doi: 10.18323/2782-4039-2023-4-66-10

The influence of frictional treatment and liquid carburizing on general corrosion resistance of chromium-nickel austenitic steels

Polina A. Skorynina*[1,3], junior researcher
Aleksey V. Makarov[1,2,4], Doctor of Science (Engineering),
Corresponding Member of RAS,
Head of Department of Materials Science, Head of Laboratory of Mechanical Properties
Roman A. Savrai[1,5], PhD (Engineering),
Head of Laboratory of Constructional Material Science
[1]*Institute of Engineering Science of the Ural Branch of RAS, Yekaterinburg (Russia)*
[2]*M.N. Mikheev Institute of Metal Physics of the Ural Branch of RAS, Yekaterinburg (Russia)*

***E-mail: skorynina@imach.uran.ru,**
polina.skorynina@mail.ru

[3]ORCID: https://orcid.org/0000-0002-8904-7600
[4]ORCID: https://orcid.org/0000-0002-2228-0643
[5]ORCID: https://orcid.org/0000-0001-9873-3621

Received 27.06.2023 *Accepted 17.11.2023*

Abstract: Currently, to increase the hardness, strength and wear resistance of thermally non-hardenable austenitic chromium-nickel steels, such methods as frictional treatment with a sliding indenter and liquid carburizing have been used. However, along with an effective increase in mechanical characteristics, the application of these types of treatment may be accompanied by a decrease in the corrosion resistance of austenitic steels. Therefore, it is reasonable to study the influence of frictional treatment and liquid carburizing on the general corrosion resistance of Cr–Ni austenitic steels. In this work, the surface microhardness of the 12Cr18Ni10Ti and AISI 321 steels was determined using the recovered indentation method after electropolishing, mechanical grinding, frictional treatment, and liquid carburizing at a temperature of 780 °C. Using scanning electron microscopy and optical profilometry, the authors studied steel surfaces subjected to the specified types of treatment and determined their roughness. The corrosion resistance of steel was studied by testing for general corrosion using the gravimetric method. When testing for general corrosion, it was found that hardening (up to 710 HV 0.025) frictional treatment leads to an increase in the corrosion rate of the 12Cr18Ni10Ti austenitic steel compared to the electropolished state (from k_m=0.35 g/(m^2·h) to k_m=0.53–0.54 g/(m^2·h)). The corrosion rate of the ground steel is k_m=0.58 g/(m^2·h), while mechanical grinding does not provide a significant increase in the microhardness of the steel under study (from 220 to 240 HV 0.025). It is shown that the corrosion behavior of 12Cr18Ni10Ti steel subjected to various types of treatment is determined by the following factors: the presence/absence of strain-induced α'-martensite in the structure, the quality of the formed surface and, apparently, the dispersion of the formed structure. Liquid carburizing of the AISI 321 austenitic steel leads simultaneously to an increase in its microhardness to 890 HV 0.025 and a certain increase in corrosion resistance compared to fine mechanical grinding. This is related to the fact that carbon embedding atoms stabilize the electronic structure of iron (austenite and martensite), thereby increasing its corrosion resistance.

Keywords: austenitic chromium-nickel steel; frictional treatment; liquid carburizing; microhardness; phase composition; roughness; corrosion resistance.

Acknowledgments: The authors express gratitude to V.V. Berezovskaya, Doctor of Science (Engineering), for participation in work.

The work was carried out within the government assignment to the Institute of Engineering Science, UB RAS on the topic No. AAAA-A18-118020790148-1 and the Institute of Metal Physics, UB RAS on the topic No. 122021000033-2. Experimental studies were carried out using the equipment of the "Plastometry" Core Facility Center of the IES UB RAS.

The paper was written on the reports of the participants of the XI International School of Physical Materials Science (SPM-2023), Togliatti, September 11–15, 2023.

For citation: Skorynina P.A., Makarov A.V., Savrai R.A. The influence of frictional treatment and liquid carburizing on general corrosion resistance of chromium-nickel austenitic steels. *Frontier Materials & Technologies*, 2023, no. 4, pp. 109–119. DOI: 10.18323/2782-4039-2023-4-66-10.

INTRODUCTION

Chromium-nickel austenitic steels of the 18Cr–10Ni type are widely used among corrosion-resistant materials. In particular, metastable austenitic 12Cr18Ni10Ti steel and its foreign analogues – AISI steels of the 300 series (AISI 304, AISI 321) are used in the food, medical, chemical, and oil refining industries. This is conditioned by a combination of their advantages, such as high workability, plasticity, heat resistance [1] and resistance to corrosion in various liquid and gas environments, as well as in solutions of salts and acids [2–4]. However, with all the listed advantages, austenitic steels are characterized by low levels of strength characteristics and wear resistance [5; 6].

Currently, to eliminate the above-mentioned disadvantages of austenitic Cr–Ni steels, various methods based

on plastic deformation [7–9] and chemical-thermal (nitriding [10, 11], carburizing [12, 13]) surface modification are used. Among the known methods of strain hardening, frictional treatment with a sliding indenter can be distinguished [10; 14; 15]. When applied to austenitic steels that are prone to adhesion during contact interaction, such treatment, along with effective strengthening of the surface layer up to 500 μm deep, allows obtaining a surface with low roughness in the absence of material continuity defects. Among the processes of chemical-thermal treatment of austenitic Cr–Ni steel, carburizing is of particular interest, which, compared to nitriding, allows forming deeper hardened layers that remain weakly magnetic [16].

It should be taken into account that the application of these types of strengthening treatment, can lead to a decrease in the corrosion resistance of metastable austenitic Cr–Ni steels due to the formation of strain-induced martensite, and carbide phases during intense deformation, and when the surface layer is saturated with carbon [1; 7]. However, the appearance of a new phase component is not always accompanied by a decrease in the corrosion properties of austenitic steels [12; 17]. Thus, in the work [17] it is shown that the pitting corrosion rate of the 12Cr18Ni10Ti steel decreases with an increase in the degree of tensile strain, and accordingly, with an increase in the α′-phase amount, which is formed in the material, and leads to an increase in its ability to passivate. Moreover, it is worth considering that the factors determining the corrosion behaviour of austenitic stainless steels may also include the topography of the surface formed during hardening treatment [7; 17; 18]. It was noted in [18] that mechanical grinding, compared to frictional treatment, leads to a twofold increase in the corrosion rate of the 03Cr16Ni14M3Ti steel due to the occurrence of microcracks and metal pits on the surface.

Thus, in the literature there is ambiguous information about the influence of the phase composition, and surface topography on the corrosion behaviour of steels of the 18Cr–10Ni type, subjected to various types of deformation and chemical-thermal surface modification. It should be noted, as well, that there are no works covering the influence of frictional treatment on the corrosion properties of metastable austenitic steels. Therefore, it is reasonable to conduct a comprehensive study that would take into account the influence of the phase composition, and topography of the surface of austenitic Cr–Ni steels formed during frictional treatment and liquid carburizing on the general corrosion resistance.

The purpose of this work is to study the influence of frictional treatment, and liquid carburizing on the corrosion properties of metastable austenitic 12Cr18Ni10Ti and AISI 321 steels.

METHODS

The authors studied the industrial austenitic metastable steels of two grades: 12Cr18Ni10Ti (GOST 5632-2014) and AISI 321. The chemical composition of the steels, which was determined using a SPECTROMAXx optical emission spectrometer, is given in Table 1. The samples for research were cut from rolled sheets. Before subsequent treatment, the samples were subjected to hardening from 1100 °C in water, mechanical grinding using M63, M50, M20 (GOST 3647-80) abrasive cloths and ASM 14/10 NOMG, ASM 7/5 NOMG (GOST 25593-83) diamond pastes with a successive abrasive grid reduction, and then electrolytic polishing in a solution of 100 g H_2SO_4 + 400 g H_3PO_4 + 50 g CrO_3 at a temperature of 60–70 °C.

12Cr18Ni10Ti steel samples with dimensions of 98×38×8.6 mm were subjected to frictional treatment with a sliding indenter made of hemispherical synthetic diamond with a hemisphere radius of R=3 mm. The treatment was carried out in a non-oxidizing argon environment with a load on the indenter of P=392 N, with an indenter displacement of d=0.1 mm for each double stroke and with a number of indenter scans over the sample surface of n=1 and n=11.

Liquid carburizing of AISI 321 steel samples with dimensions of 40×52×10 mm was carried out in molten salts with the addition of silicon carbide of the 80 % Na_2CO_3 + + 10 % NaCl + 10 % SiC composition (in wt. %) at a temperature of 780 °C for 15 h with subsequent cooling in water. For carburizing, a laboratory furnace and a crucible with a diameter of d=100 mm and a height of h=300 mm were used. To remove the oxide film, the samples after carburizing were subjected to electrolytic etching in a solution of 90 wt. % CH_3COOH + + 10 wt. % H_2ClO_4 for 30 s.

All samples were cut using electrical discharge cutting on a FANUC Robocut α-0iE machine. Microhardness was determined on a SHIMADZU HMV-G21DT device using the recovered indentation method at the load on a Vickers indenter of 0.245 N. The phase composition was determined on a SHIMADZU XRD-7000 X-ray diffractometer in CrK_α radiation (with a tube voltage of 30 kV and a tube current of 30 mA). Continuous shooting was carried out,

Table 1. *Chemical composition of steels under study, wt. %*
Таблица 1. *Химический состав исследуемых сталей, мас. %*

Steel	C	Cr	Ni	Ti	Mn	Si	Mo	Co	Nb	Cu
12Cr18Ni10Ti	0.10	17.72	10.04	0.63	1.33	0.57	0.23	0.064	0.014	0.057
AISI 321	0.05	16.80	8.44	0.33	1.15	0.67	0.26	0.13	0.03	0.31

Note. S and P content does not exceed 0.036 %, the rest is Fe.
Примечание. Содержание S и P не превышает 0,036 %, остальное Fe.

with a scanning rate of 1 °/min, a step of 0.05° and an exposure time of 3 s. The phase composition was determined by the method of homologous pairs. The amount of α-phase $V\alpha$ was calculated using the formula

$$V\alpha = \frac{100}{1+1{,}45\,\frac{I(111)\gamma}{I(110)\alpha}}, \text{ vol. \%},$$

where $I(111)\gamma$ and $I(110)\alpha$ are the integral intensities of γ-lines and α-phases [19].

The depth of the analyzed layer when determining the phase composition was ~7 μm. The surface of the samples was studied by scanning electron microscopy using a Tescan VEGA II XMU microscope. To determine the surface roughness parameters of the samples, a Wyko NT-1100 optical profilometer was used. Measurements were carried out on the 211×278 μm sections, and the arithmetic average deviation of the *Ra* profile was determined. The phase composition, and surface roughness were determined directly on samples prepared for corrosion tests.

Tests for general corrosion were carried out by the gravimetric method according to GOST R 9.905-2007 in a solution of 20 wt. % NaCl + 30 wt. % HCl (1:1) at room temperature. Due to its ability to destroy a passivation layer, this environment has a strong corrosive effect on the materials under study, thus ensuring the continuous occurrence of the corrosion process.

Samples for testing were prepared from 12Cr18Ni10Ti steel with dimensions of 10×10×2 mm in the following conditions: after electropolishing, grinding on M20 abrasive cloth (GOST 3647-80) with a grain size of 20/14 μm, and after frictional treatment at n=1 and n=11. Samples of AISI 321 steel with dimensions of 7×7×2 mm were tested in the following conditions: after grinding with ASM 14/10 NOMG diamond paste with a grain size of 14/10 μm (GOST 25593-83) and after liquid carburizing. For each condition, two samples were subjected to corrosion tests.

The prepared samples were immersed in a corrosive environment for 18 h until the corrosion rate stabilised, while the environment pH was not controlled. During testing, samples were weighed periodically. Before weighing, to remove corrosion products, the samples were washed in water, dried with filter paper, and degreased with acetone. This allowed determining accurately the weight loss of the sample after soaking in a corrosive environment. Weight loss was determined on a Demcom DA-65C laboratory scale with an accuracy of up to 0.01 mg. The corrosion rate k_m was calculated using the formula

$$k_m = \frac{\Delta m}{S \cdot \tau}, \text{ g/(m}^2\cdot\text{h)},$$

where Δm is weight loss, g;
S is surface area of test samples, m^2;
τ is testing time, h.

For a comparative assessment of the corrosion behaviour of test samples, the average corrosion rate in steady state was calculated.

RESULTS

According to the data in Table 2 and Fig. 1 a, the structure of quenched (after electrolytic polishing) 12Cr18Ni10Ti steel contains 100 vol. % γ-phase (austenite), and α′-phase (strain-induced martensite) is absent.

After mechanical grinding, except for the γ-phase, the structure of steel under study also contains the α'-phase, the volume fraction of which is 7 vol. % (Table 2, Fig. 1 b). During frictional treatment in the surface layer of the steel under study, the deformation γ→α'-transformation develops more intensively (Fig. 1 c, 1 d). The amount of α'-martensite formed in the surface layer of steel reaches 55–70 vol. % (Table 2).

The microhardness of steel in the initial electropolished state is 220 HV 0.025 (Table 2). Mechanical grinding practically, does not lead to an increase in the microhardness of the surface of the steel under study (only up to 240 HV 0.025). Frictional treatment ensures an increase in the microhardness of the steel under study by 2.5 times (up to 560 HV 0.025) already with one-fold (n=1) scanning of the indenter over the sample surface. Increasing the frictional loading multiplicity to n=11 leads to an additional increase in the microhardness of steel to 710 HV 0.025 (Table 2). This is consistent with an increase in the α′-phase amount from 55 to 70 vol. % as the number of indenter scans along the sample surface increases from n=1 to n=11.

According to the data in Table 2, the surfaces of 12Cr18Ni10Ti steel after electropolishing and mechanical grinding using fine-grained (20/14 μm) cloth are characterized by similar levels of the arithmetic average deviation

Table 2. *Microhardness HV 0.025, phase composition (amount of α'-martensite) and roughness parameter Ra of the surface of 12Cr18Ni10Ti steel samples after different types of treatment*
Таблица 2. *Микротвердость HV 0,025, фазовый состав (количество α'-мартенсита) и параметр шероховатости Ra поверхности образцов из стали 12Х18Н10Т после различных обработок*

Types of treatment	HV 0.025	α′, vol. %	*Ra*, μm
Electropolishing	220±20	0	0.06±0.01
Grinding (abrasive 20/14 μm)	240±5	7±2	0.11±0.01
Frictional treatment at *n*=1	560±27	55±3	0.17±0.01
Frictional treatment at *n*=11	710±43	70±3	0.33±0.03

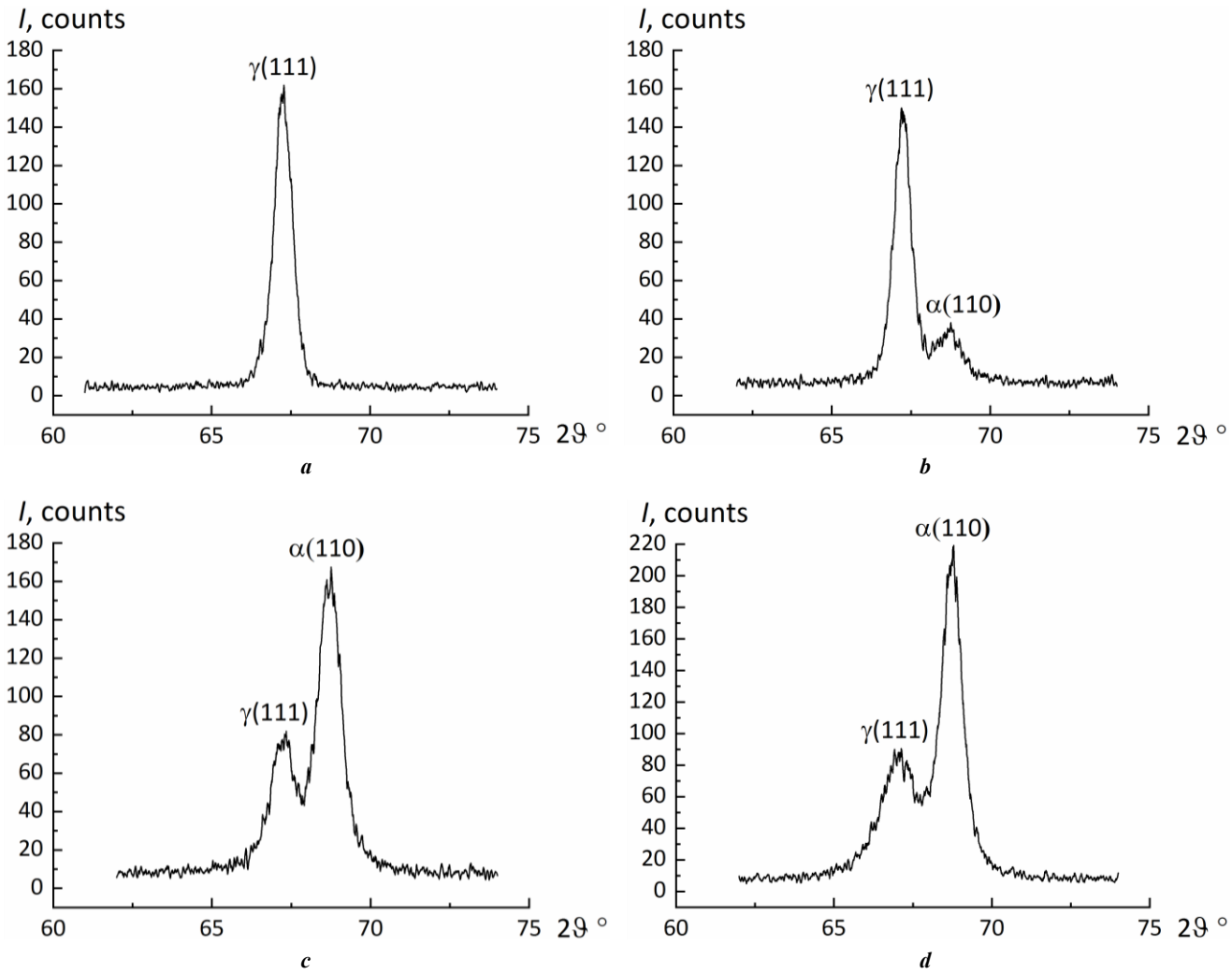


Fig. 1. *X-ray diffraction patterns of the surface of 12Cr18Ni10Ti steel in quenched condition (**a**), after grinding with an abrasive grit of 20/14 μm (**b**), and frictional treatment at n=1 (**c**) and n=11 (**d**)*
Рис. 1. *Рентгеновские дифрактограммы поверхности стали 12Х18Н10Т в закаленном состоянии (**a**), после шлифования абразивом зернистостью 20/14 мкм (**b**) и фрикционной обработки при n=1 (**c**) и n=11 (**d**)*

of the profile *Ra* (0.06 and 0.11 μm). The steel surface after frictional treatment demonstrates higher values of this parameter: *Ra*=0.17–0.33 μm.

Electrolytic polishing leads to the formation of a smooth 12Cr18Ni10Ti steel surface characterized by the presence of a small amount of shallow etching pitting (Fig. 2 a). This determines the recorded minimum values of the parameter *Ra*=0.06 μm. The steel surface after grinding is characterized by the presence of micro damages, and shallow grooves (dimples) oriented in the grinding direction (Fig. 2 b). This causes slightly higher values of the parameter *Ra*=0.11 μm than for the electropolished surface.

The recorded slightly larger values of the arithmetic average profile deviation *Ra* after frictional treatment are associated with the fact that the steel surface is characterized by the presence of plastic displacement stripes, alternating longitudinal protrusions and dimples (Fig. 2 c, 2 d). At the same time, on the surfaces under consideration after exposure to a synthetic diamond indenter, there are no continuity defects in the form of pits and cracks characteristic of a polished surface (Fig. 2 b).

From the data shown in Fig. 3, it follows that austenitic 12Cr18Ni10Ti steel with an electropolished surface is characterized by the lowest corrosion rate: k_m=0.35±0.05 g/(m^2·h). The corrosion rate of steel in the polished state is 1.6 times higher: k_m=0.58±0.12 g/(m^2·h). Steel after frictional treatment has a slightly lower corrosion rate. At the same time, for steel processed in two modes with different numbers of indenter scans (*n*=1 and *n*=11), similar levels of corrosion rate are recorded: k_m=0.53±0.09 g/(m^2·h) and k_m=0.54±0.07 g/(m^2·h).

X-ray phase analysis showed (Table 3, Fig. 4 a) that AISI 321 steel in the quenched state (after electropolishing) contains 100 vol. % γ-phase (α′-phase is absent). As a result of mechanical grinding, 9 vol. % α′-martensite is formed in the surface layer of the steel under study (Table 3, Fig. 4 b). After liquid carburizing at a temperature of 780 °C, the structure of the steel surface layer consists of carbon-rich austenite γ_C, α′-martensite, $Cr_{23}C_6$ chromium carbides and Fe_3C cementite (Fig. 4 c). In this case, the amount of α′-phase is 20 vol. % (Table 3).

The microhardness of AISI 321 steel in the initial state is 200 HV 0.025. Mechanical grinding leads to a slight

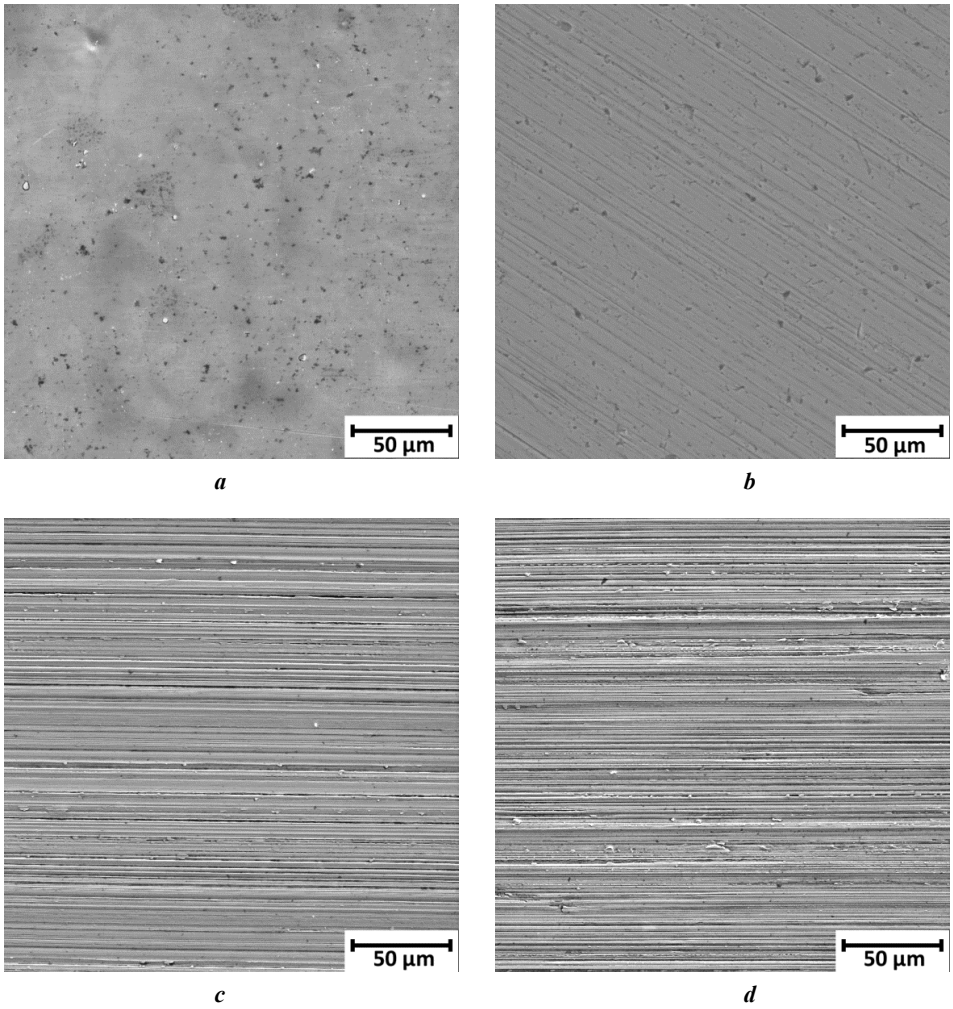


Fig. 2. *Images of the surface of 12Cr18Ni10Ti steel samples after electropolishing (**a**), grinding with an abrasive grit of 20/14 µm (**b**), frictional treatment at n=1 (**c**) and n=11 (**d**)*
Рис. 2. *Изображения поверхности образцов из стали 12Х18Н10Т после электролитического полирования (**а**), шлифования абразивом зернистостью 20/14 мкм (**b**), фрикционной обработки при n=1 (**c**) и n=11 (**d**)*

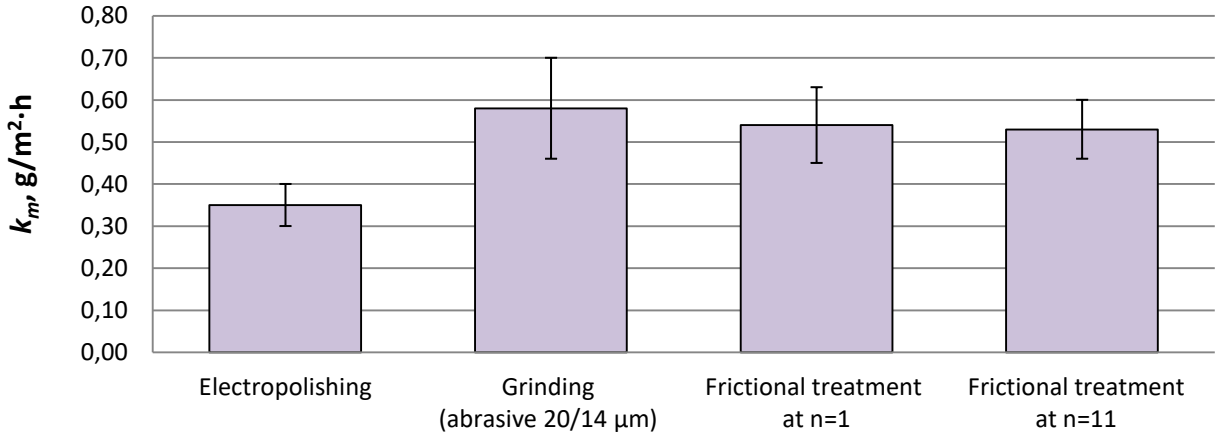


Fig. 3. *The dependence of corrosion rate k_m of 12Cr18Ni10Ti steel samples on the type of surface treatment*
Рис. 3. *Зависимость скорости коррозии k_m образцов из стали 12Х18Н10Т от вида обработки поверхности*

Table 3. *Microhardness HV 0.025, phase composition (quantity of α'-martensite) and roughness parameter Ra of the surface of AISI 321 steel samples after different types of treatment*
Таблица 3. *Микротвердость HV 0,025, фазовый состав (количество α'-мартенсита деформации) и параметр шероховатости Ra поверхности образцов из стали AISI 321 после различных обработок*

Types of treatment	HV 0.025	α′, vol. %	*Ra*, μm
Electropolishing	200±7	0	–
Grinding (abrasive 14/10 μm)	260±8	9±2	0.08±0.02
Liquid carburizing	890±110	20±2	0.52±0.13

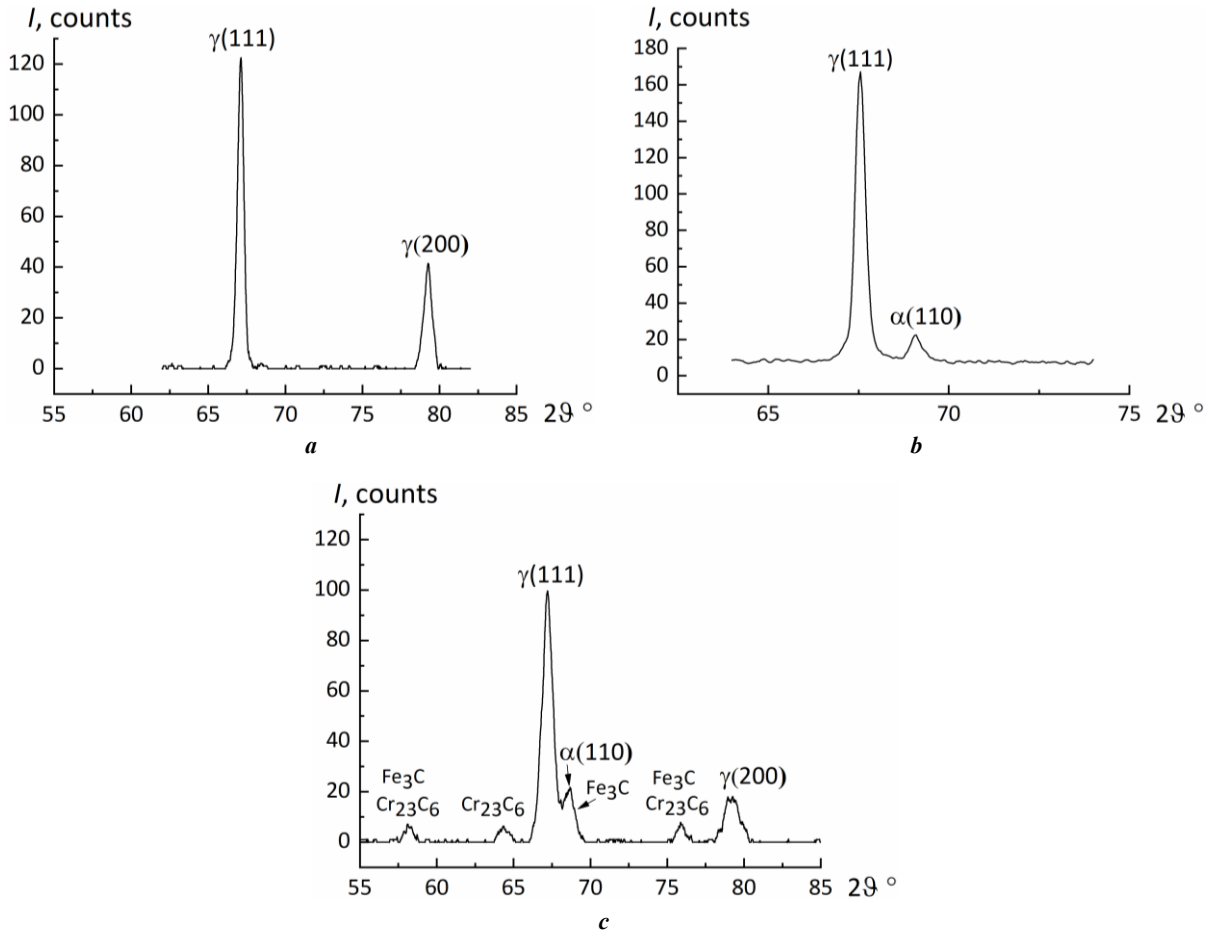
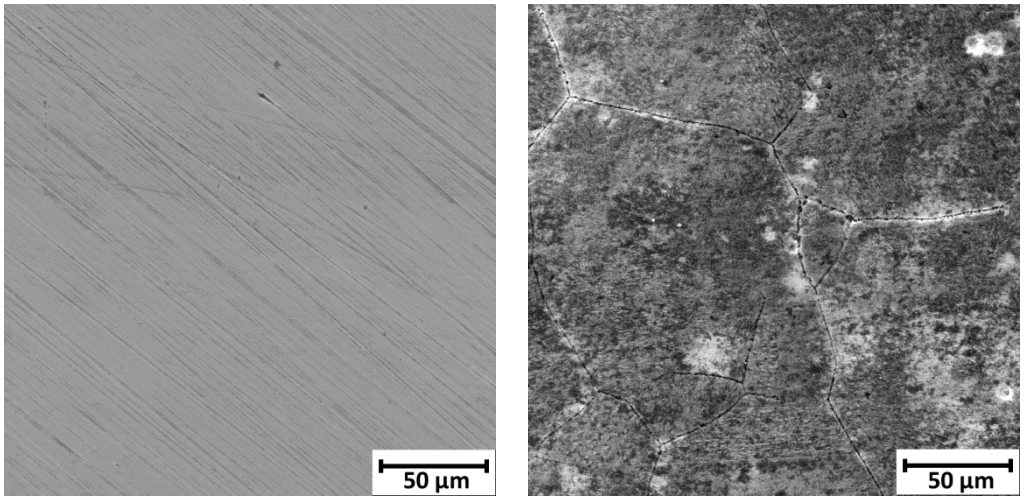


Fig. 4. *X-ray diffraction patterns of the surface of AISI 321 steel in quenched condition (**a**), after grinding with an abrasive grit of 14/10 μm (**b**), and liquid carburizing (**c**)*
Рис. 4. *Рентгеновские дифрактограммы поверхности стали AISI 321 в закаленном состоянии (**a**), после шлифования абразивом зернистостью 14/10 мкм (**b**) и жидкостной цементации (**c**)*

increase in the microhardness of the surface of the steel under study (up to 260 HV 0.025). After liquid carburizing, the microhardness of austenitic steel increases by 4.5 times – up to 890 HV 0.025.

After mechanical grinding with diamond paste, the AISI 321 steel surface is characterized by the presence of shallow grooves oriented in the grinding direction and low values of the arithmetic average profile deviation *Ra*=0.08 μm (Fig. 5 a, Table 3). The steel surface after carburizing has a higher roughness (*Ra*=0.52 μm). This may be caused by the fact that a clear relief is visible on the surface of the carburized steel along the grain boundaries, which is associated with their etching during electrolytic removal after oxide film carburizing (Table 3, Fig. 5 b).

Histograms shown in Fig. 6 indicate that austenitic AISI 321 steel after grinding and after carburizing is characterized by similar corrosion rates: k_m=0.40±0.04 g/(m^2·h) and k_m=0.32±0.02 g/(m^2·h) respectively. At the same time, the corrosion rate of carburized steel is even lower.



a *b*

Fig. 5. *Images of the surface of AISI 321 steel samples after grinding with an abrasive grit of 14/10 µm (**a**) and liquid carburizing (**b**)*
Рис. 5. *Изображения поверхности образцов из стали AISI 321 после шлифования абразивом зернистостью 14/10 мкм (**a**) и жидкостной цементации (**b**)*

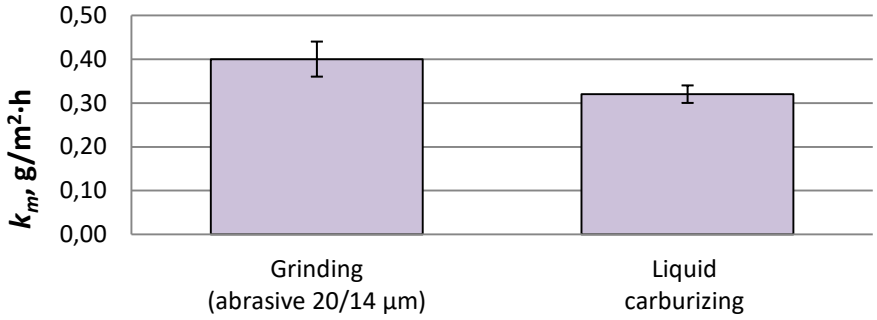


Fig. 6. *The dependence of corrosion rate k_m of AISI 321 steel samples on the type of surface treatment*
Рис. 6. *Зависимость скорости коррозии k_m образцов из стали AISI 321 от вида обработки поверхности*

DISCUSSION

The registered more than three-fold strengthening (up to 710 HV 0.025) of 12Cr18Ni10Ti steel during frictional treatment, is caused by the formation of a highly dispersed (up to nano- and submicrocrystalline state) martensitic-austenitic structure [5], and the formation of 70 vol. % strain-induced α'-martensite as a result of the implementation of the deformation phase transformation. In [15], in the surface layer of austenitic AISI 321 steel during fric-tional treatment, a complete deformation γ→α'-transformation was observed, which was facilitated by a lower content of the strong nickel austenite stabilizer in the steel (8.44 wt. % Ni) than in 12Cr18Ni10Ti steel (10.04 wt. % Ni, Table 1). However, the revealed relatively low level of microhardness on the AISI 321 steel surface (480 HV 0.025), indicates lower degrees of plastic deformation and structure dispersion achieved in the work [15]. Consequently, it is not the strain-induced martensitic transformation of low-carbon austenite, but the activation of the grain-boundary strengthening mechanism during grain refinement during frictional treatment, that contributes decisively to the strengthening of the 12Cr18Ni10Ti steel studied in this work.

The austenitic 12Cr18Ni10Ti steel surface, which is prone to setting during friction, formed during frictional treatment, is characterized by rather low values of the roughness parameter *Ra*=0.17–0.33 µm during profilemetry of areas with dimensions of 211×278 µm. In the work [20], during frictional treatment of high-nitrogen austenitic steel, a surface with a roughness parameter *Ra*=0.39 µm was formed. At the same time, during shot peening, the surface of AISI 304 steel was characterized by significantly higher roughness: *Ra*=2.8–3.8 µm [21]. Thus, frictional treatment provides both effective strengthening of 12Cr18Ni10Ti steel, and high quality of its surface.

The registered increased corrosion rate of 12Cr18Ni10Ti steel in a deformed state (after mechanical grinding and frictional treatment) (Fig. 3), may be caused by the presence of strain-induced martensite in the surface layers. In the work [22], the occurrence of pitting corrosion on the surface of 304 L steel was associated with the presence of electro-

chemical heterogeneity, which is caused by the appearance of α′-martensite. However, the volume fraction of the α′-phase formed during grinding of 12Cr18Ni10Ti steel is significantly less (7 vol. %), than during frictional treatment (55–70 vol. %), and the corrosion rate of steel in the ground state is slightly higher (Table 2, Fig. 3). The registered positive effect of frictional treatment on corrosion resistance, despite the intensive development of martensitic transformation during loading with an indenter, can be explained by the strong structure fragmentation during frictional treatment [5], which contributes to the accelerated formation of passive films on the stainless steel surface [23]. Thus, in terms of the corrosion resistance of 12Cr18Ni10Ti steel, frictional treatment has a certain advantage over mechanical grinding.

Previously, it was noted, as well, that grinding, and frictional treatment cause an increase in the surface roughness of 12Cr18Ni10Ti steel compared to electropolishing: *Ra*=0.11–0.33 μm and *Ra*=0.06 μm, respectively. In this case, the presence of defects in the material continuity (small pits and cracks, Fig. 2 b) are registered on the polished surface, and as a result of frictional treatment, pronounced traces of deformation appear on the surface in the form of longitudinal ridges, dimples and smoothed stripes (Fig. 2 c, 2 d). It has been shown that an increase in the steel surface roughness, is accompanied by a growth in the corrosion rate [18; 24], and defects can act as additional sources of corrosion destruction, and prevent material passivation [25]. Thus, apparently, the corrosion behaviour of austenitic steel is influenced significantly by the quality of its surface (roughness, presence or absence of defects).

The effective increase in the microhardness of austenitic AISI 321 steel (from 200 to 890 HV 0.025) achieved during liquid carburizing, is associated with solid solution strengthening due to austenite saturation with carbon, dispersion strengthening during the precipitation of carbide phases, the formation of α′-martensite and an increase in the density of structure defects during plastic deformation [13].

Despite the formation of 20 vol. % strain-induced α′-martensite, carbides, and a small amount of ε-martensite [13], as well as a higher surface roughness, there is a slightly lower level of corrosion rate of AISI 321 steel after liquid carburizing than after grinding (Fig. 6). This is associated with the fact that interstitial atoms, in particular carbon, stabilize the electronic state of iron, thereby increasing its corrosion resistance [26]. This is true for both austenite and martensite [27]. Along with this, oxyanions such as HCO_3^- and CO_3^{2-} are effective inhibitors for suppressing anodic corrosion [26].

CONCLUSIONS

General corrosion tests in a solution of 20 wt. % NaCl + + 30 wt. % HCl (1:1) showed that, compared to electropolishing, effective hardening of the surface of austenitic metastable 12Cr18Ni10Ti steel by frictional treatment (from 220 to 710 HV 0.025), is accompanied by an increase in the corrosion rate from k_m=0.35 g/(m^2·h) to k_m=0.53–0.54 g/(m^2·h). However, even despite the formation on the surface of steel of 55–70 vol. % strain-induced martensite, under the influence of a sliding indenter, frictional treatment does not lead to a corrosion resistance deterioration, compared to another mechanical post-processing of austenitic steel – grinding with fine-grained (20/14 μm) cloth, which does not provide a significant increase in surface microhardness (only up to 240 HV 0.025), and the development of strain-induced martensitic austenite transformation. In this case, the corrosion rate of polished steel reaches k_m=0.58 g/(m^2·h).

The corrosion behaviour of 12Cr18Ni10Ti steel subjected to electrolytic polishing, grinding, and frictional treatment is determined by the following factors: the presence/absence of strain-induced α′-martensite in the structure, the formed surface quality (roughness, presence or absence of continuity defects), and apparently, the formed structure dispersion.

It has been found that liquid carburizing at a temperature of 780 °C simultaneously leads to effective hardening (from 200 to 890 HV 0.025) of electropolished austenitic AISI 321 steel, and a slight increase in corrosion resistance compared to fine mechanical grinding with diamond paste. The corrosion rate of ground steel is k_m=0.40 g/(m^2·h), and of carburized one is k_m=0.32 g/(m^2·h). This is related to the fact that interstitial carbon atoms stabilize the electronic state of iron (both of austenite and martensite), thereby increasing its corrosion resistance.

REFERENCES

1. Borgioli F. From austenitic stainless steel to expanded austenite-S phase: formation, characteristics and properties of an elusive metastable phase. *Metals*, 2020, vol. 10, no. 2, article number 187. DOI: 10.3390/met10020187.
2. Pradhan K.K., Matawale C.R., Murarka S. Analysis of erosion-corrosion resistance and various application in domestic and industrial field of stainless steel grade 304. *International Journal of Research (IJR)*, 2015, vol. 2, no. 4, pp. 807–811.
3. Wei Xinlong, Ling Xiang, Zhang Meng. Influence of surface modifications by laser shock processing on the acid chloride stress corrosion cracking susceptibility of AISI 304 stainless steel. *Engineering Failure Analysis*, 2018, vol. 91, pp. 165–171. DOI: 10.1016/j.engfailanal.2018.04.045.
4. Kostina M.V., Kostina V.S., Kudryashov A.E., Muradyan S.O., Krivorotov V.I. The features of the chemical composition and structural-phase state determining a decrease in the corrosion resistance of 18Cr–10Ni steel parts. *Steel in Translation*, 2021, vol. 51, no. 3, pp. 168–179. DOI: 10.3103/S0967091221030050.
5. Makarov A.V., Skorynina P.A., Osintseva A.L., Yurovskikh A.S., Savray R.A. Improving the tribological properties of austenitic 12Kh18N10T steel by nanostructuring frictional treatment. *Obrabotka Metallov (Metal Working and Material Science)*, 2015, no. 4, pp. 80–92. DOI: 10.17212/1994-6309-2015-4-80-92.
6. Zagibalova E.A., Moskvina V.A., Mayer G.G. The influence of method and temperature of ion-plasma treatment on physical and mechanical properties of surface layers in austenitic stainless steel. *Frontier Materials & Technologies*, 2021, no. 4, pp. 17–26. DOI: 10.18323/2782-4039-2021-4-17-26.
7. Balusamy T., Sankara Narayanan T.S.N., Ravichandran K., Park Il Song, Lee Min Ho. Influence of surface mechanical attrition treatment (SMAT) on the corrosion

behaviour of AISI 304 stainless steel. *Corrosion Science*, 2013, vol. 74, pp. 332–344. DOI: 10.1016/j.corsci.2013.04.056.
8. Wang Cong, Han Jing, Zhao Jiyun, Song Yuanming, Man Jiaxiang, Zhu Hua, Sun Jiapeng, Fang Liang. Enhanced wear resistance of 316 L stainless steel with a nanostructured surface layer prepared by ultrasonic surface rolling. *Coatings*, 2019, vol. 9, no. 4, article number 276. DOI: 10.3390/coatings9040276.
9. Li Yang, Lian Yang, Jing Fengyu, He Tiantian, Zou Yun. Improvement in the tribological behaviour of surface-nanocrystallised 304 stainless steel through supersonic fine particle bombardment. *Applied Surface Science*, 2023, vol. 627, article number 157334. DOI: 10.1016/j.apsusc.2023.157334.
10. Makarov A.V., Savrai R.A., Skorynina P.A., Volkova E.G. Development of methods for steel surface deformation nanostructuring. *Metal Science and Heat Treatment*, 2020, vol. 62, no. 1-2, pp. 61–69. EDN: GFTTFR.
11. Petrova L.G. Strengthening of austenitic steels and alloys due to forming of solid solution by nitriding. *Uprochnyayushchie tekhnologii i pokrytiya*, 2007, no. 4, pp. 9–17. EDN: HZRRJT.
12. Liu R.L., Wang S., Wei C.Y., Yan M.F., Qiao Y.J. Microstructure and corrosion behavior of low temperature carburized AISI 304 stainless steel. *Materials Research Express*, 2019, vol. 6, article number 066417. DOI: 10.1088/2053-1591/ab104c.
13. Savrai R.A., Skorynina P.A. Structural-phase transformations and changes in the properties of AISI 321 stainless steel induced by liquid carburizing at low temperature. *Surface and Coatings Technology*, 2022, vol. 443, article number 128613. DOI: 10.1016/j.surfcoat.2022.128613.
14. Savrai R.A., Osintseva A.L. Effect of hardened surface layer obtained by frictional treatment on the contact endurance of the AISI 321 stainless steel under contact gigacycle fatigue tests. *Materials Science and Engineering: A*, 2021, vol. 802, article number 140679. DOI: 10.1016/j.msea.2020.140679.
15. Putilova E.A., Goruleva L.S., Zadvorkin S.M. Effect of friction treatment of the AISI 321 steel on changes in its hardness and magnetic characteristics. *Diagnostics, Resource and Mechanics of materials and structures*, 2022, no. 5, pp. 40–49. DOI: 10.17804/2410-9908.2022.5.040-049.
16. Tsujikawa M., Egawa M., Sone T., Ueda N., Okano T., Higashi K. Modification of S phase on austenitic stainless steel using fine particle shot peening steel. *Surface and Coatings Technology*, 2013, vol. 228, pp. S318–S322. DOI: 10.1016/j.surfcoat.2012.05.111.
17. Yarovchuk A.V., Doronina T.A., Tivanova O.V. The influence of deformation martensite on pitting resistance of 12H18N10T stainless steel. *Polzunovskiy almanakh*, 2007, no. 1–2, pp. 190–196. EDN: NNYBSW.
18. Skorynina P.A., Makarov A.V., Berezovskaya V.V., Merkushkin E.A., Chekan N.M. The influence of nanostructuring friction treatment on micromechanical and corrosive characteristics of stable austenitic chromium-nickel steel. *Frontier Materials & Technologies*, 2021, no. 4, pp. 80–88. DOI: 10.18323/2782-4039-2021-4-80-88.
19. Korshunov L.G., Sagaradze V.V., Chernenko N.L., Shabashov V.A. Friction-induced structural transformations of the carbide phase in hadfield steel. *The Physics of Metals and Metallography*, 2015, vol. 116, no. 8, pp. 823–828. DOI: 10.1134/S0031918X15080098.
20. Narkevich N.A., Mironov Y.P., Shulepov I.A. Structure, mechanical, and tribotechnical properties of an austenitic nitrogen steel after frictional treatment. *The Physics of Metals and Metallography*, 2017, vol. 118, no. 4, pp. 399–406. DOI: 10.1134/S0031918X17020090.
21. Neslušan M., Minárik P., Čep R., Uríček J., Trojan K., Ganev N., Trško L. Barkhausen noise emission of AISI 304 stainless steel originating from strain induced martensite by shot peening. *Journal of Materials Research and Technology*, 2022, vol. 20, pp. 748–762. DOI: 10.1016/j.jmrt.2022.07.107.
22. Chen Xin, Gussev M., Balonis M., Bauchy M., Sant G. Emergence of micro-galvanic corrosion in plastically deformed austenitic stainless steels. *Materials and Design*, 2021, vol. 203, article number 109614. DOI: 10.1016/j.matdes.2021.109614.
23. Balusamy T., Kumar S., Sankara Narayanan T.S.N. Effect of surface nanocrystallization on the corrosion behaviour of AISI 409 stainless steel. *Corrosion Science*, 2010, vol. 52, no. 11, pp. 3826–3834. DOI: 10.1016/j.corsci.2010.07.004.
24. Yin Songbo, Li D.Y., Bouchard R. Effects of the strain rate of prior deformation on the wear-corrosion synergy of carbon steel. *Wear*, 2007, vol. 263, no. 1-6, pp. 801–807. DOI: 10.1016/j.wear.2007.01.058.
25. Hao Yun-wei, Deng Bo, Zhong Cheng, Jiang Yi-ming, Li Jin. Effect of surface mechanical attrition treatment on corrosion behavior of 316 stainless steel. *Journal of Iron and Steel Research International*, 2009, vol. 16, no. 2, pp. 68–72. DOI: 10.1016/S1006-706X(09)60030-3.
26. Sun Jianlin, Tang Huajie, Wang Chenglong, Han Zhao, Li Shisen. Effects of alloying elements and microstructure on stainless steel corrosion: a review. *Steel Research International*, 2022, vol. 93, no. 5, article number 2100450. DOI: 10.1002/srin.202100450.
27. Kadowaki M., Saengdeejing A., Muto I. et al. First-principles analysis of the inhibitive effect of interstitial carbon on an active dissolution of martensitic steel. *Corrosion Science*, 2020, vol. 163, article number 108251. DOI: 10.1016/j.corsci.2019.108251.

СПИСОК ЛИТЕРАТУРЫ

1. Borgioli F. From austenitic stainless steel to expanded austenite-S phase: formation, characteristics and properties of an elusive metastable phase // Metals. 2020. Vol. 10. № 2. Article number 187. DOI: 10.3390/met10020187.
2. Pradhan K.K., Matawale C.R., Murarka S. Analysis of erosion-corrosion resistance and various application in domestic and industrial field of stainless steel grade 304 // International Journal of Research (IJR). 2015. Vol. 2. № 4. P. 807–811.
3. Wei Xinlong, Ling Xiang, Zhang Meng. Influence of surface modifications by laser shock processing on the acid chloride stress corrosion cracking susceptibility of AISI 304 stainless steel // Engineering Failure Analysis. 2018. Vol. 91. P. 165–171. DOI: 10.1016/j.engfailanal.2018.04.045.

4. Костина М.В., Криворотов В.И., Костина В.С., Кудряшов А.Э., Мурадян С.О. Особенности химического состава и структурно-фазового состояния, обусловившие снижение коррозионной стойкости деталей из стали 18Cr–10Ni // Известия высших учебных заведений. Черная металлургия. 2021. Т. 64. № 3. С. 217–229. DOI: 10.17073/0368-0797-2021-3-217-229.
5. Макаров А.В., Скорынина П.А., Осинцева А.Л., Юровских А.С., Саврай Р.А. Повышение триботехнических свойств аустенитной стали 12Х18Н10Т наноструктурирующей фрикционной обработкой // Обработка металлов (технология, оборудование, инструменты). 2015. № 4. С. 80–92. DOI: 10.17212/1994-6309-2015-4-80-92.
6. Загибалова Е.А., Москвина В.А., Майер Г.Г. Влияние метода и температуры ионно-плазменной обработки на физико-механические свойства поверхностных слоев в аустенитной нержавеющей стали // Frontier Materials & Technologies. 2021. № 4. С. 17–26. DOI: 10.18323/2782-4039-2021-4-17-26.
7. Balusamy T., Sankara Narayanan T.S.N., Ravichandran K., Park Il Song, Lee Min Ho. Influence of surface mechanical attrition treatment (SMAT) on the corrosion behaviour of AISI 304 stainless steel // Corrosion Science. 2013. Vol. 74. P. 332–344. DOI: 10.1016/j.corsci.2013.04.056.
8. Wang Cong, Han Jing, Zhao Jiyun, Song Yuanming, Man Jiaxiang, Zhu Hua, Sun Jiapeng, Fang Liang. Enhanced wear resistance of 316 L stainless steel with a nanostructured surface layer prepared by ultrasonic surface rolling // Coatings. 2019. Vol. 9. № 4. Article number 276. DOI: 10.3390/coatings9040276.
9. Li Yang, Lian Yang, Jing Fengyu, He Tiantian, Zou Yun. Improvement in the tribological behaviour of surface-nanocrystallised 304 stainless steel through supersonic fine particle bombardment // Applied Surface Science. 2023. Vol. 627. Article number 157334. DOI: 10.1016/j.apsusc.2023.157334.
10. Макаров А.В., Саврай Р.А., Скорынина П.А., Волкова Е.Г. Развитие методов поверхностного деформационного наноструктурирования сталей // Металловедение и термическая обработка металлов. 2020. № 1. С. 62–69. EDN: RMDMCZ.
11. Петрова Л.Г. Упрочнение аустенитных сталей и сплавов за счет формирования твердого раствора при азотировании // Упрочняющие технологии и покрытия. 2007. № 4. С. 9–17. EDN: HZRRJT.
12. Liu R.L., Wang S., Wei C.Y., Yan M.F., Qiao Y.J. Microstructure and corrosion behavior of low temperature carburized AISI 304 stainless steel // Materials Research Express. 2019. Vol. 6. Article number 066417. DOI: 10.1088/2053-1591/ab104c.
13. Savrai R.A., Skorynina P.A. Structural-phase transformations and changes in the properties of AISI 321 stainless steel induced by liquid carburizing at low temperature // Surface and Coatings Technology. 2022. Vol. 443. Article number 128613. DOI: 10.1016/j.surfcoat.2022.128613.
14. Savrai R.A., Osintseva A.L. Effect of hardened surface layer obtained by frictional treatment on the contact endurance of the AISI 321 stainless steel under contact gigacycle fatigue tests // Materials Science and Engineering: A. 2021. Vol. 802. Article number 140679. DOI: 10.1016/j.msea.2020.140679.
15. Путилова Е.А., Горулева Л.С., Задворкин С.М. Влияние поверхностной фрикционной обработка на твердость и магнитные характеристики стали AISI 321 // Diagnostics, Resource and Mechanics of materials and structures. 2022. № 5. P. 40–49. DOI: 10.17804/2410-9908.2022.5.040-049.
16. Tsujikawa M., Egawa M., Sone T., Ueda N., Okano T., Higashi K. Modification of S phase on austenitic stainless steel using fine particle shot peening steel // Surface and Coatings Technology. 2013. Vol. 228. P. S318–S322. DOI: 10.1016/j.surfcoat.2012.05.111.
17. Яровчук А.В., Доронина Т.А., Тиванова О.В. Влияние мартенсита деформации на стойкость к питтинговой коррозии нержавеющей стали 12Х18Н10Т // Ползуновский альманах. 2007. № 1–2. С. 190–196. EDN: NNYBSW.
18. Скорынина П.А., Макаров А.В., Березовская В.В., Меркушкин Е.А., Чекан Н.М. Влияние наноструктурирующей фрикционной обработки на микромеханические и коррозионные свойства стабильной аустенитной хромоникелевой стали // Frontier Materials & Technologies. 2021. № 4. С. 80–88. DOI: 10.18323/2782-4039-2021-4-80-88.
19. Коршунов Л.Г., Сагарадзе В.В., Черненко Н.Л., Шабашов В.А. Структурные превращения карбидной фазы в стали Гадфильда, инициированные фрикционным воздействием // Физика металлов и металловедение. 2015. Т. 116. № 8. С. 867–873. DOI: 10.7868/S0015323015080094.
20. Наркевич Н.А., Шулепов И.А., Миронов Ю.П. Структура, механические и триботехнические свойства аустенитной азотистой стали после фрикционной обработки // Физика металлов и металловедение. 2017. Т. 118. № 4. С. 421–428. DOI: 10.7868/S0015323017020097.
21. Neslušan M., Minárik P., Čep R., Uríček J., Trojan K., Ganev N., Trško L. Barkhausen noise emission of AISI 304 stainless steel originating from strain induced martensite by shot peening // Journal of Materials Research and Technology. 2022. Vol. 20. P. 748–762. DOI: 10.1016/j.jmrt.2022.07.107.
22. Chen Xin, Gussev M., Balonis M., Bauchy M., Sant G. Emergence of micro-galvanic corrosion in plastically deformed austenitic stainless steels // Materials and Design. 2021. Vol. 203. Article number 109614. DOI: 10.1016/j.matdes.2021.109614.
23. Balusamy T., Kumar S., Sankara Narayanan T.S.N. Effect of surface nanocrystallization on the corrosion behaviour of AISI 409 stainless steel // Corrosion Science. 2010. Vol. 52. № 11. P. 3826–3834. DOI: 10.1016/j.corsci.2010.07.004.
24. Yin Songbo, Li D.Y., Bouchard R. Effects of the strain rate of prior deformation on the wear-corrosion synergy of carbon steel // Wear. 2007. Vol. 263. № 1-6. P. 801–807. DOI: 10.1016/j.wear.2007.01.058.
25. Hao Yun-wei, Deng Bo, Zhong Cheng, Jiang Yi-ming, Li Jin. Effect of surface mechanical attrition treatment on corrosion behavior of 316 stainless steel // Journal of Iron and Steel Research International. 2009. Vol. 16. № 2. P. 68–72. DOI: 10.1016/S1006-706X(09)60030-3.
26. Sun Jianlin, Tang Huajie, Wang Chenglong, Han Zhao, Li Shisen. Effects of alloying elements and microstructure on stainless steel corrosion: a review // Steel Research International. 2022. Vol. 93. № 5. Article number 2100450. DOI: 10.1002/srin.202100450.

27. Kadowaki M., Saengdeejing A., Muto I. et al. First-principles analysis of the inhibitive effect of interstitial carbon on an active dissolution of martensitic steel // Corrosion Science. 2020. Vol. 163. Article number 108251. DOI: 10.1016/j.corsci.2019.108251.

Влияние фрикционной обработки и жидкостной цементации на сопротивление общей коррозии хромоникелевых аустенитных сталей

Скорынина Полина Андреевна*[1,3], младший научный сотрудник
Макаров Алексей Викторович[1,2,4], доктор технических наук, член-корреспондент РАН,
заведующий отделом материаловедения и лабораторией механических свойств
Саврай Роман Анатольевич[1,5], кандидат технических наук,
заведующий лабораторией конструкционного материаловедения
[1]*Институт машиноведения имени Э.С. Горкунова Уральского отделения РАН, Екатеринбург (Россия)*
[2]*Институт физики металлов имени М.Н. Михеева Уральского отделения РАН, Екатеринбург (Россия)*

***E-mail: skorynina@imach.uran.ru,**
polina.skorynina@mail.ru

[3]ORCID: https://orcid.org/0000-0002-8904-7600
[4]ORCID: https://orcid.org/0000-0002-2228-0643
[5]ORCID: https://orcid.org/0000-0001-9873-3621

Поступила в редакцию 27.06.2023 *Принята к публикации 17.11.2023*

Аннотация: В настоящее время для повышения твердости, прочности и износостойкости термически неупрочняемых аустенитных хромоникелевых сталей применение нашли такие методы, как фрикционная обработка скользящим индентором и жидкостная цементация. Однако наряду с эффективным повышением механических характеристик применение указанных обработок может сопровождаться снижением коррозионной стойкости аустенитных сталей. Поэтому целесообразно исследовать влияние фрикционной обработки и жидкостной цементации на сопротивление общей коррозии Cr–Ni аустенитных сталей. В данной работе по методу восстановленного отпечатка определяли поверхностную микротвердость сталей 12Х18Н10Т и AISI 321 после электролитического полирования, механического шлифования, фрикционной обработки и жидкостной цементации при температуре 780 °С. С применением сканирующей электронной микроскопии и оптической профилометрии изучали подвергнутые указанным обработкам поверхности сталей и определяли их шероховатость. Коррозионную стойкость стали исследовали при испытаниях на общую коррозию гравиметрическим методом. При испытаниях на общую коррозию установлено, что упрочняющая (до 710 HV 0,025) фрикционная обработка приводит к повышению скорости коррозии аустенитной стали 12Х18Н10Т в сравнении с электрополированным состоянием (от k_m=0,35 г/(м^2·ч) до k_m=0,53–0,54 г/(м^2·ч)). Скорость коррозии шлифованной стали составляет k_m=0,58 г/(м^2·ч), при этом механическое шлифование не обеспечивает значительного повышения микротвердости исследуемой стали (от 220 до 240 HV 0,025). Показано, что коррозионное поведение подвергнутой различным обработкам стали 12Х18Н10Т определяется следующими факторами: наличием/отсутствием α′-мартенсита деформации в структуре, качеством сформированной поверхности и, по-видимому, дисперсностью сформированной структуры. Жидкостная цементация аустенитной стали AISI 321 приводит одновременно к повышению ее микротвердости до 890 HV 0,025 и некоторому росту коррозионной стойкости по сравнению с тонкой механической шлифовкой. Это связано с тем, что атомы внедрения углерода стабилизируют электронное строение железа (аустенита и мартенсита), тем самым повышая его коррозионную стойкость.

Ключевые слова: аустенитная хромоникелевая сталь; фрикционная обработка; жидкостная цементация; микротвердость; фазовый состав; шероховатость; коррозионная стойкость.

Благодарности: Авторы выражают глубокую благодарность за участие в работе доктору технических наук В.В. Березовской.

Работа выполнена в рамках государственных заданий ИМАШ УрО РАН по теме № АААА-А18-118020790148-1 и ИФМ УрО РАН по теме № 122021000033-2. Экспериментальные исследования выполнены на оборудовании ЦКП «Пластометрия» ИМАШ УрО РАН.

Статья подготовлена по материалам докладов участников XI Международной школы «Физическое материаловедение» (ШФМ-2023), Тольятти, 11–15 сентября 2023 года.

Для цитирования: Скорынина П.А., Макаров А.В., Саврай Р.А. Влияние фрикционной обработки и жидкостной цементации на сопротивление общей коррозии хромоникелевых аустенитных сталей // Frontier Materials & Technologies. 2023. № 4. С. 109–119. DOI: 10.18323/2782-4039-2023-4-66-10.