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EFFECT OF ALLOYING AND HEAT TREATMENT ON EMBRITTLEMENT OF Fe-Cr-Ni ALLOYS IN HIGH-PRESSURE HYDROGEN

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The nickel content effects on the strength, plasticity, and low-cycle life of hardened and aged specimens of different modifications of austenitic iron-nickel steels and alloys in the initial state and after preliminary high-temperature hydrogenation in hydrogen at a pressure of 30 MPa and temperatures of 293, 773 and 973 K were studied. At 293 K, hydrogen embrittlement of hardened materials weakens with increasing nickel concentration from 10 to 23 wt.%; it is insignificant in the concentration range of 23–45 wt.% and significantly increases with higher nickel content. After aging, materials with a nickel content of 23 and 36 wt.% are insensitive to the action of the hydrogen environment; at higher hydrogen concentrations, embrittlement intensifies. The structural state of aged materials significantly affects the degree of hydrogen embrittlement of their various modifications during short-term tensile tests and slightly less during low-cycle fatigue tests. In the range of Ni concentrations of 23–73 wt.%, the effect of hydrogen on the relative transverse narrowing remains almost stable. The relative elongation of more hydrogen-resistant modifications of materials and low-cycle life increases with increasing nickel content. At 773 K, the effect of nickel content on the relative transverse narrowing in gaseous hydrogen at a pressure of 30 MPa is slightly smaller but qualitatively the same as at 293 K. At 973 K, more heat-resistant high-nickel alloys embrittle in a hydrogen environment much more strongly than hard dispersion steels. Thermomechanical treatment, according to the quenching scheme, tension at room temperature, and aging for 16 h at 973 K significantly increases the plasticity of materials in the presence of hydrogen at the same strength.

Keywords: austenite, intermetallics, hydrogen embrittlement, low-cycle life, strength, plasticity, thermomechanical treatment.

Introduction. The accident-free operation of critical equipment in a number of industries, the working processes of which are characterized by high levels of pressure and temperature of gaseous hydrogen, the tension of structural elements with strict requirements for specific weight indicators, is ensured by the correct choice of structural materials [1–5]. Austenitic iron-nickel steels and alloys are used in aerospace [1–3], chemical and oil and gas [1–4] industries, energy, nuclear and automotive industries [1–3, 5–9] due to the successful combination of operational characteristics in the temperature range from cryogenic to high. Their heat and corrosion resistance is provided by the chromium content of more than 11 wt.%, while high strength and heat resistance – by alloying with intermetallic (Al, Ti, Nb) and refractory (Mo, V, W) metals [6–9]. Depending on the operating temperature and force conditions, such materials contain from 8–10 [8–15] to 80 wt.% Ni [5, 6, 9, 16–26]. To improve the grain boundary

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structure and increase resistance to intergranular fracture, B, Zr, Ce, and La are introduced into dispersion-hardening high-nickel alloys [17, 18, 24–31].

The use of iron-nickel steels and alloys in hydrogen energy is limited by the sensitivity of their operational characteristics to hydrogen. It has been established that at room temperature, nickel is an alloying element that determines the surface and diffusion processes of hydrogenation and the hydrogen embrittlement degree of unstable and stable chromium-nickel steels [5, 6, 8–15] and iron-nickel steels and nickel alloys in the hardened state [5–7, 16–30]. Under electrolytic hydrogenation, an adverse effect of nickel on the plasticity of austenitic steels was found. This is caused by a stronger surface cold-hardening of nickel-enriched steels, further reducing the plasticity resource during subsequent mechanical tests [9]. In high-pressure hydrogen gas, nickel significantly improves its hydrogen resistance [5, 8–15]. At the same time, the external hydrogen environment promotes crack initiation and propagation on the surface and reduces tensile plasticity more than the internal pre-absorbed hydrogen [15, 16, 19, 20, 23]. In the range of nickel concentrations from 12.5 to 35% in the hardened state, steels are weakly sensitive to hydrogen, while the influence of minor elements and impurities (Mo, Mn, Ti, and S) is insignificant [5, 9, 15]. The minimum hydrogen embrittlement of binary Fe-Ni alloys was found at 40–50% nickel content, which correlates with their minimum hydrogen permeability [5, 9]. The strength of hardened materials is relatively low; to increase it, aging is carried out, which causes the release of various secondary phases, mainly intermetallics [5, 24–44]. The structure and mechanical properties of steels and alloys after aging often differ significantly, so the effect of nickel content on their hydrogen stability has not been analyzed. Hydrogen diffusion in aged materials is slower than in hardened materials, but the former are more sensitive to hydrogen [29, 30, 32].

The regularities of the effect of electrolytic hydrogenation have been established at room temperature [5, 9, 38, 39] and preliminary high-temperature hydrogenation – at temperatures up to 573 K, when the negative effect of internal hydrogen on the properties of steels and high-nickel alloys is significant [2, 5–7, 15, 35]. Taking into account that embrittlement of such materials was found in the temperature range of 293–1073 K during tests in high-pressure hydrogen gas [11, 19, 20, 23, 29–31, 34], it is crucial to determine the role of nickel at elevated temperatures.

Below are the results of studies of the effect of nickel content on hydrogen embrittlement at temperatures of 293, 773, and 973 K of hardened and aged iron-nickel steels and alloys under the effect of an external hydrogen atmosphere and pre-adsorbed hydrogen.

Materials and Methods. Such alloys as 12Kh18N10T, 10Kh11N23T3MR (EP-33), 10Kh15N27T3V2MR (EP-700) austenitic steels and KhN36TYu (EI-702), KhN45MBTYu (EP-915), KhN55MBYu (EP-666), KhN56MBYuD (EK-62), KhN60MBYu (EP-901), KhN62BMKTYu (EP742), and KhN73MBTYu (EI698) were subjected to short-term tensile and low-cycle fatigue tests. These alloys contained Fe- and Ni-based multicomponent γ-solid solutionswith allocated strengthening intermetallic phases and carbides. The content of intermetallics of the type $(Ni,Cr,Fe)_3(Nb,Al,Ti,Mo)$ in aged materials was determined by physicochemical phase analysis in an aqueous electrolyte with ammonium sulfate. Depending on the chemical composition and heat treatment (HT) modes, it varied from 5 to 28 wt.% [11, 18–20, 23, 29–31]. All alloys were subjected to vacuum arc remelting, which provides the formation of structures with thin grain boundaries, reduced amount of carbides and carbonitrides, increased plasticity, fracture toughness, and hydrogen resistance [30].

The results of mechanical tests of modifications of materials with different contents of alloying elements and HT modes are given in [11, 19, 20, 23, 29–31]. One of the variants of chemical composition, HT, and mechanical characteristics at room temperature in air and hydrogen under a pressure of 30 MPa after preliminary hydrogenation is given in Tables 1 and 2. The amount of alloying elements in the modifications of steels and alloys varied within limits provided by regulatory documents. The values of the strength characteristics σ_u and $\sigma_{0.2}$ and plasticity δ and ψ of standard 5-fold cylindrical specimens with a working part diameter of 5 mm were determined at a short-term tensile speed of 0.1 mm/min. The number of cycles to failure $N$of polished flat specimens with a working part of 3×6×20 mm under rigid pure zero bending was determined at a strain amplitude of 1.6% and a loading frequency of 0.5 Hz. Such loading conditions make it possible to determine the maximum hydrogen embrittlement of the studied materials [11, 18–20, 23, 29–31].

Since the purity of the hydrogen environment has a significant effect on the mechanical properties [2, 4–6, 29], the specimens were tested in hydrogen with a controlled total oxygen and water vapor content of up to 0.004 g/m^3 after double vacuuming of the experimental chamber to a pressure of 0.13 Pa and intermediate flushing with hydrogen. Some specimens were previously kept at 530 K and hydrogen pressure up to 35 MPa for 10 h to compare the effect of pre-absorbed hydrogen and hydrogen atmosphere. Comparative tests were carried out at room temperature in air, while at elevated temperatures – in helium at a pressure of 10 MPa.

TABLE 1. Chemical Composition of the Investigated Materials (wt.%)

Material	C	Si	Cr	Ni	Mo	W	Fe	Ti	Al	Nb	Others
12Kh18N10T	0.10	0.76	17.6	10.4	–	–	71.2	0.96	–	–	Cu-0.24; Mn-0.22
05Kh11N23T3MR (EP-33)	0.05	0.37	11.4	23.2	1.48	–	59.6	2.98	0.62	–	B-0.015; Mn-0.33
10Kh15N27T3V2MR (EP-700)	0.09	0.60	15.0	27.1	1.41	1.92	50.8	2.85	0.29	–	B-0.002; Co-0.01
KhN36TYu (EI-702)	0.04	0.34	12.4	36.0	–	–	47.0	3.04	1.15	–	Mn-0.95
KhN45MTYu (EP-915)	0.05	0.18	14.5	44.0	1.75	–	36.6	1.67	0.5	2.7	Cu-0.02; Zr-0.02; V-0.3
KhN55MBYu (EP-666)	0.05	0.23	19.0	55.0	8.87	–	12.0	–	1.49	1.73	Se-0.01; Cu-0.02; N-0.07
KHN56MBYuD (EK-62)	0.04	0.12	16.7	56.2	5.24	–	14.2	0.5	1.37	3.99	Cu-0.49; Zr, Ce, La- 0.01 each; V-0.4
KhN60MVYu (EP-901)	0.02	0.16	19.3	59.7	9.12	4.83	0.54	–	2.6	–	V-6.2
KhN62BMKTYu (EP742)	0.03	0.12	13.8	62.2	5.94	0.41	0.96	2.5	2.37	3.29	Co-10.2; B, Zr-0.01, La-0.1
KhN73MBTYu (EI698)	0.05	0.02	14.6	73.1	3.00	0.01	0.39	2.54	1.7	2.09	Cu-0.09; Mn-0.11; B, Zr-0.005

TABLE 2. Heat Treatment Modes and Mechanical Properties of Alloys at Room Temperature in Air (above the dash) and in Hydrogen at 30 MPa after Preliminary Hydrogenation (below the dash)

Material	Heat treatment mode		Mechanical properties					C_H, mln^{-1}
	Quenching	Aging	σ_u, MPa	$\sigma_{0.2}$, MPa	δ, %	ψ, %	N cycles to fracture	
12Kh18N10T	1373 K, 1 h	–	690 680	310 320	64 48	79 55	1950 750	11
05Kh11N23T3MR	1373 K, 1 h	1000 K, 16 h + 923 K, 5 год	1200 1210	880 880	29 20	47 23	3000 1020	15
10Kh15N27T3V2MR	1373 K, 1 h	1023 K, 16 h + 923 K, 10 h	1270 1240	870 880	17 10	23 10	2277 455	15
KhN36TYu	1210 K, 1 h	930 K, 4 h	1100 1030	710 700	31 14	52 20	2680 777	18
KhN45MBTYu	1373 K, 1 h	1023 K, 10 h + 923 K, 10 h	1160 960	780 740	25 4	38 14	2560 614	19
KhN55MBYu	1323 K, 1 h	1000 K, 15 h + 923 K, 10 h	1080 970	650 660	35 5	38 19	3200 199	24
KhN56MBYuD	1253 K, 1 h	1003 K, 15 h + 923 K, 10 h	1320 965	840 750	34 6	48 13	3108 249	20
KhN60MVYu	1423 K, 1 h	973 K, 10 h + 923 K, 10 h	1170 1070	810 760	39 5	39 15	–	23
KhN62BMKTYu	1343 K, 8 h	1123 K, 6 h + 1073 K, 13 h	1390 1220	900 880	25 4	29 9	2998 334	29
KhN73MBTYu	1393 K, 8 h, 1273 K, 4 h	1048 K, 16 h	1120 1010	720 690	31 5	38 10	2610 235	29

The hydrogen content C_{H} in the specimens after preliminary hydrogenation, determined on the ONH-836, TCH-600devices by Leco company according to the methods[45, 46], is given in Table 2. The hydrogen embrittlement degree was estimated by the coefficient β, defined as the ratio of the characteristics in hydrogen and vacuum (for example, the coefficient of hydrogen effect on low-cycle life $\beta_N = N_{\mathrm{H}}/N_{\mathrm{He}}$).

Results and Discussion. Since the strength characteristics of$\sigma_u$and$\sigma_{0.2}$ of 05Kh11N23T3MR and 10Kh15N27T3V2MR steels change insignificantly under the hydrogen effect, and the maximum reduction ofσ_u of nickel alloys does not exceed 27% of the values in air, the nickel content effect on the hydrogen embrittlement degree was estimated by the values of plasticity and low-cycle life, which decrease several times (Table 2, Figs. 1–3).

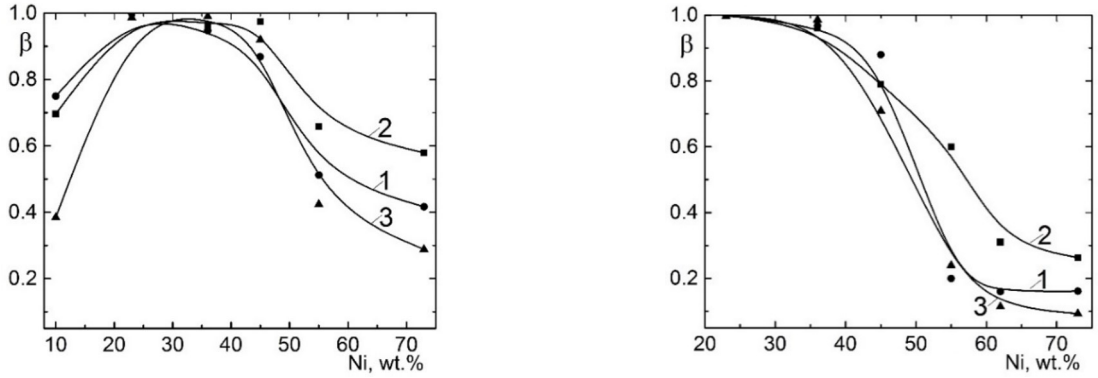
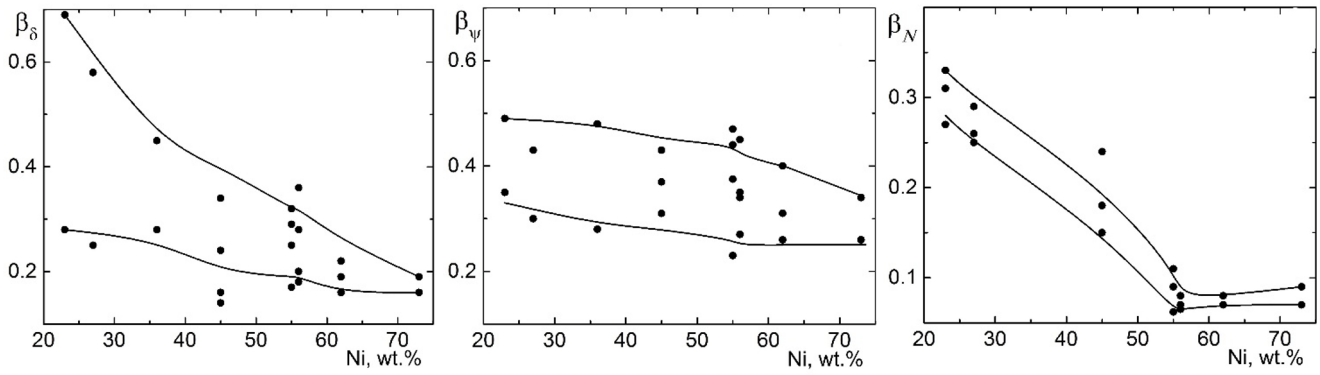


Fig. 1. Dependence of the coefficient of hydrogen influence β at a pressure of 30 MPa on the relative elongation δ (*1*), transverse narrowing ψ (*2*), and low-cycle life N (*3*) of specimens from steels and alloys in the hardened (a) and aged (b) state on the nickel content at room temperature.

Modifications of materials and quenching temperatures of preliminary non-hydrogenated hardened specimens tested in hydrogen at room temperature are given in Tables 1 and 2. In the hardened state, the strength characteristics of the materials differ insignificantly; the short-term strength and yield strength limits are in the range of 600–700 MPa and 290–330 MPa, respectively. A slightly greater difference in the values of plasticity characteristics, relative elongation, and transverse narrowing vary from 45 to 64% and from 55 to 79%. The obtained results (Fig. 1a) are in complete agreement with the available literature data [5–30]. Hydrogen embrittlement of unstable austenitic steels such as 12Kh18N10T is associated with the peculiarities of deformation martensitic transformation under loading in the presence of hydrogen [5, 8–15]. An increase in the energy of packing defects and stabilization of austenite due to an increase in the nickel content from 10 to 23 wt.% lead to the absence of hydrogen effect on the plasticity and low-cycle durability of 05Kh11N23T3MRsteel and KhN36TYualloy (Fig. 1a). The hardened specimens from KhN45MBTYualloy are slightly embrittled and more significantly from KhN55MBYu and KhN73MBTYu alloys (Fig. 1a). Increased effect of the hydrogen atmosphere was also found on aged specimens. High-nickel alloys are very noticeable in hydrogen at a pressure of 30 MPa. Thus, the relative elongation and the number of cycles to fracture of KhN62BMKTYu and KhN73MBTYu alloys decrease by six and about ten times, respectively (Table 2, Fig. 1b).

The joint effect of pre-absorbed and external hydrogen gas was assessed on several modifications of each studied material. They differ in chemical composition, modes of maintenance, to a small extent, strength characteristics in air and more significantly in the values of relative elongation, transverse narrowing, and low-cycle life, especially in the presence of hydrogen [11, 18–20, 23, 29–31]. The wide range of values of β coefficients for specimens from different modifications of all materials (Fig. 2) indicates that structural factors (grain size, number, morphology, and placement of secondary phases) play a significant role in hydrogen embrittlement. Atomic ordering with the formation of near-atomic order also increases hydrogen permeability and changes the hydrogen resistance of

steels [9, 48]. Under the same conditions of preliminary hydrogenation, the amount of absorbed hydrogen in high-nickel alloys is almost twice as high as in 05Kh11N23T3MR and 10Kh15N27T3V2MR austenitic steels (Table 2). The effect of hydrogen on the relative elongation of more hydrogen-resistant modifications of materials and low-cycle life increases with nickel content (Fig. 2a and 2c), and that on the relative transverse narrowing – remains almost stable in the range of 23–73 wt.% Ni (Fig. 2b). The degree of hydrogen embrittlement of various modifications of materials is significantly different in short-term tensile tests (Fig. 2a and2b) and slightly less in low-cycle fatigue tests (Fig. 2c) when the number of cycles to failure is determined by the state of the surface of the specimens, where the maximum mechanical stresses and hydrogen concentrations are combined. A significant (1.6 times) weakening of the effect of hydrogen on low-cycle life was found only in the best modification of the KhN45MBTYu alloy (Fig. 2c). The difference in the values of the$\beta_\delta$coefficient of 05Kh11N23T3MR steel modifications is more than 2-fold (Fig. 2a, Tables 2 and 3). Optimization of chemical composition and HT modes allows one to significantly (by 1.6 times) reduce the effect of hydrogen on the relative transverse narrowing of all materials (Fig. 2b) and the relative elongation of steels and alloys with nickel content up to 56% (Fig. 2a).



a b c

Fig. 2. Dependence of the coefficient of hydrogen effect β at a pressure of 30 MPa on the relative elongation δ (a), transverse narrowing ψ (b), and low-cycle life N (c) of pre-hydrogenated specimens of steels and alloys in the aged state on the nickel content at room temperature.

Only the modifications of materials presented in Tables 1 and 2 were tested at elevated temperatures. In the temperature range of 293–773 K, the effect of high-pressure hydrogen on the properties of pre-hydrogenated specimens made of 05Kh11N23T3MRand 10Kh15N27T3V2MRsteels and KhN45MBTYu alloy is slightly weakened, and that of non-hydrogenated specimens is enhanced [18–20]. As a result, at temperatures above 773 K, when a sufficient amount of hydrogen for maximum hydrogen degradation penetrates the metal during short-term static tension, the plasticity of hydrogenated and non-hydrogenated specimens in a hydrogen environment is almost the same [18–20]. The additional effect of absorbed hydrogen on the properties of high-nickel alloys is insignificant in the temperature range of 293–1073 K [18–20]. Therefore, the dependences of the hydrogen embrittlement degree on the nickel content at 773 and 973 K are based on the test results of preliminary non-hydrogenated specimens (Fig. 3). At a temperature of 773 K, all materials retain a sufficiently high level of strength. The effect of nickel content on the coefficient β_ψ is slightly less but qualitatively the same as at 293 K (Fig. 2b and 3a). Increasing the temperature to 973 K leads to a decrease in strength and, accordingly, to the weakening of hydrogen embrittlement of 05Kh11N23T3MR and 10Kh15N27T3V2MRsteels [18–20], therefore the effect of hydrogen on the plasticity of more heat-resistant high-nickel alloys is much stronger (Fig. 3b). The exception is the KhN55MBYu alloy with a smaller total amount of titanium, aluminum and niobium, i.e., intermetallic phase, and relatively low strength at elevated temperatures [18–20, 30]. Thus, at 973 K, the short-term tensile strength of this alloy is 620 MPa, of the KhN45MBTYu alloy is 750 MPa, and of the KhN56MBYuD and KhN62BMKTYu alloys is more than 1000 MPa.

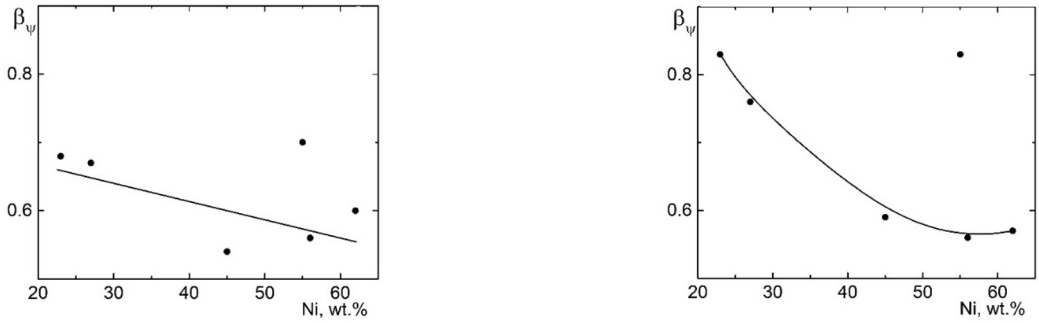


Fig. 3. Dependence of the coefficient of hydrogen effect β at a pressure of 30 MPa on the transverse narrowing ψ of specimens from steels and alloys in the aged state on the nickel content at a temperature of 773 (a) and 973 K (b).

Hydrogen causes a change in the fracture mechanism of specimens from ductile transcrystalline to intergranular fracture (Fig. 4), grinding of pits in the core of the specimen, where a small area of ductile fracture by tearing is preserved, and the nucleation of nanoscale voids at the grain boundaries and dislocation slip bands [18–20, 23, 24, 29–31, 39–43, 45–47]. Therefore, summarizing the results and literature data, it can be concluded that increasing the hydrogen resistance of austenitic iron-nickel steels and alloys is achieved by vacuum remelting [19, 30], reducing the amount of carbides and carbonitrides by minimizing the carbon content [2, 5, 18, 29–31, 39] (Tables 2 and 3), the formation of a structure with thin grain boundaries with increased cohesive energy by the introduction of boron, lanthanum, and zirconium [23, 29–31, 39–41], optimization of the morphology of intermetallics [21, 26, 32, 35]. Hydrogen embrittlement is weakened by copper alloying, which is especially effective in combination with the introduction of boron [37, 39]. The sensitivity to hydrogen and the number of intergranular fracture sites decrease with decreasing grain size, even though the hydrogen concentration in coarse-grained specimens is lower than in fine-grained ones [29, 30, 40]. Changing the grain size of the 30Ni-15Cr-1.3Mo-1.88Ti-0.36Al-0.24V-0.2Si-0.0008B-Fe alloy from 95 to 32 μm leads to the accumulation of a lower concentration of hydrogen at the grain boundaries since the number of dislocations in the slip bands that transport it is proportional to the grain size [21, 40].

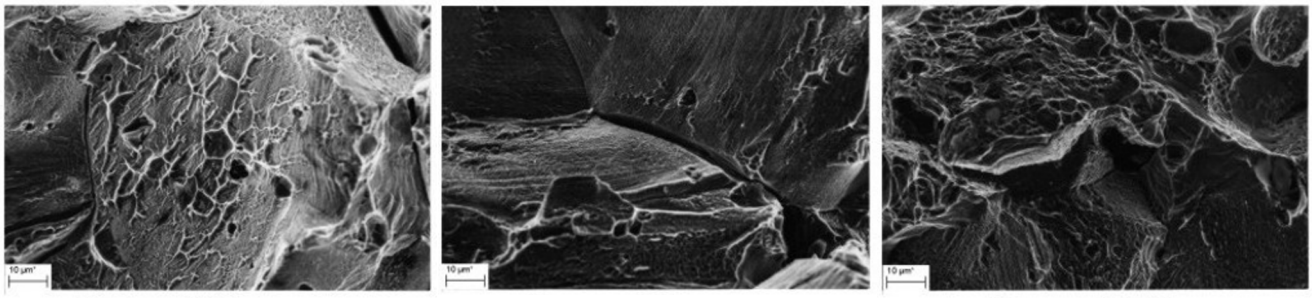
TABLE 3. Treatment Modes and Mechanical Properties of the Investigated Materials at Room Temperature

Processing mode	$\sigma_u/\sigma_u{}^1/\sigma_u{}^2$, MPa	$\sigma_{0.2}/\sigma_{0.2}{}^1/\sigma_{0.2}{}^2$, MPa	$\delta/\delta^1/\delta^2$, %	$\psi/\psi^1/\psi^2$, %
10Kh11N23T3MR				
Quenching from 1373 K	750/750/750	350/350/350	50/50/50	69/69/69
Quenching from 1373 K, aging at 1000 K, 16 h + 923 K, 5 h	1220/1190/1180	890/870/870	25/24/7	26/25/9
Quenching from 1373 K, tensile stress 10%, 293 K + aging at 973 K, 16 h	1210/1200/1190	890/890/890	24/24/16	28/28/16
KhN45MBTYu				
Quenching from 1373 K	820/820/820	500/500/500	38/35/34	39/37/37
Quenching from 1373 K, aging at 1023 K, 8 h + 923 K, 8 h	1160/1130/960	780/780/740	25/22/4	38/30/14
Quenching from 1473 K, aging at 1023 K, 8h + 923 K, 8h	1180/980/990	770/760/760	21/13/3	24/16/8
Quenching from 1473 K, tensile strength 7% at 293 K, aging at 973 K, 16 h	1260/1210/1200	820/820/820	24/22/16	46/40/28

Note. σ_u, $\sigma_{0.2}$, δ, ψ are properties in air; $\sigma_u{}^1$, $\sigma_{0.2}{}^1$, δ^1, ψ^1 are properties in hydrogen at 30 MPa; $\sigma_u{}^2$, $\sigma_{0.2}{}^2$, δ^2, ψ^2 are properties in hydrogen at 30 MPa after hydrogenation.

One of the methods for obtaining a combination of high strength, plasticity, and hydrogen resistance of stainless austenitic chromium-nickel and chromium-manganese-nickel steels [13, 49] and heat-resistant nickel alloys [25, 33] is thermomechanical treatment (TMT). After three cycles of cold rolling followed by 15-min annealing at 1173 K in an air furnace, specimens of technically pure nickel at hydrogen concentrations of more than 20 ppm^{-1} almost doubled the tensile plasticity, the proportion of intergranular fracture became much lower, and the value of J_c fracture toughness was about 20–30% higher [50].

The effectiveness of TMT (quenching, tensile at 5, 7, and 10% at room temperature and aging for 16 h at 973 K) was assessed on the modifications of 10Kh11N23T3MR steel and KhN45MBTYu alloy. They differed from those indicated in Tables 1 and 2 by the carbon content of 0.097 wt.% (10Kh11N23T3MR steel) and higher quenching temperature, i.e., coarser grain structure (KhN45MBTYu alloy) (Table 3). The hydrogen content in the pre-hydrogenated aged specimens practically did not depend on the processing mode, as indicated in Table 2.



a b c

Fig. 4. Fracture pattern of specimens made of 10Kh11N23T3MR steel: (a) air, HT; (b) hydrogen, HT; (c) hydrogen, TMT.

The external hydrogen environment does not deteriorate the properties of 10X11H23T3MP steel regardless of chemical composition and processing mode (Tables 2 and 3, Figs. 1 and 2). The structural state of the material significantly determines its hydrogen resistance under the combined action of external and pre-absorbed hydrogen. High resistance to hydrogen embrittlement in this test mode is typical only for the hardened material, in which the amount of intermetallic γ'-phase is insignificant (Table 3). An increase in the carbon content in the aged specimens of 10Kh11N23T3MR steel from 0.05 to 0.097 wt.% had a weak effect on their strength. It led to a decrease in plasticity, especially significant when tested in the presence of hydrogen (Tables 2 and 3). Under the same aging mode, the plasticity of KhN45MBTYu alloy specimens with coarse grains, when the intermetallic γ'-phase was concentrated mainly on the grain boundaries [51], decreased under all conditions of hydrogen exposure more significantly than that of specimens with a fine-grained structure (Table 3). TMT significantly increased the hydrogen resistance of materials. Thus, at the optimum deformation degree, which for 10Kh11N23T3MRsteel was equal to 10%, the strength properties of steel after TMT and step aging were the same, and the relative elongation of hydrogenated specimens increased from 7% (HT) to 16% (TMT), i.e., more than twice (Table 3). The size and number of discharges at the grain boundaries and, accordingly, the proportion of intergranular fracture in the fracture of hydrogenated specimens decreased markedly (Fig. 4). The combination of high strength and plasticity of both non-hydrogenated and pre-hydrogenated specimens from more alloyed alloyKhN45MBTYu during tests in hydrogen at a pressure of 30 MPa was achieved after TMT with the tensile strength of 7%, i.e., such treatment was effective under the action of external and absorbed hydrogen.

The increased resistance to hydrogen embrittlement after TMT was due to the following reasons. Firstly, since the γ'-phase particles released at the grain boundaries, due to interfacial stresses contributed to the segregation of hydrogen there, the reduction of their number and size [51] improved the hydrogen resistance of alloys. Secondly, dispersed dislocations in the grain body acted as barriers to mobile dislocations and hydrogen traps, reducing

hydrogen transport efficiency to grain boundaries. Consequently, a more uniform distribution of particles of strengthening phases promoted a similar distribution of hydrogen, weakening its effect on mechanical properties.

CONCLUSIONS

1. The influence of gaseous hydrogen at a pressure of 30 MPa and room temperature on the plasticity characteristics and low-cycle life of hardened iron-nickel steels and alloys decreases with increasing nickel concentration from 10 to 23 wt.%, is insignificant in the concentration range of 23–45 wt.%, and significantly increases with higher nickel content. After aging, materials with 23 and 36 wt.% nickel are insensitive to the hydrogen environment; at higher concentrations, embrittlement increases and becomes very noticeable in alloys with 55, 62, and 73 wt.% nickel when the listed characteristics decrease more than five times.

2. Under the same conditions of preliminary hydrogenation, the amount of absorbed hydrogen in high-nickel alloys is almost twice as high as in austenitic steels. The structural state of hydrogenated materials significantly affects the degree of hydrogen embrittlement of their various modifications in short-term tensile tests and slightly less in low-cycle fatigue tests. In the interval of Ni concentrations of 23–73 wt.%, the effect of hydrogen on the relative transverse narrowing remains almost stable, and on the relative elongation of more hydrogen-resistant modifications of materials and low-cycle life increases with increasing nickel content.

3. At elevated temperatures, the effect of nickel content is associated with the temperature dependencies of the strength of materials. At 773 K, all steels and alloys retain a sufficiently high level of strength characteristics. The effect of nickel content on the coefficient β_ψ in gaseous hydrogen at a pressure of 30 MPa is slightly less. Still, qualitatively the same as at 293 K. Increasing the temperature to 973 K leads to a decrease in strength and, accordingly, to a weakening of hydrogen embrittlement of steels. Hence, the effect of hydrogen on the plasticity of more heat-resistant high-nickel alloys is much stronger.

4. Thermomechanical treatment according to the quenching scheme, tension at room temperature, and aging for 16 h at 973 K leads to a decrease in the size and number of discharges at the grain boundaries, the proportion of intergranular fracture in the fracture of hydrogenated specimens and, accordingly, to an increase in the plasticity of materials in the presence of hydrogen. At the optimum degree of deformation, which for steel 10Kh11N23T3MR is equal to 10%, the strength properties of steel after TMT and step aging are the same, and the relative elongation of hydrogenated specimens increased from 7% (HT) to 16% (TMT). The combination of high strength and ductility of specimens made of KhN45MBTYu alloy when tested in hydrogen at a pressure of 30 MPa is achieved after TMO with a tensile strength of 7%. Such treatment is effective under the action of external and absorbed hydrogen.

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