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The Influence of the Components of the 06ХН28МДТ Alloy (Analogue of AISI904L Steel) and the Parameters of the Model Chloride-Containing Recycled Water of Enterprises on Its Pitting Resistance

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Two mathematical models, which describe the dependence of critical pitting temperatures of 06ХН28МДТ alloy (analogue of AISI904L steel) in model recycled water with pH 4–8 and chloride concentration from 350 up to 600 mg/l on chemical composition and structure, are developed. They are based on multivariate regressions with pairwise combinations of features and a three-layer neural network of direct signal. Applying the developed mathematical models, it is found that the critical pitting temperatures of the 06ХН28МДТ alloy increase with an increase in the pH of model recycled water, the content of Cr, Mo, Cu, the volume of titanium nitrides within it, and a decrease in the medium austenite-grain diameter, the content of nickel within the standard, and chlorides in the media. At the same time, the analysis of the developed mathematical model, which is based on multivariate regressions with paired combinations of features (alloy and media parameters), reveals that the content of Cr and Ni in the alloy in combination with the medium austenite-grain diameter most significantly affect its pitting resistance in model recycled waters, and an effect of the Cr content in combination with

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pH and chloride concentration in the media is somewhat lower, but much higher than an effect of the Mo and Cu content, and the volume of titanium nitrides in combination with the media parameters. The developed mathematical model, which is based on a three-layer neural network of direct signal propagation, is recommended for predicting the pitting resistance of heat exchangers made of 06ХН28МДТ alloy or AISI904L steel when operating in recycled water. In addition, the developed mathematical model, based on multivariate regressions with paired combinations of features (alloy and media parameters), is recommended for selecting the optimal melts of this alloy or steel, which are most resistant to pitting in recycled water.

Key words: pitting resistance, heat exchanger, recycled water, structural heterogeneity, pitting resistance prediction.

Розроблено два математичних моделі, які описують залежності критичних температур пітинґування стопу 06ХН28МДТ (аналог криці AISI904L) у модельних оборотніх водах з pH 4–8 і концентрацією хлоридів від 350 до 600 мг/л від хемічного складу та структури. Вони ґрунтуються на багатовимірних реґресіях з парними комбінаціями ознак і тришаровій нейронній мережі прямого поширення сиґналу. Із застосуванням розроблених математичних моделів встановлено, що критичні температури пітинґування стопу 06ХН28МДТ ростуть зі збільшенням pH модельних оборотніх вод, вмісту Cr, Mo, Cu, об'єму нітридів Титану в ньому та зменшенням середнього діяметра зерна аустеніту, вмісту Ніклю в межах стандарту та хлоридів у середовищі. Водночас з аналізи розробленого математичного моделю, який ґрунтується на багатовимірних реґресіях з парними комбінаціями ознак (параметрів стопу та середовища) виявлено, що вміст Cr і Ni в стопі в комбінаціях із середнім діяметром зерна аустеніту найістотніше впливають на його пітинґотривкість у модельних оборотніх водах, а вміст Cr в комбінаціях з pH і концентрацією хлоридів у середовищі — дещо менше, але набагато більше, ніж вміст Mo, Cu, й об'єм нітридів Титану в комбінаціях з параметрами середовища. Розроблений математичний модель, який ґрунтується на тришаровій нейронній мережі прямого поширення сиґналу, рекомендовано застосовувати для прогнозування пітинґотривкости теплообмінників зі стопу 06ХН28МДТ або криці AISI904L під час роботі їх у оборотніх водах. До того ж розроблений математичний модель, який ґрунтується на багатовимірних реґресіях із парними комбінаціями ознак (параметри стопу та середовища), рекомендовано використовувати для вибору оптимальних топлень цього стопу або криці, найтривкіших до пітинґування в оборотніх водах.

Ключові слова: пітинґотривкість, теплообмінник, оборотна вода, структурна гетерогенність, прогнозування пітинґотривкости.

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1. INTRODUCTION

Alloy 06ХН28МДТ and its analogue, stainless steel AISI904L, are used as a structural material for plate-like heat exchangers used in the production of acids such as sulfuric, phosphoric, orthophosphoric, hydrofluoric, *etc.* [1, 2]. Water from the recycling systems of enterprises is used to cool the products of technological processes. It contains chloride ions and other anions that can cause pitting and subsequently ulcer corrosion of heat plate-like exchanger plates on the recycled water side [3, 4]. Heat transfer plates of heat plate-like exchangers with a thickness of 0.3 to 1.0 mm are subject to perforation in case of pitting corrosion within a few months, which contributes to the spoilage of technological products due to the recycled water overflow of into the process medium, equipment failure and production shutdown [5]. Therefore, assessing the pitting resistance of 06ХН28МДТ alloy and predicting its corrosion behaviour under heat exchanger operating conditions, depending on its components and parameters of recycled water, is an actual issue. The authors of [6, 7] determined the pitting resistance of this alloy by the gravimetric method according to ГОСТ 9.192-89 [8] and evaluated the effect of the chemical composition within the standard and the structure components on the rate of corrosion losses from pits. Paper [9] determined the critical pitting temperatures (CPT) of the 06ХН28МДТ alloy in model recycled waters with pH 4–8 and chloride concentrations of 350, 400, 500, 550, 600 mg/l, which are most commonly encountered in the operation of heat exchangers, and established direct regression relationships between them and the chemical elements in the alloy and its structure components. However, the gravimetric and electrochemical methods used in [6, 7] can only be used to assess the relative pitting resistance of steels and alloys, and its assessment according to [9] is discrete and does not take into account the weightiness of alloy components to pitting resistance. Therefore, we used a multivariate regression model with paired combinations of features and a model based on a three-layer neural network of direct signal to determine the influence of alloy components and the media on its pitting resistance.

2. EXPERIMENTAL/THEORETICAL DETAILS

Five industrial melts of 06ХН28МДТ alloy have been studied (see Table 1). Their CPT and structure were determined earlier [9]. A mathematical model of the dependence of the alloy's CPT on its chemical composition, structure, and recycled water parameters was built using a multivariate regression model with paired combinations of features [10], which has the following form:

$$y^{s^*} = W_0 + \sum_{i=1}^{N} \sum_{j=i+1}^{N} W_{ij} x_i^s x_j^s,\ s = 1, 2, \ldots . \tag{1}$$

where y^s is a value of the output feature for the s-th observation of the

TABLE 1. Inclusions in 06ХН28МДТ alloy: titanium nitrides (*a*), titanium sulphides (*x*) (*b*).

Melt number	Content of alloying elements, % wt.									
	C	Si	Mn	Cr	Ni	Mo	Cu	Ti	S	P
1	0,050	0,60	0,32	24,31	27,39	2,90	2,75	0,79	0,006	0,029
2	0,067	0,57	0,46	22,68	27,65	2,78	2,68	0,59	0,005	0,027
3	0,068	0,55	0,54	21,84	27,45	2,55	2,60	0,55	0,004	0,038
4	0,048	0,62	0,57	22,67	27,73	2,56	2,53	0,67	0,006	0,028
5	0,050	0,57	0,31	23,46	27,51	2,51	2,78	0,89	0,004	0,032

sample (CPT), W_{ij} is a weight of the pair of the i-th and j-th features, x_{js} is a value of the j-th feature of the s-th sample instance.

In particular, x_1 is a pH of recycled water (4–8), x_2 is a chloride content in it (350, 400, 500, 550, 600 mg/l) [9], x_3 is a carbon (C) content in the alloy, % wt., x_4 is a manganese (Mn) content in the alloy, % wt., x_5 is a silicon (Si) content in the alloy, % wt., x_6 is a chromium (Cr) content in the alloy, % wt., x_7 is a nickel (Ni) content in the alloy, % wt., x_8 is a titanium (Ti) content in the alloy, % wt., x_9 is a sulphur (S) content in the alloy, % wt., x_{10} is a phosphorus (P) content in the alloy, % wt., x_{11} is a molybdenum (Mo) content in the alloy, % wt., x_{12} is a copper (Cu) content in the alloy, % wt. (Table 1), x_{13} is a volume of nitrides ($V_{\text{Н}}$) in the alloy (0.0931–0.1918, % vol.), x_{14} is a volume of sulphides and oxysulfides ($V_{\text{oks.}}$) in the alloy (0.0031–0.0091, % vol.), x_{15} is a d_g a medium austenite grain diameter (11–31 μm), S is a number of sample instances.

The weighting coefficients of the multivariate regression model with paired combinations of features (1) by the least squares method have been determined [10].

The model based on a three-layer neural network of direct signal propagation can be described by the formula (2) [11]:

$$y^{s^*} = \psi\left(\sum_{j=1}^{4} w_j^{(3,1)}\psi\left(\sum_{k=1}^{10} w_k^{(2,j)}\psi\left(\sum_{j=1}^{15} w_j^{(1,k)}x_j^s + w_0^{(1,k)}\right) + w_0^{(3,j)}\right) + w_0^{(3,1)}\right), \quad (2)$$

where

$$\psi(a) = 2/(1 + e^{-2a}) - 1,$$

$w_j^{(\mu,i)}$ is a weight of the j-th input of the i-th neuron of the μ-th layer of the network. The model weights determined using the Levenberg–Marquardt method [12] are shown in Table 2.

The quality of mathematical models was assessed by the sum of the

TABLE 2. Weight matrix of a neural network model.

j \ i	1	2	3	4	5	6	7	8	9	10
0	−134.844	108.552	−23.932	−13.9014	57.153	−106.352	−74.938	23.6736	−111.449	76.796
1	−0.2869	−0.4641	−1.3294	2370457	0.0684	0.3266	−0.5051	−1.1427	0.2523	−0.0827
2	−0.0239	0.0253	0.0262	−0.0060	0.1228	−0.0091	0.0168	0.0454	−0.0095	−0.0804
3	58.2442	46.4517	51.2677	12.0072	36.0747	−24.4834	−33.826	−30.0899	17.0394	46.4768
4	−2.4224	−0.0100	1064409	0.4055	218585	−2.6729	12.0717	7.1508	0.0222	−0.2617
5	−0.1886	−1.0166	4.0705	−6.4423	−1.5001	3.0751	−11.763	−5.9121	−1.5285	1402930
6	2167382	−2.4512	759372	−5.4321	2845242	−1.4168	1241097825116		485895	0.2011
7	62125	−2.4736	−2.4522	733133	−6.5408	138915	972309	−3.3467	−0.5239	−3.1939
8	570876	−4.2885	−4.1412	2.0000	−3.7966	−3.0473	−3.8027	−3.3315	3.1598	4.1664
9	−459.851	−462.602	316.348	−198.8480	586.166	679.8659	175.503	575.3475	−200.507	185.858
10	327.193	552.3413	338.974	175.9256	−9.7548	100.0848	236.977	−240.566	−106.864	346.676
11	−0.3777	1559254	2330157	6.0926	−0.1759	−1.8654	−4.3787	0.6532	−0.1543	1971641
12	1298105	2482952	−0.0359	−1.8416	1692932	0.7505	−8.6307	0.3678	−2.3054	−5.6363
13	2850232	−3.8677	−9.0446	−13.2948	91344	−6.9190	16.390	−7.3614	−4.3400	−6.2279
14	186.381	−35.4955	145.535	59.9204	127.799	−202.043	213.158	202.8595	−333.690	−17.314
15	0.2702	−0.4688	−0.2367	−0.4299	−0.0938	−0.0190	−0.0672	0.0453	0.8374	−0.0112
0	3.3239	−5.2951	−0.0394	3.5318	0,5468					
1	−6.5506	−1.9151	1.5532	−29.4449	−0.0634					
2	−3.4062	3.3580	1.0473	−18.0075	−0.0534					
3	−6.9230	13.5103	1.0144	−0.1335	−0.0775					
4	−2.3828	1.6407	−0.5092	−0.5864	−0.0884					
5	−3.0619	−3.9370	1.4130	−25.2640						
6	3.0371	5.2854	−0.0313							
7	0.8588	1.5984	0.7082							
8	−2.0264	2.8548	−0.4572							
9	−4.7197	−3.7546	0.5146							
10	−1.6440	6.1952	−0.2568	−1.3983						

squares of instantaneous errors [10]:

$$E = \sum_{s=1}^{S} (y^s - y^{s^*})^2 , \qquad (3)$$

where y^{s^*} is a model-estimated value of the output feature for the s-th observation, y^s is an experimental value of the test sample of five melts of 06ХН28МДТ alloy.

3. RESULTS AND DISCUSSION

The analysis of the developed multivariate regression model with pairwise combinations of features (3) showed that the characteristics of model recycled water pH (x_1) and the concentration of chlorides (x_2) in it have the most significant effect on the CPT of 06ХН28МДТ alloy, *i.e.*, its resistance to pitting corrosion:

$$\begin{aligned} Y(\mathrm{CTP}) = {} & -0.0028279x_1x_2 + 0.44975x_1x_6 - 0.12969x_1x_7 - \\ & -1.5328x_1x_{11} + 4.2954x_1x_{13} - 0.01219x_1x_{15} + 0.0080727x_2x_6 - \\ & -0.0023078x_2x_7 - 0.060578x_2x_{11} + 0.25833x_2x_{13} - \\ & -0.00076892x_2x_{15} - 0.47974x_6x_7 + 0.67333x_6x_{15} + \\ & +1.1452x_7x_{11} + 3.259x_7x_{12} - 0.5105x_7x_{15}. \end{aligned} \tag{4}$$

This is consistent with the results of the mathematical developed analysis models for AISI304 [13], AISI321 [14] and AISI304, AISI321, 08Х18Н10, 12Х18Н10Т together, which establish the relationship between their CPT, chemical composition, structure heterogeneity and parameters of the recycled water in which the study was conducted. In addition, it should be noted that papers [13–15] found an intensive increase in the CPT of these steels with an increase in the pH of model recycled water from 4 up to 8 and a decrease in the concentration of chlorides from 600 mg/l up to 350 mg/l. The same trend for 06ХН28МДТ alloy under similar test conditions has been found [16]. This is also consistent with well-known literature data [17–23]. The analysis of model (4) shows that the sum of the input features x_1 x_2 has a negative value of –0.0028279, which indicates a more intense effect of increasing the chloride concentration in the model recycled water from 350 mg/l up to 600 mg/l on reducing the alloys' CPT than a decrease in the pH of the medium from 8 up to 4. However, the priority effect of the chloride concentration in the model recycled water on the CPT of the 06ХН28МДТ alloy is not much more significant than its pH, since it decreases only by 9.6°C with an increase in pH (x_1) from 4 up to 8, and C_{Cl} (x_2) from 350 mg/l up to 600 mg/l.

According to the sum of the input features pH (x_1) and Cr (x_6) (see (3)), the CPT of 06ХН28МДТ alloy increases by 48.1°C with an increase in the pH (x_1) of the model recycled water from 4 up to 8 and the Cr content (x_6) in the alloy from 21.82 up to 24.29% wt.

This is due to the fact that Cr promotes the formation of dense oxide films on the surface of steels and alloys. Their resistance to pitting corrosion depends on their properties [24]. In particular, when determining the characteristics of passive films by the pitting potential of steel, which depends on temperature, pH, chloride concentration, etc. [25], it was found that stainless steels with passive films with a closer donor bond are more prone to pitting corrosion in chloride-containing media [26].

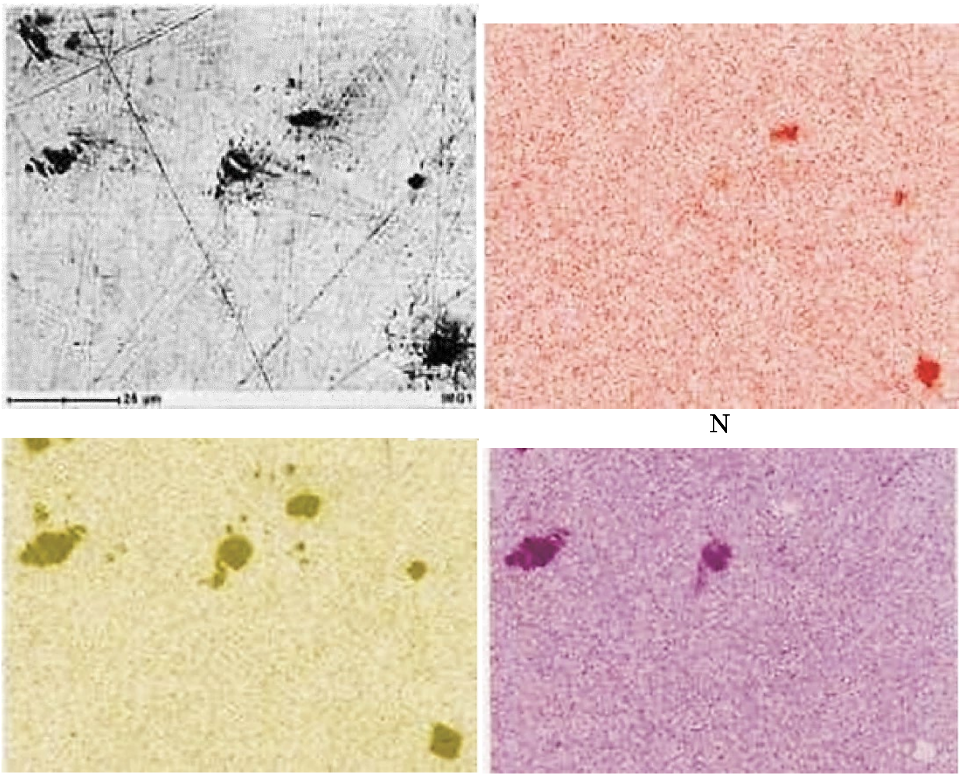
It should be noted that the pitting potential of 06ХН28МДТ alloy, which characterizes the passive film on its surface under such test conditions, equally depends on the Cr content (x_6) and pH (x_1) of model recycled water and the concentration of chlorides C_{Cl} (x_2) in it, since its CPT, as mentioned above, increases by 48.1°C with an increase in pH from 4 up to 8 and Cr content from 21.82 up to 24.29% wt. according to the sum pH (x_1)Cr (x_6) (see (4)) and by 56°C with an increase in Cr content in the same range and a decrease in chloride concentration (x_2) in model recycled water from 600 up to 350 mg/l according to the sum x_2x_6 (see (4)).

Summarizing the above, it can be noted that lowering the pH of model recycled water contributes to the formation of chromium-containing oxide films on the surface of the 06ХН28МДТ alloy with a closer donor bond than the concentration of chlorides in them. At the same time, according to paper [25] and the dependencies established above, it is obvious that the lower the chromium content in the alloy, the closer the donor properties of the oxide film as a semiconductor on its surface and the lower its pitting resistance.

Most likely, Ni and especially Mo in the alloy contribute to the formation of oxide films mixed with chromium on its surface with closer donor bonds. Since, according to the analysis of model (4), it was found that its CPT decreases by 14.5° for the sum x_1 (pH)x_7 (Ni) and 19.8° for x_1 (pH)x_{11} (Mo) with increasing media pH from 4 up to 8, Ni content from 27.4 up to 27.7% wt. and Mo from 2.53 up to 2.88% wt., respectively. A similar trend was revealed from the analysis of the mathematical model (3) for pairs of sums x_2 (Cu)x_7 (Ni) and x_2 (C_{Cl})x_{11} (Mo), since the CPT of the 06ХН28МДТ alloy decreases by 16.2 and 51°C, respectively, with an increase in the Ni content from 27.4 up to 27.7% wt., Mo from 2.53 up to 2.88% wt. and chloride concentration in the media from 350 up to 600 mg/l. It should be noted that in the case of both Cr and Ni and Mo sum, the effect of chloride concentration in the media on the CPT of the alloy is greater than its pH (x_1). This indicates that adsorption processes on the alloy surface are of priority importance in relation to its pitting corrosion. This may indicate that the dependences established according to (4) for Ni and Mo pairs are related to the porosity of oxide films, which is affected by the content of these chemical elements. It is known [27] that an increase in the porosity of oxide films on the surface of steels and alloys contributes to a decrease in their pitting resistance in chloride-containing media.

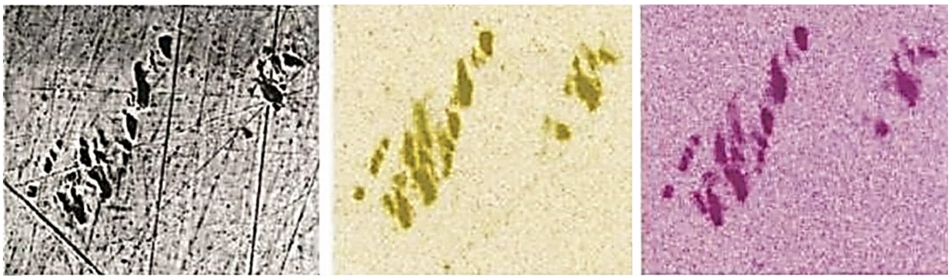
To summarize the above, it should be noted that the pH (x_1) and chloride concentration (x_2) in the media and the content of Cr, Ni and Mo in the alloy significantly affect its pitting resistance. In particular, the concentration of chlorides in the media most significantly determines the semiconductor properties of Cr, Ni and Mo-containing oxide films on the alloy surface and their resistance to pitting.

From the analysis of the mathematical model (4), it was found that the CPT of the 06ХН28МДТ alloy increases by 4.7°C with an increase in the volume of titanium nitrides (see Fig. 1) from 0.0931 up to 0.1918% vol. and the pH of the model recycled water from 4 up to 8. At the same time, it increases by 20.3°C with an increase in the volume of titanium nitride in the same interval and a chloride concentration from 350 up to 600 mg/l. This tendency may indicate that the formation of pitting in the vicinity of titanium nitride inclusions is caused by adsorption processes of chlorides from a chloride-containing media in



a

Fig. 1. Inclusions in 06ХН28МДТ alloy: titanium nitrides (*a*), titanium sulphides (*x*) (*b*).

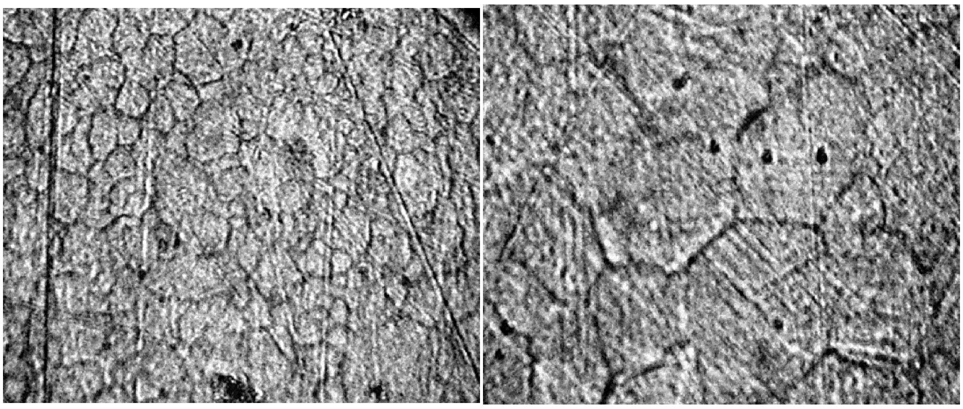


Continuation of Fig. 1.

places of the greatest accumulation of imperfections in the structure of oxide films on the alloy surface. Moreover, these processes depend more on the chloride concentration in the media than on its pH (x_1).

At the same time, it should be noted that works [9, 28] revealed a decrease in the CPT of AISI321 steel and 06ХН28МДТ alloy with an increase in the volume of titanium nitrides involved in pitting corrosion under similar test conditions. Thus, it follows that the more pitting sites on the surface of a steel or alloy in the vicinity of titanium nitride inclusions, the lower the resistance of the oxide film on their surface to pitting corrosion. At the same time, titanium nitrides in the 06ХН28МДТ alloy have a positive effect on the protective properties of the oxide film, which, according to paper [26], may be due to a decrease in the strength of their donor bonds.

It should also be noted that the semiconductor properties of the oxide film on the surface of the 06ХН28МДТ alloy depend much more on the content of Cr, Mo, and Ni than on the volume of titanium nitrides, which is based on a comparison of the above pairs of sums of these chemical elements and the volume of titanium nitrides with the parameters of model recycled water pH (x_1) and (x_2) chloride concentration. The influence of the medium austenite grain diameter (see Fig. 2) of the alloy on its CPT was not as significant as the content of Cr, Ni, and Mo, since it decreases by 2.5°C for the sum x_1 (pH)x_{15} (d_g) with an increase in the pH parameter (x_1) from 4 up to 8 and the medium austenite grain diameter (x_{15}) from 11 up to 31 μm. At the same time, for the pair of the sum x_2 (C_{Cl})x_{15} (d_g), a decrease in the CPT of the alloy by 11.3°C was found with an increase in its parameter x_{15} (d_g) from 11 up to 31 μm and a chloride concentration in the model recycled water from 350 up to 600 mg/l. It should be noted that the influence of the latter, as well as in pairs of sums of the media parameter x_2 (C_{Cl}) with the alloy parameters Cr (x_6), Mo (x_{11}), Ni (x_7), is significantly higher than the pH (x_1) of the media with these alloy parameters.



a *b*

Fig. 2. Austenite grain in 06ХН28МДТ alloy (×450): minimum, $d_g = 11$ μm (*a*) and maximum, $d_g = 31$ μm (*b*) meaning of medium austenite grain diameter.

The decrease in the CPT of 06ХН28МДТ alloy with an increase in the medium diameter of the austenite grain x_{15} (d_g) is most likely due to an increase in the degree of incoherence between the atoms of adjacent austenite grain lattices and, accordingly, an increase in the number of imperfections in the austenite structure at the intersection of inclusions with the boundaries of austenite grains, where stable pitting occurs and develops [29, 30]. However, this is not the main factor that determines the resistance of the 06ХН28МДТ alloy to pitting corrosion in recycled water, since according to (4), it was found that its CPT increases at conditional 345°C for a pair of sums x_6 (Cr)x_{15} (d_g) with an increase in the parameter x_{15} (d_g) from 11 up to 31 μm and the Cr content in the alloy from 21.82 up to 24.29% wt.

In addition, according to (3), the CPT of the alloy decreases by conditional 284°C for a pair of the sum x_7 (Ni)x_{15} (d_g) with an increase in the parameter x_{15} (d_g) in the same interval and the Ni content (x_7) in the alloy from 27.4 up to 27.7% wt. Thus, it turns out that an increase in the degree of incoherence between the atoms of adjacent austenite grain lattices due to an increase in its average diameter d_g (x_{15}) contributes to a decrease in the CPT (y) and pitting resistance of the 06ХН28МДТ alloy, but this effect is offset by an increase in the Cr content (x_6) due to the formation of chromium-containing oxide films with a lower donor bond on its surface. Most likely, an increase in the Ni content in the alloy contributes to an increase in the degree of donor bonding in the oxide film on the alloy surface, which reduces its resistance to pitting corrosion. It should be noted that the negative impact of increasing the Ni (x_7) content in the alloy within the standard is quite significant, since analysis (3) shows that its CPT decreases at a conditional 35.9°C with an increase in the Cr (x_6) and Ni (x_7) content in the intervals according to the data in Table 1. At the same time, it should be noted that the negative effect of an increase in the Ni (x_7) content within the standard on the pitting resistance of the alloy is levelled out by an increase in the Mo (x_{11}) and Cu (x_{12}) content, since the CPT for the pair of the sum Ni (x_7)Mo (x_{11}) increases by 12, and for Ni (x_7) Cu (x_{12}) by 22.5°C with an increase in the content of these chemical elements in the above intervals (Table 1).

Summarizing the above, it can be noted that in model recycled waters with pH 4–8 and chloride concentration from 350 up to 600 mg/l, the pitting resistance of 06ХН28МДТ alloy increases with an increase in their pH (x_1), Cr (x_6), Mo (x_{11}), Cu (x_{12}) content and a decrease in chloride concentration (x_2) and medium austenite grain diameter. The influence of media parameters x_1, x_2, and Cr, Ni alloy and medium austenite grain diameter is the most significant. This is consistent with the results of studies [13–16]. The developed model based on a three-layer direct signal propagation neural network (2) makes it possible to more accurately determine the pitting resistance of 06ХН28МДТ alloy depending on changes in its parameters and model recycled water (x_1, x_2), but the weighting coefficients $w_j^{(\mu,i)}$ of the neural network of model (2) do not provide useful information for analysing the effect of alloy and medium parameters on its CPT.

The minimum value of the CPT error of the 06ХН28МДТ alloy determined by means of Eq. (3) is $E_{\min} = 0.0186$°C, the maximum $E_{\max} = 5.3207$°C, the average $E_{\text{av}} = 1.381508$°C, and the accumulative value $E_{\text{sum}} = -172.68.85$°C. However, the minimum value of the alloys' CPT error determined by calculation with (2) is $E_{\min} = 0.0001$°C, $E_{\max} = 1.0261$°C, $E_{\text{av}} = 0.10192$°C, and $E_{\text{sum}} = 12.72$°C. Therefore, it is recommended to use model (2) to predict the pitting resistance of 06ХН28МДТ alloy during the operation of heat exchangers, and model (3) to select the optimal melt in terms of pitting resistance.

4. CONCLUSION

Two statistical models based on multivariate regression with pairwise combinations of features and a three-layer neural network of direct signal have been developed. They are proposed to be used to select the optimal melts of 06ХН28МДТ alloy and to predict the pitting resistance of heat exchangers made of it or its analogue, AISI904L steel, when operating in recycled water. It was found that the pitting resistance of the alloy increases with an increase in the pH of recycled water, the content of Cr, Mo, Cu, and the volume of titanium nitrides in it, and a decrease in the medium austenite grain diameter, the content of nickel within the standard and chlorides in the media. The influence of Cr and Ni content in pairs of sums with the medium austenite grain diameter on the pitting resistance of the alloy is most significant, and that of chromium in pairs with the media parameters is somewhat less.

REFERENCES

1. *Tekhnicheskie Usloviya. ТУ 3.17.–00217417-024-97. Teploobmenniki Plastinchastyye Razbornyye* [Technical Specifications ТУ 3.17.–00217417-024-97. Plate-Like Heat Exchangers] (PrAT Zavod 'Pavlogradkhimmash': 1998) (in Russian).
2. G. Ya. Vorob'eva, *Korrozionnaya Stoykost' Materialov v Agressivnykh Sredakh Khimicheskikh Proizvodstv* [Corrosion Resistance of Materials in Aggressive Environments of Chemical Industries] (Moskva: Khimiya: 1985) (in Russian).
3. O. E. Narivs'kyi, *Mater. Sci.*, **41**: 122 (2005).
4. O. E. Narivs'kyi, *Mater. Sci.*, **43**: 124 (2007).
5. V. A. Kachanov and D. G. Nikitin, *Issledovanie Sklonnosti Stali 12X18H10T k Tochechno-Yazvennoy i Shchelevoy Korrozii v Neytral'nykh Sredakh Primenitel'no k Razbornym Plastinchatym Teploobmennikam* [Study of 12X18H10T Steel Susceptibility to Pitting and Crevice Corrosion in Neutral Media as Applied to Plate Like Heat Exchangers] (Kharkiv: UkrNIIhimmash: 1985) (in Russian).
6. A. Narivskiy, R. Atchibayev, A. Muradov, K. Mukashevand Y. Yar-Mukhamedov, *Int. Multidisciplinary Sci. Conf. Surveying Geology and Mining Ecology Management—SGEM*, p. 267 (2018).
7. A. Narivskiy, G. Yar-Mukhamedova, E. Temirgaliyeva, M. Mukhtarova, and Y. Yar-Mukhamedov, *Int. Multidisciplinary Sci. Conf. Surveying Geology and Mining Ecology Management—SGEM*, vol. **1**, p. 63 (2016).
8. *GOST 9.912-89. Metody Uskorennykh Ispytaniy na Stoykost' k Pittingovoy Korrozii* [ГОСТ 9.912-89. Accelerated Pitting Resistance Test Methods] (Izdatel'stvo Standartov: 1989) (in Russian).
9. O. E. Narivs'kyi and S. B. Belikov, *Mater. Sci.*, **44**: 573 (2008).
10. D. A. Frudman, *Statistical Models: Theory and Practice* (Cambridge: Cambridge University Press: 2005).
11. S. O. Haykin, *Neutral Networks and Learning Machines* (London: Pearson: 2008).
12. J. Nacedal and S. Wright, *Numeral Optimisation* (New York: Springer-Verlag: 2006).
13. O. E. Narivskyi, S. A. Subbotin, T. V. Pulina, and M. S. Khoma, *Mater. Sci.*, **58**: 41 (2022).
14. O. E. Narivskyi, S. B. Belikov, S. A. Subbotin, and T. V. Pulina, *Mater. Sci.*. **57**: 291 (2021).
15. O. Narivs'kyi, R. Atchibayev, A. Kemelzhanova, G. Yar-Mukhamedova, G. Snizhnoy, S. Subbotin, and A. Beisebayeva, *Eurasian Chem.-Tech. J.*, **24**, No. 4: 295 (2022).
16. P. C. Pistorius and G. T. Burstein, *Corrosion Sci.*, **33**, Iss. 12: 1885 (1992).
17. P. C. Pistorious and G. T. Burstein, *Corrosion Sci.*, **36**, Iss. 3: 525 (1994).
18. J.-O. Nilsson, *Mater. Sci. Technol.*, **8**, Iss. 8: 685 (1992).
19. N. Bastos, S. M. Tavares, Francis Dalard, and R. P. Nogueira, *Scripta Mater.*,

57: 913 (2007).
20. R. J. Brigham and E. W. Tozer, *Corrosion*, **29**: 33 (1973).
21. J. M. Salinas-Bravo and R. C. Newman, *Corrosion Sci.*, **36**: 67 (1994).
22. Y. Tsutsumi, A. Nishikata, and T. Tsuru, *Corrosion Sci.*, **49**: 1394 (2007).
23. P. C. Pistorious and G. T. Burstein, *Corrosion Sci.*, **36**, Iss. 3: 525 (1994).
24. L. Martinez, B. Melki, G. Berthome, B. Baroux, and F. Perez, *Surf. Coat. Technol.*, **201**, Iss. 3–4: 1671 (2006).
25. C. Alonso, M. Castellote, and C. Andrade, *Electrochem. Acta*, **47**: 3469 (2002).
26. W. S. Li and J. L. Luo, *Corrosion Sci.*, **44**: 1695 (2002).
27. J. H. Wang, C. C. Su and Z. Szklarska-Smialowska, *Corrosion*, **44**, Iss. 10: 732 (1988).
28. O. E. Narivs'kyy, *Mater. Sci.*, **43**: 256 (2007).
29. J. O. Park, S. Matsch, and H. Böhni, *J. Electrochem. Soc.*, **149**: 34 (2002).
30. U. M. Ehrnsten, J. Likonen, L. I. Carpen, and O. A. Varjonen, *Mater. Characterization*, **36**, Iss. 4–5: 279 (1996).