Nitrogen Steels and High-Nitrogen Steels: Industrial Technologies and Properties

Alexandr Svyazhin, Liudmila Kaputkina, Inga Smarygina, and Dmitry Kaputkin*

Nitrogen pressure during melting can be a basis for the most general classification of steels alloyed by nitrogen. Nitrogen steels are made under normal pressure, and high-nitrogen steels are made under pressure, being higher atmospheric in special units. Nitrogen, as well as carbon, strengthens and increases the thermal stability of austenite. The smaller size of the nitrogen ion compared with carbon results in smaller nitrides, lower surface energy and higher strengthening effect, and the ability to increase both the strength and corrosion resistance of austenite. Herein, the mechanisms of the influence of nitrogen on the properties of steel, the thermodynamics and kinetics of alloying with nitrogen, the critical concentration of nitrogen, and the influence of nitrogen on the properties of steels are considered. Examples of nitrogen and high-nitrogen steels, including weld joints, steels with special properties, such as corrosion-resistant steels in bioactive environments, bactericidal steel, and steels alloyed by C + N, are given.

1. Introduction

Today, nitrogen is not an exotic element anymore; it has become more widespread as one of the most promising alloying elements, providing new opportunities in the creation of materials based on iron alloys. Small variations in nitrogen and main alloying element levels can result in the creation of steels with particular functional properties for different types of technical devices.[1]

Considerable progress has been made in recent years in understanding alloying steels with nitrogen under normal and high pressures and studying the nature of the processes of forming the structure and properties of nitrogen steels, and new areas of applications of these steels have been set out. The commercial-scale production of alloying steels with nitrogen for different branches of the industry has grown.[2] Currently, nitrogen-alloyed steels of different structural classes (austenitic, martensitic, and multiphase) are used in nuclear and power energy, chemical industry, medicine, aviation, automobile construction, shipbuilding, general engineering, mining engineering, and defence technology.[3] However, it should be noted that the potential of nitrogen in improving the properties of steel has not been exhausted.

Nitrogen, as an austenite-forming element, is a substitute for nickel. A decrease in nickel content in the steel even for 1% will result in a significant decrease in steel production cost. Classic stainless steel Cr18Ni(8-10) in many cases could be substituted with steel with low nickel content or even with steel without nickel with better properties. Moreover, nickel has proved to be an allergen, which also favors the spreading of nickel-free steels.

In case of alloying steels with nitrogen, it is possible to expand fields of effective applications due to improving specific properties. Nitrogen can provide specific properties to steels. Therefore, the development of new steels with special functional properties such as resistance in a bioactive environment, bactericidal properties, high constructional strength, etc.[1] can be also a perspective direction of the development and application of alloying steels with nitrogen. Thus, the main global trend is expansion of production and consumption of cost-effective low-nickel or nickel-free alloying steels with nitrogen of different structural classes.

2. Classification

The term high-nitrogen steels, commonly used for alloying with nitrogen, is not very informative for the widespread use of these steels. This only shows that the nitrogen content of steel is higher when nitrogen is treated as an impurity. For example, high-nitrogen steels mean steels with nitrogen content between 0.1 and 1.0%. This means that the development of more defined terminology is required.

Nitrogen content in steel depends on steel composition, temperature, and nitrogen pressure during alloying and the formation of δ-phase upon crystallization. By any way of introduction of nitrogen into steel, its content in the metal will be determined by gas-phase pressure. Therefore, nitrogen pressure during alloying can be the basis for the general classification of steels alloyed with nitrogen. We identified three groups of nitrogen steels depending on nitrogen pressure during melting: nitrogen microalloyed steels, nitrogen steels, and high-nitrogen steels.[4,5] Such a classification provides information about the technology of the
production process and the possible nitrogen content for a given ratio of other elements.

Nitrogen and nitrogen microalloyed steels are alloyed at normal pressure. They differ in chemical composition. Microalloyed steels are basically carbon and low-alloyed steels with ferrite matrix. Solubility of nitrogen in ferrite is lower than in austenite and liquid metal. Total nitrogen content in these steels is limited also by discharge of nitrogen dissolved in the metal into the gaseous phase during crystallization through δ-ferrite and formation of bubbles in the ingot. Nitrogen dissolution in the nonalloyed ferrite is low and nitrogen affects steel properties via nitride and carbonitride.

Nitrogen-containing steels contain elements that increase the solubility of nitrogen in liquid or solid metal, such as Cr and Mn. These steels crystallize via austenitic and the mixed γ + δ mechanism. Nitrogen solubility in alloyed austenite is higher than in liquid metal. In such a case, it is possible to keep all nitrogen dissolved at melting temperature without bubble formation. Nitrogen content in nitrogen steels can be ≥1%. Such level of nitrogen sufficiently changes steel properties. Nitrogen affects properties of nitrogen steels through the solid solution and the excess phase.

High-nitrogen steels (HNS) have nitrogen content higher than equilibrium with $P_{N_2} = 0.1$ MPa. A special hyperbaric reactor is required to produce such steels. Superequilibrium content of nitrogen in the steel can be reached with plasma arc welding at atmospheric pressure. Nitrogen content in high-nitrogen austenite steels can be more than 1%. At high pressure, the maximum nitrogen content is reached and the unique properties of nitrogen as an alloying element are fully exploited. So, melting at high nitrogen pressure allowed to obtain austenite nonmagnetic chromium steel Cr24N1 without austenite-forming elements Ni, Mn, and Co. Nitrogen and high-nitrogen steels can have a comparable nitrogen content, but in case of nitrogen steels, it is possible only at significantly higher chromium and manganese content. For example, the nitrogen contents of Boehler grades P558 (high-nitrogen steel) and P563 (nitrogen steel) are the same (0.5%)[7]. However, P558 contains 10% of Mn and 17% of Cr and is manufactured with electroslag remelting (ESR) under pressure, but P563 contains 23% Mn and 18% Cr and is produced at normal pressure using the argon–oxygen decarburization (AOD) converter.[7]

Properties of the steels are different. The assignment of steel to nitrogen or high-nitrogen steel provides information on the manufacturing method and expected cost of manufacture and archived level of properties.

3. Mechanism of Nitrogen Influence on Steel Properties

Nitrogen and carbon are typical interstitial elements in iron steels. However, the effect of nitrogen as the alloying element differs from carbon effect. Carbon hardens austenite but decreases its corrosive resistance due to chromium carbide precipitation. Nitrogen also hardens austenite but increases austenite thermal stability, it has smaller ion sizes and higher solubility in γ- and α-phases. Austenite and nitrides have the equivalent crystalline lattice. Nitrogen atoms in nitrides occupy octahedral interstices, and disposition of their nearest neighbors is similar as in austenite. It results in smaller nitride sizes, smaller surface energy, and bigger strengthening effect and possibility of simultaneous increase in strength and corrosive resistance of austenite.[8] They also have different electronic structures. Carbon and nitrogen atoms are electron donors. Transfer of electron from interstitial atom to iron is higher in nitrogen austenite compared with carbon one, so interatomic bonding in the first case is stronger. Spatial charge distribution in the nitrogen austenite lattice is more symmetric. Alloying with nitrogen results in electron allocation, that is, strengthening of covalent binding in austenite.[8] Nitrogen in contrast to carbon decreases stacking fault energy, that is, splits dislocations. The split of dislocations results in stronger interaction of dislocations with nitrogen atoms and to decrease in dislocation mobility, which results in a high strain-hardening coefficient, wear resistance, and relaxation resistance of nitrogen austenite.[8] Specified effects determine high thermal stability of nitrogen austenite and therefore they provide opportunity to obtain a homogenous solid solution with high level of nitrogen and relatively high strength without discharge of excess phases.

Solubility of nitrogen in α solid solution is higher than the same for carbon, but significantly lower than in γ. Nitrogen and carbon as interstitial elements increase strength but decrease plasticity of ferrite. Due to low solubility of nitrogen, its influence on properties of ferrite steels is mainly due to excess phases of nitrides and carbonitrides.

4. Nitrogen Solubility in Ferroalloys

At standard condition, nitrogen is a gas. As an interstitial element, it has limited solubility both in liquid and in solid ferroalloys. Not only technologists but also engineers require knowledge about nitrogen solubility in metals at different temperatures and nitrogen pressures with high accuracy if possible.

Up to date, numerous studies of nitrogen solubility in ferroalloys were conducted. However, in this case, the quantity did not result in quality. There is no well-balanced database and thermodynamic model. Proposed models correspond only to the experimental data, based on which they were developed. In the commercial databases, a statistical averaging of different experimental data for various alloys obtained by different methods was used. That is incorrect, because observed difference in the raw data mainly result from measurement errors. In other articles,[9,10] a significant difference for the value $A$ in Equation (3) obtained with various methods with probability 0.95 by Sievert’s method, $A = 395 ± 120$, and by sample method, $A = 760 ± 120$, was established. This excludes the joint statistical processing of data obtained by different methods. Thus, the obtained results do not correspond to the experiment, but also with calculation for separate models.[7]

Solution thermodynamics in liquid ferrous alloys

\[
\frac{1}{2}N_2 = [N] \quad (1)
\]

\[
K_N = \frac{[N] \times f_N}{\sqrt{P_{N_2}}} \quad (2)
\]
\[ gK_N = \frac{A}{T} + B = -\frac{\Delta H^0}{2.3R} + \frac{\Delta S^0}{2.3R} \]  

\[ f_N = \frac{\left| N_{Fe}^0 \right|}{\left| N \right|} \text{ at } T = \text{ Const.} \]  

\[ \log [N] = \log K_N - \log f_N + 1/2 \cdot \log p_{N_2} \]  

\[ \log f_N = \sum_{i=1}^{n} e_i \times [i] + \sum_{i=1}^{n} r_i \times [i]^2 + \sum_{i=1}^{n} \sum_{j \neq i}^{n} r_{ij} \times [i] \times [j] \]  

\[ + \sum_{i=1}^{n} r_i \times [i]^3 + \sum_{i=1}^{n} \sum_{j \neq i}^{n} r_{ij} \times [i]^2 \times [j] + \sum_{i=1}^{n} \sum_{j \neq i}^{n} r_{ij} \times [i] \times [j] \times [k] \]  

where \( K_N \) and \( f_N \) are the equilibrium constant and nitrogen activity coefficient; \( p_{N_2} \) is nitrogen pressure in atm; \( e_i, r_i, t_N \) are the first-, second-, and third-order interaction parameters including nitrogen self-interaction parameters \( e_i^{\text{self}}, r_i^{\text{self}} \); \( \Delta H^0 \) and \( \Delta S^0 \) are enthalpy and entropy change at nitrogen dissolution, respectively; \( R \) is the universal gas constant in J (mol K)^{-1}; and \( T \) is temperature in K.

Equation (1)–(6) represent thermodynamic model of nitrogen solutions in ferroalloys, including the case of high-nitrogen levels, which are accounted in Equation (6) with interaction of third-order parameters \( t_{ij} \). In pure iron, \( f_N = 1 \); therefore, in accordance with Equation (2) equilibrium constant equals nitrogen solubility in pure iron at \( P_{N_2} = 1 \) atm.

At present, the interaction parameter method (Equation (6)) is commonly used for description of concentration dependence of the nitrogen activity coefficient in alloys. Limits of applicability of this method are discussed in detail in the study by Svazhin et al.\(^{[11]} \) The nitrogen solubility in the iron disobeys Sievert's law for high-nitrogen steels. Deviations from Sievert's law were first established in the study by Rashev et al.\(^{[12]} \) in Fe–Cr–N alloys at \( P_{N_2} > 1 \) MPa. Therefore, both for nitrogen alloys with high-chromium and vanadium levels and for high-nitrogen steels to obtain maximum accuracy possible currently in Equation (6), first-, second-, and third-order parameters should be used. Self-interaction parameter \( e_i^{\text{self}} \), third-order nitrogen interaction parameter by chromium and vanadium, and molybdenum\(^{[16]} \) were established. In accordance with data\(^{[16]} \)

\[ t_{N,\text{Cr}}^{\text{N, Cr, Cr}} = -\frac{0.07}{T} + 1.03 \times 10^{-5} \]  

\[ t_{N,\text{N,N}}^{\text{N, N, N}} = \frac{0.29}{T} - 0.0002 \]  

\[ t_{N,\text{Cr,N}}^{\text{Cr, Cr, Cr}} = -\frac{0.60}{T} + 2.1 \times 10^{-4} \]  

\[ t_{N,\text{Cr,V}}^{\text{Cr, V, V}} = -\frac{4.3}{T} + 8.9 \times 10^{-4} \]  

For example, with respect to all known interaction parameters, the nitrogen solubility equation for Fe–C–Cr–Mn alloys is as follows.

\[ \log [N] = \log K_N + 1/2 \log p_{N_2} - \left( [N] + [C] + [Cr] + [Mn] + [C]^2 + [Cr]^2 + [Mn]^2 + [C][Mn] + [N][Mn] \right) \]  

\[ + [N][Cr] + [N][Cr]^2 \]  

Equation (11) is solved by the method of successive approximations. After substitution with numeric values for equilibrium constant and known interaction parameters from other studies\(^{[9]} \) or,\(^{[13]} \) the lengthy equation is obtained. Though separate values of such parameters as \( e_i^{\text{self}}, r_i^{\text{Cr, N}}, t_{N,\text{Cr, Cr}}^{\text{N}} \) are small, they should be considered because in sum they provide noticeable correction to nitrogen solubility at high levels of Cr, Mn and \( P_{N_2} \) > 1 atm.

Activity coefficients and interaction parameters are calculated from the nitrogen solubility value in pure iron, that is, interaction parameters are correlated with the equilibrium constant value in a specific work and are valid only for this specific group of experimental data. Therefore, correct choice of equilibrium constant values and interaction parameters by tabular data decrease accuracy of calculations. In the current situation, it is better to use experimental data for the specific alloy from the original studies. The following reference values are preferable during data selection: \( K_N = 0.044 \) and \( A \geq 600 \). For example, for Fe–C–Mn–Cr–Si–Ni alloys, data can be recommended in a relatively broad temperature interval and element levels.\(^{[13]} \)

Acceptable results for nitrogen solubility in liquid ferroalloys can be obtained by the equation provided in the work by Sokolov et al.\(^{[17]} \) by processing of huge datasets based on one value for the equilibrium constant \( (A = 850) \) by the equivalent concentration method. Program Thermo Calc with database TCFE of various versions is widely used for determination of nitrogen solubility.

5. Critical Nitrogen Concentration

Nitrogen solubility in liquid metal α and γ phases is significantly different. Therefore, one of the technological problems is the precipitation of nitrogen into gas phase upon the solidification of steels and the formation of nitrogen bubbles and porosity in ingots. To maximize the nitrogen affect as alloying element, it is necessary to increase its content in steels. From the other side to obtain solid ingot, it is necessary to limit nitrogen level in steels before solidification. Therefore, during steel crystallization through δ-ferrite, capabilities of nitrogen as alloying element are not used at a full extent. Critical nitrogen level \( N_k \), exceeding of which will result in the formation of bubbles and pores, depends on steel composition. During solidification, liquid-phase composition and evolving solid phase continuously change at the temperature change and liquid-phase quantity. At the same time, local nitrogen solubility in the liquid phase changes also. The nature of this change depends on crystallization type, austenitic, ferrite, or combined, and on ratio of phase quantity.\(^{[18]} \)

At present, acceptable results can be obtained by the thermodynamic method. Such a relatively simple way allows to obtain the relatively accurate preliminary assessment of value of \( N_k \), which can be later defined experimentally. The following condition should be met during the solidification period and such a condition is a basis for \( N_k \) determination.\(^{[18]} \)
\[ [N]_{LT} < [N]_{LEq, Ptot} \]  \hspace{1cm} (12)

where \([N]_{LT}\) is the nitrogen content in residual liquid at temperature \(T\) and \([N]_{LEq, Ptot}\) is the equilibrium nitrogen level together with total pressure in the system in liquid metal at the same temperature \(T\).

In Figure 1, equilibrium and nonequilibrium (by Shell’s model) crystallization of nitrogen steel Fe-0.12C-18Cr-18Mn-N is provided.\(^{[18]}\) Calculation is done using program Thermo Calc with thermodynamic base TCFE6.

In such a case, condition (12) is met at the initial nitrogen content \(<0.6\%. At initial content, 0.6\% actual nitrogen content in liquid phase exceeds its equilibrium solubility (marked as the bold dash-and-dot line) at total pressure 1 atm; nitrogen is precipitated in the form of gas. Nitrogen quantity precipitated into the gas phase is provided in the table in Figure 1. At the end of the solidification, because of the formation of \(\gamma\) phase with high nitrogen solubility, nitrogen level in the liquid phase is lower than its solubility (Figure 1). Therefore, based on Figure 1, it can be concluded that for this case \(N_k < 0.60\%. In the work,\(^{[18]}\) \(N_k = 0.50\%\) is more precisely obtained. Based on the study by Stein et al.\(^{[19]}\) nitrogen content in industrial ingot is 0.50\%, but in accordance with Kolpishon et al.,\(^{[20]}\) it is 0.60\%.

6. Nitrogen Alloying of Steel

The technology of the volumetric alloying of steel with nitrogen in the solid condition was not developed. At present, nitrogen alloying is produced in liquid condition during steel melting.

During HNS production at commercial size, the following three technologies are used: plasma arc welding, electric-slag melt under pressure, and pressure melting in induction furnace. Considering high efficiency of nitrogen as an alloying element, at present, only technologies, which allow obtaining the nitrogen-assigned level in narrow limits, are used.

Plasma arc welding (PAW) is performed at pressure close to standard;\(^{[21]}\) nitrogen in plasma is in the ionized and excited state. Therefore, PAW allows under normal pressure in a system to obtain the nitrogen content in ingot equivalent to equilibrium 1 under nitrogen pressure 0.3-0.5 MPa.\(^{[21]}\) Technology PAW was not widespread, as saturation of metal with nitrogen is hard to control; therefore, its stable content in the ingot within narrow limits is not provided.

ESR used for HNS production differs from classic ESR in that the ingot and consumable electrode have different compositions; in the process of remelting, the additional materials are introduced into the system, that is, nitrogen carriers. Nitratred ferroalloys Mn, Cr, and V can be used as nitrogen carriers. The current standard technology of metal nitration at ESR is the automatic transfer to slag of silicon nitride Si\(_3\)N\(_4\), corresponding to remelting velocity. The manufacture of high-nitrogen steels by the ESR method is mainly located in companies such as Boehler, Sandvik, and Energietechnik Essen for specialized products for energetics, transport and chemistry, where manufacturing costs are covered by unique properties, achieved through the nitrogen alloying of these steels at high pressure. For example, Boehler produces both high-nitrogen and nitrogen steels, as shown in Table 1.\(^{[7,22]}\) They differ in Cr and Mn content and at comparable content of nitrogen. The nitrogen steels noted in Table 1 were specially designed for melting at atmospheric pressure. This reduces the cost of their

Table 1. Some austenite steels of the company Boehler.\(^{[7]}\)

| Steel | Content [wt%] | Melting type |
|-------|---------------|--------------|
|       | C  | Mn | Cr | Mo | Ni | N  |
| P557  | 19 | 18 | –  | –  | –  | 0.6 |
| P557  | 0.20| 10 | 17 | 3.1| –  | 0.5 |
| P559  | 18 | 18 | 1.9| –  | –  | 0.8 |
| P555  | 20 | 18 | 0.3| 1  | 0.6 |
| P560  | 24 | 21 | 0.3| 2  | 0.9 |
| P562  | 0.15| 18 | 22| –  | –  | 0.7 |
| P563  | 0.10| 23 | 18 | 2.5| 4  | 0.5 |

![Figure 1. Nitrogen content in liquid (L) and austenite (γ) phases during the crystallization of steel Cr\(_{18}\)Mn\(_{18}\) with initial nitrogen concentration of 0.6%. a) at equilibrium crystallization and b) at nonequilibrium.\(^{[18]}\)](image-url)
production. The mentioned company uses ESR method mainly for steels with high-purity requirement.[7]

One expects that the next step of ESR development will be arc-slag remelting (ASR) under pressure,[23] which can reduce specific consumption of electricity for the process and increase crystalline and chemical homogeneity of the ingot. Approbation by Energietechnik Essen of this process on the working equipment of ESR did not provide expected results.[24] Energy consumption was reduced by 30%, a smoother surface of the ingot was obtained, but nitrogen consumption from gas phase and metal purity by nonmetal impurities was insufficient. Authors believe that disadvantages can be eliminated by modifying the automatic process control system. ESR method is relatively widespread, also at pilot scale.[25,26]

Melting of HNS in the induction furnace under pressure, the method of using the big steel-melting bath (SMB), is given.[12] Maximum melting weight was 10 g and pressure was up to 1.6 MPa. A number of installations for melting and teeming HNS with metal weight from 2 to 10 g at a pressure up to 1.6 MPa[23] has been developed. Nitrated ferroalloys and gaseous nitrogen can be used as nitrogen carriers. In practice, nitrogen alloying is carried out mainly with nitrated ferroalloys, that reduces the duration of metal holding at high pressure. Equipment for 10 ton includes two chambers, for melting and for casting, that result in reduction of the total production cycle. Upon melting and adjusting of the metal by chemical composition in the melting chamber, the pressure was high to define the value and metal was alloyed with nitrogen. Then finished steel is transferred into a tundish via a chute located in the casting chamber. The casting chamber is sealed air tight, a pressure required for teeming of this steel is set (equals or higher than pressure at alloying), and teeming into one or more ingots is done. At the same time, next melting is prepared in the melting chamber. Difference in pressure in melting and teeming chambers are important for steels, crystallized with the formation of δ-ferrite. Preserving nitrogen content obtained in liquid steel pressure at the teeming chamber for this steel should be higher than in liquid steel at the temperature of liquids. Thereby, higher nitrogen content in steel can be obtained in comparison with ESR at the same pressure during alloying. This technology does not have any limitations for melting duration, composition of melted steels, and composition of nitrogen carriers. The induction mixing of melting guarantees homogeneity of chemical composition and temperature of liquid metal. The ESR method has multiple stages: melting in arc furnace, forming of ingot and production of electrode for remelting, and remelting of electrode. Melting in induction furnace is a one-step method, including only melting on a regular furnace burden. Moreover, specific consumption of electricity at ESR is higher than at induction melting under pressure.[27] The SMB method is also used in laboratory testing. Daido Steel has a pilot machine, 0.5 g with pressure 2 MPa.[28] Industrial unit at 1.8 g with pressure 0.5 MPa was developed by Materials and Metallurgical Research, Czech Republic.[29]

Nitrogen steels are melted under atmospheric pressure in accordance with technologies for melting of stainless steel. Gaseous nitrogen is widely used as the nitrogen source during melting of nitrogen steels along with nitrated alloys. While using nitrated alloys, nitrogen consumption is 60–80%. Simultaneously with nitrogen, other elements are transferred into the metal; therefore, a selection of respective nitrated alloys is required for each type of steel. Gaseous nitrization is significantly cost effective; at the same time, there is no limitation for metal composition. Therefore, the major number of nitrogen steels is manufactured using processes of AOD or vacuum oxygen decarburization (VOD). Steel alloying is possible by gaseous nitrogen in a ladle. The typical scheme of nitrogen steel melting is AOD or VOD–ladle furnace–teeming to ingot or continuous teeming. However, depending on local condition, it can have some options. 1) For Cr–Mn steels, for example for Cr18Mn18 with a content of \( N = 0.60\% \), the scheme includes VOD – ladle-furnace whis Mn introducing – blowing in ladle through immersed tuyere – teeming into ingots.[109] 2) The scheme of manufacturing of sheets of various classes of nitrogen steels includes AOD or VOD – ladle–furnace – continuous casting machine (slab or bloom).[31] 3) In Schmiedewerke Groeditz (Germany), nitrogen alloying is done by steel blowing in a 35 ton ladle through an immersed tuyere at specified nitrogen content \( N > 0.080\% \) and blowing through a porous plug to the bottom at \( N < 0.080\% \).[32] During blowing through tuyere at gas rate up to 3000 \( L \) \( min^{-1} \), the nitrogen consumption rate is higher, blowing time and metal cooling is lower (up to 70 °C), but nonmetal impurities’ content in the finished steel is higher due to the decomposition of tuyere lining and uptake of slag. Blowing through the bottom of the ladle is done with gas rate up to 600 \( L \) \( min^{-1} \). Blowing time and temperature loss are higher (up to 120 °C), but blowing is still and there is no slag uptake.[33] At atmospheric pressure, the nitrogen solubility rate in steel decreases due to decrease in metal temperature compared with aggregate and increasing of influence of surface-active elements oxygen and sulfur. Therefore, before introduction of nitrogen, the metal should be strongly deoxidized and desulfurized. To saturate steel with nitrogen for a technologically acceptable time, a relatively high gas rate is required. Therefore, at blowing steel with nitrogen in the ladle, a free ladle side is required, in the same way as in the VOD process. A model of the gas-alloying process is necessary to control nitrogen absorption and receive its content in required narrow limits.

In other works,[33,34] a universal kinetic model for the blowing case of different steels has been obtained including high-nitrogen alloys in 1–300 ton ladle.

7. Nitrogen Influence on Steel Properties

Impurities complicate the obtaining of the specified structure and properties and they decrease effect of nitrogen introduction on steel. Therefore, as a rule, nitrogen steels, and first of all high-nitrogen steels, are melted in accordance with pure steel technology. Alloying with nitrogen is followed with the complex change of phase and structural condition of steel during thermal treatment. High efficiency of nitrogen strengthening is reached by implementation of all strengthening mechanisms: deformation, solid solution, dispersion, and grain boundary. Solid-solution strengthening with nitrogen is higher than with carbon. Structural and grain boundary strengthening in nitrogen steels can also be effective, as nitrides can preserve fine grains up to higher temperatures than carbides.

Nitrogen decreases temperature at the beginning of martensitic conversion Mn, that is, it increases stability of austenite during cooling but due to decrease in stacking fault energy, it
increases the tendency for formation of deformation martensite and can change conversion type from $\gamma \rightarrow \alpha$ to $\gamma \rightarrow \epsilon \rightarrow \alpha$ and respectively it increases smoother development of the transformation-induced plasticity (TRIP) effect. Therefore, the structural hardening of nitrogen steels requires more strict following of the processing methods of the treatments of such steels.[5]

In general nitrogen alloying is applicable for steels with different compositions and applications (structure, tool, corrosion resistant, steels with specific properties). It can be low-alloyed low-carbon steels with small additions of nitrogen to obtain fine grains or alloyed and highly alloyed corrosion-resistant and heat-resisting steels, in which nitrogen content can reach greater than that of nitrogen-free ones with the same ductility and toughness. Corrosion resistance of these steels is very susceptible to their structural condition; therefore, upon strengthening of these steels, a clear following of their production and treatment modes is required.

The achieved strength level after high-temperature thermomechanical treatment (HTMT) of austenitic, martensitic, and two-phase aging nitrogen and high-nitrogen steels is significantly higher than that of nitrogen-free ones with the same ductility and toughness. Corrosion resistance of these steels in the weak corrosion environment corresponds to corrosion resistance of ferromagnetic phase was identified by magnetic method only in the neck area (Table 3). Intensive formation of martensitic deformation in nitrogen steel type Cr18Ni10N results in higher trend for formation of deformation martensite compared with nitrogen-free classic Cr18Ni10.

Steel Cr18Ni5Mn9Mo2N remained nonmagnetic (austenitic) in all the area of homogenous deformation (up to 20%) and only after deformation to fracture (92%) a small amount of ferromagnetic phase was identified by magnetic method only in the neck area (Table 3). Intensive formation of martensitic deformation in nitrogen steel type Cr18Ni10N results in their strong mechanical hardening and determines high ratio of $\sigma_b/\sigma_0$.

So, at room temperature, parameters for classic stainless steel increase with increase in nitrogen content and are equal to $\sigma_b = 231–399$ MPa and $\sigma_0 = 514–748$ MPa at plasticity at the level $\delta = 47%–63%$. Temperature during the beginning of martensitic conversion is noticeable, decreasing $M_T$ from +23 to −13°C upon increasing nitrogen content up to 0.22%.

Low-nickel steels 5 and 6 are the most strengths of note in Table 2. Steel 5 (Cr18Ni5Mn9Mo2N) at a room temperature has $\sigma_0 = 543$ MPa and $\sigma_b = 835$ MPa at good plasticity $\delta = 50%$. Due to increase in the nitrogen content in this steel up to 0.31% (steel 6), strength is significantly increased, $\sigma_0 = 691$ MPa and $\sigma_b = 926$ MPa, and plasticity remains at the acceptable level $\delta = 33%$. Compared with stainless steel Cr18Ni10N, temperature of martensitic transformation is significantly reduced up to −254°C for steel No6 (Cr18Ni5Mn10Mo2N).

Steels 5 and 6 are the most thermally and deformation stable, relative to martensitic transformation compared with nitrogen-alloyed classic Cr18Ni10.

### Table 2. Mechanical properties and temperature estimate of the beginning of martensitic transformation.

| № | Steel   | $T_{\text{ass}}$ [°C] | HV, [MPa] | $\sigma_0$, [MPa] | $\sigma_0.2$, [MPa] | $\delta$ [%] | $\psi$ [%] | KCU (KCV) [MJ m]$^{-2}$ | $M_T$ [°C] |
|---|---------|----------------------|-----------|------------------|-------------------|-------------|-----------|--------------------------|----------|
| 1 | Cr18Ni5Ti | +20                  | 210       | 514              | 231               | 47          | 51        | (2.2)                    | 23       |
| 2 | Cr18Ni5N (N = 0.135%) | +20           | 258       | 527              | 316               | 29          | 63        | (2.2)                    | −14      |
| 3 | Cr18Ni5N (N = 0.186%) | +20           | 241       | 714              | 354               | 25          | 67        | (1.7)                    | −7       |
| 4 | Cr18Ni5N (N = 0.220%) | +20           | 240       | 748              | 399               | 63          | 84        | 3.9                      | −15      |
| 5 | Cr17Ni5Mn9Mo2N (N = 0.240%) | +20           | 255       | 835              | 543               | 50          | 72        | 2.6                      | −126     |
| 6 | Cr17Ni5Mn10Mo2N (N = 0.310%) | +20           | 298       | 926              | 691               | 33          | 62        | −                          | −254     |

### Table 3. Assessment of austenite at mechanical tests.

| № | Steel grade | TRIP [°C] | Magnetism in the region of homogenous deformation | Magnetism in neck | Shock bending test |
|---|-------------|-----------|-----------------------------------------------|-------------------|-------------------|
| 4 | Cr18Ni5N (N = 0.220%) | +20       | Weakly magnetic | Weakly magnetic | Magnetism away from damaged area |
|    |             | −163      | Strongly magnetic | Strongly magnetic | Nonmagnetic |
| 5 | Cr17Ni5Mn9Mo2N (N = 0.240%) | +20       | Nonmagnetic | Nonmagnetic | Magnetism around the area of fracture |
|    |             | −163      | Nonmagnetic | Weakly magnetic | Nonmagnetic |

### Notes:
- $\sigma_b$ at −196°C.
- Region of homogenous deformation and; $\psi$ Quantity of austenite in undeformed samples determined by X-Ray.
for austenitic steels, increases the tendency to martensite formation under load, especially close to or below $M_n$, that is, it limits working temperature of such steels.

Nonmagnetic nitrogen steels based on Cr18Ni10N with nitrogen content up to 0.22% can be used as cryogenic, with high hardness, for nondeforming products; otherwise, at temperatures below −70 °C, martensite deformation will always form in them. Simultaneously high hardness, plasticity, and viscosity (especially in case of increased purity by harmful impurities) for such steels can be reached only by the TRIP effect or fine grains.

Nitrogen alloying of classic stainless-steel type Cr18Ni10N up to 0.22% in the absence of the additional introduction of nitrides shows potential for increasing the corrosion stability in weak aggressive media (sea salt), as shown in Table 4. At the same time, corrosion resistance of these steels in strongly aggressive media (H₂SO₄ and especially H₂SO₄) and sea water (3% NaCl) by various parameters (IGC, total, pitting, and crevice corrosion) is not higher or lower than that of nitrogen steel-type Cr18Ni10N and traditional nitrogen-free stainless steel.

At the same time, content of nickel in Cr₁₈Ni₅Mn₉Mo₂N steel is two times lower. Though solid-solution hardening of austenite and ferrite due to nitrogen is relatively high (2–4 times), but due to relatively low total nitrogen and carbon achievable level in solid solution, maximum high hardening in these steels is reached by precipitation hardening of austenite (martensite deformation will always form in them). Simultaneously high hardness, plasticity, and viscosity (especially in case of increased purity by harmful impurities) for such steels can be reached only by the TRIP effect or fine grains.

Nitrogen corrosion resistance of chromium nitrides from 600 to 1100 °C and decrease in optimal austenitization. With increase in nitrogen content in steel Cr₁₈Mn₁₂, pitting corrosion resistance and to piping effect are also increased.[39] Steels Cr₁₈Mn₁₄N and Cr₁₈Mn₁₂ are widely used as high-strength, corrosion-resistant nonmagnetic material.

8. Steels with Specific Properties

Nitrogen can add specific properties to steel. Therefore, the development of new steels with specific functions such as resistance in the bioactive environment, bactericidal properties, high constructional strength, etc. is prospective.[1]

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. We studied the ability of nitrogen-alloyed chromium–nickel steels to microbiological corrosion in environments rich with hydrogen sulfide and advantageous for sulfate-reducing bacteria generation. In our experiments, we used cumulative cultures of hydrocarbon-oxidizing and sulfate-reducing bacteria extracted from reservoir water of Kuedino-Krasnoyarskoye deposit. Research results are represented in Table 5 and 6.[40] Chromium–nickel nitrogen-alloyed steels demonstrate much less tendency to adhesion, that is, greater resistance to corrosive

### Table 4. Steels’ resistance to different types of corrosion.[33]

| Steel                  | Number of adhered microorganisms [cells cm⁻²] | Ability to adhesion |
|-----------------------|---------------------------------------------|--------------------|
| 36CrMnMo₆N, N ≤ 0.01% | (8.4 ± 0.4) x 10⁶                           | High               |
| 07Cr₁₈Ni₅Mo₃N, N ≤ 0.01% | (4.3 ± 0.4) x 10⁷                       | Low                |
| 05Cr₁₈Ni₅Mo₃N, N = 0.12% | (0.3 ± 0.2) x 10⁴                      | Low                |
| 05Cr₁₈Ni₅Mo₃N, N = 0.12% | (0.2 ± 0.1) x 10⁴                      | Low                |

### Table 5. Steels’ ability for microorganism adhesion.

| Steel | Total parameters | Total parameters | Acid medium (0.5 M H₂SO₄) | 0.5M H₂SO₄ with H₂S blowing | Sea water (3% NaCl) | 0.5M H₂SO₄ + 0.01M KSCN | Pitting corrosion FeCl₃·6H₂O |
|-------|------------------|-----------------|---------------------------|-----------------------------|---------------------|-------------------------|-----------------------------|
| 3. Cr₁₈Ni₅N (N = 0.186%) | 2                | unstable         | 3                         | 2                          | 3                    | 3                                      |
| 4. Cr₁₈Ni₅N (pure, N = 0.220%) | 3               | unstable         | 2                         | 1                          | 2                    | 2                                      |
| 5. Cr₁₈Ni₅Mn₉Mo₂N | 1                | unstable         | 1                         | 3                          | 1                    | 1                                      |
Adhesion and resistance to microbic fouling and corrosive film formation compared with common construction steel 36CrMnMo. Introduction of even 0.12% of nitrogen into steel is more effective than addition of nickel. The number of adhered microorganisms on 07Cr14Ni3Cu2MoNbN steel sample surface without nitrogen is about eight times more than that on the 07Cr14Ni3Cu2MoNbN steel sample surface with 0.12% of nitrogen. Increase in nickel content in steel by 2% and 4% decreases the number of adhered microorganisms on steel samples surfaces only two times, as shown in Table 5.

Copper is the second (after silver) bacterial-active element. Disinfection activity of chromium–nickel steel additionally alloyed by Cu and N was investigated.[41] Test results show (Table 6) that steels with high copper and nitrogen content during direct contact with solution with bacteria exhibit bactericidal activity related to S. aureus and Escherichia coli, and efficiency depends on bacteria concentration. If metal samples are contaminated with S. aureus culture, bacteria number decrease on steel specimens alloyed by copper (5%) is 100% in 24 h and 10.71% on specimen containing 1.5% of copper (Table 7).

Thus, samples of chromium–nickel steels containing 5% copper exhibit a disinfecting ability, in contrast to similar steels containing up to 1.5% copper. High copper content in steel (over 5%) significantly increases the ability of the studied material to kill bacteria of S. aureus and Escherichia coli classes. Bactericidal properties of steels alloyed with nitrogen are about 10% higher in prolonged tests compared with steels containing no nitrogen. Furthermore, nitrogen increases processability of copper-alloyed steel. These steels are highly deformable in both hot and cold conditions in case of heating in the austenite area before rolling.

### Table 6. Bactericidal activity of steel specimen contaminated with S. aureus at microbial cell count 10²/ml.

| Steel⁵ | Exposure [h] | [CFU] at 1 cm² | [S]. aureus |
|--------|--------------|----------------|-------------|
| Cr18Ni10Cu5N, N = 0.22%, [cc] | 1 | 5.2 × 10⁴ | |
| | 4 | 3.9 × 10⁴ | |
| | 24 | 0 | |
| Cr18Ni10Cu5N, N = 0.22%, [ht] | 1 | 4.9 × 10⁴ | |
| | 4 | 3.7 × 10⁴ | |
| | 24 | 0 | |
| Cr18Ni10Cu5, N = 0.02%, [cc] | 1 | 4.9 × 10⁴ | |
| | 4 | 3.8 × 10⁴ | |
| | 24 | 0 | |
| Cr18Ni10Cu5, N = 0.02%, [ht] | 1 | 4.9 × 10⁴ | |
| | 4 | 4.0 × 10⁴ | |
| | 24 | 0 | |
| Cr18Ni10 + 1.5% Cu, N = 0.01%, [ht] | 1 | 5.3 × 10⁴ | |
| | 4 | 4.0 × 10⁴ | |
| | 24 | 25 | |
| Cr18Ni10, N = 0.02%, Control plate | 1 | 5.4 × 10³ | |
| | 4 | 4.1 × 10³ | |
| | 24 | 28 | |

⁵cc: cast condition; ht: after hot treatment.

### Table 7. Composition of tested steels.

| Grade⁶ | C | Cr | Ni | Mn | Mo | Cu | Si | Al | P | [S] | [N] |
|--------|---|----|----|----|----|----|----|----|---|----|-----|
| 10Cr19Mn10Ni6Mo2N⁷ | 0.10 | 18.7 | 6.1 | 10.1 | 1.68 | 0.01 | 0.23 | 0.015 | 0.011 | <0.005 | 0.31 |
| 0.9Cr19Mn10Ni6Mo2Cu2N⁸ | 0.09 | 19.2 | 6.0 | 10.1 | 1.69 | 2.05 | 0.20 | 0.015 | 0.014 | <0.005 | 0.35 |
| AISI 304 | 0.04 | 18.5 | 8.6 | 1.2 | 0.05 | <0.01 | 0.20 | <0.01 | 0.014 | 0.015 | 0.02 |
| AISI 304 N | 0.04 | 18.4 | 8.9 | 1.3 | 0.05 | 0.01 | 0.22 | 0.017 | 0.014 | 0.009 | 0.18 |

⁶the base is Fe.

### Table 8. Mechanical properties of tested steel.

| Grade | Testing temperature [°C] | Tensile strength [MPa] | Yield strength [MPa] | Relative elongation [%] | Relative reduction of area [%] | Impact strength KCU [MJ m⁻²] |
|-------|--------------------------|------------------------|---------------------|------------------------|-------------------------------|-----------------------------|
| 10Cr19Mn10Ni6Mo2N | +100 | 970 | 615 | 25 | 52 | 3.15 |
| | +20 | 925 | 690 | 33 | 62 | 2.90 |
| | -100 | 1410 | 1140 | 47 | 83 | 2.25 |
| | -175 | 1775 | 1405 | 33 | 84 | 1.55 (at −196 °C) |
| 0.9Cr19Mn10Ni6Mo2Cu2N | +100 | 910 | 625 | 27 | 55 | 2.55 |
| | +20 | 940 | 700 | 27 | 56 | 2.50 |
| | -100 | 1285 | 970 | 45 | 84 | 2.00 |
| | -175 | 1825 | 1440 | 40 | 84 | 1.35 (at −196 °C) |
| AISI 304 | +20 | 570 | 250 | 60 | 70 | – |
| AISI 304 N | +20 | 750 | 400 | 63 | 84 | 3.90 |
| | -163 | 1065 | 645 | 39 | 78 | 2.50 |
Nonmagnetic condition is preserved by 83% after deformation at room temperature. At that, hardness is close to martensite structure.

Motivation for steels alloyed with nitrogen (at atmospheric pressure) and microalloyed with nitrogen is an alloying system C + N. Combined alloying with C + N allows to increase strength, viscosity, and plasticity and at the same time preserves high corrosion resistance of steels. For example, Cr18Mn18 steel with (C + N) content from 0.85% to 1.0% can have a stable homogeneous austenitic structure with yield stress of about 600 MPa, that is, three times higher than for standard stainless CrNi steel and elongation about 70%.[42]

High-strength construction steel 40CrNiMoV microalloyed with nitrogen with (C + N) = 0.42% and C/N > 5 and N = 0.024% after HTMT with deformation by radial-displacement rolling and low-temperature tempering has values of ĵ0.2 = 1900 MPA, δ = 15%, and Ψ = 52%, HRC = 58, and gets high resistance to impact-wave load.[43]

### 9. Laser Welding

A reason for the limited use of nitrogen and high-nitrogen steels often is low studying of its behavior in welding joints produced by usual methods. Laser welding seems to be a prospective one, especially for nitrogen steels.[44,45] Most advantages of laser welding are contactless, ability to process geometrically complex surfaces, as well as vary sizes of affected areas and provide ultrahigh rates of heating and cooling (up to 10⁷ – 10⁸ °C s⁻¹). Such high heating/cooling rates allow to prevent both grain growth and nitride precipitation in the weld seam area.[46,47] Negative effects, such as porosity, hot cracking, and less of N and Mn in the weld joint,[48-50] can be prevented through the optimization of laser welding parameters.[47,51-54]

Sheets (3 or 4 mm in thickness) of two new nitrogen steels (Table 7) and two standard steels after thermomechanical treatment were butt welded at room temperature by a laser according to modes that prevent the formation of defects of the welding seam.[55] According to experimental data and computer modeling of the laser welding of more thick sheets requires preheating.[56-58] The austenitic structure of new steels is stable not only at all testing temperatures[59] but also after thermal cycling according to the regime 400 cycles – 100 to +100 °C.[60] Mechanical properties (Table 8) as well as resistivity to general, pitting, and intercrystallite corrosion[61] are high for all tested steels.

The laser weld seams for all nitrogen steels are 500 ÷ 1500 μm in width; any porosity or particles of others phases aren’t detected.[55] The seam structures were fine grained (≈1 ÷ 5 μm) with the thin bond area of uniaxial crystallites and symmetrical area of columnar crystallites junked in the center of the seam. The cooling rate, evaluated based on the crystallite size, was ≈10⁴ ÷ 10⁵ °C s⁻¹. Compositions of the weld seam and main metal were the same. The hardness and strength of the weld seam is usually slightly less than one of the main metal (not more than on 20 ÷ 50 HV for the hardness and 85 ÷ 130 MPa for the tensile strength (Table 9) due to low dislocation density. 180° bending test demonstrated no cracks in the seam area. The low-temperature tensile test showed increased strength of the weld

| Grade                  | Testing temperature [°C] | Tensile strength of the weld seam [MPa] | Tensile strength of the base metal [MPa] |
|------------------------|--------------------------|----------------------------------------|----------------------------------------|
| 10Cr13Mn10Ni3Mo2N      | +20                      | 840                                    | 925                                    |
| 09Cr9Mn10Ni3Mo2Cu2N     | +20                      | 810                                    | 940                                    |
| AISI 304 N             | –70                      | 770                                    | 750                                    |

| Studied area Corrosion potential [mV] | Corrosion current density, [mA m⁻²] |
|----------------------------------------|-------------------------------------|
| General Intercrystallite Pitting Pitting formation | Intercrystallite Pitting |
| 0.5M H₂SO₄, initial state               |                                    |
| Weld seam                              | –                                   | –                                   | –                                   | 69.0                                  |
| Main metal                              | –29                                 | 112                                 | –                                   | 142                                  | 109.5 |
| 0.5M H₂SO₄, after thermal cycling      |                                    |
| Weld seam                              | –49                                 | 45                                  | –                                   | 115                                  | 40.5  |
| Main metal                              | –19                                 | 112                                 | –                                   | 226                                  | 21.2  |
| 0.5M H₂SO₄ + H₂S bubbling, initial state|                                    |
| Weld seam                              | –181                                | 362                                 | 378                                 | –885                                 | 865   |
| Main metal                              | –163                                | 222                                 | 234                                 | –553                                 | 253   |
| 3% NaCl, initial state                 |                                    |
| Weld seam                              | –90                                 | –                                   | 904†                                 | –                                   | –     |
| Main metal                              | –124                                | –                                   | 915†                                 | –                                   | –     |
| 3% NaCl, after thermal cycling         |                                    |
| Weld seam                              | –57                                 | –                                   | 808†                                 | –                                   | –     |
| Main metal                              | 34                                   | –                                   | 758†                                 | –                                   | –     |

| Table 11. Resistance of studied steels against pitting corrosion (100 g l⁻¹ FeCl₃·6H₂O in water) and against intercrystallite corrosion (0.5M H₂SO₄ + 0.01 M KSCN). |
| Grade                  | Studied area | Average arbitrary rate of pitting corrosion [g m⁻²·p⁻¹] | Q²/Q₀ | Resistance against intercrystallite corrosion |
|------------------------|--------------|--------------------------------------------------------|-------|---------------------------------------------|
| Initial state          |              |                                                        |       |                                             |
| 10Cr13Mn10Ni3Mo2N      | Weld seam    | 6.15                                                   | 0.020 | Resistant                                   |
| 10Cr9Mn10Ni3Mo2Cu2N    | Main metal   | 2.12                                                   | 0.002 | Resistant                                   |
| AISI 304 N            | Main metal   | 6.61                                                   | –     | –                                           |
| After thermal cycling (1000 cycles in the range +20 ↔ –163 °C) |              |                                                        |       |                                             |
| 10Cr13Mn10Ni3Mo2N      | Weld seam    | 1.74                                                   | 0.057 | Resistant                                   |
| 10Cr9Mn10Ni3Mo2Cu2N    | Main metal   | 1.82                                                   | 0.004 | Resistant                                   |

†Pitting formation potential corresponds to the current density of: – 30 mA m⁻² and; 10–5 mA m⁻².
seam due to the fine-grained structure and a little width of both the seam and thermally affected area.\textsuperscript{[63]}

The laser weld seam and the main metal demonstrated similar resistance against general sea water corrosion, general acid corrosion (including the case with H$_2$S bubbling), pitting corrosion, and intercrystallite corrosion, both immediately after the welding and after 1000 thermal cycles in the range $+20 \leftrightarrow -163^\circ$C (Table 10 and 11). After tests for general corrosion in the sea water, the seam was invisible, but after the tests in more aggressive acid environments, especially after H$_2$S bubbling, it was more marked (Figure 2). The structure, phase composition, and hardness of laser weld joints of both new nitrogen steels (10Cr$_{19}$Mn$_{10}$Ni$_6$Mo$_2$N and 09Cr$_{19}$Mn$_{10}$Ni$_6$Mo$_2$Cu$_2$N) also were saved after 1000 thermal cycles in the range $+20 \leftrightarrow -163^\circ$C.

10. Conclusion

Nitrogen is currently the widely used alloying element together with Cr, Ni, Mn, Mo, etc. It provides the unique combination of strength, plasticity, and corrosion resistance for steel. An industry uses many nitrogen-alloyed steels of various structure classes, such as austenitic, ferritic, martensitic, and two-phase ones. In future, these steels may replace light and nonferrous alloys. Steels with nitrogen content not over its equilibrium concentration in the austenite demonstrate high manufacturability in smelting and processing, obtaining welded joints with properties close to the main metal. For a relatively thin product, laser welding is especially effective. Alloying steels with nitrogen is very promising to give special functional properties, for example, corrosion resistance in bioactive environments, bactericidal or disinfecting activity, high resistance to special types of interactions, etc.

The maximum effect occurs when nitrogen is inside the solid solution (austenite). This is quite easy to implement by choosing the modes of thermal and thermomechanical treatment, if the nitrogen content is in equilibrium for melting and casting and does not exceed its solubility in austenite. Conventional solid-solution quenching during thermomechanical treatment or as a finishing treatment ensures the absence of coarse nitrides that reduce resistance to corrosion, especially localized ones.

Totally, both the manufacturing and using of the austenitic steels with the equilibrium nitrogen content are more workable because they don’t require uncommon equipment for the melting, the casting, and the welding. Such steels have more stable structure and properties in a wide temperature range: from cryogenic to much over climatic ones. The main problems for expanding the scope of nitrogen steels is the lack of necessary databases, standards, etc. This is due to little experience compared with conventional carbon and alloy steels.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

high-nitrogen steels, nitrogen steels, properties of steels with nitrogen, welding of nitrogen steels

Received: March 1, 2022
Revised: April 6, 2022
Published online: May 31, 2022

[1] A. G. Syazhazhin, L. M. Kaputkina, in Proc. 11th Intern. Conf. on High Nitrogen Steels and Interstitial Alloys (HNS 2012), VRK Printing House, Chennai, India 2013, pp. 11–22.
[2] T. S. Rashev, Proc. Bulgarian Acad. Sci. 1995, 270.
[3] G. Balachandran, in Proc. of the 11th Intern. Conf. on High Nitrogen Steels and Interstitial Alloys (HNS 2012), VRK Printing House, Chennai, India 2013, pp. 41–62.
[4] A. G. Syazhazhin, Hutmik-Wiadomosci Hutnicze 1996, 8, 5264.
[5] A. G. Syazhazhin, L. M. Kaputkina, Steel Industry 2005, 10, 36.
[6] O. A. Bannykh, Y. M. Blinov, V. V. Berezovskaiia, et al. Russian Metall. 2005, 4, 310.
[7] G. Saller, J. Bernauer, H. Leitner, H. Clemens, in Proc. 7th Inter. Conf. High Nitrogen Steels (HNS 2004), Ostend, GRIPS media, 2004, pp. 283–292.
[8] V. G. Gavrilyuk, H. Berns, in High Nitrogen Steels, Springer Verlag, Berlin 1999, p. 378.
[9] A. G. Syazhazhin, M. Chursin, A. F. Vishkarev, V. I. Yavoiskii, Proc. USSR Acad. Sci. Metals 1974, 5, 24.
[10] A. G. Syazhazhin, Trans. Indian Inst. Metals 2002, 55, 297.
[11] A. G. Syazhazhin, Steel Industry 1996, 5, 1
[12] T. S. Rashev, R. Ivanov, L. Sar’ivanov, Industrial Laboratory 1978, 44, 637.
Svyazhin Anatoly Grigorievich is a professor, Dr.Sci. (Eng.), at National University of Science and Technology “MISIS”. Svyazhin is a specialist in the development of the theory of the interaction of gases with liquid metals, the development of the theory and practice of the production of high-purity steels with a controlled nitrogen content, and the development of compositions of high-tech high-strength corrosion-resistant cryogenic nitrogen steels.

Kaputkina Liudmila Mikhailovna is a professor, Dr.Sci. (Phys.-Math.), honored scientist of the Russian Federation, National University of Science and Technology “MISIS”. Areas of interest include phase and structural transformations in steels and alloys of different classes, thermal and thermomechanical processing, functional properties of special alloys, study of the nature of hardening and the behavior of nitrogen in steels, and development of compositions and technologies for thermomechanical treatment of new high-strength corrosion-resistant cryogenic nitrogen steels.

Smarygina Inga Vladimirovna has a Ph.D. from National University of Science and Technology “MISIS”. Areas of interest include development of new research and testing methods and phase and structural transformations during various types of thermal and thermomechanical treatments, including nitrogen steels.

Kaputkin Dmitry Efimovich is a professor, Dr.Sci. (Eng.), Moscow State University of Civil Aviation. He is a specialist in the fields of phase and structure transformations of steels, fracture of steels, and surface treatment by high-energy flows.