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High Nitrogen Steels with special functional properties

Production expansion of High Nitrogen Steels, both with low nickel content and without nickel, in various structural classes will be the main trend. Alloying steels with nitrogen is very promising to give them special functional properties for example corrosion resistance in bioactive environments, bactericidal activity or disinfecting ability, high resistance to special impacts, lightweight steels. Nitrogen is currently a quite normal alloying element together with C, Cr, Mn, Ni, etc. It provides unique combination of strength, plasticity and corrosion resistance for steels. Industry uses a lot of nitrogen-alloyed steels of various structure classes — austenitic, ferrite, martensite and two-phased. In future these steels are quite possible to replace light and non-ferrous metals' alloys. Alloying steels with nitrogen is very promising to give them special functional properties for example corrosion resistance in bioactive environments, bactericidal activity or disinfecting ability, high resistance

to special impacts, lightweight steels with lower density and high strength and plasticity.

Key words: high nitrogen Steels, steels for bioactive environments, biocidal steels, lightweight steels. nickel, corrosion resistance.

1. Introduction

The significant application of nitrogen as an alloying element commenced in the 80s of the past century. The steels produced then, which contained 0.5–1.0% of nitrogen, were called High-Nitrogen Steels (HNS) or nitrogen "hyperequilibrium" steels. At such its contents, nitrogen imparts unique properties to the steel; for example, stainless high-nitrogen steels are characterized by high strength and high corrosion resis-

tance at the same time, and therefore the high-nitrogen steels have initiated a new branch in physical metallurgy. Since 1988, international conferences devoted to these steels have been regularly held. More than 20 years have already passed since the first HNS conference (1988, Lille, France). During this time, a new branch in metallurgical science and international cooperation between researchers and engineers involving in the problems of HNS have been established. A considerable progress has been made in recent years in the understanding of alloying steels with nitrogen under normal and high pressures and in studying the nature of the processes of forming the structure and properties of HNS, and new areas of application of these steels have been set out. The commercial-scale production of high-nitrogen steel products for the power industry, transport, the chemical and food industries, and medicine has grown.

Nitrogen, as an austenite-forming element, is a substitute for nickel. The nickel prices are growing at an accelerated rate. At least two causes of this phenomenon can be mentioned, namely: the increased demand for nickel for production of nickel-based special alloys, and the systematic growth in the production of the classical 18-8 stainless steel, though in many instances this steel could be substituted with a high-nitrogen steel with a low nickel content, or even with this type of steel without nickel. In addition, nickel has proved to be an allergen, which also favours the spreading of use of nickel-less steels. In this situation, the basic trend will be an unavoidable spread of the production and use of economically advantageous nitrogen-alloyed steels with low nickel content or steels not containing this expensive metal, of various structural types (austenitic, martensitic, and multiphase).

With any method of introducing nitrogen to the liquid steel the nitrogen content will be determined by the pressure of the nitrogen gaseous phase. According to the classification proposed earlier [1], the alloying of steels with nitrogen can be divided into three groups, depending on the nitrogen pressure during their smelting: micro-alloy steels with nitrogen, nitrogen steels and high-nitrogen steels. Nitrogen steels and micro-nitrogen steels can be smelted at the normal pressure. The difference between them is determined by the chemical composition of the steels. Micro-nitrogen steels have a ferritic matrix. The solubility of nitrogen in ferrite is much lower than in liquid metal. Therefore, in order to avoid the bubbles and porosity in an ingot, the nitrogen content in micro-nitrogen steels prior to their casting must be lower than the equilibrium content for $P_{N_2} = 0.1$ MPa. Nitrogen steels contain Cr, Ni, Mn and crystallize following the austenite mechanism. The solubility of nitrogen in alloyed austenite is higher than in liquid metal. For this reason, in austenitic steels smelted under normal pressure the nitrogen content can be as high as from 0.4 to 0.5%. High-nitrogen steels, in international terminology called HNS, have nitrogen contents higher than the equilibrium content for $P_{N_2} = 0.1$ MPa, and therefore specialized hyperbaric reactors are required for the production of these

steels. The nitrogen content in austenitic high-nitrogen steels may be higher than 1.0%.

Under its normal condition, nitrogen is a gas. This makes it different from other alloying elements. The solubility of nitrogen in liquid metal, the phases α and γ , is variable. Therefore, two technological tasks are performed in the production of nitrogen-alloyed steels: to achieve the required nitrogen content of the finished metal without nitrogen bubbles formation during metal solidification, and to employ the appropriate heat treatment method ensuring the required structure of the steel and the correct nitrogen distribution among phases. The nitrogen content should not be too high, but optimal in order to prevent nitrogen not only from bubbles, but also from excessive precipitating in the form of nitrides during crystallization and in the solid state in the high temperature range [2]. The more nitrides and the higher their precipitation temperature, the larger and the less soluble they are during successive treatments – heating, which means the redundancy of the excess nitrogen. Moreover, rational selection of composition with respect to the remaining alloying elements is necessary. At every stage of treatment, the formation of large, sparingly soluble nitrides must be avoided, because their contribution to hardening is low, and the adverse effect on plasticity and impact strength is relatively high. It has been established previously that in order to dissolve high-temperature and crystallizing nitrides, higher temperatures and long times of holding at those temperatures are needed, which induces negative phenomena, such as grain growth and denitriding of the surface layer. For example for steel Cr18Ni10, 30 minutes of holding at 1200 °C will be needed, with the depth of the “denitrided” surface layer reaching 1 mm. For these reasons, steels with alloying nitrogen require the precise determination of the concentration ratio of nitrogen and other alloying elements, as well as increased crystallization rates. During solidification of industrial ingots, the cooling rates amount to several K/s. Hence, the fraction of nitrogen forming nitrides during solidification is considerably higher. Respective ingot zones are characterized by different cooling rates during solidification and, consequently, the magnitudes of nitrogen distribution between the solid solution and nitrides are different, with a particularly great difference appearing for two-phase steels (Table 1).

Table 1. Chemical and phase compositions of two-phase steels – the as-cast structure [2]

Parameter	Cooling rate, K/s		
	50	8	2
05Cr ₁₅ Ni ₅ CuMo			
[N] _f , %	0.21	0.20	0.20
[N] _γ , %	0.21	0.11	0.07
[N] _α , %	20	30	40
02Cr ₁₅ Ni ₅ CuV			
[N] _f , %	0.14	0.14	0.13
[N] _γ , %	0.16	0.11	0.08
[N] _α , %	0.11	0.09	0.08
η _α , %	40	50	60

Therefore, the structure is very inhomogeneous within the volume of metal. In the zones with low cooling rates, high-temperature nitrides occur in large quantities. In this situation, in respect of the as-cast structure of a slow-solidifying ingot, it is not possible to regulate the phase composition and to avoid the precipitation of large quantities of high-temperature nitrides. The correct selection of deformation cycles and heat treatment, and in particular the application of thermo-mechanical treatment, will enhance the effectiveness of alloying steels with nitrogen [3].

Nitrogen is currently a quite normal alloying element together with C, Cr, Mn, Ni, etc. Standard techniques of nitrogen containing steels are developed, such as PESR, EAF-AOD, EAF-VOD processes. These steels are being further developed with improved properties or optimized alloy addition pattern to obtain strength – ductility – corrosion resistance balance needed for certain operation conditions. Possibilities of nitrogen as an alloying element are far from being exhausted in this respect [4].

The most advantageous economic effect resulting from using nitrogen as an alloying element, from the present day’s point of view, is gained for smelting steel at atmospheric pressure, as there is no need for using any special equipment. A large number of economical corrosion-resisting nitrogen-alloyed steels with a nickel content from 2 to 4% have been developed and applied to date in many areas [5].

For example as an alternative to high-quality materials, such as super-austenitic nickel-based stainless steels, the Sandvik company [6] has developed two-phase steels smelted at atmospheric pressure, which distinguish themselves by high corrosion resistance, excellent mechanical properties, good weldability and a relatively low price (Table 2).

For unique constructions (high-rise buildings, bridges, viaducts, etc.) austenitic corrosion resistant steel 22Cr-16Mn-0,6N is developed for production of high-strength fittings and fixing elements of the units working in hostile environment [7].

The effect associated with introducing nitrogen to steel increases as a result of applying high-temperature thermo-mechanical treatment. For example, a number of high-strength and corrosion-resisting steel based on the following alloying system: 15–17% Cr; 5–10% Ni; 2% Cu; 1–2% Mo; 0.1–0.2% V; 0.12–0.15% N have been developed at the Moscow Institute of Steels and Alloys (Fig. 1). These are economical steels in terms of

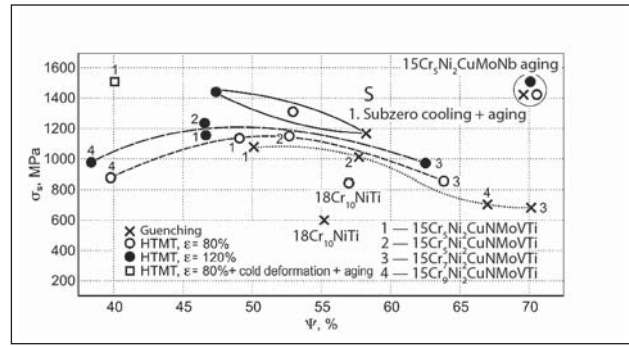


Figure 1. Diagram of the constructional strength of nitrogen steels ([N] = 0.12–0.15%) after different treatments. HTMT — High Temperature Thermo-mechanical Treatment. Structure: 1–3 — austenite + martensite; 4 — austenite

their contents of alloying elements and in terms of their production technology, because they can be smelted at normal pressure. Depending on the nitrogen content and the thermo-mechanical treatment regime, these steels may exhibit a structure varying from austenitic to martensitic, while having the complex of mechanical properties corresponding to those structures, as shown in Figure 1.

The strength level achieved after the high-temperature thermo-mechanical treatment of austenitic, martensitic and two-phase aged nitrogen steels is higher by 1.5 to 2 times compared to similar steels not containing alloying nitrogen, with the same toughness and plasticity. By changing the HTMT cycle, the region of correlation between σ and ψ , as necessary for different applications, can be established. The highest strength is achieved by steels with a martensitic matrix, which are hardened by nitrides and carbonitrides. At the same time, they retain their corrosion resistance in moderately aggressive environments, as in the case of steel Cr18N10.

High-strength nitrogen-alloy steels has strength/weight ratio as high as for Ti, Mg, Al alloys. But high-nitrogen steels are more technological and less power-consuming. Furthermore, their production is much less environmentally harmful. Therefore their wider use for replacement of non-ferrous metal alloys is quite possible in the future [8].

A new factor stimulating the production of nitrogen-alloyed steels at atmospheric pressure has appeared to be the C+N alloying system. Joint C+N alloying makes it possible to enhance strength, impact resistance and plasticity, while retaining sufficiently high corrosion resistance. Works [9, 10] provide the results of investigation and development of steel Cr18Mn18 with a C+N content in the range from 0.85 to 1.07%. With the optimal ratio of C to N, a stable homogeneous austenitic structure can be produced in these steels, with a yield stress of approx. 600 MPa, i.e. 3 time greater than for the standard CrNi stainless steel, and with an elongation of approx. 70% (Figure 2).

Development of new steels with special functional properties, such as bioactive environments resistance, high-strength structural steels, light-

Grade	UNS	C _{max}	Cr	Ni	Mo	N	PRE *
Sandvik SAF 2507	S32750	0.03	25	7	4	0.3	42.5
Sandvik SAF 2707 HD	S32707	0.03	27	7	5	0.4	48
Sandvik SAF 3207 HD	S33207	0.03	32	7	3.5	0.5	50

Note: * materials for pipes. For two-phase stainless steels, resistance to pitting corrosion is proportional to the pitting resistance equivalent, PRE (PRE = % Cr + 3.3% Mo + 16% N).

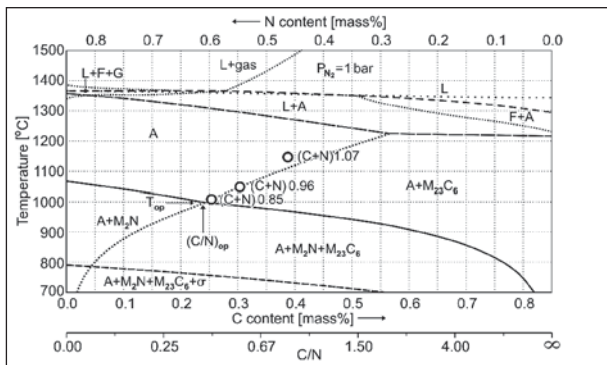


Figure 2. Phase diagram for steel Cr18Mn18 with C+N = 0.85 and C/N = 0.43.

T_{op} and $(C/N)_{op}$ – optimal values the temperatures of the start of precipitation of M26C6 carbides are indicated by cross marks [9]

weight steels etc. could be a prospective way of nitrogen-alloy steels development an application.

2. Corrosion resistant steels for bioactive environments

Biochemical corrosion stimulates local equipment destruction processes and fastens corrosion 1.5–2 times. Furthermore, some bacteria can directly contribute to such a specific stress-corrosion mechanism as hydrogen embrittlement.

Table 3. Chemical composition of alloys, (mass.%)

Steel grade	Cr	Ni	Mn	Si	Cu	Nb	Mo	C	N
36CrMnMo	0.89	0.20	1.03	0.46	–	–	0.20	0.36	0.01
07Cr14Ni5Cu2MoNb	14.0	5.0	0.6	0.3	1.7	0.04	0.2	0.07	0.01
02Cr13N	12.9	0.25	0.34	0.44	–	–	–	0.02	0.12
05Cr15Ni5Cu2MoNbN	15.0	5.0	0.6	0.3	1.7	0.04	0.2	0.05	0.12
05Cr14Ni7Cu2MoNbN	14.0	7.0	0.6	0.3	1.7	0.04	0.2	0.05	0.12
05Cr14Ni9Cu2MoNbN	14.0	9.0	0.6	0.3	1.7	0.04	0.2	0.05	0.12

Table 4. Steels' ability to microorganisms adhesion

Steel grade	Quantity of microorganisms, cage/cm ²	Ability to microorganisms adhesion
36CrMnMo	$(8,4 \pm 0,4) \cdot 10^6$	high
07Cr14Ni5Cu2MoNb	$(4,3 \pm 0,4) \cdot 10^2$	low
02Cr13N	$(9,6 \pm 0,8) \cdot 10^2$	low
05Cr15Ni5Cu2MoNbN	$(0,5 \pm 0,2) \cdot 10^2$	low
05Cr14Ni7Cu2MoNbN	$(0,2 \pm 0,1) \cdot 10^2$	low
05Cr14Ni9Cu2MoNbN	$(0,2 \pm 0,1) \cdot 10^2$	low

Table 5. Rate of corrosion in the bioactive environment

Steel grade	Mass decrease, g	Corrosion rate, g/(m ² ·h)
36CrMnMo	0.1727	0.3198
02Cr13N	0.0004	0.0007

Table 6. Chemical composition of the studied alloys, (mass.%)

Steel grade	C	Cr	Ni	Mn	Mo	Si	Cu	V	N
Cr18Ni10	0.02	17.8	8.8	1.45	0.15	0.38	0.27	0.15	0.02
Cr18Ni10Cu2	0.03	18.7	10.1	1.22	0.29	0.50	1.57	0.15	0.01
Cr18Ni10Cu5	0.03	17.9	9.8	1.6	0.26	0.70	5.00	0.12	0.02
Cr18Ni10Cu5N	0.03	18.1	9.4	1.41	0.32	0.39	5.02	0.15	0.22

We have studied a ability of nitrogen-alloyed chromium-nickel steels to microbiological corrosion in environments rich with H₂S and advantageous for sulphate-reducing bacteria generation¹¹. In our experiments we used cumulative cultures of hydrocarbon-oxidizing and sulphate-reducing bacteria extracted from reservoir water of Kuedino-Krasnoyarskoye deposit. Steels composition are listed in **table 3**.

Research results are represented in **tables 4 and 5**.

One can see that stainless steel 07Cr14Ni5Cu2MoNb and especially chromium-nickel nitrogen alloyed steels being studied demonstrate much less tendency to adhesion, i.e. greater resistance to corrosive microorganisms adhesion and also resistance to microbic fouling and corrosive films formation compare to common construction steel 36CrMnMo. Introduction of even 0.12% of nitrogen into steel is effective than addition of nickel. The amount of adhered microorganisms on 07Cr14Ni5Cu2MoNbN steel sample surface is about 8 times less than on 07Cr14Ni5Cu2MoNb steel sample surface. Increase in nickel content in steel by 2 and 4% decreases the amount of adhered microorganisms on steel samples surfaces only 2 times, table 4.

3. Antibacterial (biocidal) steels.

Copper is the second (after silver) bacterial-active element. Structure and properties of chromium-nickel steel additionally alloyed by Cu and N were investigated in works [12, 13]. Steels composition is shown in **table 6**.

Disinfecting activity of steels was studied in a certified laboratory of Sanitary and Epidemiological Service in Moscow. Plates containing no antimicrobial additives (control) and plates and cylinders of steels containing antimicrobial additives Cu and Ag (0.01%) were used as test objects. The following bacteria cultures were used as microorganisms: S. Aureus (strain 906), E. coli (colon bacterium) (strain 1257). CFU/ml and CFU/cm² were used for quantitative evaluation of disinfecting ability of tested specimens. This unit means the number of colony-forming units in 1 ml of liquid or on 1 cm² of specimen surface. Bacteria content decrease was defined by the number of colonies grown in experiment and control, assuming the number of colonies in control specimens as 100%.

Table 7. Bactericidal activity of steel specimens contaminated with *S. aureus* at microbial cells concentration 10²/ml

Steel grade	Exposure, hours	<i>S. aureus</i> , CFU/cm ²	Decrease of microbes quantity, %
Cr18Ni10Cu5N (cc)	1	5,2·10 ³	3.7
	4	3,9·10 ³	4.88
	24	0	100
Cr18Ni10Cu5N (ht)	1	4,9·10 ³	9,26
	4	3,7·10 ³	9,76
	24	0	100
Cr18Ni10Cu5 (cc)	1	4,9·10 ³	9,26
	4	3,8·10 ³	7,32
	24	0	100
Cr18Ni10Cu5 (ht)	1	4,9·10 ³	9,26
	4	4,0·10 ³	2,44
	24	0	100
Cr18Ni10 + 1,5% Cu (ht)	1	5,3·10 ³	1.85
	4	4,0·10 ³	2.44
	24	25	10.71
Control (plate)	1	5,4·10 ³	
	4	4,1·10 ³	
	24	28	

cc — cast condition; ht — after hot treatment

Test results show (table 7) that steels with high copper and nitrogen content exhibit bactericidal activity related to *S. aureus* and colon bacterium during immediate contact with solution, and efficiency depends on bacteria concentration. If metal samples are contaminated with *S. aureus* culture, bacteria content decrease on steel specimens alloyed by copper (5%) is 100% in 24 hours and 10.71% on specimen containing 1.5% of copper (table 5). Study of metal specimen bactericidal activity during immersion in various volumes (10 and 2 ml) of *S. aureus* suspended with initial concentration of bacterial cells 10⁴/ml and 10³/ml has shown that during the study period (between 1 hour and 5 days) microorganisms concentration in the studied suspensions decreases insignificantly (between 0.4 and 18%). Thus, samples of chromium-nickel steels containing 5% of copper has disinfecting ability as opposed to similar steels containing up to 1.5% of copper. High copper content in steel (over 5%) significantly increases the ability of the material in question to kill bacteria of *S. aureus* and colon bacteria classes. Bactericidal properties of steels alloyed with nitrogen are about 10% higher in prolonged tests compared to steels containing no nitrogen. Furthermore, nitrogen increases processability of copper-alloyed steel. These steels are highly deformable in both hot and cold condition in case of heating in austenite area before rolling. Non-magnetic condition is preserved by 83% after deformation at room temperature. At that hardness is close to martensite structure.

Addition of antibacterial properties to steels opens perspectives of significant broadening of

their application area in medicine, food, oil and gas industries, in water cleaning systems and public utilities.

4. High-strength structural steels microalloyed with nitrogen

The investigated steels [14] are listed in table 8.

Reasonable heating modes for HTMT hardening are defined. The final operation after hardening and HTMT was tempering at 185 °C to obtain high-strength condition. Heating for treatment was conducted at 920–950 °C, i.e. in two-phase area $\gamma + M(C,N)$. Nearly austenitic structure containing carbonitrides V max. 0.01% was obtained. Intensive grain growth took place at higher temperatures. For HTMT blanks were heated to 950–970 °C. Grain size in austenitic area grows with increasing C+N content in steel. Then, grain decreases after HTMT due to recrystallization. Steel hardness increases together with C+N content increase. Steels properties after HTMT and tempering at 185 °C are listed in table 9.

As we can see, HTMT use with further low-temperature tempering allows obtaining extremely high strength and significant plasticity for steels in question, especially after HTMT with RSR deformation. HTMT with RSR deformation creates anisotropy of steel properties with higher properties in axial direction. Therefore these steels are prospective for use in fixtures and long items production [14]. Steel 40CrNiMoV with (C+N) = 0.42% and C/N > 5 after HTMT and low temperature tempering gets high resistance to impact-wave load application.

Table 8. Chemical composition of the studied structural steels, (mass.%)

Steel grade	Cr	Ni	Mo	V	Mn	Si	C	N	C+N
20CrNiMoV	1,22	0,97	0,36	0,21	0,35	0,26	0,170	0,037	0,207
30CrNiMoV	1,29	0,99	0,31	0,24	0,34	0,18	0,300	0,001	0,301
35CrNiMoV	1,50	1,30	0,66	0,25	0,50	0,23	0,340	0,020	0,360
40CrNiMoV	1,38	1,25	0,50	0,24	0,35	0,29	0,368	0,024	0,392
50CrNiMoV	1,78	1,43	0,30	0,50	0,55	0,39	0,510	0,023	0,533

Table 9. Mechanical properties of steels after HTMT with deformation bei longitudinal rolling and radial-shear rolling

Steel grade	Rolling at HTMT	R_m , MPa	$R_{0,2}$, MPa	δ , %	Ψ , %	HRC
20CrNiMoV	RSR	1607	1566	10	50	58
30CrNiMoV	RSR	2011	1796	11	56	56
35CrNiMoV	LR	2052	1850	7	39	58
35CrNiMoV	RSR	2379	1956	8	30	57
40CrNiMoV	LR	2296	1911	7	33	58
40CrNiMoV	RSR	2156	1900	15	52	58
50CrNiMoV	LR	2475	2044	4	13	62
50CrNiMoV	RSR	2284	1979	11	14	60

SR — radial-shear rolling; LR — longitudinal rolling

5. Lightweight steels

Today's and future car manufacturing requires high-strength and highly plastic steels with good damping properties and lower density. These requirements can be met using high-strength Fe-Mn-Al-C based alloys, representing a new group of TRIPLEX alloys with high manganese and aluminum content.

We used methods of metallographic, X-ray diffraction, and magnetometric analysis, phase-rule diagram analysis, and hot compression analysis with the aid of "Gleeble System 3800" test system to investigate structure, properties and processes during hot deformation of cast alloys [15] Fe + (16.8–25.6)% Mn + (0–14.4)% Al + (0.02–2.18)% C + (0.001–0.135)% N, **table 10**.

Cast alloy specimens were cylinders $\varnothing = 5.50\text{--}6.20$ mm, and 9.70–11.45 mm high, which underwent thermal and thermal-mechanical treatment with hot compression deformation at temperature $T = 950\text{--}1000$ °C with deformation rate $\dot{\epsilon} = 0.1$ s⁻¹ along the axis. Specimens after deformation were cooled sharply (at least 50 °C/s) using air nozzles. Cast alloys phase composition calculated according to Thermo-Calc and obtained using X-ray diffraction analysis is shown in **table 11**.

Any alloys, including high-carbon high-alloy Fe-Mn-Al-C alloys deform well at high temperatures up to 40–50% of reduction without hot cracking. Hot deformation resistance (**table 12**) σ_{\max} grows together with increasing of aluminum, carbon and nitrogen content and is naturally lower for ferrite compared to austenite.

Thus, it is possible to obtain high-alloys based on Fe-Mn-Al-C-N in broad range of alloying elements concentration. By adjusting alloy composition and thermo-mechanical treatment modes we can obtain triplex-structure ($\gamma - \alpha - k$ -carbide; $\gamma - \epsilon - k$ -carbide; $\gamma - \epsilon - \alpha$) with various ratio, sizes and distribution of phases that provides various complexes of mechanical and physical properties. Nitrogen addition decreases fusion decomposition, stabilizes austenite, decreases martensitic transformation temperature, and therefore decreases amount of ϵ -martensite that forms during cooling [15]. The investigated alloys are non-magnetic (or low-magnetic) in thermal-processed condition, and thanks to 10–20% decreased density can be used in car manufacturing, for partial replacement of austenitic chrome-nickel corrosion-resistant steels for use in non-critical aggressive environments, units for liquefied gases storage and transport and in cryogenic equipment.

Table 10. Chemical composition of the studied alloys, (mass.%)

Alloy	Mn	Al	Si	Mo	C	N*
1(32K)	16,8	0,01	0,86	2,0	1,62	0,020
2 (35K)	21,2	6,2	0,50	0,20	1,10	0,006
3 (36K)	19,1	7,5	0,60	1,20	1,47	0,002
4 (33K)	19,1	9,0	0,50	0,03	2,18	0,001
5 (34K)	23,9	4,0	0,54	0,01	1,80	0,032
6 (38K)	25,3	0,01	0,20	<0,001	0,02	0,014
7 (39K)	23,7	7,5	0,20	<0,001	0,05	0,008
8 (40K)	22,6	14,4	0,20	<0,001	0,05	0,007
9 (45K)	23,8	4,6	0,20	<0,001	0,05	0,020
10 (41K)	25,6	0,01	0,20	<0,001	0,03	0,135
11 (42K)	23,7	8,1	0,20	<0,001	0,05	0,008
12 (43K)	24,3	11,5	0,20	<0,001	0,03	0,045
13 (44K)	24,1	5,3	0,32	<0,001	0,04	0,024

* – total content of nitrogen in alloy on chemical analysis.

Table 11. Phase composition of cast alloys

Alloy	Phases in cast condition by 25 °C	
	Calculation on Thermo-Calc	Experiment
2	$\alpha + \gamma + Me_xC_y$	$\gamma + \text{kappa}$ (Traces)
4	$\alpha + Me_xC_y + \text{kappa}$	$\gamma + \text{kappa}$
5	$\alpha + AlN + Me_xC_y (+\text{kappa}+AlN)^*$	γ
6	$\gamma + \alpha (+\epsilon+AlN)$	$\gamma + \epsilon + \beta\text{-Mn}$
7	$\alpha (+\gamma)$	α
8	α	$\alpha + \epsilon$
9	$\alpha + \gamma(+AlN)$	$\gamma + \epsilon$ (Traces)
10	$\gamma + \alpha + AlN(+\epsilon)$	$\gamma + \epsilon + \beta\text{-Mn}$
11	$\alpha (+\gamma)$	$\alpha + \epsilon$
12	$\alpha(+AlN)$	$\alpha + \gamma$ (Traces)
13	$\alpha + \gamma(+AlN)$	γ

* – In brackets the phases which are present at a small amount.

Table 12. Phase composition and hot deformation resistance of alloys at $\dot{\epsilon} = 0.1$ s⁻¹

Parameter	Alloys										
	2	4	5	6	7	8	9	10	11	12	13
$T_{\text{def}}, \text{°C}$	1000	1000	1000	1000	950	950	1000	1000	950	1000	1000
PhC*	γ	$\gamma+\text{kappa}$	$\gamma(+AlN)$	γ	$\alpha(+\gamma)$	α	$\gamma(+\alpha)$	γ	$\alpha(+\gamma)$	$\alpha(+\gamma)$	$\gamma(+\alpha)$
PhC**	$\gamma+\text{kappa}$	$\gamma+\text{kappa}$	$\gamma+\alpha++\text{kappa}$	$\gamma+\epsilon+\beta\text{-Mn}$	$\alpha+\gamma$	$\alpha(+\gamma+\epsilon)$	γ	$\gamma+\epsilon+\beta\text{-Mn}$	$\alpha(+\gamma)$	$\gamma(+\alpha)$	γ
$\sigma_{\max}^{1000}, \text{MPa}$	119	198	170	135	67	53	160	150	70	153	180
$\epsilon_{\max}, \%$	12	8	4	45	44	24	23	45	28	21	18

* – Phase composition at deformation temperature on Thermo-Calc.
 ** – Phase composition defined experimentally on X-ray diffraction.

Conclusion

Nitrogen is currently a quite normal alloying element together with C, Cr, Mn, Ni, etc. It provides unique combination of strength, plasticity and corrosion resistance for steels. Industry uses a lot of nitrogen-alloyed steels of various structure classes — austenitic, ferrite, martensite and two-phased. In future these steels are quite possible to replace light and non-ferrous metals' alloys. Alloying steels with nitrogen is very promising to give then special functional properties for example corrosion resistance in bioactive environments, bactericidal activity or disinfecting ability, high resistance to special impacts, lightweight steels with lower density and high strength and plasticity.

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Simulation of hydrodynamics and heat transfer in implementation of hard particles in metal melt

The mathematical models for the introduction of a one-dimensional refractory spherical particles in the liquid metal and its thermal state are proposed. The simulation of the heating of silicon carbide particles at their introduction into the steel melt at different fineness of the powder has been conducted.

Using computer modeling the dependences of the maximum depth of penetration of the powder of silicon carbide in the

melt and the kinetics of its heating from the particles diameter have been found. The computer program “Hydrodynamics and HMTE of introducing solid particles into the melt” in the Mathcad 14 environment, allowing to conduct computer simulation of introducing of the refractory particles in the melt and their thermal state with regard to freezing and melting of a solid crust on their surface, have been created. It is seen that the diameter of the particles and their