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ЗАСТОСУВАННЯ МЕТОДУ ПОЛЯРИЗАЦІЙНОГО ОПОРУ СТАЛЕЙ ДЛЯ КОНТРОЛЮ ДЕГРАДАЦІЇ МЕТАЛОКОНСТРУКЦІЙ ПОРТОВИХ КРАНІВ

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Анотація. *Розглянуто проблему, яка пов'язана з застосуванням методу поляризаційного опору сталей для контролю деградації металоконструкцій портових кранів. Досвід експлуатації портового обладнання показує, що його окремі компоненти та елементи викладені значному циклічному навантаженню, яке додається до звичайного статичного навантаження відповідно до регламенту, через постійний та випадковий вплив різних факторів (наприклад, вітрове навантаження, вібрація від аномальної роботи електроприводів, ривки від включення/відключення приводів механізмів підйому вантажу, повороту, зміни вильоту, пересування тощо). У низьколегованих сталях під впливом тривалої комбінованої дії статичних і циклічних навантажень відбуваються значні зміни їх структури та властивостей, переважно через розвиток деформаційного старіння, відомого як експлуатаційна деградація сталей. Ці зміни, які часто відомі як експлуатаційне старіння сталей, не завжди впливають на їх міцність, проте істотно знижують їх стійкість до крихкого руйнування, особливо за низьких температур. Деформаційне старіння обумовлене наявністю домішок вуглецю та азоту у металі, які, взаємодіючи з дислокаційною структурою, викликають зміцнення сталей та ускладнюють розслаблення еластичних напруг за рахунок пластичної деформації. Були встановлені кореляційні залежності між поляризаційним опором та ударною в'язкістю експлуатованих сталей, що становлять основу для розробки електрохімічного методу прогнозування стійкості до крихкого руйнування довготривало експлуатованого металу. Процедура діагностики металу вузлів портальних кранів включала підготовку портативного потенціостата до роботи, під'єднання допоміжного та порівняльного електродів, включення автоматичного режиму потенціодинамічної розгортки, експорт даних у графічні програми та розрахунок значення поляризаційного опору.*

Отримані дані поляризаційного опору та ударної в'язкості для різних вузлів досліджених портових кранів свідчать про значне зниження цих характеристик під час тривалої експлуатації. Зокрема, ударна в'язкість падає набагато швидше, що робить її найбільш консервативним та інформативним показником для визначення експлуатаційної деградації сталей портових кранів.

Для перевірки запропонованого підходу з використанням вирізання металу з вузлів крана були виготовлені та протестовані на міцність зразки. Отримані результати механічних випробувань відповідають діагностованим даним, що підтверджує ефективність запропонованого підходу.

Ключові слова: *Металоконструкція, деградація сталі, поляризаційний опір сталей, міцність, ударна в'язкість, портові крани, дислокаційна структура, електрод, потенціодинамічна розгортка, стійкість, крихке руйнування.*

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THE APPLICATION OF THE POLARIZATION RESISTANCE METHOD FOR MONITORING THE DEGRADATION OF STEEL IN PORT CRANE METAL STRUCTURES

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Abstract. *The problem associated with the application of the polarization resistance method for monitoring the degradation of steel structures of port cranes has been examined. The experience of operating port equipment indicates that its individual components and elements are subjected to significant cyclic loading, which is superimposed on the usual static loading according to regulations, due to the constant and random influence of various factors (such as wind loads, vibration from abnormal operation of electric drives, jerks from the switching on/off of mechanisms for lifting cargo, rotation, changes in trajectory, movement, etc.). In low-alloy steels, under the influence of prolonged combined action of static and cyclic loads, significant changes occur in their structure and properties, mainly due to the development of deformation aging, known as operational steel degradation. These changes, often referred to as operational aging of steels, do not always affect their strength, but significantly reduce their resistance to brittle fracture, especially at low temperatures. Deformation aging is caused by the presence of carbon and nitrogen impurities in the metal, which, interacting with the dislocation structure, strengthen the steels and complicate the relaxation of elastic stresses due to plastic deformation. Correlation dependencies between polarization resistance and impact toughness of operated steels have been established, which form the basis for the development of an electrochemical method for predicting the resistance to brittle fracture of long-term operated metal. The metal diagnostic procedure of portal crane nodes included preparation of a portable potentiostat for operation, connection of auxiliary and reference electrodes, activation of the automatic mode of potentiodynamic polarization, export of data to graphic programs, and calculation of the polarization resistance value. The obtained data of polarization resistance and impact toughness for different nodes of investigated port cranes indicate a significant decrease in these characteristics during prolonged operation. In particular, impact toughness decreases* *much faster, making it the most conservative and informative parameter for determining the operational degradation of port crane steels. To verify the proposed approach using metal cutting from crane nodes, samples were manufactured and tested for strength. The obtained results of mechanical tests correspond to the diagnosed data, confirming the effectiveness of the proposed approach.*

Keywords: *Metal structures, steel degradation, polarization resistance of steels, strength, impact toughness, port cranes, dislocation structure, electrode, potentiodynamic polarization, stability, brittle fracture.*

Introduction. In Ukrainian ports, the operational lifespan of port cranes significantly exceeds regulatory terms, making the expert evaluation of the technical condition of crane metal structures a pertinent issue. This evaluation extends beyond the detection of operational damage to assessing the condition of metal structures with regards to potential degradation, i.e., deterioration of properties that determine the structure's functionality. It is important to distinguish between surface degradation due to corrosion damage and material degradation «in bulk», which involves changes in its physico-mechanical properties.

The monitoring of the technical condition of metal structures is typically based on diagnosing actual wear or existing damage – fatigue, mechanical, or corrosion-related – the types and limit standards of which are outlined in regulatory and organizational documents developed for equipment and its components operating within the calculated resource or service life. However, recent research indicates significant degradation of the physico-mechanical properties of structural steels used in port handling equipment, which have been in service beyond the normative term.

The operational practice of port handling equipment indicates that certain nodes and elements undergo significant cyclic loading in addition to regular static operational loads, due to constant and random influences such as wind loads, vibration from abnormal operation of electric drives, jerks from the activation/deactivation of drive mechanisms for cargo lifting, rotation, change of outreach, movement, etc. Prolonged exposure to combined static and cyclic loads in low-alloy steels results in significant changes in their structure and properties primarily due to the development of deformation aging. These changes, also known as operational steel degradation, do not always lead to a decrease in their strength but significantly reduce their resistance to brittle fracture, especially at low temperatures. Deformation aging is caused by the presence of carbon and nitrogen impurities in the metal, which, interacting with the dislocation structure, induce embrittlement of steels by reducing the possibility of stress relaxation through plastic deformation.

As the processes of movement and multiplication of dislocations in localized volumes of metal occur at stresses significantly lower than the static yield strength, it has been shown that static and dynamic deformation aging in low-carbon steel during repeated stretching is observed at stresses significantly lower than the endurance limit.

Objective. The purpose of the article is to establish correlation dependencies between polarization resistance and impact toughness of used steels, which will serve as the basis for developing an electrochemical method for predicting the resistance to brittle fracture of long-term used metal.

The presentation of the main material. The polarization resistance method involves polarizing the investigated metal within the corrosion potential range (not exceeding 30 V in both anodic and cathodic directions). In many «metal-environment» systems, a linear relationship between «polarization potential-polarization current» is observed within this potential range, and therefore this method is also known as the linear polarization method. In this context, polarization resistance is defined as the ratio of the potential difference (E2-E1) to the current difference (i2-i1). However, often the linear segment on the polarization curve exists within a limited range of potentials or may be completely absent. In this case, a tangent is drawn to the polarization curve at the point corresponding to the corrosion potential E_{cor} (where $E_{cor} = 0$). The slope of this tangent determines the value of polarization resistance.

$$R_P = \left(\frac{E2 - E1}{i2 - i1} \right). \tag{1}$$

To determine the electrochemical characteristics of steels used in port cranes during their operation, which can serve as a basis for predicting resistance to brittle failure, a portable three-electrode electrochemical device has been developed. This device is attached to the studied surface of the crane using a hinge suspension (Figure 1) or mounting washer (Figure 2).

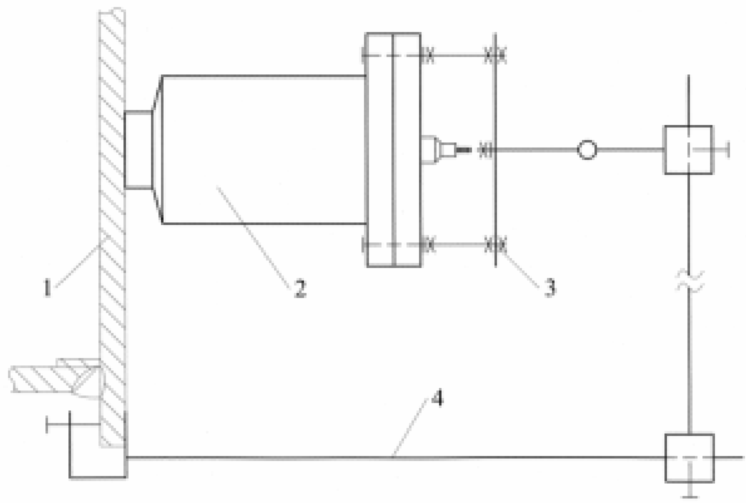

Fig.1. Diagram of mounting the portable electrochemical device to the investigated section of the crane with a hinge suspension:
1 – investigated section;
2 – TEHP;
3 – clamping device;
4 – hinge lever

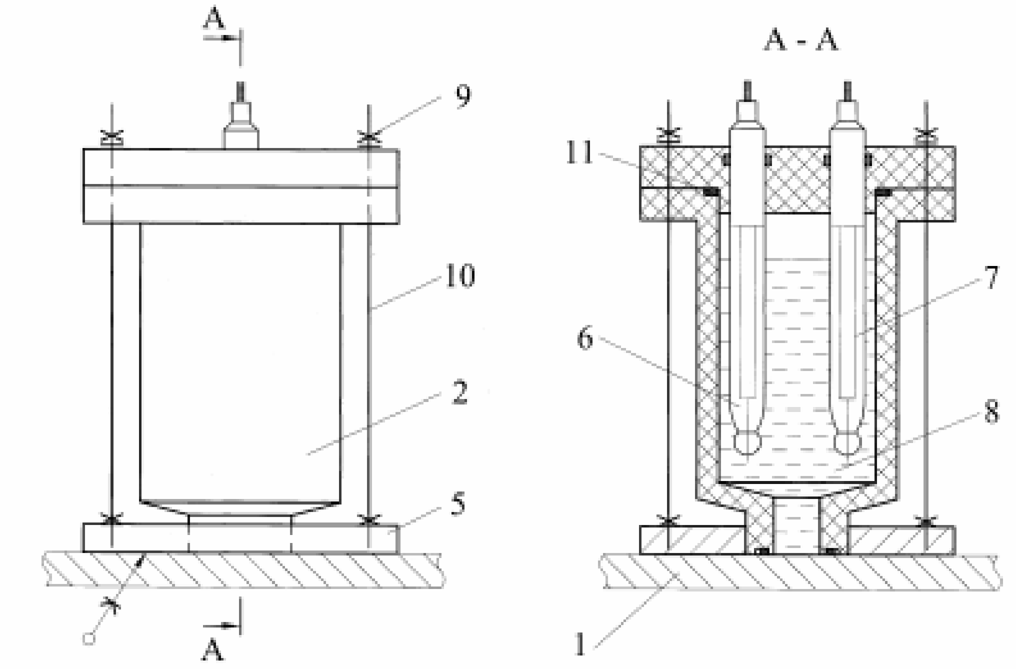

Fig. 2. Diagram of the portable electrochemical device mounted to the investigated section of the crane with a mounting washer:
1 – investigated section;
2 – Three-Electrode Electrochemical Device;
5 – mounting washer;
6 – auxiliary electrode;
7 – reference electrode;
8 – corrosive solution;
9 – nut with washer;
10 – threaded bolt.
11 – rubber gasket.

The fluoroplastic cylinder serves as the three-electrode electrochemical device, containing a 20 mm diameter hole. This hole tightly fits onto the metal surface belonging to the crane under study, thanks to a rubber gasket, and serves as the point of contact between the corrosive environment and the metal. The housing of the Three-Electrode Electrochemical Device is connected to a cover made of organic glass, which has five holes. Two of them are used for placing the reference electrode and the auxiliary electrode, while the other three are for introducing the corrosive solution into the cell and releasing air during filling, equipped with fluoroplastic stoppers. The Three-Electrode Electrochemical Device is sealed and can be installed horizontally, vertically, or at an angle (except for the overhead position).

Figure 3 proposes schematically another method of attaching the electrochemical device to the working surface of the sheet material.

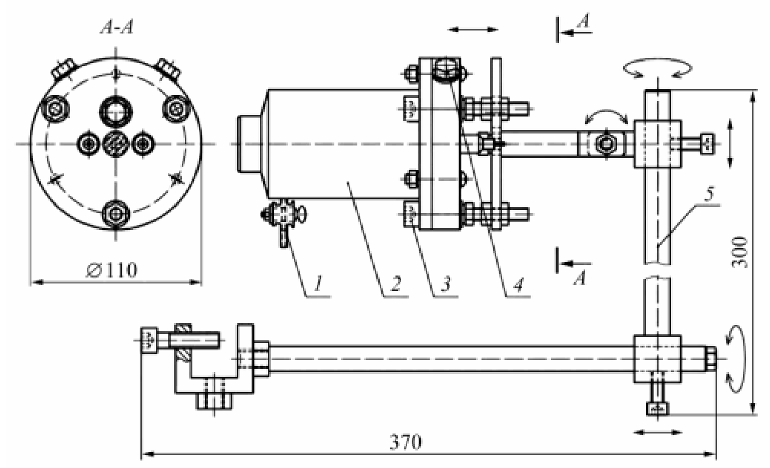

Fig. 3. Example of mounting a portable three-electrode electrochemical device:
1 – fluoroplastic valve;
2 – Three-Electrode Electrochemical Device;
3 – mounting elements;
4 – cork;
5 – hinge suspension

To assess the electrochemical characteristics under real operating conditions, a portable electrochemical complex was used (Fig.4).

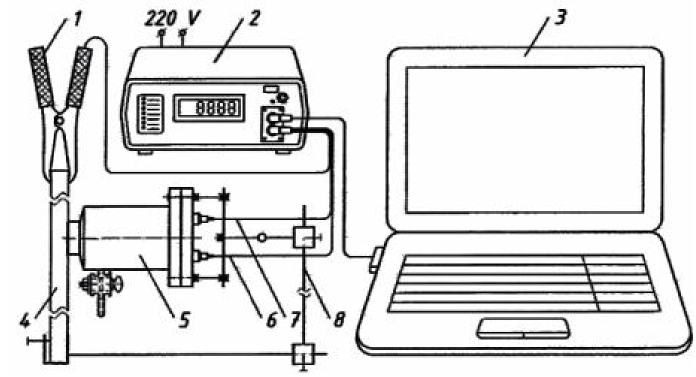

Fig. 4. Portable electrochemical complex:
1 - metal clamp;
2 - potentiostat;
3 - computer with software;
4 - investigated element of the port crane metal structure;
5 - electrochemical device;
6 - auxiliary electrode;
7 - reference electrode;
8 - hinge suspension

Using this complex, measurements of electrochemical parameters were conducted on cleaned and polished surfaces of the two most critical sections of the crane, constructing polarization curves and determining their polarization resistance R_p^e: 300 and 266 ohm·cm². Assuming R_p^0 = 311 ohm·cm² (for unused steel St3sp), the ratio R_p^e / R_p^0 was calculated for both cases. Subsequently, utilizing this ratio and considering the previously determined correlation between KCV and KCV^0 and R_p^e / R_p^0, the ratio KCV^e/ KCV^0 and, thus, the forecasted values of KCV^e were obtained (Table 1).

Table 1

Polarization resistance of crane steel A4 in 0,3 % NaCl solution and its corresponding impact toughness.

Node	R_p^e, Ohm см²	$\frac{R_p^e}{R_p^0}$	$\frac{KCV^e}{KCV^0}$	KCV^e, J/см²	
				Forecast	Experiment
The upper shelf of the boom	300	0,966	0,939	61	64
Right column wall	266	0,855	0,739	48	50

Samples taken from the metal elements were cut and subjected to impact toughness testing (Table 1). The obtained KCV^e values were in good agreement with the predicted values, albeit slightly higher. In other words, the non-destructive method provided a conservative estimate of the impact toughness of the studied crane elements.

There are specific application features for assessing the polarization resistance measurement method in operational conditions. For example, in «Albrecht» and «Sokil» type port cranes, which have been in operation for 36-45 years, certain nodes are particularly important, such as the back shelf of the jib, the back shelf of the boom, the upper shelf of the counterweight lever, and the back shelf of the column, as the development of crack-like defects and, consequently, brittle fracture is possible.The surfaces subjected to electrochemical analysis must meet certain requirements: the position in space-horizontal, vertical, or at an angle (except for the «ceiling» position); the surface roughness should not exceed R_a = 1,6 μm; the size of the area for installing the electrochemical device should have a diameter of at least 30 mm. To determine the polarization resistance of the steel in the selected crane, two areas were chosen (Fig. 5): a horizontal shelf, which is hardly loaded during operation, and a vertical one, which is the most loaded. Before conducting electrochemical studies, the metallic area to which the cell was attached was prepared according to the following procedure: the surface to be inspected was cleaned of dirt and coatings; it was ground with abrasive papers and polished with diamond pastes of various grits; it was degreased with acetone, alcohol; dried with filter paper; rinsed with distilled water. During the electrochemical studies, a portable electrochemical complex was used, which included a portable clamping three-electrode electrochemical device with a silver chloride reference electrode and a platinum auxiliary electrode, a portable potentiostat, and a portable computer with software for controlling the potentiostat and recording the results of electrochemical measurements.

The uniqueness of the structure of the electrochemical device lies in its fabrication from fluoroplastic and the presence of a hole through which, thanks to a rubber seal, it is tightly pressed against the surface of the studied area of the metal structure (see Fig. 5).

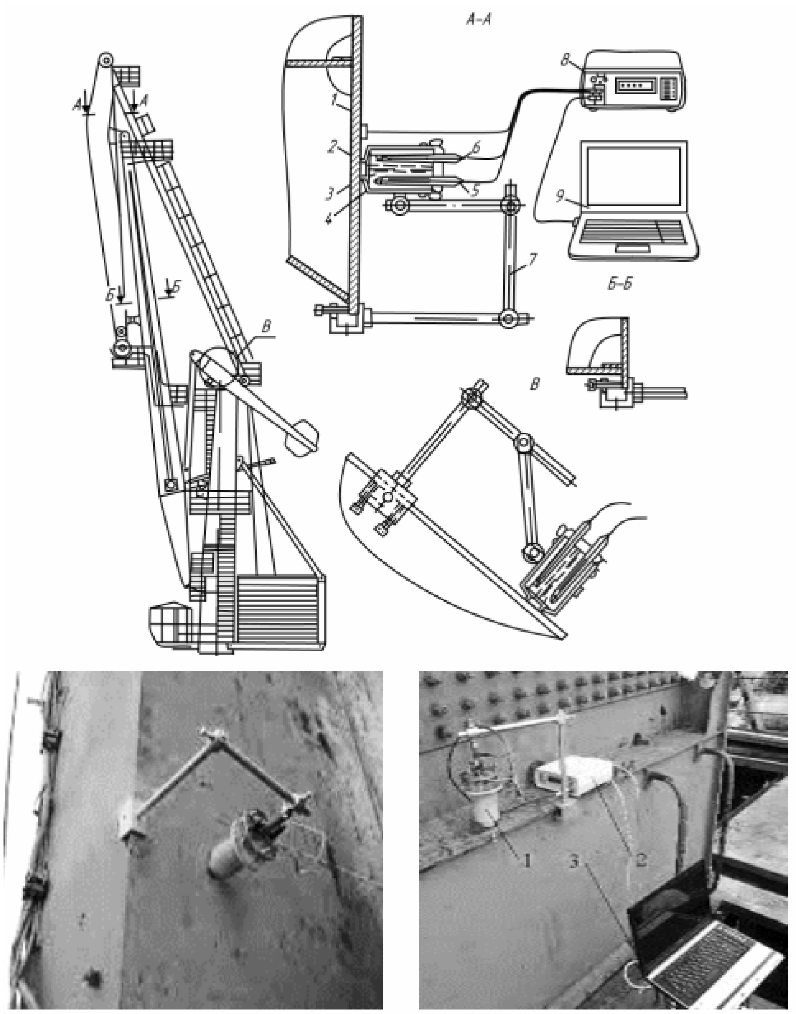

Fig. 5. Examples of mounting the electrochemical device to the metal structure of the crane

A 0,3 % NaCl solution was used as the aggressive environment. Polarization curves were recorded in a potentiodynamic mode (with a potential scan rate of 1 mV/s), representing the dependencies of cathodic and anodic electrode reaction currents on the polarization potential.

The ECP can be securely installed both horizontally, at an incline, and vertically on the metal structure of the crane (see Figure 6).

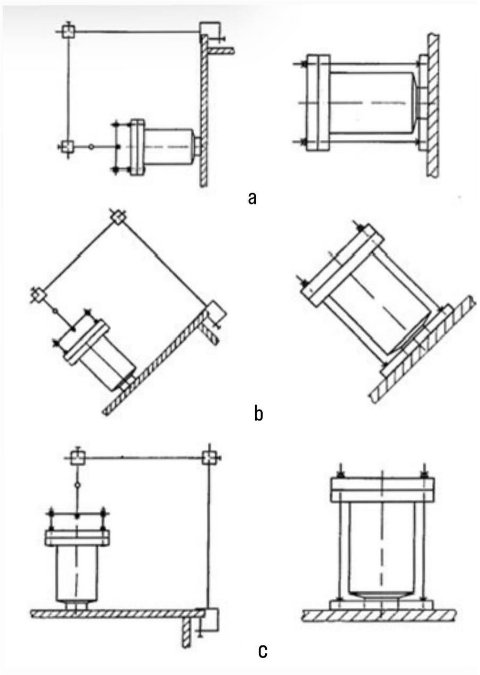

Fig.6. Mounting options of the ECP to the investigated section of the metal crane structure:
a – horizontal;
b – inclined;
c – vertical

To establish a correlation between R_p and KCV, electrochemical investigations were conducted on steels used in the metal structures of port loading machines (Figure 7). The ECP was attached to the metal surface using a hinge-lever bracket, which was secured to the metal structure by screws or two-component adhesive through a mounting washer.

The ECP was filled with the medium, and the top opening was sealed with a cover made of organic glass, which included holes for the auxiliary electrode and the reference electrode. The absence of medium leakage in the area around the cell opening, through which the medium contacted the diagnosed surface of the metal structure, was checked. The metal diagnosis procedure for gantry crane nodes included:

• preparing the portable potentiostat for operation and checking its functionality using the electrical equivalent of the electrochemical cell «Equivalent E-4»;

• connecting the auxiliary electrode (platinum) and the reference electrode (saturated silver chloride) and waiting for the establishment of a stationary potential value of the metal;

• activating the automatic potentiodynamic sweep mode using the computer to obtain a polarization curve;

• exporting the obtained experimental data to graphical software and plotting a graphical polarization dependency «potential – current»;

• calculating the value of the polarization resistance based on the slope of the polarization curve or its tangent.

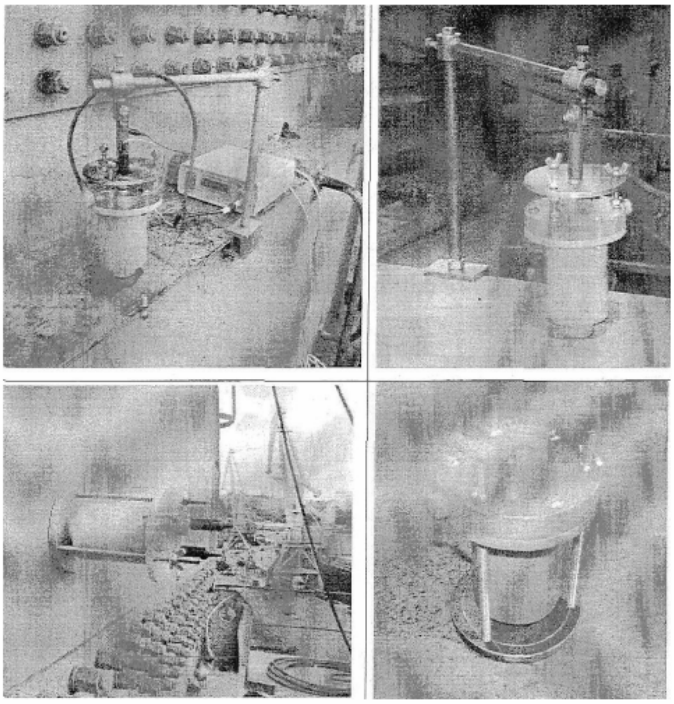

Fig. 7. Features of using the developed ECP on the metal structures of port loading machines

The obtained values of polarization resistance and impact toughness for different components of the investigated port cranes indicate a significant decrease in these characteristics during prolonged operation (Table 2). It is important to note that impact toughness decreases much more actively, making it the most conservative and informative parameter for determining the operational degradation of port crane steels.

It should be noted that the correlation dependence presented in the work between mechanical and electrochemical parameters reflects not absolute, but relative changes over time during operation. Therefore, to use the correlation dependence, it is also necessary to have values of the corresponding indicators for the non-operated metal.

In the study, the initial values of KCV for St 38b-2 steel in the pre-operational state were taken as its maximum value for crane steels, considering strain hardening – 65 J/cm². As for R_p, the initial state was equated to the value measured on St3sp steel (the domestic equivalent of St 38b2 steel). Thus, relative changes were calculated by comparing the results of laboratory and field studies (Table 2, Figure 8).

Table 2

Mechanical and electrochemical properties of port crane steels

Crane	Years in service	Metal structure element	KCV^e, J/cm² Min.	KCV^e, J/cm² Mid.	$\frac{KCV^e}{KCV^0}$ Mid.	R_p^e, Ohm·cm²	$\frac{R_p^e}{R_p^0}$
Initial state (St3sp)			-	-	1	925	1
A1	45	Lever	8,5	8	0,89	879	0,95
		Boom	10,5	11	0,47	611	0,66
A2	38	Lever	54	62	0,95	870	0,94
		Cantilever arm	41,5	50	0,77	722	0,78
		Boom	35,5	38,5	0,59	675	0,73
A3	40	Lever	27	42	0,64	777	0,84
		Cantilever arm	37,5	38	0,58	657	0,71
		Boom	29	43	0,66	712	0,77
C1	39	Boom	49	61,5	0,95	827	0,89
C5	36	Boom	41	51	0,78	733	0,79

From Figure 8, it can be observed that even with data dispersion, there is a clear trend towards a decrease in informative parameters, such as electrochemical resistance (R_p^e) and mechanical toughness (KCV^e), compared to the initial state (R_p^0, KCV^0). The assessment of the degree of correlation between changes in R_p and KCV by the correlation coefficient indicates its satisfactory tightness: R = 0,859. Checking the significance of this relationship against critical values of the correlation coefficient confirms its non-random nature. Regression analysis of the obtained dependency using the method of least squares resulted in obtaining an approximate equation:

$$KCV^0 / KCV^0 = -0{,}41 + 1{,}39(R_p^e / R_p^0). \qquad (2)$$

The analysis of variance of this relationship confirmed its reliability at the level of 0,975. Therefore, this correlation can be used as the basis for developing a non-destructive electrochemical method for diagnosing the degradation of mechanical properties of port crane steels.

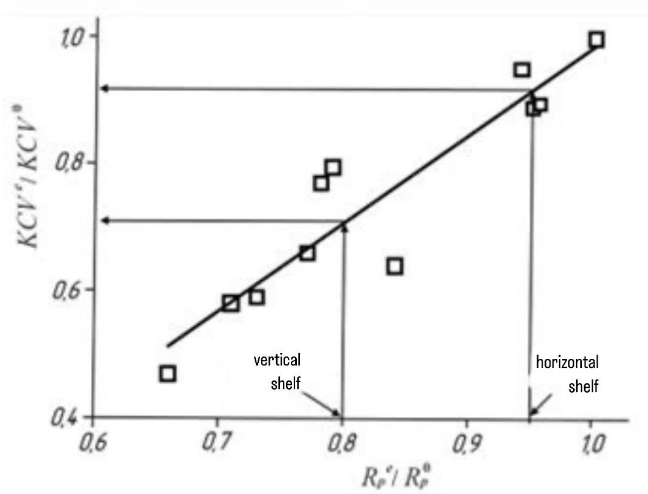

Fig. 8. Correlation between relative changes (the ratio of the impact toughness of the used material KCV^e to the impact toughness in the initial state KCV^0) and polarization resistance (the ratio of the polarization resistance of the used material R_p^e to the polarization resistance of the steel in the initial state R_p^0) of different crane components. The arrows indicate the values of R_p^e determined on crane

Figure 9 shows the polarization curves obtained on crane for two different positions, which allowed establishing two values of R_p: 740 Ohm·cm² and 883 Ohm·cm² (Table 3).

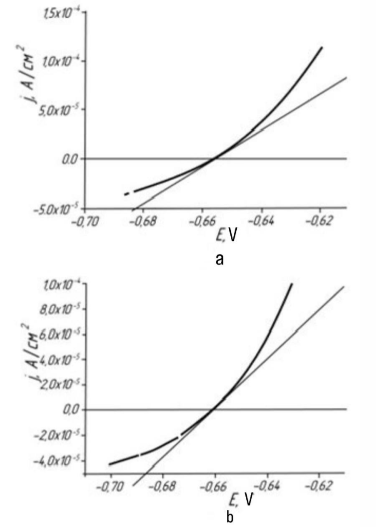

Fig. 9. Polarization curves of crane steel in 0,3% NaCl solution:
a – horizontal shelf;
b – vertical shelf

As can be seen from the graph, the obtained polarization curves do not exhibit linearity. In such cases, the polarization resistance was determined using the tangent method (highlighted by a thin line in the figure). By using the calculated ratio R_p^e / R_p^0 and the correlation dependence KCV^e / KCV^0 – R_p^e / R_p^0, the values of KCV^e / KCV^0, and thus KCV^e, were obtained (Table 3, numerator).

Table 3

Polarization resistance in a 3 % NaCl solution and impact toughness of crane steel

Research site	R_p, Ohm·см^2	$\frac{R_p^e}{R_p^0}$	$\frac{KCV^e}{KCV^0}$	KCV^e, J/см^2
Horizontal area	883	0,95	0,916	59,5 / 65
Vertical area	740	0,80	0,707	46 / 50

To verify the proposed approach, metal samples were cut from the components of crane and tested for strength. The obtained results of mechanical tests were matched with the diagnosed data.

Conclusions. Absolute values of the diagnosed parameters show some decrease compared to the experimental ones, indicating that the proposed approach provides a conservative estimate of impact toughness. However, the relationship between changes depending on the selected area remains preserved.

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