

DOI: <https://doi.org/10.37434/tpwj2024.01.07>

NITROGEN ABSORPTION BY 04Cr18Ni10 STEEL IN PLASMA-ARC MELTING UNDER SLAG OF CaO–Al₂O₃ SYSTEM

V.O. Shapovalov¹, V.G. Mogylatenko^{1,2}, R.V. Lyutyi², R.V. Kozin¹¹E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine²National Technical University of Ukraine “Igor Sikorsky Kyiv Polytechnic Institute”
37 Prospect Beresteiskyi (former Peremohy), 03056, Kyiv, Ukraine

ABSTRACT

Nitrogen as an alloying element of steel is a strong austenitizer, and it has an essential influence on mechanical properties of steels of different grades. It is rational to use gas phases for nitrogen alloying, and the process can be intensified with the application of highly-concentrated energy sources, for instance, plasma. One of the determining factors of metal alloying is the partial pressure of nitrogen and the process temperature. It is difficult to find works, dealing with nitriding of metal melts in plasma-slag process. The paper gives experimental data on dissolution kinetics and nitrogen solubility in 04Cr18Ni10 steel. The derived mathematical models of nitrogen dissolution in plasma melting are highly significant, which is indicated by the respective determination coefficients. At less than 0.1 atm partial pressure of nitrogen above the melt, the temperature in the range of 1823–2323 K practically does not influence the content of nitrogen in steel, and at a higher partial pressure, the content of nitrogen in steel decreases with the temperature rise. The melt temperature under the experimental conditions was assessed as 2385 K. It was determined that the coefficient of nitrogen distribution between the metal and slag changes only slightly at up to 1 atm partial pressure of nitrogen and is equal to 1.1–1.2.

KEYWORDS: nitrogen-containing steels, plasma-slag melting, nitrogen, absorption kinetics, solubility, distribution coefficient

INTRODUCTION

04Cr18Ni10 steel, along with other chromium-nickel steels, is one of the most common structural austenitic steels used in industry, as its products can operate in various aggressive environments (solutions of salts, alkalis, acids) and has an operating temperature of up to 900 K under the normal conditions and up to 600 K in aggressive environments.

Any high-temperature metallurgical process of steel production is a process of interaction of several phases. As a rule, it is liquid metal, liquid slag and gas phase or vacuum. The main gases interacting with the slag and metal are oxygen, hydrogen and nitrogen. The presence of the first two gases in the gas atmosphere in the absence of melt protection inevitably leads to the formation of defects in ingots and castings: nonmetallic inclusions, gas and gas shrinkage porosity, flakes. And only nitrogen can perform both a negative and a positive function. The first one consists in the formation of strengthening inclusions in steel under certain conditions, and the second one is in the fact that nitrogen is a substitute for nickel.

Nitrogen, known for a long time [1, 2] as an alloying element of chromium-nickel and chromium-manganese steels, is a strong austenitizer along with nickel. The effect of nitrogen in the γ -region of iron is several

times stronger than the effect of nickel. It is known that 0.15 % of nitrogen in chromium-nickel steels is equivalent to 2–4 % Ni, and 0.25 % of nitrogen is equivalent to 2.5–6.0 % Ni. Considering the cost of nickel, substitution of its part with nitrogen significantly increases the cost-effectiveness of stainless steel production [3].

Nitrogen-containing steels with an over-equilibrium nitrogen content should be melted under the excess nitrogen pressure or by the plasma-arc remelting (PAR) method with alloying of metal with nitrogen directly from the gas phase. Arc-slag remelting (ASR) [4] allows performing alloying of metal with nitrogen from the gas phase and treatment of metal with slag. Thus, the formation of ingots of various cross-sections is provided, that have satisfactory surface, chemical and structural homogeneity. The nitrogen content in steel is determined by the composition of the slag and, depending on the method of melting, changes both in the metal and in the slag.

The process of alloying steels with nitrogen from plasma is characterized by a high rate of gas absorption by the liquid metal, which is an order of magnitude higher than in conventional metallurgical units. Therefore, plasma-slag remelting (PSR), which combines plasma as a source of metal heating and activation of nitrogen molecules, with slag treatment to refine the melt from undesired impurities and nonme-

tallic inclusions, is more promising from the point of view of obtaining an superequilibrium nitrogen content in the metal.

Taking into account that the absorption of nitrogen by liquid steel in the ternary gas–slag–metal system depends on the transfer capacity of the slag, the problem of studying the kinetics of the process of nitrogen absorption by the slag and through the slag by metal during plasma-slag melting on the example of steel 04Cr18Ni10 arises.

STATE OF THE PROBLEM

Nitrogen significantly affects the mechanical properties, phase stability, corrosion and heat-resistant properties, crack resistance and fatigue strength of ledeburite tool and high-speed steels, stainless steels of the austenitic, ferritic-austenitic, ferritic-martensitic and martensitic grades [5–8]. The effect of nitrogen on the strength of austenitic steels is stronger than the effect of carbon (Table 1).

Melting in a nitrogen-containing gas environment, especially at elevated pressure, allows alloying with nitrogen directly from the gas phase. Plasma-arc remelting (PAR) provides a higher efficiency of alloying steel with nitrogen at a low gas pressure compared to pressure melting [9]. For chromium-manganese steels scarcely alloyed with nickel, such as Cr21Mn10Ni4, plasma-arc melting at nitrogen partial pressures of 60–120 kPa allows obtaining a nitrogen content that exceeds its standard solubility. The content of nitrogen in ingots during PAR is regulated by the change in the partial pressure of nitrogen in the plasma-forming gas, the total pressure in the melting chamber of the furnace, and the rate of ingot extraction, i.e., the melt temperature [9].

Thus, the partial pressure of nitrogen in the plasma-forming gas and the process temperature are one of the determining factors of alloying metal in an superequilibrium amount with nitrogen during PAR.

SOLUBILITY OF NITROGEN IN METAL MELT

The equilibrium solubility of nitrogen in the metal melt is subjected to the Sieverts' law or the square root law:

Table 1. Influence of alloying elements (1 %) on yield strength of 04Cr18Ni10 steel [2]

Alloying element	Type of solution	Yield strength of steel, kg/mm ²
N	Penetration	70
C	→→	40
Cr	Substitution	0.4
Mo	→→	1.5

$$[N]_{Me} = K_N \sqrt{P_{N_2}},$$

where $[N]_{Me}$ is the equilibrium solubility of nitrogen, %; K_N is the Sieverts' constant, %·atm^{-1/2}; P_{N_2} is the equilibrium partial pressure of nitrogen in the gas phase, atm.

During plasma heating, the square root law for nitrogen absorption is also fulfilled, but here the proportionality factor is much higher than the Sieverts' constant. Alloying of metal with nitrogen will occur if the inequality is observed [10]:

$$P_{N_2} > P_{N_2}^* = ([N]_{Me} / K_N)^2,$$

where P_{N_2} is the partial pressure of nitrogen in the gas phase.

The temperature dependence of the nitrogen dissolution constant in a liquid iron has been studied by many researchers. The most probable results are satisfactorily described by the equation [11]:

$$\lg K_{N_2} = (-293 / T) - 1.16.$$

According to the specified dependence at 1600 °C, $K_{N_2} = 0.048$ %. Thus, for this temperature we can write:

$$[N]_{Me} = 0.048 \sqrt{P_{N_2}}.$$

Alloying elements and impurities in iron change the ability of iron to dissolve nitrogen [12].

In real steelmaking processes, nitrogen dissolution occurs in parallel with oxidation processes. A flow of oxygen causes a counter flow of nitrogen. It was established [13] that the behavior of nitrogen in Fe–C alloy and killed steel (0.3 % C) and 15MnAlTi steel as well as pure iron is determined by the rate of metal saturation with oxygen and when the maximum concentration of oxygen in metal is reached, the absorption of nitrogen by steels stops. The higher the rate of oxygen absorption, the sooner nitrogen absorption stops and the lower its concentration is achieved in steels.

The solubility of nitrogen in steels can be calculated theoretically having known values of interaction parameters [10]. In [14], a thermodynamic model for predicting the solubility of nitrogen in liquid stainless steels depending on the concentrations of alloying elements, temperature and pressure is given, which takes into account a new factor of the pressure effect on the coefficient of nitrogen activity. The results of the calculations, which agree well with the experiment, are subjected to the Sieverts' law. However, at a high pressure (> 1 atm) and especially at a high concentration of alloying elements, a deviation from the Sieverts' law occurs and the nitrogen pressure begins to negatively affect the solubility.

SOLUBILITY OF NITROGEN IN SLAGS

As for the sorption capacity of slag in relation to impurities, it depends on the oxidation-reduction potential of the medium, which can be determined by the equilibrium partial pressure of oxygen (P_{O_2}). Unlike the Sieverts' law for metals, in the case of slag, the following dependence is fulfilled [15]:

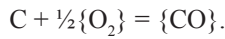
$$(G) = K_{(G)} p_{(G)}^{1/2} p_{(O_2)}^{V_G/4},$$

where V_G is the degree of oxidation or valence of G element in the slag.

Since the valence of nitrogen in the slag $V_N = -3$, then

$$(N) = K_{(N)} p_{(N_2)}^{1/2} p_{(O_2)}^{-3/4}.$$

If the slag contains carbon, the following reaction occurs:



At the same time, from 1 mole of oxygen, 2 moles of CO are formed, which reduce the partial pressure of nitrogen above the slag, which should be taken into account during calculations of the solubility. In real conditions, in the presence of nitride-forming ele-

ments due to the formation of nitrides, the maximum solubility of nitrogen in the slag usually does not exceed 2% [15].

Unfortunately, in the scientific literature, absorption of nitrogen by slags is most often associated with the presence of carbon in the slag or in the atmosphere above the slag. Pure experiments without the influence of carbon are not available. According to [16, 17], the simultaneous increase in the concentrations of carbon and nitrogen, as well as reaching the saturation, indicate that nitrogen and carbon in the slag are combined into one compound, for example, cyanide or cyanamide. Nitrogen at different content of CaO dissolves in the form of free nitrogen N^{3-} and binds to Ca^{2+} (Ca_3N_2) or Al^{3+} (AlN) ions. The mechanism of nitrogen dissolution is very complex, because, as is known, it reacts and substitutes all three types of slag oxygen: free (O^{2-}), final type (O^-) and bridging or one which combines (O°).

When carbon and nitrogen are dissolved simultaneously in molten slags [17] or there is carbon in the slag, they can be dissolved in the form of cyanide CN^- . In [17], analysis of literature data on the relationship between the solubility of nitrogen, cyanide,

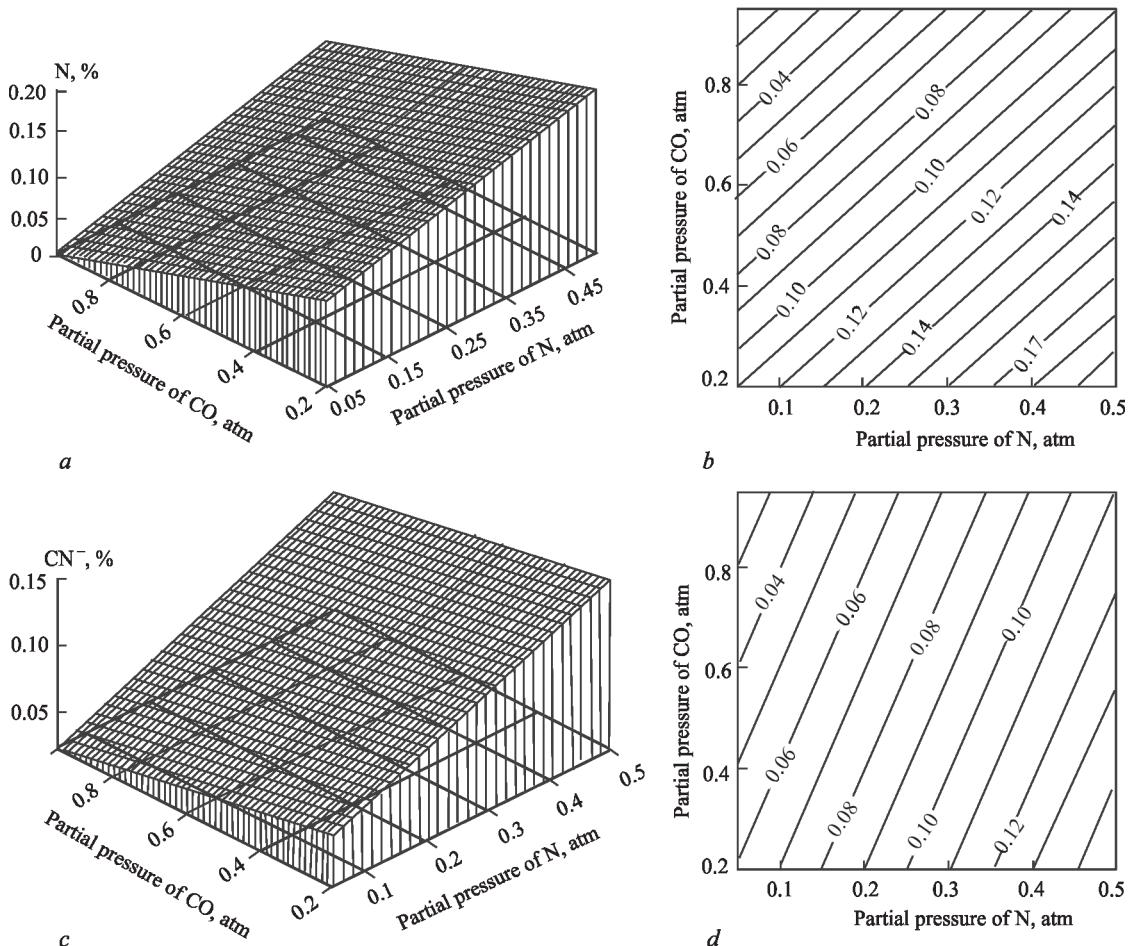


Figure 1. Dependence of total nitrogen content in the slag (a, b) and CN^- (c, d) on the partial pressure of nitrogen and CO above the slag 50% CaO–50% Al_2O_3 [17]: a, c — volume image; b, d — surface topography

and carbon in CaO–Al₂O₃ slag with the partial pressures of nitrogen, CO and argon in the system was performed, and model calculations of the solubility of nitrogen in various forms of existence in the slag were performed. Figure 1 shows the graphical dependences built based on the results of this work for 50 % CaO–50 % Al₂O₃ slag.

The main conclusions from these graphical dependencies are the following:

- both an increase in the partial pressure of nitrogen and a decrease in the partial pressure of CO above the slag lead to an increase in the content of nitrogen and cyanide CN⁻ in it;
- the partial pressures of nitrogen and CO have a stronger effect on the total nitrogen content than on the cyanide content;
- the higher partial pressure of CO, the higher the oxygen content and lower nitrogen content in the slag.

It is known that aluminium-oxygen anions of (AlO₂⁻, AlO₃³⁻, AlO₄⁵⁻) slag as well as silicon-oxygen ones are able to associate with each other and form complex anions of large sizes [10]. During dissolution of nitrogen, it can be embedded in the complex anions instead of oxygen [18].

The solubility of nitrogen in the main slags two to three times exceeds the solubility of nitrogen in iron. In acidic slags with an increase in temperature, nitrogen dissolves almost three times faster [16] than in iron, which may be associated with the formation of complex anions. Studying the dependence between nitrogen and carbon content in ANF-7 (80 % CaF₂ + 20 % CaO) flux showed that the concentration of nitrogen in the initial flux is much lower than the equilibrium one and this slag not only cannot be a source for enrichment of metal with nitrogen, but can even facilitate the removal of this gas from it.

NITROGEN IN THE GAS–SLAG–METAL SYSTEM

The interaction in the nitrogen–slag–metal system consists of the following links: convection and diffusion transfer of nitrogen to the slag surface in the gas phase; adsorption, dissociation, transition of nitrogen atoms through the gas–slag interface; diffusion, con-

vection and again diffusion transfer of nitrogen in the slag to the slag–metal interface; transition through the slag–metal interface; distribution of nitrogen over the volume of metal until equalizing the chemical potential of nitrogen in the metal phase (dissolution).

Depending on the speed of elementary links, one or the other link can determine the overall speed of the process.

The largest amount of information in the scientific literature concerns the interaction of nitrogen with melts based on iron, and at the second place — interaction with slags. A little attention is paid to the processes of saturation of melts with nitrogen from the gas phase through the slag. It was established [19] that nitriding from the gas phase is possible when the slag is deoxidized by metallic calcium and aluminium, but a clear dependence of the nitrogen content in Cr6WV steel on the content of oxygen in metal was not detected by the authors (Figure 2). Moreover, it can be said that the oxygen content in steel does not affect the content of nitrogen in it.

The content of nitrogen in Cr6WV steel, which is melted under CaO–Al₂O₃–15 % TiO₂ slag, is 0.035 %, and under Al-295 slag, it is 0.026 %. These values are lower than the equilibrium content (0.17 %) calculated for the conditions of interaction of liquid metal with nitrogen [19].

The amount of nitrogen dissolved in metal is directly proportional to the amount of slag nitrogen and inversely proportional to the distribution factor $L = \frac{[N]}{[N]}$. Taking into account the practical permanency of the dependencies shown in Figure 2, in the conditions of the experiment, the coefficient of nitrogen distribution between the slag and metal does not change.

Nitriding of metal under the slag occurs at a lower rate, than in the case of contact of the metal melt directly with the gas phase [20]. The highest rate of nitriding is fixed in arc melting conditions ($2.6 \cdot 10^{-5}$ – $1.55 \cdot 10^{-4}$ m/s), and the lowest is in melting in a resistance furnace ($(1.5$ – $3.0) \cdot 10^{-6}$ m/s).

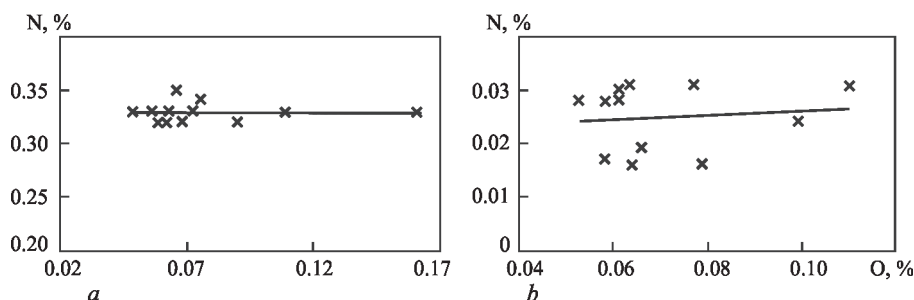


Figure 2. Effect of oxygen content in Cr6WV steel, melted under the deoxidized slag, on the content of nitrogen in it: *a* — ANF-1P + 7 % Ca slag; *b* — ANF-1P + 7 % Al [19]

Today, it is very difficult to find works that would combine kinetic dependences of the slag and steel saturation with nitrogen in a one process. Therefore, it was the aim of this work.

RESEARCH PROCEDURE

As a slag composition, binary slag of the composition of 50 % Al_2O_3 and 50 % CaO was selected. In the area of this concentration, there are low-melting slags with eutectic at a temperature of 1658–1668 K. To prepare slag, calcium oxide CaO powders and aluminium oxide Al_2O_3 of fine grade (clean for analysis) were used. The slags were preliminary melted in a graphite crucible in an induction furnace with a protective atmosphere. As a protective atmosphere, argon of the first grade was used: 0.002 % O_2 ; 0.01 % N_2 ; 0.03 g/m^3 of pair H_2O . The carbon content in the slag was 0.29 %, CaO — 49.3, Al_2O_3 — 50.

As a metal specimen, 04Cr18Ni10 steel of the following composition was used, %: 0.04 C, 18.1 Cr, 10.65 Ni, 0.8 Si, 1 Mn. This steel does not contain nitride-forming elements, that allows detecting nitrogen in the dissolved state.

The determination of nitrogen content in the slag and steel specimens was carried out in the equipment by the Kjeldahl procedure, which was updated in relation to the determination of nitrogen in slags, and its detailed description is given in [21].

The study of the kinetics of nitrogen absorption was carried out in the UPI installation [22], which allows studying the absorption of gas from plasma by the melt in the conditions, where its entire surface is covered with a plasma plume and active gas contacts with liquid pool.

After melting a weighted specimen of steel with the slag and its necessary holding in nitrogen-argon plasma, the plasmatron was switched off with simultaneous opening of the wedge mould for quenching the melt from liquid state and fixing the amount of nitrogen in it.

EXPERIMENTAL RESULTS AND THEIR DISCUSSION

The initial experiments were carried out with steel in contact with the gas atmosphere in the absence of a slag. The results are shown in Figure 3.

The main results of the statistical processing of the obtained results are as follows. Polynomial regression (dependence 1) has the following appearance:

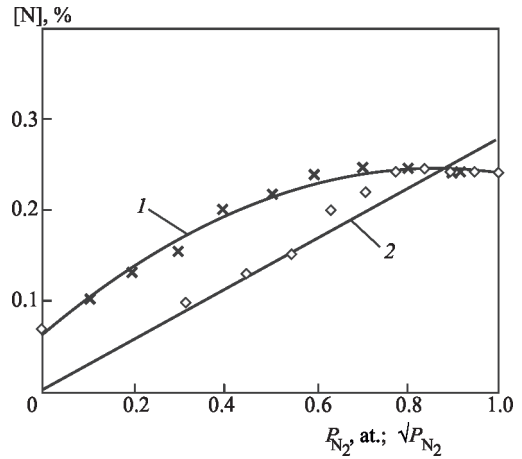


Figure 3. Content of nitrogen in 04Cr18Ni10 steel depending on the partial pressure of nitrogen above the metal (1) and the square root from this pressure (2)

$$[\% \text{N}] = 0.0604545 + 0.0436667P_{\text{N}_2} - 0.257576P_{\text{N}_2}^2.$$

The coefficients of determination (R^2) are equal to 0.845973 and 0.982467 for degrees 0, 1 and 2, respectively. Zero value means that the first coefficient is a constant.

The dependence 2 in Figure 3 indicates that the content of nitrogen in the melt of 04Cr18Ni10 steel is subjected to the Sieverts' law. The Sieverts constant for the conditions of the experiment amounts to 0.277674, and the obtained dependence is the following:

$$[\% \text{N}] = 0.27764\sqrt{P_{\text{N}_2}}. \quad (1)$$

The coefficient of determination (R^2) is 0.979081, and the mean square deviation is 0.00091. The proximity of the coefficient of determination to 1 indicates that the model has a high significance.

The theoretical calculations were carried out to determine the solubility of nitrogen in the investigated steel. To do this, the Chipman–Corrigan equation was used [23]. The solubility of nitrogen in iron is described by the equation

$$\lg K_{\text{N}} = -\frac{850}{T} - 0.905 + \frac{1}{2} \lg P_{\text{N}_2}. \quad (2)$$

The interaction parameters [14, 23] of the first and second order required for the calculation are given in Table 2.

The equilibrium constant of nitrogen dissolution in liquid iron at a temperature (T) amounts to:

Table 2. Parameters of interaction of elements in iron at a temperature of 1873 K

Alloying element (j)	Cr	Ni	Mn	Si	C	Cr–Ni
1 st order interaction parameter (e_{N}^j)	−0.047	0.0063	−0.02	0.047	0.118	–
2 nd order interaction parameter (f_{N}^j)	0.00032	0.00007	0.000032	–	–	−0.00008

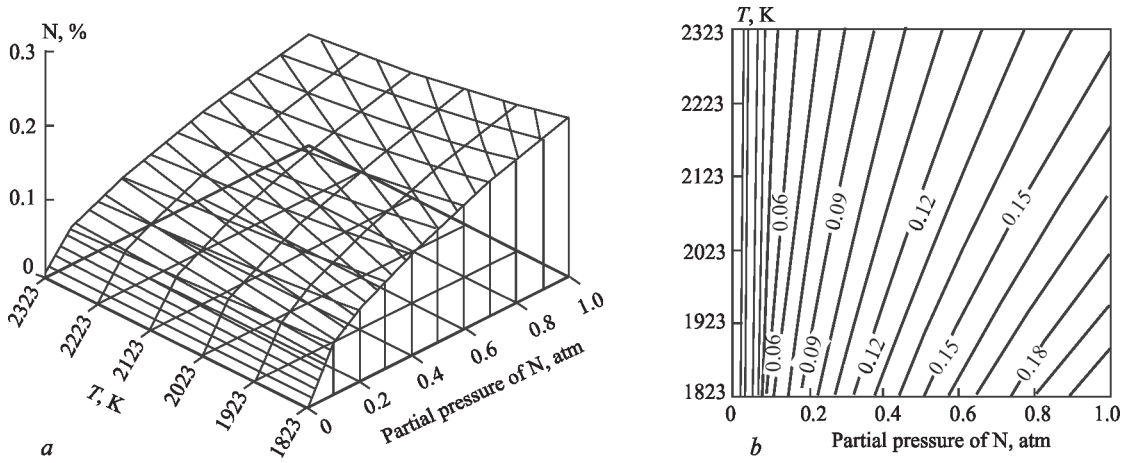


Figure 4. Effect of temperature and pressure of nitrogen on its content in 04Cr18Ni10 steel (a) and surface topography (b)

$$K_N = \frac{f_{N(T)}[\% N]}{P_{N_2}^{1/2}}. \quad (3)$$

Tacking of the logarithm we have:

$$\lg[\% N] = \frac{1}{2} \lg P_{N_2} + \lg K_N - \lg f_{N(T)}. \quad (4)$$

The activity coefficients at a certain temperature can be determined by the known data at a temperature of 1873 K and by the equation

$$\lg f_{N(T)} = \left(\frac{3280}{T} - 0.75 \right) \times \left\{ \sum_j \left(e_{N(1873)}^j [j] \right) + \sum_j \left(r_{N(1873)}^j [j]^2 \right) + \sum_{j,k} \left(r_N^{j,k} [j][k] \right) \right\}. \quad (5)$$

Then after substitution of the equations (2) and (5) into the equation (4) we obtain:

$$\lg[\% N] = \frac{1}{2} \lg p_{N_2} - \frac{850}{T} - 0.905 - \left[\left(\frac{3280}{T} - 0.75 \right) \left\{ \sum_j \left(e_{N(1873)}^j [j] \right) + \sum_j \left(r_{N(1873)}^j [j]^2 \right) + \sum_{j,k} \left(r_N^{j,k} [j][k] \right) \right\} \right]. \quad (6)$$

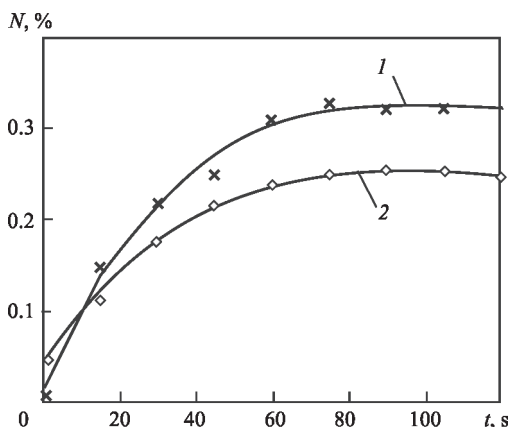


Figure 5. Kinetic dependence of nitrogen absorption at PSR ($p_{N_2} = 0.7$ atm): 1 — for slag; 2 — for steel

After the data is substituted, we obtain the equation:

$$[\% N]_{04Kh18Ni10} = \sqrt{p_{N_2}} 10^{\left(\frac{1328}{T} - 1.4029 \right)}. \quad (7)$$

During plasma melting, the distribution of temperatures over the surface of the melt is very non-uniform. The region of the highest temperatures is concentrated inside the plasma plume and can reach 18000–19000 K [24]. On the axis of the nozzle section, depending on the electrical mode of melting, pressure and composition of the gas atmosphere, the temperature usually exceeds 12000 K, and the surface of the metal pool is not lower than 2000 K in the areas adjacent to the anode spot.

The obtained dependence (7) made it possible to evaluate the melt temperature at PSR. The experimental dependence of the nitrogen content in 04Cr18Ni10 steel is described by the dependence (1), and the dependence (7) shows the calculated change in the solubility of nitrogen in steel from the temperature.

It can be written that experimental and calculated values with the consideration of temperature are equal to each other:

$$[\% N] = [\% N]_{04Kh18Ni10}, \quad 0.277674 \sqrt{P_{N_2}} = \sqrt{p_{N_2}} 10^{\left(\frac{1328}{T} - 1.4029 \right)},$$

from which the temperature of the steel melt is about 2385 K.

The results of the calculation by the formula (7) in graphical form are shown in Figure 4.

The obtained data showed that in the conditions of melting without the use of plasma at small partial pressures of nitrogen, of approximately up to 0.1 atm, the temperature within 1823–2323 K has practically no effect on the content of nitrogen in steel; at higher partial pressures with an increase in temperature,

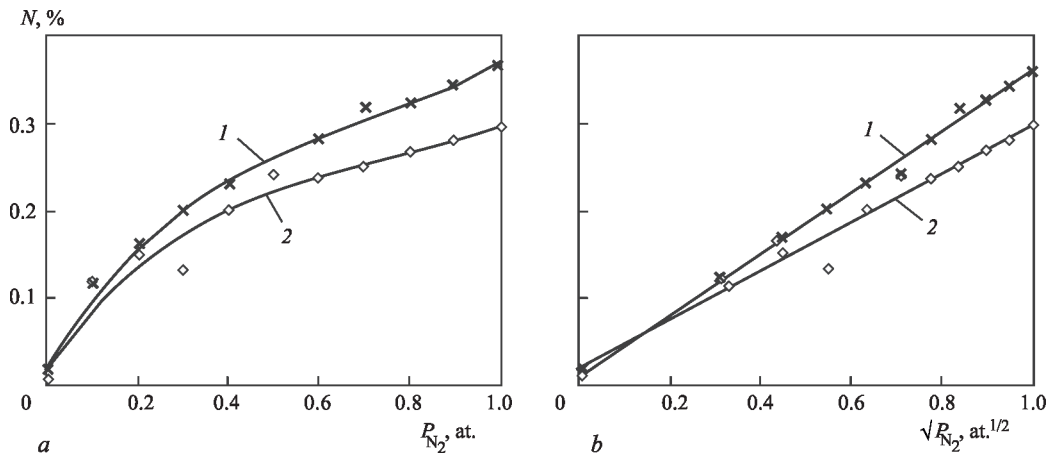


Figure 6. Effect of nitrogen pressure on the nitrogen content in the slag and 04Cr18Ni10 steel in PSR: 1 — slag; 2 — metal

the nitrogen content in the melt of 04Cr18Ni10 steel decreases; the maximum nitrogen content that can be achieved at a nitrogen pressure of 1 atm and a temperature of 2323 K is 0.145 %, and at a temperature of 1823 K and the same pressure it is 0.21 %.

The comparison of calculated and experimental data shows that the obtained calculated data are lower than the experimental, which may be associated with an increase in the energy of molecules in the plasma plume and the appearance of active nitrogen atoms and ions. It affects the intensity of gas absorption by the melt.

An example of a kinetic dependence of simultaneous nitrogen absorption by a liquid 04Cr18Ni10 steel and a slag at a partial nitrogen pressure of 0.7 atm in the furnace atmosphere is shown in Figure 5.

On all kinetic dependencies at pressures lower than 1 atm, the content of nitrogen in steel is lower than in the slag and not higher than in the steel produced at a direct contact of liquid metal with plasma.

The derived dependencies of changing the nitrogen content in the molten PSR steel on the partial pressure of nitrogen and the square root from this pressure are shown in Figure 6.

In the conditions of plasma-slag melting, the content of nitrogen in steel grows with an increase in the nitrogen pressure in the atmosphere above the melt (Figure 6, *a*) and is subjected to the Sieverts' law (Figure 6, *b*).

The linear dependence of the nitrogen content in the slag is described by the equation

$$(\% \text{ N}) = 0.360025 \sqrt{p_{\text{N}_2}} + 0.00336233 \quad (8)$$

with the coefficient of determination $R^2 = 0.995207$ and the mean square deviation of $6.31644 \cdot 10^{-5}$, which indicates a high significance of the model. The free member of the last equation indicates the initial (residual) content of nitrogen in the slag.

The same can be said about the dependence of the nitrogen content in steel under the slag. The linear dependence is as follows:

$$[\% \text{ N}] = 0.286549 \sqrt{p_{\text{N}_2}} + 0.0129405, \quad (9)$$

the coefficient of determination is 0.964987, and the mean square deviation is $3.01468 \cdot 10^{-4}$. The comparison of the Sieverts' constant of steel in PSR (1) with the constant in PAR (9) shows the proximity of their values. The difference amounts to 0.008875, which corresponds to 3.2 % of the error.

The coefficient of the nitrogen distribution between the slag and metal $\left(L = \frac{[\text{N}]}{[\text{N}]} \right)$ determined according to the obtained data at a partial nitrogen pressure of not more than 1 atm changes slightly and is equal to 1.1–1.2.

CONCLUSIONS

1. The kinetic dependences of nitrogen absorption by a liquid 04Cr18Ni10 steel from nitrogen-argon plasma were obtained in the range of nitrogen partial pressure from 0.05 to 1.0 atm. In all cases, the nitrogen content in the slag exceeded its content in steel. It was determined that in plasma-slag melting, the absorption of nitrogen by the slag and 04Cr18Ni10 steel occurs in accordance with the Sieverts' law. The obtained mathematical models of nitrogen dissolution in plasma melting have a high significance and their coefficients of determination are close to 1. The value of the Sieverts' constant in the conditions of both plasma-slag melting, as well as by the calculation way in the equilibrium conditions for 04Cr18Ni10 steel was experimentally determined.

2. It was determined that at a partial nitrogen pressures of up to 0.1 atm and a temperature within 1823–2323 K, the content of nitrogen in steel is practically independent of the temperature unlike higher partial pressures. With an increase in temperature, the amount of equilibrium nitrogen dissolved in steel decreases.

3. It was established that in the conditions of the experiments, i.e., when the plasma plume complete-

ly covers the molten specimen, the melt temperature reaches 2385 K. In the conditions of PSR, the coefficient of nitrogen distribution between the slag and metal is 1.1–1.2.

REFERENCES

- Houdremont, E. (1966) *Special steels*. Moscow, Metallurgiya [in Russian].
- Lakomsky, V.I., Lakomsky, V.V. (2012) *Nitrogen in liquid steels and slags*. Kyiv, Naukova Dumka [in Russian].
- Koroliyov, M.L. (1961) *Nitrogen as an alloying element in steel*. Moscow, Metallurgizdat [in Russian].
- Paton, B.E., Saenko, V.Ya., Pomarin, Yu.M. et al. (2004) Arc slag remelting for high strength steel & various alloys. *J. Mater. Sci.*, **39**, 7269–7274. DOI: <https://doi.org/10.1023/B:JM-SC.0000048741.47509.b3>
- Cieřla, M., Ducki, K.J. (2008) Effect of increased nitrogen content on the structure and properties of tool steels. *J. of Achievements in Materials and Manufacturing Engineering*, **29**(1), July. <https://www.researchgate.net/publication/26872202>
- Cieřla, M., Ducki, K.J. (2008) Influence of increased nitrogen content on tool steels structure and selected properties. *J. of Achievements in Materials and Manufacturing Engineering*, **27**(2), July. <https://www.researchgate.net/publication/26872252>
- Saeed Nabil Ghali, Mamdouh Eissa, Hoda El-Faramawy et al. (2013) Production and application of advanced high nitrogen steel. In: *Proc. of Int. Conf. on Science and Technology of Ironmaking and Steelmaking (November 2013, Jamshedpur, India)*. 1. https://www.researchgate.net/publication/262698868_Production_and_Application_of_Advanced_High_Nitrogen_steel
- Grigorenko, G.M., Pomarin, Yu.M., Lakomsky, V.V. (2010) Properties of steels of X13 type, alloyed with nitrogen. *Sovrem. Elektrometall.*, **4**, 26–29 [in Russian].
- Burnashev, V.P., Nikitenko, Yu.O., Yakusha, V.V. et al. (2020) Some aspects of melting high-nitrogen steel Kh21G17AN2 in plasma arc furnace. *Suchasna Elektrometall.*, **2**, 23–26 [in Ukrainian]. DOI: <https://doi.org/10.37434/sem2020.02.04>
- Shurkhal, V.Ya., Larin, V.K., Chernega, D.F. et al. (2000) *Physical chemistry of metallurgical systems and processes: Manual*. Kyiv, Vyshcha Shkola [in Ukrainian].
- Pomarin, Yu.M., Byalik, O.M., Grygorenko, G.M. (2007) *Influence of gases on structure and properties of metals and alloys*. Kyiv, NTUU KPI [in Ukrainian].
- Shapovalov, V.O., Biktagirov, F.K., Mogylatenko, V.G. (2023) *Out-of-furnace processing of steel: Methods, processes, technologies: Manual*. Ed. by I.V. Krivtsun. Kyiv, Khimjest [in Ukrainian].
- Enders, V.V. (2002) Nitrogen in steelmaking processes. *Lityo i Metallurgiya*, **1**, 95–100 [in Russian].
- Zhouhua Jiang, Huabing Li, Zhaoping Chen et al. (2005). The nitrogen solubility in molten stainless steel. *Steel Research Int.*, **76**(10), 730–735. <https://www.researchgate.net/publication/281642445>
- Grigoryan, V.A., Belyanchikov, L.N., Stomakhin, A.Ya. (1987) *Theoretical fundamentals of electric steelmaking processes*. Moscow, Metallurgiya [in Russian].
- Grigorenko, G.M., Kozin, R.V. (2018) Nitrogen solubility in fluxes for electroslag technologies. *Suchasna Elektrometall.*, **2**, 37–40 [in Russian]. DOI: <http://dx.doi.org/10.15407/sem2018.02.04>
- In-Ho Jung (2006) Thermodynamic modeling of gas solubility in molten slags (I)–carbon and nitrogen. *ISIJ International*, **46**(11), 1577–1586.
- Eloy Martinez, R., Victor Espejo, O., Francisco, Manjarrez (1993) The solubility of nitrogen in the CaO–CaF–Al₂O₃ system and its relationship with basicity. *ISIJ International*, **33**(1), 48–52.
- Lakomsky, V.V., Pomarin, Yu.M., Ryabtsev, A.D., Grigorenko, G.M. (2006) Metal nitriding from gas phase in ESR. *Sovrem. Elektrometall.*, **4**, 3–5 [in Russian].
- Lakomsky, V.V., Grigorenko, G.M. (2012) Kinetics of gas phase nitrogen interaction with metal covered with molten slag. *Sovrem. Elektrometall.*, **3**, 35–37 [in Russian].
- Kozin, R.V., Kuznetsova, L.V., Gulyanytska, N.E., Mosokovska, I.A. (2019) Determination of nitrogen content in CaO–Al₂O₃ systems by Kjeldahl method. *Metrologiya ta Prylady*, **3**, 55–60 [in Ukrainian].
- Zabarilo, O.S., Lakomsky, V.I. (1968) Carbon behavior in plasma-arc remelting of alloy 50N and Armco iron. *Spec. Elektrometallurgiya*, **4**, 78–85 [in Russian].
- Grigoryan, V.A., Stomakhin, A.Ya., Utochkin, Yu.I. et al. (2007) *Physical-chemical calculations of electric steelmaking processes: Coll. of Problems with Solutions*. 2nd Ed. Moscow, MISiS [in Russian].
- Grigorenko, G.M., Pomarin, Yu.M. (1989) Hydrogen and nitrogen in metals during plasma melting. Kyiv, Naukova Dumka [in Russian].

ORCID

V.O. Shapovalov: 0000-0003-1339-3088,
V.G. Mogylatenko: 0000-0002-6550-2058,
R.V. Lyutyi: 0000-0001-6655-6499,
R.V. Kozin: 0000-0002-8501-0827

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

V.G. Mogylatenko
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.
E-mail: vmogilatenko@gmail.com

SUGGESTED CITATION

V.O. Shapovalov, V.G. Mogylatenko,
R.V. Lyutyi, R.V. Kozin (2024) Nitrogen absorption
by 04Cr18Ni10 steel in plasma-arc melting under
slag of CaO–Al₂O₃ system. *The Paton Welding J.*, **1**,
43–50.

JOURNAL HOME PAGE

<https://patonpublishinghouse.com/eng/journals/tpwj>

Received: 31.08.2023

Received in revised form: 18.10.2023

Accepted: 15.01.2024