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STUDY OF CORROSION CHARACTERISTICS OF 65G AND 45 STEELS BEFORE AND AFTER ELECTROLYTIC-PLASMA HARDENING

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This article presents the results of studies of the corrosion resistance of steel grades 65G and 45, which were subjected to electrolytic plasma hardening (EPH). The main objective of the study was to identify changes in the corrosion properties of steels depending on the type of environment: water, urea, superphosphate and ammonium nitrate. The study showed that after EPH, the corrosion rate of steel 45 decreased by 8 times compared to the original sample, reaching a value of 2.58×10^{-4} mm/year. For steel 65G, a significant improvement in corrosion resistance was also observed, especially in the environment of urea and superphosphate. The corrosion potential of these steels shifted to a more positive value, indicating an improvement in the protective properties of the surface. Polarization curves showed a decrease in the corrosion current for steel 45 before EPH in a solution of edible salt from 562.34 μA/cm² to 111.75 μA/cm² in urea, and to 132.67 μA/cm² in superphosphate. For steel 65G before EPH, the corrosion current in a edible salt environment was 67.23 μA/cm², decreasing to 57.28 μA/cm² in urea and to 60.73 μA/cm² in ammonium nitrate after the EPH process.. The results confirm that EPH significantly increases the corrosion resistance of the studied steels, which makes this treatment method promising for improving the durability of metal products used in aggressive chemical conditions.

Keywords: *electrolytic plasma hardening, steel 45, corrosion, wear resistance, electrochemical corrosion.*

INTRODUCTION

The study of the corrosion resistance of steels plays a key role in the development and improvement of processing technologies and their application in various industries. Steels of grades 65G and 45 possess high mechanical properties and are widely used in mechanical engineering and other fields where material durability in aggressive environments is required. However, extending the service life of such steels is possible not only through classical heat treatment methods but also with the help of modern surface hardening techniques, such as EPH [1–4].

The aim of this study is to investigate the changes in the corrosion characteristics of 65G and 45 steels after treatment using the EPH method. EPH represents an innovative approach that significantly enhances the corrosion resistance and fatigue properties of metals by forming a protective layer on their surface. The key feature of this technology lies in the use of plasma generated in an aqueous electrolyte solution, ensuring both high efficiency and environmental friendliness of the process [5, 6].

During the research, a series of experiments were conducted, including corrosion tests in various aggressive environments. Electrochemical corrosion tests were carried out on samples treated under different EPH conditions. The samples were exposed to 3% aqueous solutions of table salt (NaCl), urea ($(NH_2)_2CO$), and other aggressive environments. The goal of this study was to analyze the effect of EPH on the corrosion resistance of 45 and 65G steel samples [7–9].

It is expected that the results of this study will not only assess the effectiveness of EPH in improving the corrosion resistance of steels but also help develop recommendations for optimizing processing parameters for industrial applications.

MATERIALS AND METHODS

The tests were carried out using an electrochemical corrosion system, consisting of a potentiostat-galvanostat and an electrochemical cell, in which the samples were immersed in an aqueous solution of laboratory-grade table salt for the first group of tests on 45 steel samples and in mineral fertilizers for the second group of tests on 45 and 65G steel samples (Figure 1). For each sample, a polarization curve was measured, reflecting the dependence of the corrosion potential on the corrosion current density. The polarization curve is an essential tool for studying the corrosion resistance of materials. It allows for determining the corrosion potential and corrosion current, which are key parameters characterizing the material's corrosion resistance. The corrosion potential represents the thermodynamic tendency of the material to corrode, while the corrosion current reflects the corrosion rate [9–14].

EPH of 45 and 65G steels was carried out in a thermocyclic mode, which is implemented by alternating high (UH) and low voltages (UL). This method allows for precise control of the heating process, preventing steel remelting while ensuring the formation of a hardened layer of greater depth. The use of thermocycling is aimed at studying the effect of heating rate on hardening characteristics. By alternating voltages, it is possible to accurately regulate temperature changes during the quenching process, which is critical, as excessively fast heating may lead to uneven microstructural changes and potential overheating, whereas too slow heating may fail to achieve the required depth and uniformity of the hardened layer. The electrolyte used for EPH consisted of 20% sodium carbonate and 80% distilled water, which further improves control over electrochemical conditions, directly affecting heat generation and resulting microstructural transformations in steel. This mode allows for a detailed analysis of how different heating rates influence the properties of the hardened layer, including its thickness, hardness, and microstructural characteristics. The electrical and time parameters of EPH in thermocyclic mode are presented in Table 1.

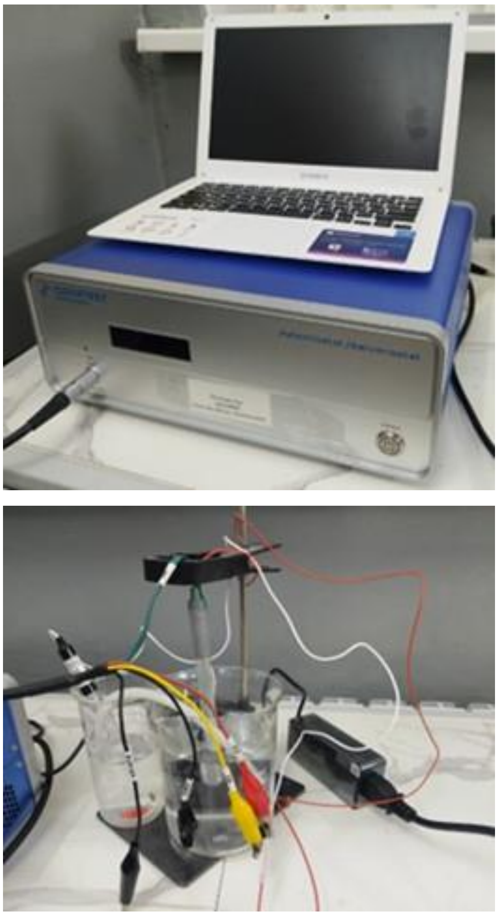
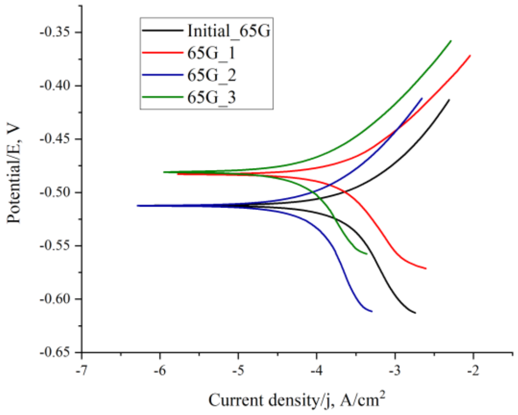


Figure 1. Potentiostat-galvanostat and electrochemical cell

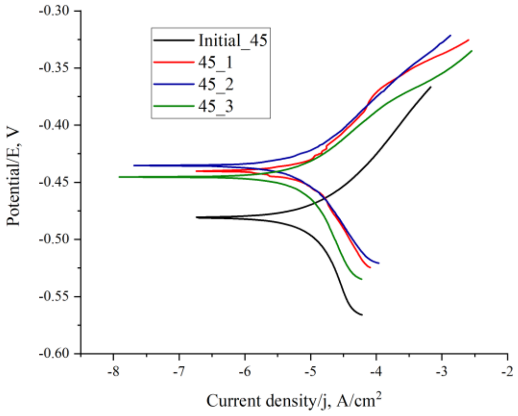
For the study of the corrosion characteristics of 65G and 45 steels after electrolytic plasma hardening in mineral fertilizer environments, the samples were treated using EPH according to Table 2.

RESEARCH RESULTS AND CONCLUSIONS

Figure 2 presents the polarization curves in the coordinates of potential – current density (E – i) when measuring the corrosion of 45 and 65G steels before and after EPH according to the modes in Table 1.



a) 45 steel before and after EPH



b) 65G steel before and after EPH

Figure 2. Potentiodynamic polarization curves

Table 1. Parameters of EPH modes for 45 and 65G steels

Sample	U_{H1}, B	t_{H1}, c	I_{H1}, A	U_{L1}, B	t_{L1}, c	U_{H2}, B	t_{H2}, c	I_{H2}, A	U_{L2}, B	t_{L2}, c	U_{H3}, B	t_{H3}, c	I_{H3}, A
45_1	320	3	100	50	5	0	0	0	50	5	0	0	0
45_2	320	3	100	50	5	200	2	75	50	5	0	0	0
45_3	320	3	100	50	5	200	2	75	50	5	200	2	75
65Г_1	320	3	100	50	5	0	0	0	50	5	0	0	0
65Г_2	320	3	100	50	5	200	2	75	50	5	0	0	0
65Г_3	320	3	100	50	5	200	2	75	50	5	200	2	75

Table 2. Parameters of EPH modes for corrosion test samples in mineral fertilizer environments

Sample	Anode area, m^2	Electrolyte concentration	Electrolyte consumption, L/min	U, B	t, c
Steel 45	0.05	20% Na_2CO_3+80% Water	100	300	4
Steel 65G	0.05	20% Na_2CO_3+80% Water	100	300	4

The corrosion resistance test showed a significant reduction in the corrosion rate after electrolytic plasma hardening of 45 and 65G steels. In samples 45_2 and 65G_3 (average corrosion rate 2.58×10^{-4} mm/year), this indicator improved 8 times compared to the initial sample. At the same time, for samples 45_1 and 65G_1, the reduction in corrosion rate was less pronounced. The analysis of the polarization curves, which show the dependence of corrosion potential on corrosion current, confirms that the corrosion potential for samples No. 2–3 shifted in a more positive direction compared to the initial sample, indicating increased corrosion resistance. A similar study [15] also reports an improvement in corrosion resistance after electrolytic plasma treatment, as evidenced by a decrease in corrosion potential and corrosion current density.

Studies of the corrosion resistance of 45 and 65G steel samples before and after EPH showed significant changes in the material's behavior in different corrosive environments [16, 17]. After EPH, a modified layer forms on the metal surface, increasing corrosion resistance. This is due to changes in the steel microstructure, including densification and an increase in the number of carbide phases, which make it difficult for corrosive agents to penetrate the deeper layers of the material. Figure 3 presents the results of X-ray phase analysis, which reveal characteristic peaks corresponding to iron carbide (Fe_3C) formed after electrolyte-plasma treatment. These peaks indicate the formation of Fe_3C as a result of processing in a sodium carbonate (Na_2CO_3) environment [18–20].

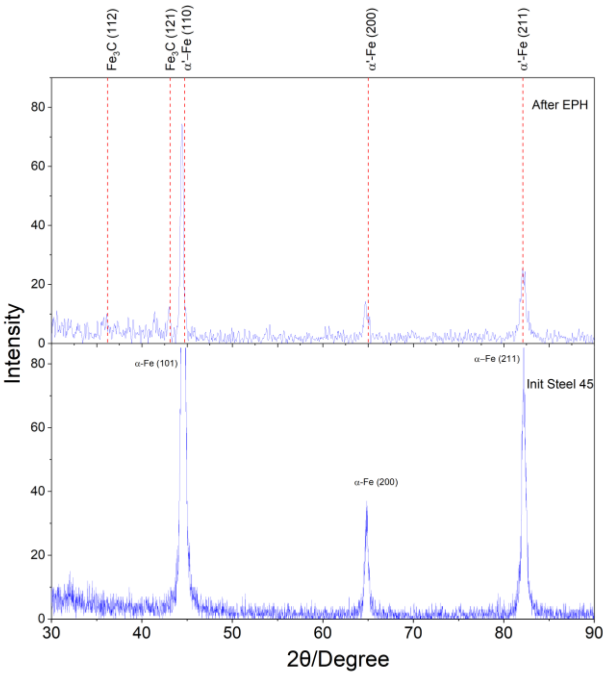


Figure 3. X-ray diffraction patterns of steel 45 samples before and after EPH

The hardening effect is achieved through the formation of high-temperature phases and metal processing, which not only increases the surface hardness but also alters the chemical and phase stability of the steel. At the same time, the surface layer becomes more homogeneous and dense, preventing the formation of corrosion centers and processes leading to material degradation in aggressive environments. Figure 4 presents polarization curves obtained from electrochemical corrosion tests of 45 steel after EPH.

During the experiments, it was established that after EPH, 45 steel demonstrates enhanced resistance in environments containing mineral fertilizers, such as urea, superphosphate, and ammonium nitrate. This is explained by the formation of complex protective structures on the steel surface, which effectively block corrosion processes. Such a change in properties is of great interest for applications in agricultural equipment and in conditions of high chemical aggressiveness.

Based on the data presented in Figure 4 and Table 3, the following conclusions can be made about the corrosion resistance of steel 45 after EPH treatment in various environments. In an aqueous environment, steel 45 demonstrates the lowest corrosion current – 18.97 µA/cm², which indicates a relatively low corrosion activity. The corrosion potential in this environment is −481 mV, which also indicates a moderate aggressiveness of the environment. In a urea environment, an increase in the corrosion current to 111.75 µA / cm² is observed, which indicates an increase in corrosion activity compared to water. At the same time, a more negative corrosion potential (−509 mV) may indicate the formation of a more stable passive layer. Mineral fertilizers such as superphosphate and azophoska have a more aggressive effect: the corrosion current is 132.67 and 486.78 µA/cm², respectively. At the same time, the corrosion potentials of -492 mV (superphosphate) and −499 mV (azofoska) indicate a noticeable increase in corrosion processes. However, among all the studied environments, ammonium nitrate showed the highest corrosion activity (597.7 µA/cm²), despite a comparable corrosion potential (−499 mV), which confirms its high aggressiveness towards steel 45 after EPH.

Table 3. Corrosion current (I_{corr}) and corrosion potential (E_{corr}) values for 45 steel after EPH in different environments

Environment	**I_{corr} (µA/cm²)**	**E_{corr} (mV)**
Water	18.97	−481
Urea	111.75	−509
Superphosphate	132.67	−492
Azophoska	486,78	−499
Ammonium sulfate	160.44	−451
Ammonium nitrate	597.7	−499

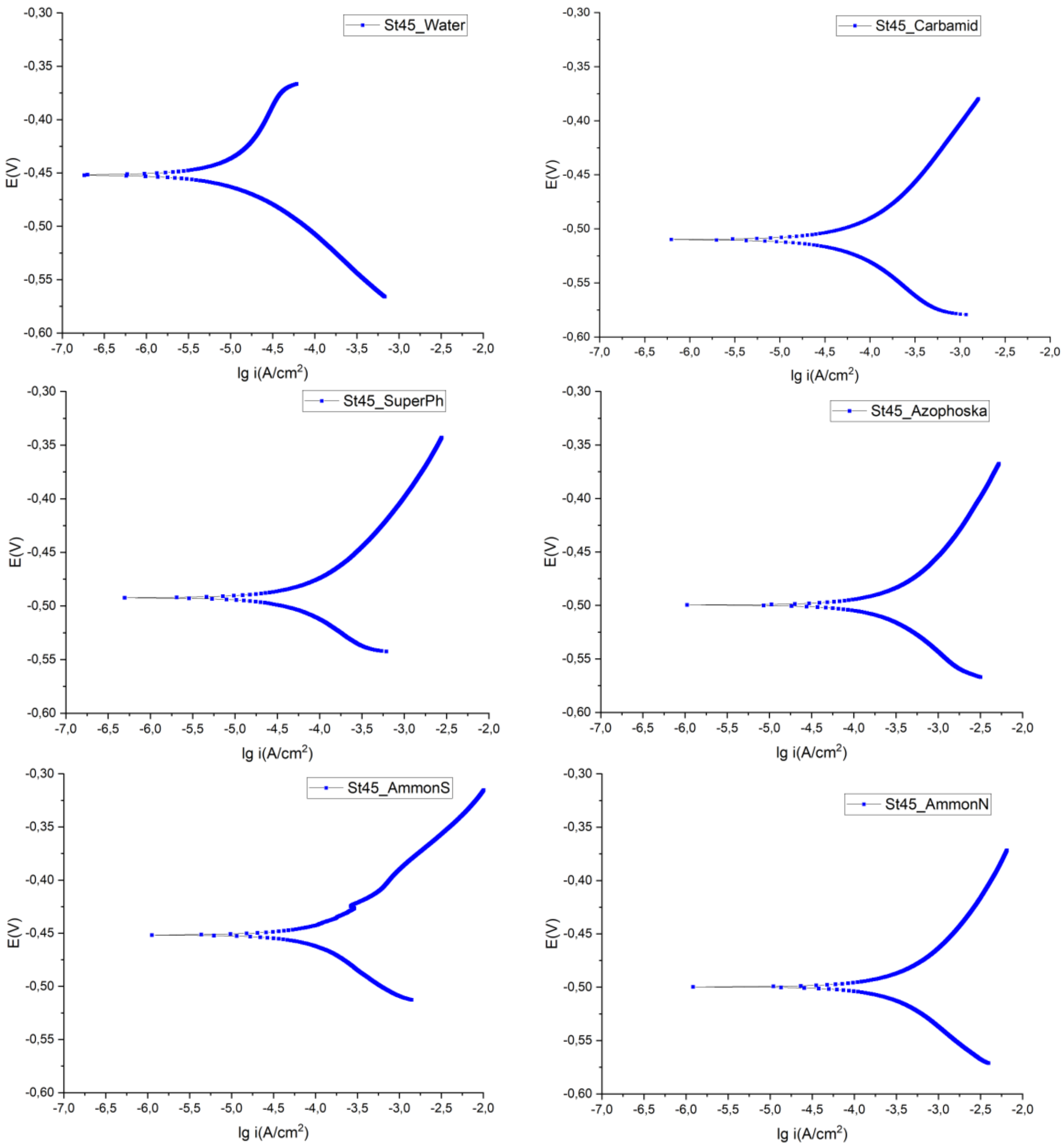


Figure 4. Polarization curves obtained from electrochemical corrosion tests of 45 steel after EPH in water and mineral fertilizer solutions

The analysis shows that steel 45 after EPH demonstrates different resistance to corrosion depending on the chemical composition of the environment [21, 22]. The most aggressive impact is exerted by mineral fertilizers such as azophoska and ammonium nitrate, while in aqueous and urea environments the steel demonstrated greater resistance to corrosion. This suggests that when selecting operating conditions for EPH-treated parts, the chemical nature of the environments in contact with them should be taken into account.

Figure 5 presents polarization curves obtained during electrochemical corrosion tests of 65G steel after EPH. The study was also conducted in various environments, including water and mineral fertilizer solutions, such as urea, superphosphate, azophoska, ammonium sulfate, and ammonium nitrate.

The values of corrosion potential (E_{corr}) and corrosion current (I_{corr}) of the polarization curves for 65G steel after EPH during electrochemical corrosion tests in mineral solutions are presented in Table 4. Each curve in the graphs of Figure 4 reflects the characteristic behavior of 65G steel after electrolytic-plasma treatment in various corrosive environments. The data obtained show that the lowest value of the corrosion current is recorded in water (53.80 µA/cm²) and indicates the lowest corrosion activity. Similar current values are observed in a solution of urea (57.28 µA/cm²) and ammonium nitrate (60.73 µA/cm²), which indicates a relatively moderate impact of these environments. Higher current values are noted for superphosphate (67.98 µA/cm²), azophoska (78.55 µA/cm²) and especially for ammonium sulfate (82.25 µA/cm²), which indicates an increased intensity of corrosion processes in their presence.

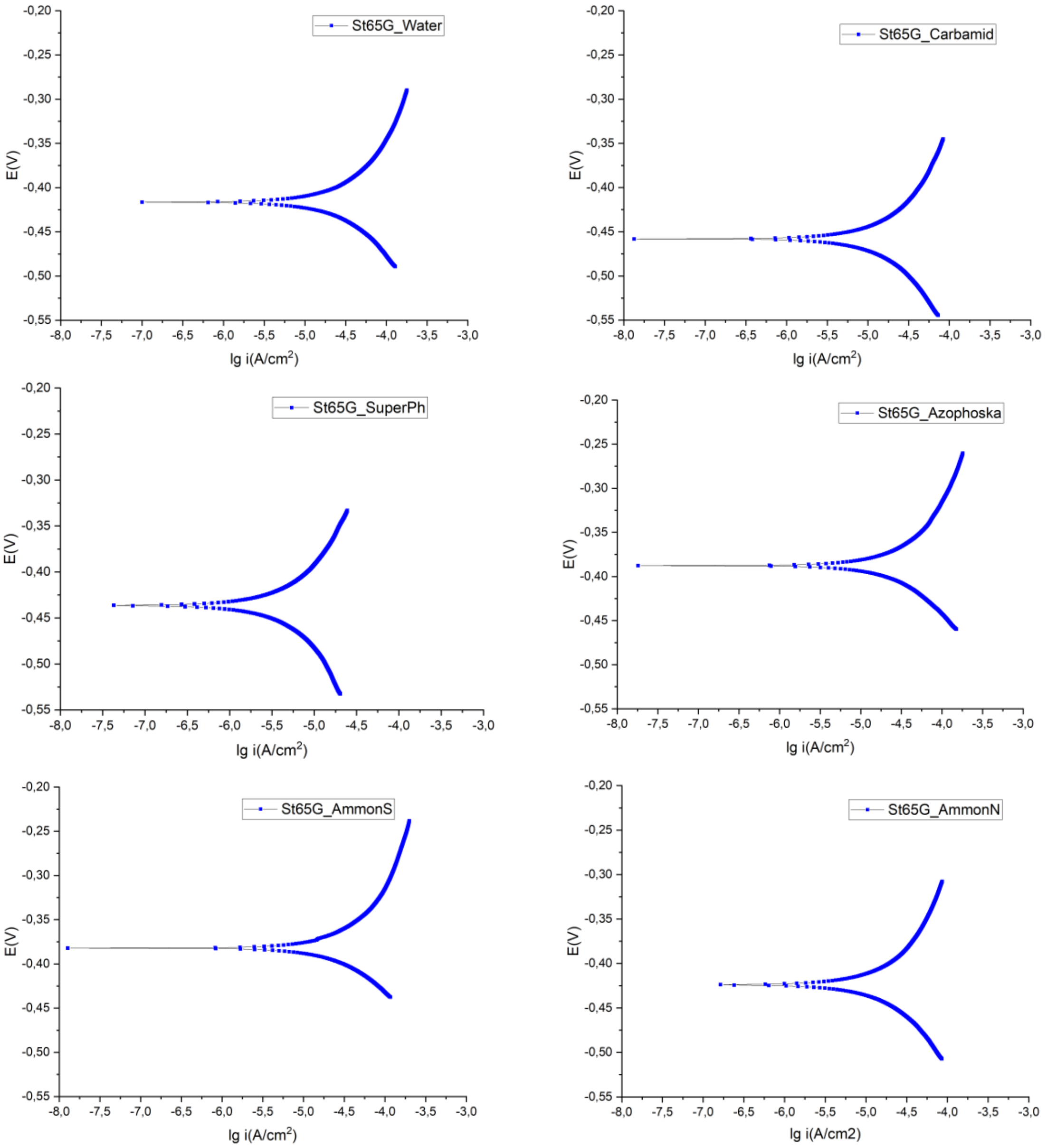


Figure 5. Polarization curves obtained from electrochemical corrosion tests of 65G steel after EPH in water and mineral fertilizer solutions

Table 4. Corrosion current (I_{corr}) and corrosion potential (E_{corr}) values for 65G steel after EPH in different environments

Environment	**I_{corr} (μA/cm^2)**	**E_{corr} (mV)**
Water	53.80	−416
Urea	57.28	−458
Superphosphate	67.98	−436
Azophoska	78.55	−387
Ammonium sulfate	82.25	−382
Ammonium nitrate	60.73	−423

Regarding the corrosion potential, the least negative values are noted for ammonium sulfate (−382 mV) and azophoska (−387 mV), which may indicate the formation of a more stable passive layer. On the contrary, the most negative potential is observed in the urea solution (−458 mV), despite the moderate current, which indicates a more active electrochemical reaction, but the possible presence of a protective film. Thus, the obtained data confirm the significant influence of the chemical composition of the environment on the corrosion resistance of 65G steel after EPH and emphasize the need to take these features into account when choosing operating conditions.

Experimental studies of 45 and 65G steels after EPH in various mineral fertilizer environments revealed differences in corrosion characteristics. The polarization curves obtained from electrochemical tests provide quantitative data on corrosion potential and corrosion current density, which are key indicators of corrosion resistance in different chemical environments.

For 45 steel, the results indicate improved corrosion resistance after EPH when exposed to environments such as water and urea compared to more aggressive environments such as ammonium nitrate and azophoska. The EPH process generally increases surface hardness and changes the surface chemistry, which can improve localized corrosion resistance, but can also make the steel more susceptible to certain aggressive agents depending on environmental conditions and the composition of the electrolyte used during hardening.

In comparison, 65G steel exhibits similar trends but with differences in the degree of corrosion resistance improvement. The effectiveness of EPH in enhancing the corrosion resistance of 65G steel is particularly noticeable in environments containing ammonium nitrate and urea, which are commonly found in agricultural applications [23–26].

CONCLUSIONS

Electrolytic plasma hardening enhances surface properties by forming a denser, more protective layer capable of withstanding the corrosive effects of aggressive chemical agents, such as mineral fertilizers commonly used in agriculture. The optimization of key process parameters – particularly the duration of exposure, applied voltage and number of repetitions – plays a critical role in determining the corrosion behavior of treated materials.

Under thermocyclic treatment conditions, steel 45 treated in two cycles and steel 65G in three cycles demonstrated the best corrosion resistance compared to the untreated samples. Steel 45 demonstrated superior resistance in environments containing ammonium nitrate and azofoska, whereas steel 65G performed best in ammonium nitrate and urea solutions. The enhanced corrosion resistance is partly attributed to the formation of iron carbide phases, which act as a protective barrier against corrosive agents.

These findings emphasize the importance of customizing the EPH process to match the specific service conditions. Such adaptation ensures maximum corrosion protection and extends the service life of components treated by electrolytic plasma hardening.

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65Г ЖӘНЕ 45 БОЛАТТАРЫНЫҢ ЭЛЕКТРОЛИТТІК-ПЛАЗМАЛЫҚ ҚАТАЙТУ ДЕЙІНГІ ЖӘНЕ КЕЙІНГІ КОРРОЗИЯ ҚАСИЕТТЕРІН ЗЕРТТЕУ

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Бұл мақалада электролитті-плазмалық қатайту (ЭПҚ) әдісімен өңделген 65Г және 45 маркалы болаттардың коррозияға төзімділігін зерттеу нәтижелері келтірілген. Зерттеудің негізгі мақсаты ортаның түріне байланысты болаттардың коррозиялық қасиеттеріндегі өзгерістерді анықтау болды: су, карбамид, суперфосфат және аммоний нитраты. Зерттеу ЭПҚ-дан кейін 45 Болаттың коррозия жылдамдығы бастапқы үлгіден 8 есе төмендеп, жылына $2{,}58\times10^{-4}$ мм мәнге жеткенін көрсетті. 65Г болат үшін коррозияға төзімділіктің айтарлықтай жақсаруы байқалды, әсіресе карбамид пен суперфосфат ортасында. Бұл болаттардың коррозиялық потенциалы оң мәнге ауысты, бұл беттің қорғаныс қасиеттерінің жақсарғанын көрсетеді. Поляризациялық қисықтар коррозиялық токтың 45 болаттан ЭПҚ-ға дейін, ас тұзының ерітіндісінде 562,34 мкА/см^2-ден карбамидте 111,75 мкА/см^2-ге дейін, ал суперфосфатта 132,67 мкА/см^2-ге дейін төмендегенін көрсетті. ЭПҚ-ға дейінгі 65Г болат үшін ас тұзы ортасындағы коррозия тогы 67,23 мкА/см^2 болды, карбамидте 57,28 мкА/см^2 дейін және ЭПҚ процесінен кейін аммиак селитрасында 60,73 мкА/см^2 дейін төмендеді. Нәтижелер ЭПҚ зерттелетін болаттардың коррозияға төзімділігін айтарлықтай арттыратынын растайды, бұл өңдеу әдісін агрессивті химиялық жағдайларда қолданылатын металл өнімдерінің беріктігін жақсарту үшін перспективалы етеді.

Түйін сөздер: *электролиттік-плазмалық қатайту, 45 болат, коррозия, тозуға төзімділік, электрохимиялық коррозия.*

ИССЛЕДОВАНИЕ КОРРОЗИОННЫХ ХАРАКТЕРИСТИК СТАЛЕЙ 65Г И 45 ДО И ПОСЛЕ ЭЛЕКТРОЛИТНО-ПЛАЗМЕННОГО УПРОЧНЕНИЯ

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В данной статье представлены результаты исследований коррозионной стойкости сталей марок 65Г и 45, которые были подвергнуты обработке методом электролитно-плазменного упрочнения (ЭПУ). Основной целью исследования было выявление изменений в коррозионных свойствах сталей в зависимости от типа среды: воды, карбамида, суперфосфата и аммиачной селитры. Исследование показало, что после ЭПУ скорость коррозии стали 45 снизилась в 8 раз по сравнению с исходным образцом, достигая значения $2{,}58\times10^{-4}$ мм/год. Для стали 65Г также наблюдалось значительное улучшение коррозионной стойкости, особенно в среде карбамида и суперфосфата. Коррозионный потенциал данных сталей сместился в положительную сторону, что указывает на улучшение защитных свойств поверхности. Поляризационные кривые показали уменьшение коррозионного тока для стали 45 до ЭПУ в растворе пищевой соли с 562,34 μA/см² до 111,75 μA/см² в карбамиде, и до 132,67 μA/см² в суперфосфате. Для стали 65Г до ЭПУ ток коррозии в среде пищевой соли составил 67,23 μA/см², уменьшаясь до 57,28 μA/см² в карбамиде и до 60,73 μA/см² в аммиачной селитре после процесса ЭПУ. Результаты подтверждают, что ЭПУ значительно повышает коррозионную стойкость исследуемых сталей, что делает этот метод обработки перспективным для улучшения долговечности металлических изделий, используемых в агрессивных химических условиях.

Ключевые слова: *электролитно-плазменное упрочнение, сталь 45, коррозия, износостойкость, электрохимическая коррозия.*