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CORRELATION BETWEEN THE CORROSION RESISTANCE AND THE HARDNESS SCATTERING OF STRUCTURAL METALS TREATED WITH A PULSED ELECTRIC CURRENT

KORELACIJA MED ODPORNOSTJO PROTI KOROZIJI IN RAZTROSOM TRDOTE PRI KONSTRUKCIJSKIH MATERIALIH, OBDELANIH S PULZIRANJEM ELEKTRIČNEGA TOKA

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The results of corrosion tests of two kinds of structural metals initially treated by a pulsed electric current of high density are presented. According to the data obtained, the treatment influences the corrosion of metals. There is a correlation between the corrosion test results and the hardness scattering of the metals.

Key words: corrosion, hardness scattering, pulse electric current

Predstavljeni so rezultati korozijskih preizkusov za dve vrsti kovin, ki sta bili obdelani s pulziranjem električnega toka z veliko gostoto. Dobljeni rezultati kažejo, da obdelava s tokom vpliva na korozijo kovin. Opredeljena je bila korelacija med rezultati preizkusov korozije in raztrosom meritev trdote.

Ključne besede: korozija, raztros trdote, pulzirajoči električni tok

1 INTRODUCTION

The interest relating to corrosion in structural metals remains high because it is related to considerable financial costs. Corrosion leads not only to a loss of metal, but also to the degradation of its mechanical and physical properties, which decreases the lifetime of components and sometimes leads to catastrophic failure. For example, a majority of failures in oil-field pipes occurs because of corrosion damage, and similar damage may occur in ships and other structures [1,2].

Existing methods of metal and alloy protection from corrosion include the use of coatings with deposition, electrochemical methods of protection (e.g., cathodic protection) and others. However, there is considerable interest in developing new and more effective corrosion-protection methods.

One of the common types of metal and alloy corrosion is electrochemical corrosion, which leads to damage in conductive environments (electrolytic solutions). In general, the electrochemical corrosion mechanism involves the appearance of short-circuited micro-galvanic elements on the metal surface with different values of e.m.f. as a result of the formation of anodic (with low electrode potential) and cathodic (with high electrode potential) zones [3]. These zones are generated by differences in the metal structure, surface roughness, the existence of protective films and other factors. The difference in the metal microstructure (due to a difference of the grain size, composition, crystal anisotropy, the emergence of dislocations on the surface, the presence of impurities, inclusions, non-uniform mechanical stresses) can activate the corrosion processes. The role of mechanical stresses is important because in presence of tensile stresses in the metal, anode zones can appear. These zones evolve to become corrosion centers [4].

It is known that a pulsed electric current (PEC) treatment causes the relaxation of the mechanical stresses in metals [5,6], and also the homogenization of their microstructure [7]. Based upon common considerations, these data can serve as a basis for the creation of a new technology for the corrosion protection of metals.

The structural homogeneity of a metal can be estimated by a measurement of its indentation hardness [8,9]. The specifics of the indentation hardness are based on the existence of a quantity correlation with other mechanical properties (e.g., tensile strength, fatigue limit). Consequently, if a representative array of hardness measurements is obtained, it is possible to assess the variation of the mechanical properties of the metal and its microstructural homogeneity. For example, the authors [9] have shown that the lowest level of hardness scattering corresponded to the metal with the most uniform microstructure in the initial state. On the other hand, the highest hardness scattering was registered for the metal with accumulated damage after long-term performance.

The results of the investigation presented here aim to clarify the possibilities of a PEC treatment to improve the corrosion resistance of steel and an aluminum alloy and also to define a correlation between the corrosion resistance and the hardness scattering in the metals after the treatment.

2 METHOD OF EXPERIMENTAL RESEARCH

Metallic sheet specimens of high-strength low-alloy steel HSLA of 100 mm length, 13 mm width and 1.1 mm thickness and an aluminum alloy 5182 of 100 mm length, 13 mm width and 1.4 mm thickness were used for the investigation (the compositions of the metals are in **Table 1**).

Table 1: Composition of the metals used (mass fraction, *w*/%)
Tabela 1: Sestava uporabljenih kovin (masni delež, *w*/%)

Specimens	*w*(Mn) /%	*w*(Mg) /%	*w*(Ti) /%	*w*(C) /%	*w*(S) /%	*w*(P) /%
Steel HSLA	0.25	–	0.30	0.02	0.02	0.02
Al-alloy 5182	0.3	4.5	–	–	–	–

The corrosion was performed at 35 °C (± 1.5 °C) in a salt-spray chamber using a 5 % NaCl solution (in distilled water) according to the ASTM B117-97. The total time of exposure was 1000 h. The treatment was carried out in hourly cycles that involved sequences of spraying the samples with a fog spray (salt spray) for 10 minutes at a flow rate of 0.7 L/h and 50 min of hot air (drying). The sequence was repeated every hour.

The samples were initially hand cleaned in hot water and further cleaned for 12 min in an ultra-sonic chamber with water at 48 °C. This process took place twice because a change of water was necessary. Then the specimens were washed with propanol and dried for 30 min at 70 °C, weighed and placed in the corrosion salt-spray chamber. At the end of the corrosion test the samples were cleaned in hot water to remove the deposits of salt and then washed with propanol and dried at 70 °C and weighed.

Table 2: Regimes of PEC treatment
Tabela 2: Režimi obdelave z električnim tokom

No.	Steel HSLA	Aluminum alloy 5182
	Current density, j(kA/mm^2)	
1	1.3	1.3
2	1.3	1.3
3	2	2
4	2	2
5	3	3
6	3	3

Remark: specimens No. 1, 3, 5 were treated using three pulses with a 1 min. interval, specimens No. 2, 4, 6 were treated using three pulses with a 3 min. interval

The PEC treatment of the samples was undertaken using a pulsed current generator [10]. Three electric current pulses were passed through each sample with the maximum current density as indicated in **Table 2**.

To obtain reliable values of the metal hardness and exclude the operator's mistakes, a computerized hardness tester COMPUTEST SC (ERNST, Switzerland) was used. The hardness *HRB* was measured before the PEC treatment and after the treatment under an indentation load of 49 N.

3 TEST RESULTS AND THEIR ANALYSIS

The corrosion test results are presented in **Table 3** and in **figures 1 a, 1 b and 2**. The different corrosion behavior of the steel and aluminum alloys must be considered. In the test result analysis on steel, the corrosion products (Fe_2O_3 oxides) flake off the base material causing the reduction of the specimen weight after the corrosion tests, while, in the case of the aluminum alloy, an increase in the specimen weight is observed after the corrosion tests because Al_2O_3 oxides have high adhesion to the base material.

The estimation of the influence of the PEC treatment on specimens corrosion was carried out in two steps. In the first step, the relative change, δ_m, of the weight of each specimen after the corrosion test was calculated,

$$\delta_m\ /\ \% = \frac{m_c - m_0}{m_0} \cdot 100$$

where m_0 and m_c are the weights of the samples before and after the corrosion test, respectively. In the second step, the influence factor of the PEC treatment on the specimen corrosion, k_c, was determined as:

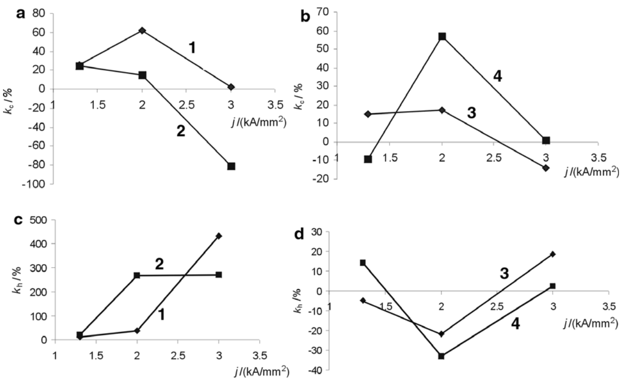

Figure 1: Change of the effect of PEC treatment on metal corrosion k_c (a, b) and hardness scattering k_h (c, d) against the metal (a, c – HSLA steel; b, d – aluminium alloy 5182), density of PEC, and interval between electric current pulses (1, 3 – 1 min interval; 2, 4 – 3 min interval).

Slika 1: Sprememba učinka obdelave z električnim tokom na korozijo kovine k_c (a, b) in raztros trdote k_h (c, d) v odvisnosti od kovine (a, c – konstrukcijsko jeklo; b,d – zlitina aluminija), gostota toka in interval med električnimi pulzi (1, 3 – 1 min interval; 2, 4 – 3 min interval)

$$k_c\ /\ \% = \frac{\left|\delta_m^{\text{untreat}}\right| - \left|\delta_m^{\text{treat}}\right|}{\left|\delta_m^{\text{untreat}}\right|} \cdot 100$$

where $\delta_m^{\text{untreat}}$ is the relative change of the weight of the untreated specimens (the mean value of the 6 specimens in the bottom row in **Table 3**) and δ_m^{treat} is the relative change of the weight in percent of the six specimens treated by PEC (**Table 3**).

Table 3: Results of the corrosion tests
Tabela 3: Rezultati korozijskih preizkusov

No. (corresponds to **table 2**)	Steel HSLA		Aluminum alloy 5182	
	After PEC treatment			
	δ_m/%	k_c/%	δ_m/%	k_c/%
1	–0.5224	+26	+0.1217	+15
2	–0.5310	+25	+0.1571	–9
3	–0.2706	+62	+0.1188	+17
4	–0.60 10	+15	+0.0614	+57
5	–0.6890	+2	+0.1640	–14
6	–1.2729	–81	+0.1426	+1
Without PEC treatment				
Mean for 6 specimens	δ_m/%		δ_m/%	
	–0.7050		+0.1437	

The corrosion test results suggest that the PEC treatment with the above regimes substantially influences the behavior of the investigated metals. The treatment causes considerable deceleration of the corrosion processes for both the HSLA and aluminum alloy 5182. Here, the results presented show that the regimes of the PEC treatment with maximum effect exist.

Table 4: Results of indentation tests
Tabela 4: Rezultati meritev trdote

No. (corresponds to table 2)	Steel HSLA		Aluminum alloy 5182	
	σ_μ	k_h/%	σ_μ	k_h/%
1 – untreated	0.0152	+11	0.0615	–5
1 – treated	0.0168		0.0584	
2 – untreated	0.0120	+20	0.0501	+14
2 – treated	0.0144		0.0572	
3 – untreated	0.0153	+39	0.0751	–22
3 – treated	0.0212		0.0587	
4 – untreated	0.0171	+267	0.0847	–33
4 – treated	0.0627		0.0566	
5 – untreated	0.0186	+431	0.0531	+19
5 – treated	0.0986		0.0630	
6 – untreated	0.0150	+271	0.0512	+2
6 – treated	0.0557		0.0525	

The indentation test results are presented in **Table 4** and in **Figures 1 c, 1 d**. On average, 120 measurements of hardness per condition (treated and untreated) were fulfilled for each specimen. The results were processed and a relative value σ_μ, with σ as the standard deviation and μ as the hardness average were calculated for each specimen and condition. Then the influence factor of the PEC treatment on the metal hardness scattering, k_h, was determined, as presented below:

$$k_h = \frac{\sigma_\mu^{\text{treat}} - \sigma_\mu^{\text{untreat}}}{\sigma_\mu^{\text{untreat}}} \cdot 100\%$$

The indentation test results demonstrate the sensitivity of the hardness scattering to the regimes of PEC treatment and the corrosion resistance. The PEC-treated HSLA sample sets 4 and 5 showed a lower increase of the corrosion resistance than the sample sets 1, 2 and 3, and the set 6 showed an increase of corrosion (**Table 3** and **Figure 1 a**). At the same time, the samples sets 4, 5 and 6 exhibited a substantial increase in the hardness scattering (**Table 4** and **Figure 1 c**). In the case of the aluminum alloy 5182, the effect of the PEC treatment on the corrosion resistance is mixed as shown in **Table 3** and **Figure 1 b** with the PEC-treated sample sets 1, 3 and 4 with a lower corrosion intensity, sets 2 and 5 with a stronger corrosion, while the values for set 6 are practically similar. At the same time, the PEC-treated sample sets that corroded less (1, 3 and 4), also exhibited a lower level of scattering of the hardness value, indicating a more homogeneous composition and microstructure (**Table 4** and **Figure 1 d**). On the other hand, sets 2 and 5 corroded more, but showed a higher degree of scattering of the hardness data, implying a less uniform structure and composition.

Macrographs of the surface appearance of the investigated HSLA specimens after the corrosion tests are

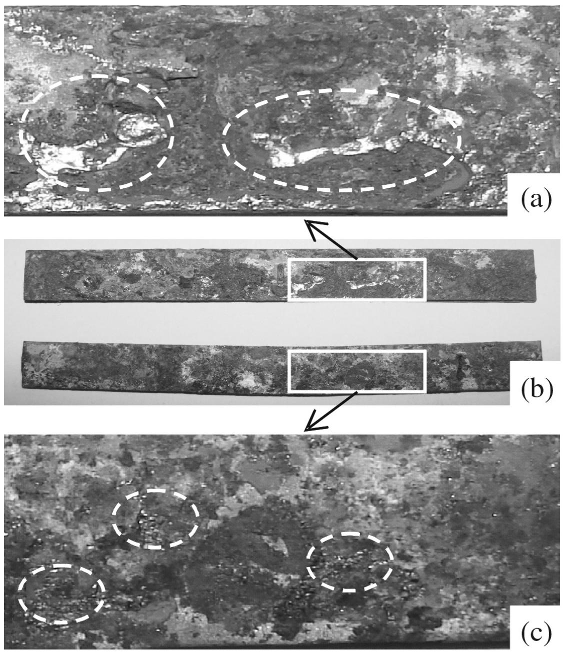

Figure 2: Surface appearances of HSLA steel specimens after corrosion tests: a, b (top photo) – metal in initial condition; b (bottom photo), c – after PEC treatment
Slika 2: Videz površine konstrukcijskega jekla po korozijskem preizkusu: a, b (zgornja slika) – kovina pred preizlkusom; b (slika spodaj), c – po obdelavi s tokom

presented in **Figure 2** (the difference in the appearance of the treated and untreated specimens in the case of the aluminum alloy specimens is visibly insignificant). A substantial difference in the corrosion damage of the alloy surface took place for the HSLA specimens; in the case of the specimens without the PEC treatment, zones with selective, localized corrosion are visible in **Figure 2 b** (top) and more obviously it is visible in the areas bordered by the dashed lines in **Figure 2 a**. The PEC treatment was observed to cause weaker, more uniform and homogeneous corrosion on the whole surface of specimen, see **Figure 2 b** (bottom). Only small pittings are visible there, see the areas bordered by the dashed lines in **Figure 2 c**.

The obtained results may be related to the different microstructure and the surface homogeneity of the treated and untreated specimens. The differences may arise during the production of the sheet with the cold-working that builds up non-uniform residual stresses. On the other hand, the PEC treatment may relieve these stresses, providing a more homogeneous material.

4 CONCLUSIONS

The results of the investigation have shown that the PEC treatment influences the corrosion behavior of structural metals. Based on these observations, the following conclusions can be drawn:

The regimes of the PEC treatment causing the deceleration of the corrosion with maximum effect exist for both the HSLA and aluminum alloy 5182.

A correlation between the corrosion resistance and the hardness scattering of the PEC-treated metals exists. The specimens with the lower hardness scattering show the better corrosion resistance.

As a result of the PEC treatment, the corrosion on the surface of HSLA steel samples became smaller and more homogenous and the zones of localized corrosion observed on the untreated samples are absent on the surface of PEC-treated HSLA.

The investigation was based on one sample per variant of PEC treatment. Further research will be carried out using more samples, aiming to accumulate experimental data on the influence of the PEC treatment on the characteristics of the corrosion of structural metals, as well as to investigate the reasons and physical mechanisms of such effects.

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