materials and methods

NZ30K magnesium alloy samples, alloyed with Ag, were produced by smelting in an aging process [17], [19]. Cylindrical samples measuring 12 mm in diameter and 30 mm in length were prepared. The chemical composition of the samples was determined using the X-ray spectral method using the Scanning electron microscope EVO-40XVP, ZEISS, with INCA Energy 350 microanalysis system (Oxford) EHT=12.00 kV, as summarized in Table 1. The elemental composition is given as it was obtained from the instrument's software. These values are used to characterize the nominal composition of the alloy being analyzed.

Table 1. Chemical composition of the NZ30K+Ag alloy of the studied samples

Alloy	Content of chemical elements, wt. %				
	Mg	Zn	Zr	Nd	Ag
NZ30K+Ag	95.57	0.69	0.86	2.79	0.09

The samples of the alloy under study were clad with a layer of silver 200-300 and 500 nm thick using a 600 mA DC magnetron sputtering system (DXT-450) equipped with a circular source and a target with Ag (50 mm in diameter) in a gas discharge. The vacuum chamber of the system was a cylinder with an internal diameter and height of 500 mm cylindrical samples made of silver-alloyed NZ30K (Table 1) were chemically

degreased and cleaned by ultrasonication in a hot ethanol bath for 10 minutes and dried in warm air. Then they were mounted on a rotating (9 Hz) fixture located 90 mm from the sputtering source. Before deposition of the silver coating, air was evacuated the chamber using a diffusion oil pump to achieve a residual pressure of $1 \cdot 10^{-3}$ Pa. The samples were ion-etched at a bias potential of 1000 V for 15 minutes at a pressure of 1.5 Pa. An unbalanced magnetron, supplied from, was used in a 600 mA DC mode at 400 V. The silver coating was applied at a constant magnetron power of 240 W and a substrate bias voltage of 100 V. The argon pressure in the deposition chamber was 1.0 Pa. The time of silver deposition on the surface of the studied magnesium alloy was 5 and 15 minutes for coating thicknesses of 200-300 and 500 nm. Two coating thicknesses were selected to evaluate the influence of the silver layer thickness on the corrosion behavior of the alloy under the same deposition conditions.

Corrosion tests of silver-clad samples were carried out in a Ringer-Locke solution (an aqueous solution of un-distilled water with the following chemical reagents, procured from Beijing Chemical Works, in mg/l: NaCl - 9; NaHCO_3 ; CaCl_2 ; KCl 0.2; CHO_{6126} - 1) at a temperature of $20 \pm 1^\circ\text{C}$.

The establishment of a stationary value of the corrosion potential E_{corr} on the tested samples on the PN-2MK-10A potentiostat in automatic mode has been recorded. The polarization curves were plotted on this potentiostat after the corrosion potential was established on them, and then the potentials of the samples were shifted in the forward and reverse directions at a scan rate of 1 mV/s. The surfaces of corrosion damage on the samples on a JSM6360 scanning electron microscope with a JED-2300 energy dispersive microanalyzer has been researched. The characteristic features of the selective degradation of NZ30K+Ag alloy components in local corrosion damage were studied using the calculated selective degradation coefficients Z_{Zn} , Z_{Zr} , Z_{Nd} , and Z_{Ag} , which were calculated by the formula:

$$Z_{(\text{Zn,Zr,Nd,Ag})} = \frac{\Delta(\text{Zn,Zr,Nd,Ag}) \times \text{Mg}}{\Delta\text{Mg} \times (\text{Zn,Zr,Nd,Ag})},$$

where $\Delta(\text{Zn,Zr,Nd,Ag})$ is the difference between the content of Zn, Zr, Nd, Ag in the alloy before testing and in localized corrosion damage, wt. %. Mg is magnesium content in NZ30K+Ag alloy, wt. %. ΔMg is the difference between the Mg content in the alloy before testing and in localized corrosion damage, wt. %. Zn, Zr, Nd, Ag are the content of Zn, Zr, Nd and Ag in the alloy before testing. Depletion of the element under study relative to Mg occurs at $Z > 1$. Relative depletion occurs at $Z = 1$. $Z < 1$ indicates that the element is depleted less rapidly than Mg or is relatively enriched in the analyzed region.

3. Results and discussion

The metallographic analysis of the surface of a localized pitting corrosion on an NZ30K+Ag alloy sample, clad with a silver layer 200-300 nm thickness, revealed a distinctive microrelief pattern. This microrelief is characteristic of the selective degradation observed in steels and alloys at anode regions (Figure 1). In particular, corrosion pores, channels (Figures 1(a) and (b)) and tunnels (Figures 1(c) and (d)) have been observed. At the same time, corrosion degradation of the alloy in the vicinity of the intermetallic inclusion was recorded in (Figures 1(a) and (b)). Selective corrosion is caused by local heterogeneity in the alloy's composition and structure. This promotes preferential dissolution near defects and intermetallic inclusions. Further hydrolysis of the corrosion products and chlorides accumulation in these areas can acidify the local environment and accelerate the formation of pits, pores, channels, and corrosion tunnels.

This is attributed [20] to defects in the alloy structure in these places and the increased porosity of oxide films formed as a result of vacancy coagulation during the solid-phase diffusion of alloy components between the solid solution and the inclusion. An acidic chloride-containing environment that accumulates in corrosion damage due to the hydrolysis of corrosion products often leads to intensive growth of corrosion products by the mechanisms inherent in pitting [21-22]. Under such conditions, corrosion losses from pitting decrease with an increase in the specific magnetic susceptibility of steels and alloys [23].

The chemical composition of the alloy surface in the pitting corrosion formed as a result of contact corrosion between the alloy and the coating in the Ringer-Locke solution by energy dispersive microanalysis has been determined (Figure 1(a)), Table 2. An analysis of the data presented in Tables 1 and 2 indicate a reduction in the content of Mg from 95.57 wt.% (Table 1) down to 94.23 wt.% (Table 2), Zn from 0.69 wt.% (Table 1) to 0.37 wt.% (Table 2) and Nd from 2.79 wt.% (Table 1) to zero (Table 2). Conversely, Zr content

increased from 0.86 wt.% (Table 1) to 1.04 wt. % (Table 2). This led to the selective degradation of metals in the pitting corrosion (Figure 1(a)).

The characteristic features of this process were evaluated by the coefficients of selective degradation (Z) of zinc, zirconium, neodymium, and silver, calculated according to the above formula, using the data from Tables 1 and 2. The calculated coefficients Z_{Zn} , Z_{Zr} , Z_{Nd} , and Z_{Ag} for the spectrum 1 location (Figure 1(a)) are given in Table 3. According to the data from Table 3, the values were found to be greater than one. This showed that Zn, Zr, Nd, and Ag dissolved from the surface of the pitting corrosion more intensively than magnesium. In addition, the higher the value of the Z coefficients, the more intense the degradation of the chemical element from the surface of the corrosion damage. Under these conditions, it can be noted that the degradation rate of the components of the NZ30K+Ag alloy increased in the following order: Mg, Zr, Zn, Ag, Nd. Compared with the initial alloy composition, the analysed region of pitting corrosion showed enrichment in Zr and depletion in Mg, Zn, and Ag. The oncoming solid-phase diffusion of Zr, Zn, and O atoms in the surface layers of the localized corrosion damage suggests increased formation of oxygen-containing corrosion products or oxide species, since a sufficiently high oxygen content (4.36 wt. %) was found from Table 2. In addition, it is known [24, 25], about the ability of Zn and Zr to form dense oxide films on the surface of magnesium alloys that can resist corrosion, including in the Ringer-Locke solution. At the same time, it should be noted that the degradation of solid solutions with a high content of electronegative component is mainly accompanied by surface reorganization by solid-phase diffusion [25].

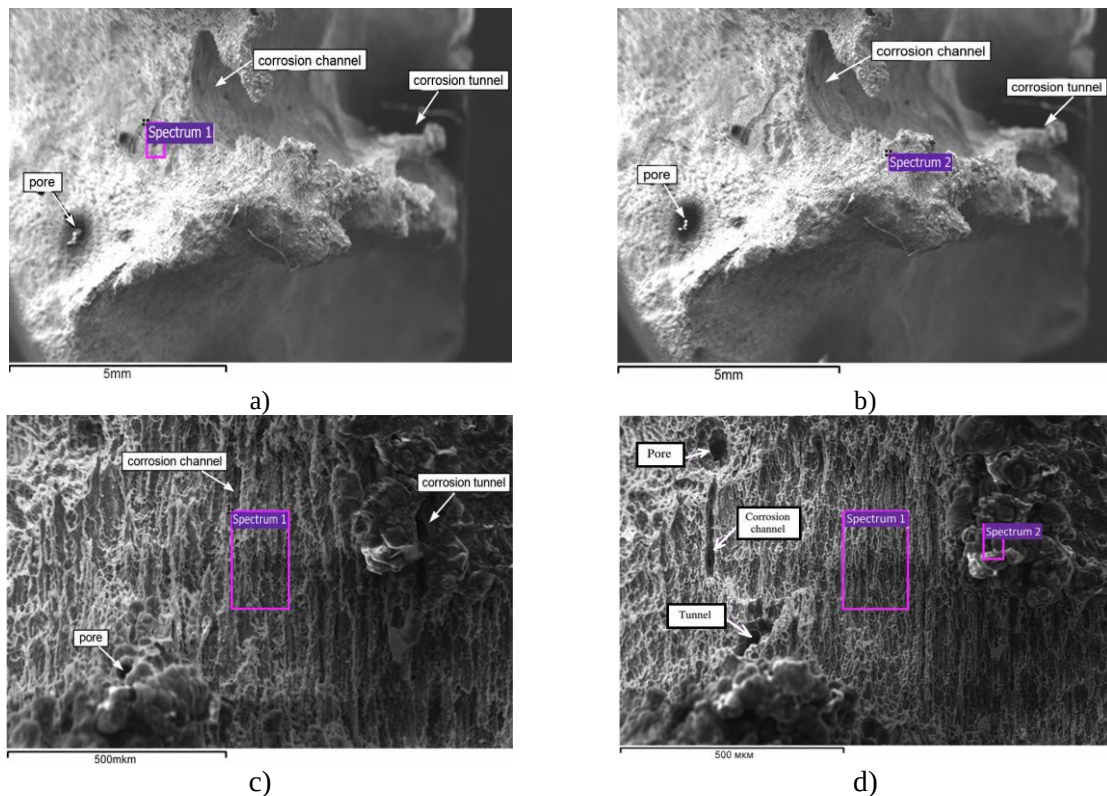


Fig.1. SEM micrographs and localized analysis areas of corrosion damage surfaces of a sample made of NZ30K+Ag alloy clad with a silver layer 200-300 nm thick. (a) Damage 1, spectrum 1. (b) Damage 1, spectrum 2. (c) Damage 2, spectrum 1. (d) Damage 2, spectrum 2.

Table 2. Chemical composition of the surface of localized corrosion damage of a sample clad with a silver layer of 200-300 nm thickness (Figure 1)

No.	Localized corrosion damage to the sample	Content of chemical elements, wt. %					
		Mg	Zn	Zr	Nd	Ag	O
1	Figure 1(a)	94.23	0.37	1.04	0.00	0.00	4.36
2	Figure 1(b)	90.66	0.42	0.63	0.00	1.94	6.25
3	Figure 1(c)	90.10	0.69	1.13	0.81	0.04	7.24
4	Figure 1(d)	77.31	0.53	0.53	0.00	2.01	19.62

Table 3. Coefficients of selective degradation of Zn (Z_{Zn}), Zr (Z_{Zr}), Nd (Z_{Nd}), and Ag (Z_{Ag}) metals on the surface of localized corrosion damage of a sample of silver clad with a thickness of 200...300 nm

No.	Localized corrosion damage to the sample	Coefficients of selective degradation of metals from localized corrosion damage			
		Z_{Zn}	Z_{Zr}	Z_{Nd}	Z_{Ag}
1	Figure 1(a)	25.9	11.7	55.9	55.9
2	Figure 1(b)	7.6	5.2	19.5	40.2
3	Figure 1(c)	0.0	5.5	12.4	9.8
4	Figure 1(d)	1.2	2.2	5.2	60.9

Research outlined in study [25] highlights that the selective degradation of metals from alloys facilitates solid-phase diffusion and characterized by critical potentials. At these potentials, significant reorganization of the surface layers occurs, resulting in the formation of pores, corrosion tunnels, and pitting. These surface changes increase the material's defectiveness and significantly reduce its corrosion resistance. Such damage was found on the surface of localized corrosion damage of a sample made of NZ30K+Ag alloy clad with a silver layer 200-300 nm thick (Figure 1), so its corrosion potential E_{corr} -1.444 V, established during electrochemical tests (Table 4), was critical for these processes. Under these conditions, the corrosion current density i_{corr} was quite high, 0.5012 mA/cm², which correlates with the nature of the corrosion fracture of the sample. It should be noted that the coefficients of the Tafel equation for the anodic $b_a = 0.113$ and cathodic $b_k = -0.110$ reactions are close (Table 4). However, the coefficient b_k is 0.003 less than b_a . This indicates that the activation energy of the cathodic reaction is higher [26]. This may be the reason for the slowdown in the corrosion degradation of the alloy.

Table 4. Electrochemical parameters of the studied samples of NZ30K+Ag alloy clad with a layer of silver in Ringer-Locke solution

No.	Coating thickness, nm	Corrosion potential, E_{corr}	Corrosion current density, i_{corr} , mA/cm ²	Tafel coefficients	
				b_k	b_a
1	200-300	-1.444	0.5012	-0.110	0.113
2	500	-1.466	0.3981	-0.113	0.103

The energy dispersive analysis of the surface of the test sample in the aforementioned pitting corrosion (Figure 1(b), spectrum 2) showed that its chemical composition changed significantly, particularly, the content of Mg and Zr decreased down to 90.66 and 0.63 wt. %, respectively (Table 2). This determined the nature of the selective degradation of metals in the corrosion damage. From the analysis of the data in № 2 of Table 2, it can be noted that the intensity of degradation of alloy components in it increased in the following order: Mg, Zr, Zn, Nd, and Ag. Under such conditions, the surface of the corrosion damage (Figure 1(b), spectrum 2) was enriched with Mg and depleted in Zr, Zn, Nd, and Ag. The observed redistribution of elements may involve surface diffusion processes associated with selective dissolution, as reported for metal alloys undergoing dealloying [24]. In contrast to spectrum 1 (Figure 1(a)), the intensity of selective degradation of these chemical elements was much lower, since its selective degradation coefficients were less than № 1.2 (Table 3). This trend led to the formation of a denser oxide film at the site of spectrum 2 (figure 1(b)), since the oxygen content here was 1.4 times higher than in spectrum 1 (Figure 1(a) and Table 2).

It was found that the content of Mg in another pitting corrosion on the surface of the sample clad with a silver layer 200-300 nm thick (Figure 1 c) decreased, and Zn, Zr, and Nd increased relative to its content on the surface (Figures 1(a) and (b)), № 1, 2 (Table 2). It should be noted that the Ag content decreased by 48.5 times. This contributed to a significant decrease in the coefficients of selective degradation Z_{Zn} , $Z_{Nd,Ag}$ №3 from table 3. The analysis of these coefficients showed that the intensity of degradation of alloy components in the pitting corrosion spectrum 1 from Figure 1(c) increased in the following order: Zn, Mg, Zr, Ag, and Nd. This caused the enrichment of its surface with Zn and the depletion of Mg, Zr, Ag, and Nd. Under such conditions, the solid-phase diffusion of Zn atoms was directed to the nanovolume of the alloy, and Mg, Zr, Ag, and Nd to the surface of the pitting corrosion. The accumulation of Zn in the surface layers contributed to the formation of self-protective oxide films in this area, since the oxygen content here increased up to 7.24 wt. % of № 3 (Table 2). However, in the upper left corner (Figure 1(b)), pores, corrosion channels, and tunnels were found, which, according to [24], may be due to the selective degradation of the alloy components Mg and Nd with the most electronegative values of the standard electrode potential. At the same time, the corrosive

medium in the pores could be acidified due to the hydrolysis of corrosion products, which caused its development into localized corrosion damage of the alloy up to 100 μm in size (upper left corner of Figure 1(c)), which grew by mechanisms inherent in pitting corrosion [26].

A decrease in the content of Mg, Zn, Zr, and Nd and an increase in Ag up to 2.01 wt. % were found on the surface of the pitting corrosion located 200 μm to the right of spectrum 1 (Figure 1(c)). % spectrum 2 (Figure 1(d)). This affected its selective degradation coefficients, № 4 of Table 2. From the analysis of these coefficients, it can be noted that the intensity of corrosion degradation of alloy components increased in the following order: Mg, Zn, Zr, Nd, and Ag. Thus, it turns out that the surface of the localized corrosion damage was enriched with Mg and depleted in Zn, Zr, Nd, and Ag. This compositional redistribution may be associated with selective dissolution and possible solid-state redistribution of alloying elements of Mg atoms into the alloy nanovolume, and Zn, Zr, Nd, and Ag to the surface of the localized corrosion damage. Summarizing the above, it can be noted that the NZ30K+Ag alloy sample clad with a 200-300 nm silver layer underwent intense contact and crevice corrosion with the formation of localized corrosion damage, where the alloy components dissolved selectively.

Table 5. Chemical composition of the surface of localized corrosion damage of a sample clad with a silver layer of 500 thickness (Fig. 2)

No.	Localized corrosion damage to the sample	Content of chemical elements, wt. %					
		Mg	Zn	Zr	Nd	Ag	O
1	Figure 2(a)	89.53	0.54	3.6	1.39	0.0	4.94
2	Figure 2(b)	90.76	0.52	0.0	0.0	2.68	6.04

Table 6. Coefficients of selective degradation of Zn (Z_{Zn}), Zr (Z_{Zr}), Nd (Z_{Nd}) and Ag (Z_{Ag}) from the surface of localized corrosion damage of a 500-thick silver clad sample (Fig. 2)

No.	Localized corrosion damage to the sample	Coefficients of selective degradation of metals from localized corrosion damage			
		Z_{Zn}	Z_{Zr}	Z_{Nd}	Z_{Ag}
1	Figure 2(a)	3.4	50.4	7.9	15.8
2	Figure 2(b)	0.58	19.9	19.9	619.8

In particular, the surface of the corrosion damage was mainly enriched with Mg, and in some areas with Zn, but severely depleted in Nd and, especially, Ag. The latter have the most negative ($\text{Nd} = -2.7\text{V}$) and positive ($\text{Ag} = +0.799\text{V}$) values of the standard electrode potential, which could be the reason for the acceleration of solid-phase diffusion of Nd atoms to the surface of corrosion damage by silver. A sample of NZ30K+Ag alloy clad with a 500 nm thick silver layer was also subjected to contact and crevice corrosion. According to the results of energy dispersion analysis of the surface of localized corrosion damage (Figure 2(a)), it was found that the content of Mg, Zn, Nd, and Ag decreased and Zr increased (Tables 1 and 5).

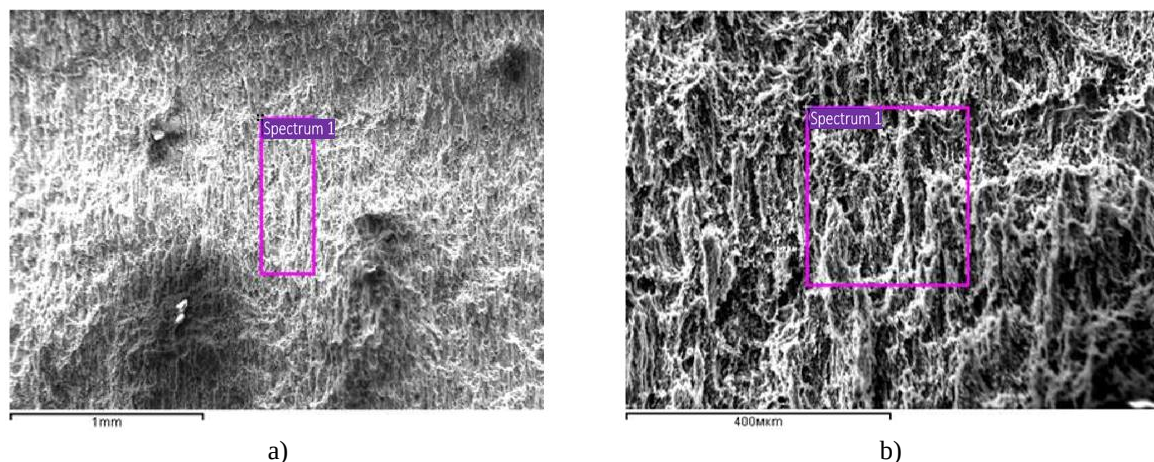


Fig. 2. SEM micrographs and localized analysis areas of corrosion damage of a sample of NZ30K+Ag alloy clad with a 500 nm thick silver layer. (a) Spectrum 1. (b) Spectrum 2.

The values in Tables 2 and 5 correspond to individual EDS measurements performed at the regions marked in Figures 1 and 2 and therefore represent local chemical compositions rather than surface-averaged

values. Analysis of the coefficients of selective degradation of alloy components (Table 6) showed that they dissolved in the following order: Mg, Zn, Nd, Ag, and Zr. This resulted in the enrichment of the surface of corrosion damage with Mg and the depletion of Zn, Nd, Ag, and Zr, which caused its solid-phase diffusion to its surface, and Mg atoms in the opposite direction. It should be noted that on the surface of the corrosion damage of the sample, localized degradation of the alloy in the vicinity of intermetallic inclusions was also detected (Figure 2(a)) and the microrelief is inherent in the selective degradation of steels and alloys, as mentioned above. Under such conditions, the corrosion potential $E_{corr} = -1.466\text{V}$ and the corrosion current density $i_{corr} = 0.3981\text{ mA/cm}^2$ were established on the surface of the sample (table 4). Thus, the potential E_{corr} of the sample was 0.022 V negative, and i_{corr} was 0.1031 mA/cm^2 less than that of the sample with a coating thickness of 200-300 nm.

Zr and Nd were not detected on the surface (Figure 2(b) and Table 5), but the content of Ag and oxygen increased. The initial Ag content of the alloy was very low (0.09 wt%, Table 1), while local EDS analysis revealed 2.68 wt% Ag (Table 5). This increase is most likely due to the presence of residual silver coating or localized accumulation of Ag-containing corrosion products. This influenced the nature of the selective degradation of the alloy components; particularly, it was found that the intensity of its degradation in the local corrosion damage increased in the following sequence: Zn, Mg, Zr, Nd, and Ag. Under such conditions, the surface became enriched with Zn while experiencing a depletion of Mg, Zr, Nd, and Ag. This redistribution triggered the solid-phase diffusion of Zn atoms into the alloy's nanovolume, with Mg, Zr, Nd, and Ag migrating in the opposite direction. The solid-phase diffusion of Mg atoms, as the main component of the NZ30K+Ag alloy with a high negative value of the standard electrode potential (-2.363V), contributed to the formation of nonequilibrium vacancies that coagulated into pores [27] (Figure 2(b)). Acidified corrosion products accumulated in them [25], which formed corrosion tunnels due to leakage from the pores under the influence of gravity. This tendency was observed in work [26] on heat exchanger plates subjected to pitting and crevice corrosion.

In summary, it can be noted that the sample of NZ30K+Ag alloy coated with a 500 nm thick layer of silver was subjected to contact and crevice corrosion. The intensity of its corrosion destruction was lower than that of the sample with a coating thickness of 200-300 nm. This is due to the above characteristic features of its selective degradation in longitudinal corrosion damage.

4. Conclusions

NZ30K+Ag alloy samples with silver coatings of 200-300 and 500 nm thickness were tested for contact and crevice corrosion in Ringer-Locke solution. Potentiodynamic polarization tests revealed corrosion potentials (E_{corr}) of -1.444 V and -1.466 V , and corrosion current densities of 0.5012 and 0.3981 mA/cm^2 , respectively. These values reflect the alloys susceptibility to selective degradation during localized corrosion.

The surface analysis of corrosion-damaged areas indicated that for the 200-300 nm coated samples, the sequence of selective degradation followed either Mg, Zr, Zn, Nd, Ag or Mg, Zn, Zr, Nd, Ag, with Mg enrichment observed in the affected regions. For the 500 nm coating, the selective degradation sequence depended on the analyzed localized corrosion region. For Figure 2(a), the sequence was Mg, Zn, Ag, Zr, whereas for Figure 2(b) it was Zn, Mg, Zr, Nd, and Ag.

Further surface characterization revealed Zn enrichment in localized corrosion zones of 200-300 nm coatings, with degradation proceeding as Zn, Mg, Zr, Ag, and Nd. For the 500 nm coatings, the sequence was Zr, Mg, Nd, Zn, and Ag. These degradation patterns are characteristic of progressive localized corrosion and suggest concurrent repair and stabilization processes occurring at the corrosion sites.

Conflict of interest statement

The authors confirm that they have no conflicts of interest – financial, personal, authorship-related, or any other – that could influence this research or the results presented in this paper.

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Statement on the use of Artificial Intelligence.

The authors declare that no artificial intelligence tools were used to generate scientific content, results, or conclusions of this article.

Data Availability Statement

The data that support the findings of this study are available upon reasonable request from the corresponding author.

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