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Dependence of Corrosion Resistance of Austenitic Chromium-Nickel Steels on the Magnetic State of Austenite

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Abstract

Corrosive behavior of austenitic chromium-nickel steels from the magnetic state (parameter χ_0) of austenite, pre-formed to interact with aggressive media are research. Correlation between the rate K of pitting corrosion and the specific magnetic susceptibility χ_0 of austenite was experimentally established. It is experimentally established that the corrosion resistance of austenitic steels AISI304, 08Cr18Ni10, AISI 321, 08Cr18Ni10Ti (containing a low amount of δ -ferrite $\sim 0.005 \dots 0.5\%$) depends on the magnetic state of austenite: the corrosion rate of steel decreases with increases χ_0 austenite. The tendency of change in the corrosion rate of austenitic alloy with a high nickel content 06Crh28NiMoCuTi (not contain δ -ferrite) has the opposite character: with increasing χ_0 , the corrosion rate of the alloy increases is revealed. For austenitic chromium-nickel steels, the corrosion rates of the individual (austenite (A), δ -ferrite (F), strain-induced α' -martensite (M)) and total ($A + F$, $A + M$ and $A + F + M$) phases are determined. It is proposed to predict corrosion according to the specific magnetic susceptibility χ_0 of austenite and the amount δ -ferrite.

Keywords: austenite, steel, specific magnetic susceptibility, ferrite, martensite, plastic deformation, corrosion

1. Introduction

Progress in increasing competitiveness, i.e. the application of operational and more cost-effective control of corrosion properties, requires new approaches to the study of austenitic steels. In general, these steels are studied in terms of the atomic-crystalline state of austenite, as the main component of their structural state, namely, the parameters of the crystal lattice, grain size, the presence of packaging defects and dislocations, and so on. However, a comprehensive assessment of properties for one parameter is complicated, and in some cases impossible.

Since the bulk of these steels is paramagnetic austenite, and with a certain chemical composition or hardening, its amount can reach 100%, it is proposed to study these steels from the standpoint of the atomic-magnetic state. That is, to consider austenite primarily as a paramagnetic, which is characterized by a peculiar electronic structure, for which the supersensitive parameter is the specific

paramagnetic susceptibility χ_0 (the total magnetic moment per unit mass of austenite at a single value of the magnetic field). In this case, the parameter χ_0 is an integral characteristic of the formed austenite due to various factors (chemical composition, smelting conditions, deformation, heat treatment, etc.). It should be noted that most studies are devoted to the study of the magnetic susceptibility of χ steel (not χ_0 austenite), which may contain both austenite and α -phase: δ -ferrite, α' -martensite of deformation (after cold compressive plastic deformation).

There is almost no information about the relationship between the magnetic state of austenite and corrosion properties. Thus, the assumption of predicting the corrosion properties of austenitic steels by the structural-magnetic state (parameter χ_0) of austenite, which does not contain or contains a very low amount of α -phase (δ -ferrite, α' -martensite), requires theoretical, experimental and practical confirmation.

Establishing a correlation between the atomic and magnetic state of austenite and corrosion is of theoretical and practical importance. Some of the information related to this problem is debatable and insufficiently researched.

It is known from scientific sources that the low content ($\sim 0.005 \dots 0.5\%$) of the α -phase can dramatically affect the corrosion properties, which necessitates the introduction of supersensitive methods for its determination. The question of the influence of individual phases, which are simultaneously present in the austenitic matrix, remains unresolved.

The corrosion properties of chromium-nickel steels are affected by the casting temperature, chemical composition, carbides, heat treatment, deformation, harmful impurities, etc. No single physical parameter has been identified that would simultaneously and unambiguously take into account the influence of these factors on the properties of these steels. Therefore, for this purpose, a sensitive parameter is proposed—the specific paramagnetic susceptibility of χ_0 austenite.

Therefore, when determining the performance of austenitic steel products, along with the study of the crystal structure, it is advisable to study the relationship between the atomic and magnetic state of austenite with the corrosion properties.

2. Relationship between corrosion resistance of austenitic chromium-nickel steels AISI 304, 08Cr18Ni10, AISI 321, 08Cr18Ni10Ti (contain low amount of δ -ferrite) and paramagnetic state of austenite

Despite numerous studies of corrosion processes of various materials [1–4], the problems that arise require a comprehensive study of the mechanisms of corrosion behavior to ensure reliable and safe operation of modern structural materials. It should be noted that even in one smelter of industrial steel δ -ferrite is distributed unevenly, for example for steel 08Cr18Ni10Ti—the width of the sheet perpendicular to the rolling the amount of δ -ferrite varied from 0.01% to 0.4%. Chromium-nickel austenitic steels contain little δ -ferrite, which due to the small contact surface cannot significantly affect the corrosion behavior of austenitic steels [5]. We can assume that corrosion is affected by the pre-formed atomic-magnetic state of the whole austenitic matrix (austenite), which is characterized by the sum of magnetic moments of atoms per unit mass (specific magnetization) and described by an external parameter—specific magnetic susceptibility χ_0 . In [6] it was noted that the presence of a low content of δ -phase ($P_\delta < 2\%$) in steel 12X18H10T is not detected by radiography, metallographic methods show its presence, and the phase content was determined by the magnitude of the magnetization.

To study the dependence of corrosion resistance on the paramagnetic state of the austenitic matrix (parameter χ_0) and evaluate the effect of low δ -ferrite content on

corrosion behavior, two groups of the most common steels were selected: AISI 304, AISI 321 and their analogues 08Cr18Ni10, 08Cr18Ni10Ti in **Table 1**.

The samples were made of rolled sheet metal with a thickness of 1 mm of industrial melts of these steels. Taking into account that the uneven distribution of δ -ferrite over the width of the cold-rolled sheet [5] and for further averaging of the obtained results 7 ... 10 flat samples with dimensions of $\sim 7 \times 3 \times 1 \text{ mm}^3$ were cut from different places of the sheet of each smelting. Specific magnetic susceptibility χ was determined by a magnetometric unit (Faraday balance). The content of δ -ferrite and the specific magnetic susceptibility χ_0 of austenite (according to [7]) of these samples were determined. The average content of δ -ferrite P_δ and χ_0 for each melt was calculated. The obtained results (P_δ and χ_0) [8] and corrosion rate K (attracted from the source [9]) in chloride-containing solution are given in **Table 2**.

Analysis of experimental hyperbolic dependences of the corrosion rate K [9] on the specific magnetic susceptibility of χ_0 austenite steels AISI 304, 08Cr18Ni10 and AISI321, 08Cr18Ni10Ti shows (**Figure 1**) [8]: that the larger the value χ_0 , the higher the corrosion resistance (lower corrosion rate K). Since χ_0 determines the atomic-magnetic structure of austenite, it can be assumed that the corrosion behavior of austenitic chromium-nickel steels depends on the atomic-magnetic (paramagnetic) state of austenite, pre-formed to interact with the chloride-containing medium.

Steel	Melt	C	N	Mn	Si	S	P	Cr	Ni	Ti
AISI 304	1	0.071	0.048	1.23	0.22	0.001	0.027	17.96	9.34	—
		$\Sigma 0.119$								
	2	0.067	0.046	1.74	0.50	0.001	0.028	18.22	8.09	—
		$\Sigma 0.113$								
	3	0.075	0.055	1.65	0.43	0.004	0.024	18.25	8.09	—
08Cr18Ni10		$\Sigma 0.130$								
	4	0.050	0.044	1.70	0.41	0.002	0.028	18.30	8.10	—
		$\Sigma 0.094$								
	5	0.030	0.039	1.81	0.39	0.001	0.034	18.10	8.20	—
		$\Sigma 0.069$								
AISI 321	6	0.060	—	1.34	0.32	0.006	0.035	17.44	9.77	0.03
	1	0.035	0.012	1.66	0.54	0.001	0.026	17.10	9.10	0.32
		$\Sigma 0.047$								
	2	0.060	0.011	1.59	0.66	0.002	0.027	16.43	9.14	0.34
		$\Sigma 0.071$								
08Cr18Ni10Ti	3	0.064	0.012	1.22	0.52	0.001	0.026	17.43	9.70	0.41
		$\Sigma 0.076$								
	4	0.030	0.013	1.62	0.41	0.002	0.028	17.41	9.24	0.31
		$\Sigma 0.043$								
	5	0.040	0.013	1.70	0.49	0.001	0.026	17.70	9.10	0.35
		$\Sigma 0.053$								
08Cr18Ni10Ti	6	0.070	—	1.70	0.49	0.007	0.027	17.97	10.46	0.46

Table 1.
Chemical composition of the investigated steels, % wt.

Steel	Melting number	P_{δ} , %	χ_o , $10^{-8} \text{ m}^3/\text{kg}$	K , $\text{g}/(\text{m}^2 \text{ h})$
AISI 304	1	0.0335	2.27	47.65
	2	0.0448	2.25	57.76
	3	0.0138	2.23	86.64
	4	0.1130	2.31	43.37
	5	0.0329	2.24	67.87
08Cr18Ni10	6	0.0054	2.23	98.19
AISI 321	1	0.0453	2.55	113.0
	2	0.160	2.56	98.6
	3	0.2920	2.59	89.9
	4	0.1760	2.68	76.8
	5	0.036	2.54	126.1
08Cr18Ni10Ti	6	0.0142	2.52	165.2

Table 2.
The average values of P_{δ} , χ_o , K of each investigated steelmaking.

Figure 1.
Relationship between the corrosion rate K and the specific amagnetic susceptibility χ_o of austenite of the studied steels. *a*—AISI 304 (melt 1–5) and 08Cr18Ni10 (melt 6); *b*—AISI 321 (melt 1–5) and 08Cr18Ni10Ti (melt 6).

In [4], an electron-probe analysis of the distribution of chemical elements for two local regions (without corrosion and with corrosion) of steel 12X18H10T (heat exchange tube) was performed. According to the results of microanalysis in the vicinity of corrosive ulcers, the chemical composition of the main elements was as follows (% wt.): 72.4 Fe; 15.2 Cr; 10.8 Ni; 1.1 Ti, which practically corresponds to the composition of steel 12X18H10T, except for the tendency to decrease the concentration of chromium. However, as the authors [4] showed, the chemical composition of steel has changed radically in the ulcer itself, where locally, along with the increase in carbon concentration, the concentration of chromium has increased significantly. Excess carbon content causes the formation of chromium carbides and depletion of the surrounding austenite with chromium with a concentration below 12%, which no longer ensures the corrosion resistance of steel.

Other authors [10] showed that the level of concentration fluctuations of chemical elements from the boundary into the grain grain of austenitized steel

12X18H10T decreases: for nickel—~1.5 times its average content in steel, chromium—20% of the average content, for sulfur and phosphorus—dozens of times. Therefore, it should be expected that in industrial austenitic chromium-nickel steels the corrosion is local and depends on the atomic-magnetic structure of austenite, the content of which in the studied steels ~99.5% (δ -ferrite not more than 0.5%). Many works are devoted to the ambiguous (sometimes opposite) influence of the α -phase (δ -ferrite, α' -martensite) on the corrosion resistance of austenitic chromium-nickel steels [11]. At the content of 0.06...0.08% of δ -ferrite in the austenitic paramagnetic matrix, the magnetic moments of δ -ferrite and austenite are equal. Therefore, to more accurately determine the amount of δ -ferrite in the sample by magnetometric method, the magnetization of the austenitic matrix was taken into account.

In **Figure 2** shows the relationship between the corrosion rate K and the content of P_δ δ -ferrite in steels AISI 304 and AISI 321. As you can see, the amount of δ -ferrite can determine the corrosion rate. However, a significant effect of this amount of P_δ δ -ferrite (0.005...0.12% in steels AISI 304, 08X18H10 and 0.01...0.30% in steels AISI 321, 08X18H10T) is unlikely due to insignificant (compared with austenite) the contact surface of δ -ferrite with an aggressive environment.

To further elucidate the role of low δ -ferrite content on the corrosion process, an experimental dependence of P_δ on χ_0 was constructed (**Figures 3 and 4**).

The low amount of P_δ δ -ferrite correlates with the specific paramagnetic susceptibility χ_0 of austenite (the amount of which is ~99.7%), and hence with the atomic-magnetic (paramagnetic) state of austenite (χ_0). In the studied steels, the amount of δ -ferrite is in thermodynamic equilibrium with the paramagnetic state of austenite, the smallest violation of which causes a change in the amount of δ -ferrite in the austenitic matrix. Hence there is an indirect dependence of the corrosion rate K on the content of P_δ δ -ferrite, which, in turn, corresponds to the atomic-magnetic state of austenite (parameter χ_0). Therefore, it is assumed that the low content of δ -ferrite indirectly (not directly) affects corrosion, i.e. is a measure (indicator) of the corrosion rate K .

It is experimentally established that the corrosion resistance of austenitic chromium-nickel steels depends on the atomic-magnetic state of almost 100% austenite—paramagnet, which is characterized by a specific magnetic susceptibility

Figure 2.
The relationship between the corrosion rate K (involved with [9]) and the content of P_δ δ -ferrite in the studied steels. a—AISI 304 (melt 1–5) and 08Cr18Ni10 (melt 6); b—AISI 321 (melt 1–5) and 08Cr18Ni10Ti (melt 6).

Figure 3.
Tendency of change of low amount of P_δ δ -ferrite from atomic-magnetic state of austenitic matrix (parameter χ_0) in steels AISI 304 (melt 1–5) and 08Cr18Ni10 (melt 6).

Figure 4.
Tendency of change of low amount of P_δ δ -ferrite from atomic-magnetic state of austenitic matrix (parameter χ_0) in steels AISI 321 (melt 1–5) and 08Cr18Ni10Ti (melt 6).

χ_0 : the greater χ_0 , the higher the corrosion resistance (lower corrosion rate K), and vice versa. It is assumed that the low content of P_δ δ -ferrite (0.005...0.5%) is an indicator of corrosion intensity, because P_δ depends on χ_0 (with increasing χ_0 austenite increases P_δ), and K depends on χ_0 (with increasing χ_0 decreases K). It should be noted that as the amount of P_δ δ -ferrite increases, the magnetic susceptibility χ of steel (rather than χ_0 austenite), which contains both austenite and δ -ferrite, increases. It is shown that with increasing P_δ (at low δ -ferrite content) the corrosion rate K decreases (and vice versa), i.e. low δ -ferrite content can also be a measure (indicator) of the corrosion process in austenitic chromium-nickel steels.

3. Investigation of corrosion resistance of different melts of one brand of austenitic Fe-Cr-Ni alloys that do not contain δ-ferrite

Considerable attention has been paid to the study of the influence of various factors on the corrosion process of austenitic chromium-nickel steels. In the previous section, the dependence of the corrosion rate K of AISI 304, 08Cr18Ni10, AISI 321, 08Cr18Ni10Ti steels containing δ-ferrite on the atomic-magnetic state of austenite, i.e. on the specific paramagnetic susceptibility χ_0 of austenite, which is an integral value and many factors on corrosion behavior. In this regard, it is necessary to investigate the corrosion of austenitic Fe-Cr-Ni alloys that do not contain α-phase. Five melts of 08Cr28Ni27 alloy, which does not contain δ-ferrite, were selected. The chemical composition of the melts of this alloy are given in **Table 3**.

Samples were selected from sheet (thickness 1 mm) industrial supplies of alloy 08Cr28Ni27. Since the numerical values of the specific magnetic susceptibility across the width of the cold-rolled sheet were locally unevenly distributed, in order to average from different places in a checkerboard pattern from each melting cut 10 samples in the form of parallelepipeds ($\sim 6 \times 4 \times 1 \text{ mm}^3$). The obtained values of the specific paramagnetic susceptibility to corrosion tests are given in **Table 4**. For melts 1...5 of alloy 08Cr28Ni27 the average values of specific paramagnetic susceptibility χ_0 of austenite are received: $2.95 \cdot 10^{-8}$; $2.86 \cdot 10^{-8}$; $3.58 \cdot 10^{-8}$; $3.09 \cdot 10^{-8}$; $2.96 \cdot 10^{-8} \text{ m}^3/\text{kg}$, respectively [12].

In order to accelerate chemical corrosion, a model aggressive medium was used: a mixture of concentrated acids—hydrochloric and nitric (HCl:HNO₃ 3:1) and the samples were kept continuously for 0.5 h at $t = 30^\circ\text{C}$. The corrosion rate K was determined by the formula $K = \Delta m / (S \cdot \tau)$, where Δm is the loss of mass before and after corrosion, S is the surface area of the sample, τ is the exposure time in an aggressive environment. **Table 5** shows the obtained average values of corrosion rate: 1381, 1397, 1519, 1540, 1470 g/(m² h), respectively, for melts 1...5.

Analysis of the experimental dependences of the corrosion rate K on the paramagnetic susceptibility χ_0 of austenite (to corrosion tests) of different melts, but one grade of alloy 08Cr28Ni27, which does not contain δ-ferrite (**Figure 5**) shows: the greater χ_0 , the greater the corrosion rate K [12], i.e. there is an opposite dependence compared to austenitic chromium-nickel steels that contain δ-ferrite (see **Figure 1**).

Therefore, the selected sensitive parameter χ_0 , able to distinguish the corrosion rate of similar chemical composition of different melts of the same brand of alloy 08Cr28Ni27. For the existence of a paramagnetic effect, it is necessary that the electronic shells of matter have uncompensated orbital and spin magnetic moments, which are oriented in the magnetic field H . Hence, by studying the magnetic

Melt №	Element, % wt.									
	C	Mn	Si	Cr	Ni	Ti	S	P	Mo	Cu
1	0.050	0.34	0.49	24.29	27.40	0.80	0.006	0.028	2.88	2.73
2	0.067	0.43	0.56	22.69	27.62	0.60	0.005	0.029	2.77	2.68
3	0.068	0.50	0.55	21.82	27.47	0.57	0.004	0.032	2.56	2.62
4	0.048	0.55	0.71	22.69	27.70	0.67	0.006	0.028	2.56	2.54
5	0.050	0.29	0.57	23.44	27.48	0.90	0.004	0.032	2.53	2.76

Table 3.
Chemical composition of melts of 08Cr28Ni27 alloy.

№ sample	$\chi_0, 10^{-8} \text{ m}^3/\text{kg}$				
	Melting number				
	№1	№2	№3	№4	№5
1	2.99	2.85	3.37	3.05	2.94
2	2.94	2.83	3.42	3.05	2.92
3	3.06	2.86	3.32	2.92	3.03
4	3.01	2.88	3.33	3.11	2.96
5	2.96	2.85	3.44	3.12	2.93
6	2.95	2.89	3.35	3.09	2.95
7	2.91	2.88	3.40	3.10	3.00
8	2.89	2.81	3.38	3.13	3.04
9	2.92	2.90	3.41	3.16	2.91
10	2.90	2.87	3.43	3.12	2.94
Average	2.95	2.86	3.38	3.09	2.96
$\pm \Delta_{\text{abs.}}$	0.04	0.02	0.04	0.05	0.04
$\pm \Delta_{\text{rel.}, \%}$	1.41	0.77	1.03	1.52	1.24

Table 4.
The value of the specific magnetic susceptibility χ_0 of austenite cut samples from the melts № 1...5 alloy 08Cr28Ni27.

№ sample	$K, \text{ g}/(\text{m}^2 \cdot \text{h})$				
	Melting number				
	№1	№2	№3	№4	№5
1	1385	1385	1541	1545	1486
2	1420	1439	1508	1510	1467
3	1355	1366	1510	1555	1451
4	1388	1365	1498	1560	1485
5	1313	1359	1494	1570	1464
6	1398	1466	1528	1569	1447
7	1385	1432	1507	1525	1485
8	1378	1388	1527	1505	1453
9	1402	1369	1529	1549	1485
10	1388	1399	1546	1510	1479
Average	1381	1397	1519	1540	1470
$\pm \Delta_{\text{abs.}}$	19.5	29.7	15.4	21.8	13.8
$\pm \Delta_{\text{rel.}, \%}$	1.41	2.13	1.01	1.41	0.93

Table 5.
The value of corrosion rate K cut samples of the alloy 08Cr28Ni27.

properties of austenite, it is possible to obtain information about the behavior of austenite under the influence of external factors, such as its corrosion resistance.

The obtained results do not contradict the value of the corrosion rate K (attracted from [9]) for these 1...5 melts of alloy 08Cr28Ni27 (respectively: 0.095;

Figure 5.
Tendencies of change of corrosion rate K in a mixture of concentrated acids-hydrochloric and nitric ($\text{HCl}:\text{HNO}_3$ 3:1) and specific magnetic susceptibility χ_0 austenite of different melts of alloy 08Cr28Ni27, which do not contain δ -ferrite.

0.095; 0.143; 0.190 and 0.143 $\text{g}/(\text{m}^2 \cdot \text{h})$). In the environment that contains chlorine (**Figure 6**).

Compare the graphs of **Figures 5 and 6**. From **Figure 6** it follows that the corrosion rates for two pairs of swimming trunks 1, 2 and 3, 5 are the same (0.095 and 0.143 $\text{g}/(\text{m}^2 \cdot \text{h})$), and according to our studies, the corrosion rates of all these

Figure 6.
The relationship of borrowed values of the corrosion rate K [9] in a chloride-containing medium and found the specific magnetic susceptibility χ_0 [12] of austenite of the same melts of the alloy 08Cr28Ni27, which do not contain δ -ferrite.

five swimming trunks are different (which corresponds to different χ_0), i.e. the resolution is slightly better, but coincides qualitatively with the general nature of the curves (**Figures 5 and 6**).

It is experimentally established that the corrosion resistance of the austenitic alloy 08Cr28Ni27 (analog AISI 904L) correlates with the atomic-magnetic state of austenite, which is determined by the susceptibility χ_0 : the less χ_0 , the higher the corrosion resistance (lower corrosion rate), in contrast to austenitic chromium-nickel steels, which contain δ -ferrite. The obtained results can be used to predict the local corrosion resistance of austenitic alloys that do not contain δ -ferrite.

4. Magnetometric evaluation of corrosion resistance of austenitic chromium-nickel steels depending on the phase composition (A , F , M) after deformation by compression and bending of specimens

Despite numerous studies of corrosion processes in stainless austenitic steels, which are widely used in aviation and nuclear energy, questions concerning the nature of corrosion still remain unclear. Many works are devoted to the influence of α -phase (δ -ferrite, α' -martensite deformation) on the corrosion resistance of steels [4, 5, 13, 14]. However, the corrosion resistance of austenite (A), δ -ferrite (F) and α' -martensite deformation (M) and the phases $A + F$, $A + M$, $A + F + M$ present together are insufficiently studied. In [13] it was found that the significant cause of corrosion resistance of austenitic steels is not the low content of the α -phase, but the atomic-magnetic state of the austenitic matrix, which is determined by the specific magnetic susceptibility.

To clarify the role of paramagnetic austenite (A), δ -ferrite (F), α' -martensite deformation (M) in the individual and total influence of the phases $A + M$, $A + F$, $A + F + M$ on the corrosion resistance of chromium-nickel steels austenitic class were selected two industrial stainless steels (№1 and №2) of one grade 08Cr18Ni10Ti (sheets with a thickness of 1 mm) with a slight difference in the content of Ni and other elements.

Chemical composition of steels (% wt.): №1—0.08 C; 17.74 Cr; 10.56 Ni; 0.259 Ti; 0.982 Mn; 0.23 Si; 0.04 S and №2—0.09 C; 18.2 Cr; 10.1 Ni; 0.56 Ti; 0.75 Mn; 0.7 Si; 0.01 S; 0.026 P; 0.14 Cu; 0.05 Co; 0.04 V; 0.04 W; 0.06 Mo.

The samples were cut by cold mechanical method in the form of rectangular parallelepipeds of approximately the same size $7 \times 3 \times 1 \text{ mm}^3$. The degree of residual deformation D was calculated by the ratio of thickness before (d_0) and after (d) deformation ($D = (d_0 - d)/d_0$). After compression deformation, the samples were tested for corrosion. In order to accelerate chemical corrosion, the test samples were placed in a mixture of concentrated acids-hydrochloric and nitric ($\text{HCl}:\text{HNO}_3$ 3:1) and kept for 1 h. To visually detect changes in the corrosion rate, we used the coefficient of intense corrosion K , which was defined as the relative mass loss $K = (\Delta m / (m \cdot \tau)) \cdot 100\%$.

Austenitization of steel №1 was performed in the standard way (annealing at 1050°C , holding for 30 min, followed by quenching in water). After such heat treatment, the steel №1 in the initial state was paramagnetic, ie single-phase (A) with a specific magnetic susceptibility of austenite $\chi_0 = 2.81 \cdot 10^{-8} \text{ m}^3/\text{kg}$.

Samples of №2 steel containing δ -ferrite in the initial state were not subjected to austenitization, i.e. in the initial state it was two-phase ($A + F$), which were tested after bending at an angle of 180° . After testing the samples with a length of 7 mm per bend, the amount of deformation martensite was distributed unevenly from the

ends to the ribs. Therefore, the average value of the amount of α' -martensite for the whole sample was approximated. Due to the fact that the low content of δ -ferrite is unevenly distributed over the width of the cold-rolled sheet in steel №2 [5] and in order to further average the results from different places were cut three, adjacent samples, which after averaging were assigned numbers 1...6.

Steel №1 was tested under uniaxial compression, and steel №2—under deformation by bending.

4.1 Corrosion resistance of austenite of single-phase (A) steel 08Cr18Ni10Ti (№1) at uniaxial compression of specimens to the formation of deformation martensite

The effect of “growth” of the paramagnetic state, i.e. increase of the specific magnetic susceptibility of austenite χ_0 (A) from $2.81 \cdot 10^{-8} \text{ m}^3/\text{kg}$ to the maximum value of $3.2 \cdot 10^{-8} \text{ m}^3/\text{kg}$ of steel №1 at uniaxial compression D from 0 to 4.85%. With a further increase in deformation (accumulation of α' -martensite) from $D_S = 4.85\%$ (true martensite point [7]), the specific magnetic susceptibility of austenite did not change and remained equal to $\chi_0^{\text{max}} = 3.2 \cdot 10^{-8} \text{ m}^3/\text{kg} = \text{const}$.

Table 6 shows the results of experimental studies of steel №1 (at 20°C) [15].

In **Figure 7** (figures indicate the sample numbers from **Table 6**) shows the change in the corrosion rate $K(A)$ of austenite samples of single-phase (A) steel №1, deformed before the formation of α' -martensite, from changes in the atomic-magnetic state, which is characterized by specific magnetic susceptibility χ_0 (A) austenite.

With uniaxial compression of austenitic specimens, the corrosion rate $K(A)$ increases with the “increase” of the atomic-magnetic state ($\chi_0(A)$), i.e., with an

№ sample	D, %	$\chi_0(A)$, $10^{-8} \text{ m}^3/\text{kg}$	χ_0 , $10^{-8} \text{ m}^3/\text{kg}$	P_α , %	$K(A)$, %/h	$K(A + M)$, %/h	$K(M)$, %/h
1	0	2.81	2.81	0	16.80	16.80	0
2	0.90	2.82	2.82	0	17.30	17.30	0
3	1.30	2.83	2.83	0	18.10	18.10	0
4	1.41	2.84	2.84	0	18.20	18.20	0
5	1.52	2.91	2.91	0	20.42	20.42	0
6	2.70	3.01	3.01	0	22.14	22.14	0
7	4.73	3.09	3.09	0	24.03	24.03	0
8	6.51	3.20	3.15	0.02	24.1	24.45	0.35
9	7.35	3.20	3.81	0.05	24.1	24.95	0.85
10	8.15	3.20	3.99	0.14	24.1	25.02	0.92
11	9.95	3.20	4.27	0.19	24.1	25.71	1.61
12	12.43	3.20	6.72	0.45	24.1	27.40	3.30
13	19.13	3.20	10.52	0.79	24.1	29.91	5.81
14	26.17	3.20	18.11	2.18	24.1	33.35	9.25
15	36.0	3.20	27.9	3.14	24.1	36.50	12.40

Table 6.
The value of the amount of ferrophase P_α , the specific magnetic susceptibility $\chi_0(A)$, the resulting magnetic susceptibility χ_∞ of the sample and the corrosion rate K after deformation by compression of steel samples №1, 08Cr18Ni10Ti.

Figure 7.

Change in the corrosion rate $K(A)$ of austenite steel samples 08Cr18Ni10Ti (№1), deformed by compression (degree of deformation—number near points) to the emergence of α' -martensite deformation ($\gamma \rightarrow \gamma'$), from changes in the magnetic state of austenite (χ_0).

increase in the specific magnetic susceptibility $\chi_0(A)$ of austenite, the corrosion rate $K(A)$ increases (corrosion resistance decreases).

4.2 Corrosion resistance of two-phase ($A + M$) steel 08Cr18Ni10Ti (№1) at uniaxial compression (occurrence of α' -martensite)

With increasing degree of plastic deformation compression after the actual deformation point $D_S = 4.85\%$ occurs and accumulates α' -martensite deformation, i.e. the continuation of the curve (see **Figure 7**) is the curve after D_S , which is presented in **Figure 8**. Hence we have that the corrosion rate of two-phase ($A + M$) steel №1 increases with increasing plastic deformation. As indicated, after deformation $D_S = 4.85\%$ and above, the value of $\chi_0^{\max}(A) = 3.2 \cdot 10^{-8} \text{ m}^3/\text{kg}$ remains constant, i.e. $\chi_0^{\max}(A) = \text{const}$. Therefore, the corrosion of austenite after this point (D_S) is constant. Therefore, the corrosion rate of steel 08Cr18Ni10Ti (№ 1) in the area $D = 0 \dots 4.85\%$ increases due to the deformation of austenite, and in the area $D \geq 4.85\%$ increases due to corrosion of α' -martensite deformation that accumulates when a constant value of the corrosion rate of austenite [15].

The dependence of the corrosion rate $K(A + M)$ on the amount of α' -martensite deformation $P_{\alpha'}$ occurring during steel compression №1 is shown in **Figure 9**. As we can see, the corrosion rate increases with increasing amount of α' -martensite $P_{\alpha'}$.

4.3 Corrosion resistance of deformation α' -martensite (M), which occurs during uniaxial compression of steel 08Cr18Ni10Ti (№1)

The maximum value of the specific paramagnetic susceptibility of austenite $\chi_0^{\max}(A) = 3.2 \cdot 10^{-8} \text{ m}^3/\text{kg} = \text{const}$ corresponds to $K(A) \approx 24\%/h$ (see **Figure 8**). If we subtract this value of the corrosion rate of austenite $K(A)$ from the final

Figure 8.
 Change in the corrosion rate of steel samples 08Cr18Ni10Ti (№1) during the transition from single-phase state $K(A)$ to two-phase state $K(A + M)$ (amount of α' -martensite deformation—number near points). D_s —real deformation martensitic point (beginning $\gamma \rightarrow \alpha'$ transformation).

Figure 9.
 Change in the corrosion rate $K(A + M)$ from the content of α' -martensite deformation under uniaxial compression (degree of deformation—number near the points) of steel samples 08Cr18Ni10Ti (№1).

corrosion rate $K(A + M)$ (see **Figure 9**), we obtain the value of the corrosion rate $K(M)$ from the amount of α' -martensite (**Figure 10**). Hence, we have that the corrosion rate $K(M)$ increases with increasing amount of $P_{\alpha'}$ α' -martensite deformation.

In **Figure 11** presents a model of corrosion processes for single-phase (separately austenite (A) and α' -martensite deformation (M)) and two-phase ($A + M$) states of steel 08Cr18Ni10Ti (№1) [15].

Figure 10.
Change of corrosion rate $K(M)$ from the content of α' -martensite deformation $P_{\alpha'}$ under uniaxial compression (degree of deformation—number near points) of steel samples 08Cr18Ni10Ti (N_{21}).

Figure 11.
Change of corrosion rate $K(A + M)$, $K(M)$, $K(A)$ from the degree of deformation D by compression of steel samples 08Cr18Ni10Ti (N_{21}). D_s —real deformation martensitic point (beginning $\gamma \rightarrow \alpha'$ transformation); $P_{\alpha'}$ —amount of α' -martensite deformation (numbers near the points of the curve $K(M)$).

4.4 Corrosion resistance of three-phase ($A + F + M$) steel 08Cr18Ni10Ti (№ 2) after bending of samples at an angle of 180° from the initial atomic-magnetic state ($\chi_0(F + M)$) of austenitic matrix containing δ -ferrite and α' -martensite deformation

From the industrial sheet steel №2 were cut from different cities on 3 adjacent samples with the subsequent averaging of the measured values (amount of δ -ferrite, α' -martensite, corrosion rate K , specific magnetic susceptibility χ_0 austenite). A total of 18 samples were cut, from which 6 averaged samples were grouped, i.e. 6 “points”. The average values of the amount of δ -ferrite and the specific magnetic susceptibility of $\chi_0(F)$ austenite in the presence of δ -ferrite were measured before bending deformation, and the amount of total δ -ferrite and α' -martensite after bending deformation (180°).

Six samples were obtained with averaged values of P_δ before deformation and $P_{\delta+\alpha'}(180)$ after bending at an angle of 180° . For each of the three neighboring samples according to the method determined $\chi_\infty(F)$ and from the graphical dependence $\chi_\infty(F) = f(P_\delta)$ by extrapolation ($P_\delta \rightarrow 0$) found the specific paramagnetic susceptibility of the austenitic matrix $\chi_0(F)$, which contains δ -ferrite. The results obtained are given in **Table 7**. According to the literature, the amount of δ -ferrite P_δ during deformation does not change and subtracting it from the experimentally found values of $P_{\delta + \alpha'}(180)$, found the amount of formed α' -martensite deformation $P_{\alpha'}(180)$ (**Table 7**).

From the graphical dependence of $\chi_\infty(F + M)$ on $P_{\delta + \alpha'}$ (by analogy with steel №1) by the method of extrapolation, when $P_{\delta + \alpha'} \rightarrow 0$ (both ferrophases are absent) found the value of the specific magnetic susceptibility of austenite $\chi_0^{\max}(A) = 2.2 \cdot 10^{-8} \text{ m}^3/\text{kg} = \text{const}$ (for austenitic matrix of steel №2, which contained δ -ferrite (F) and α' -martensite (M)).

In **Figure 12** [15] presents the change in the corrosion rate $K(A + F + M)$ of three-phase ($A + F + M$) steel №2 after bending the samples at an angle of 180° from the magnetic state ($\chi_0(F + M)$) of the austenitic matrix, which contains δ -ferrite and α' -martensite.

From **Figure 12** we have that the corrosion rate of three-phase ($A + F + M$) steel №2 after bending of two-phase ($A + F$) samples by an angle of 180° increases with increasing specific magnetic susceptibility $\chi_0(F + M)$ of the original samples with δ -ferrite. Thus, the content of phases ($A + F + M$) increases the corrosion rate. A similar dependence of $K(A + F + M)$ on $P_{\delta + \alpha'}$ is shown in **Figure 13**.

№ sample	P_δ , %	$P_{\delta + \alpha'}(180)$, %	$P_{\alpha'}(180)$, %	$\chi_0(F)$, $10^{-8} \text{ m}^3/\text{kg}$	$K(A + F + M)$, %/h
1	0.04	0.87	0.83	1.9	12.2
2	0.27	1.47	1.20	3.6	18.0
3	0.12	1.07	0.95	2.9	19.5
4	0.09	1.35	1.26	2.5	17.0
5	0.07	0.90	0.83	2.35	15.5
6	0.26	1.29	1.03	3.5	18.3

Table 7.
The value of the amount of ferrophase, the specific magnetic susceptibility $\chi_0(F)$ of the original samples and the corrosion rate $K(A + F + M)$ after deformation by bending at an angle of 180° steel samples №2.

Figure 12.
Relationship between the corrosion rate $K(A + F + M)$ of three-phase $(A + F + M)$ steel 08Cr18Ni10Ti (N_{22}) after bending two-phase $(A + F)$ samples at an angle of 180° and the atomic-magnetic state $(\chi_0(F + M))$ austenitic matrix of samples containing δ -ferrite (F) and α' -martensite deformation (M).

Figure 13.
Relationship between the corrosion rate $K(A + F + M)$ of three-phase $(A + F + M)$ steel 08Cr18Ni10Ti (N_{22}) after bending the two-phase $(A + F)$ samples at an angle of 180° and the total number of $P_{\delta + \alpha'}$ samples containing δ -ferrite (F) and α' -martensite deformation (M).

Figure 14.
Change in the corrosion rate $K(A + F)$ from the specific magnetic susceptibility $\chi_0(F)$ (a) of the austenitic matrix of samples (containing δ -ferrite) and the content of P_δ δ -ferrite (b) steel 08Cr18Ni10Ti (№2).

4.5 Corrosion resistance of two-phase (A + F) steel 08Cr18Ni10Ti (№2) to bending deformation depending on the initial atomic-magnetic state ($\chi_0(F)$) of austenitic matrix containing δ -ferrite

To systematize the magnetometric assessment of the corrosion resistance of all types of phases, we use two graphical dependences $K(A + F)$ on $\chi_0(F)$ and $K(A + F)$ on P_δ shown in **Figure 14** [13].

From **Figure 14a** it follows that this dependence has the following character: with the “increase” of the atomic-magnetic state of the austenitic matrix ($\chi_0(F)$) the corrosion rate decreases. Similarly, for the dependence of $K(A + F)$ on P_δ (**Figure 14b**): with increasing amount of δ -ferrite, the corrosion rate decreases (corrosion resistance increases) (**Figure 15**).

4.6 Corrosion resistance of deformation martensite after bending of steel samples 08Cr18Ni10Ti (№2) at an angle of 180° from the initial atomic-magnetic state ($\chi_0(F)$) of the austenitic matrix containing δ -ferrite

If we subtract the value of the corrosion rate $K(A + F)$ (see **Figure 14a**) from the final corrosion rate $K(A + F + M)$ (see **Figure 15**), we obtain a change in the corrosion rate $K(M)$ of α' -martensite from atomic-magnetic state ($\chi_0(F)$) of the austenitic matrix containing δ -ferrite [15]. In **Figure 16** presents a model of corrosion processes for three-phase (A + F + M), two-phase (A + F) and single-phase (M) states of steel 08Cr18Ni10Ti (№2).

4.7 Dependence of corrosion resistance of δ -ferrite of steel 08Cr18Ni10Ti (№2) on the initial atomic-magnetic state ($\chi_0(F)$) of austenitic matrix containing δ -ferrite

Taking into account the tendency of change of corrosion rates $K(A)$ and $K(A + F)$ (see **Figures 7** and **14a**), we can propose the dependence of $K(F)$ on $\chi_0(F)$,

Figure 15.
Change in the corrosion rate $K(M)$ from the specific magnetic susceptibility $\chi_0(F)$ of the austenitic matrix containing δ -ferrite, steel 08Cr18Ni10Ti (№2).

Figure 16.
Change of corrosion rate $K(A + F + M)$, $K(A + F)$ and $K(M)$ from the specific magnetic susceptibility $\chi_0(F)$ of the austenitic matrix containing δ -ferrite, steel 08Cr18Ni10Ti (№2).

which is presented in **Figure 17**. As we can see, the corrosion rate of $K(F)$ δ -ferrite decreases (corrosion resistance increases) [15].

Based on experiments, it was found that austenite steels 08Cr18Ni10Ti (single-phase state A after austenitization), deformed by compression to the actual deformation martensitic point D_S , acquires an increased corrosion rate $K(A)$. At

Figure 17.

Change in the corrosion rate of individual phases: $K(A)$ austenite, $K(F)$ δ -ferrite and $K(M)$ α' -martensite after deformation by bending from the initial atomic-magnetic state of the austenitic matrix (parameter $\chi_0(F)$), which contains δ -ferrite, steel samples 08Cr18Ni10Ti (№2).

deformations D_5 and above, the corrosion rate $K(A)$ of austenite remains constant, and the corrosion rate $K(M)$ α' -martensite increases.

The corrosion rates of $K(F)$ δ -ferrite and $K(M)$ α' -martensite of the studied steels are opposite: $K(F)$ decreases, and $K(M)$ increases with increasing deformation, i.e. with increasing atomic-magnetic state of austenite ($\chi_0(F)$).

Corrosion rates $K(A + F)$ and $K(A + M)$ of the studied steels in accordance with the two-phase states $A + F$ and $A + M$ have the opposite tendency: $K(A + F)$ with increasing $\chi_0(F)$ decreases (corrosion resistance increases), and $K(A + M)$ on the contrary—increases.

The corrosion rate $K(A + F + M)$ of three-phase steel increases with deformation, ie with increasing atomic-magnetic state ($\chi_0(F + M)$) of the austenitic matrix, which contains δ -ferrite and α' -martensite deformation.

5. Conclusions

1. It was experimentally established that the corrosion rate K correlates with the specific paramagnetic susceptibility χ_0 of austenite steels AISI 304, 08Cr18Ni10, AISI 321, 08Cr18Ni10Ti, containing a low content of δ -ferrite ($\sim 0.005 \dots 0.5\%$): the greater χ_0 , the higher the corrosion resistance (lower corrosion rate K) of steel.
2. It was found that the corrosion rate K of austenitic alloys 08Cr28Ni27, which do not contain δ -ferrite, in contrast to austenitic chromium-nickel steels with a low content of δ -ferrite, has the opposite character: the greater χ_0 , the less corrosion resistance (more corrosion rate K) of the alloy.
3. Since χ_0 determines the atomic-magnetic structure of austenite, it is assumed that the corrosion behavior of austenitic chromium-nickel steels depends on

the atomic-magnetic (paramagnetic) state of austenite, previously formed before the interaction with the aggressive environment.

4. The direct effect of low content of δ -ferrite ($\sim 0.005\ldots 0.5\%$) in austenitic chromium-nickel steels is questionable due to the small (compared to austenite) contact surface with the aggressive environment. An indirect dependence of the corrosion rate K on the low content of P_δ δ -ferrite, which, in turn, depends on the atomic-magnetic (paramagnetic) state of austenite, i.e. on the parameter χ_0 . Therefore, it is assumed that the low content of δ -ferrite indirectly affects the corrosion, i.e. is a measure (indicator) of the corrosion rate of K . It is proposed to predict the intensity of corrosion by the parameters χ_0 and P_α .
5. For austenitic chromium-nickel steels the corrosion rate of separate phases is established: austenite (A), ferrite (F), α' -martensite deformation (M) and total phases $A + F$, $A + M$ and $A + F + M$. Thus, the corrosion rates $K(A)$ and $K(M)$ increase with increasing $\chi_0(F)$ of the austenitic matrix containing δ -ferrite. For two-phase steels $A + F$ and $A + M$, respectively, the corrosion rates $K(A + F)$ and $K(A + M)$ have the opposite character, namely $K(A + F)$ with increasing $\chi_0(F)$ decreases, and $K(A + M)$ on the contrary increase. For three-phase steel $A + F + M$, the corrosion rate $K(A + F + M)$ increases after plastic deformation with increasing $\chi_0(F + M)$ of the austenitic matrix, which contains δ -ferrite and α' -martensite deformation.

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