DOI: https://doi.org/10.37434/tpwj2024.02.05

PLASMA-ARC SKULL MELTING AND CASTING OF AUSTENITIC STEEL WITH SUPER EQUILIBRIUM NITROGEN CONTENT

V.O. Shapovalov, V.P. Burnashev, T.I. Grishchenko, V.V. Yakusha, Yu.O. Nikitenko

E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine

ABSTRACT

Shown is the possibility of melting and casting high-nitrogen Kh21G17AN2 steel under the conditions of plasma-arc skull melting. Boundary conditions of nit riding Kh12G17|N2 steel in order to produce sound castings were determined. Castings in the form of 12 mm wire were produced. Casting quality and properties were studied. Investigation of weldability of the produced steel with super equilibrium nitrogen content was conducted at manual argon-arc welding.

KEYWORDS: plasma-arc skull melting, Kh12G17N2 steel, nitrogen,, casting, properties, weldability

INTRODUCTION

Nitrogen n the composition of alloyed steels demonstrates austenite stabilizing properties, and it is used as a replacement of expensive nickel, which is traditionally added to form the austenite phase [1–3]. So far, a significant progress has been achieved in metallurgical production of steels alloyed by nitrogen. Development of high-nitrogen steels with special functional properties (high strength, corrosion resistance, biocompatibility, etc.) stimulates the increase of the scope of industrial application of nitrogen-containing steels in manufacture of products for critical purposes [4–6]. Steels containing nitrogen in the quantity greater than its solubility under equilibrium conditions are usually considered as high-nitrogen steels.

Ingots and castings from steels with super equilibrium nitrogen content are produced by a number of special electrometallurgy methods, namely high-pressure induction melting, electroslag remelting in a controlled atmosphere, plasma-arc remelting [7–10]. At present the method of autoclave induction melting is the most widely accepted technique for producing nitrogen-containing steels. Not considering the popularity of this method, it has certain significant disadvantages, which are associated with the long-time process of melting and soaking of the liquid metal at excess pressure and complexity of the technological equipment, while the obvious advantages of this method occurring in production of steels with nitrogen concentration below the equilibrium one (approximately 0.4 %), are practically absent, when producing high-nitrogen steels. Contrarily to the above-mentioned melting processes, at plasma-arc remelting of nitrogen-containing steels nitrogen additionally interacts with the liquid metal surface in an excited condition, which allows obtaining its super equilibrium concentration in the metal, and significantly intensifying the absorption process, shortening the processing duration by an order [8]. Relative simplicity of the technological equipment, performance of metal remelting at significantly lower gas pressures, no need for long-term soaking of liquid metal at excess pressure show the good prospects for plasma-arc processes when producing steels with super equilibrium nitrogen content.

Alongside the need to produce ingots from high-nitrogen steels, not less important is producing shaped castings from them. Increase of the requirements to casting quality, as well as expansion of manufacturing of cast products from nigh-nitrogen steels, requires development of new technology solutions, which will ensure the high quality of the melted and cast metal. The complex of practical measures to improve the casting quality is chiefly aimed at improvement of the processes of melting and treatment of liquid metal, including deoxidizing, refining, alloying; metal pouring into moulds in modes ensuring high physical-mechanical properties of the castings; engineering casting moulds based on materials with high physical-mechanical and thermophysical properties to ensure maximum closeness of casting dimensions to those of the finished parts.

As a variety of plasma-arc processes, the method of plasma-arc skull melting [11, 12] allows conducting melting and pouring of nitrogen-containing steel in one process installation. For melting sound metal and ensuring high technical and economic indices of the melting process the skull crucible should meet the following requirements: prevent interaction of crucible material with the molten metal, ensure the required time of metal soaking in the liquid state; and provide the maximal coefficient of metal pouring (K_p).

Interaction of liquid metal with the crucible material can be prevented, using a metal, for instance, copper water-cooled crucible, which improves the operational conditions of the melting installation and contributes to casting quality.

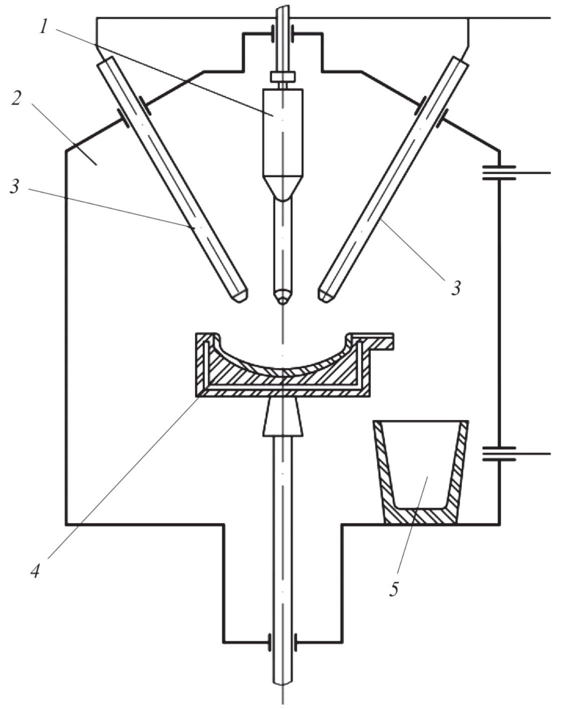

Figure 1. Block-diagram of UPG-1L plasma-arc installation: *1* — consumable billet; *2* — furnace chamber; *3* — PDM-7 plasmatrons; *4* — crucible; *5* — mould

Development of methods to join nitrogen-containing steels by welding is one of the priority tasks for rational manufacture of both the individual parts, and elements of structures from them [6, 13]. Austenitic steels with super equilibrium nitrogen content have limited weldability when arc welding methods are used. Steels containing more than 0.5 % nitrogen are prone to porosity. Weld porosity in welding is influenced not only by absolute nitrogen content, but also by the conditions of weld pool existence (volume, shape, welding speed, preheating temperature). It is noted that lowering of welding energy input promotes reduction of the total number of defects and their dimensions. Lowering of welding current to 80 A, and increase of the number of passes to 3–4 promotes a reduction of the total number of pores in the welds [14].

RESEARCH OBJECTIVE

The objective of research conducted in this work, consisted in optimizing the technological modes of plasma-arc skull melting (PASM) and casting of Kh-21G17N2 steel sparsely-alloyed by nickel with super equilibrium nitrogen content, studying the features of nitrogen influence on its structure, determination of the parameters of TIG welding of high-nitrogen steel samples and welded joint characteristics.

Figure 2. Copper water-cooled mould

EQUIPMENT AND MATERIALS

Investigations of the technological features of the process of PASM and casting of high-nitrogen steel were conducted in plasma-arc skull installation UPG-1L developed by PWI (Figure 1). Plasma-arc installation was fitted with a copper water-cooled crucible of 1000 cm^3 volume (Figure 2) and DC plasmatrons of PDM-7 type with up to 500 A admissible current.

The melting-pouring installations with a radial heating scheme enable either dispersing heat input to the pool surface or concentrating it in the specified zones, adjusting the heating of different regions of the liquid metal pool. With such a heating scheme the surface of the billet being remelted partially shields the plasma arc radiation, thus increasing the thermal efficiency of melting.

Two-phase austenitic-ferritic Kh21G17N2 steel was selected as the initial material for investigations. Chromium of Kh98 grade, Armco iron, cathode nickel of N1 grade, metallic manganese MP-1 were applied to produce the grade chemical composition. Initial charge was used to melt under PASM conditions samples of steel, the chemical composition of which is given in Table 1.

Results of chemical analysis of steel of melt 1 showed a lower content of manganese and nickel, compared to calculated values. Correction of the composition of charge materials for subsequent melts 2 and 3 ensured melting steel of the required grade composition. Obtained steel compositions were used to melt samples with super equilibrium nitrogen concentration.

Table 1. Chemical composition of produced steel, wt.%

Melt	Cr	Mn	Ni	C	S	P	[O]	[N]
1	20.4	13.9	1.67	0.1	0.025	0.02	0.042/0.03	0.016/0.73
2	20.9	16.8	1.90	–»–	–»–	–»–	–»–	0.018/0.74
3	21.0	16.9	2.10	–»–	–»–	–»–	0.023/0.028	0.017/0.90

Note. [O] and [N] content in the initial metal is shown in the numerator; in the metal after nitriding — in the denominator.

EXPERIMENTAL INVESTIGATIONS

MELTING AUSTENITIC Kh21G17AN2 STEEL WITH SUPER EQUILIBRIUM NITROGEN CONTENT

Under the conditions of excess gas pressure in the melting chamber and distributed heating of liquid metal pool chromium evaporation is practically absent, small losses of manganese are observed, which can grow somewhat with lowering of total gas pressure and increase of plasma-forming gas flow rate.

Dependence of nitrogen solubility on melt temperature and partial pressure of nitrogen in the furnace atmosphere was calculated for the respective chemical composition of the produced steels (Table 1), using an equation given in work [10]:

$$\lg k = -\frac{293}{T} - 1.16 - \left(0.042 - \frac{167}{T}\right)[\mathrm{Cr}\,\%] -$$
$$-0.5\left(\frac{3,3}{T} - 0.001\right)[\mathrm{Cr}\,\%]^2 - \left(0.022 - \frac{73}{T}\right)[\mathrm{Mn}\,\%] -$$
$$-\left(\frac{18.4}{T} + 0.00042\right)[\mathrm{Ni}\,\%] - \left(\frac{171}{T} - 0.031\right)[\mathrm{Si}\,\%] -$$
$$-\left(\frac{274}{T} - 0.06\right)[\mathrm{C}\,\%] - \left(\frac{1640}{T} - 1.14\right)[\mathrm{O}\,\%] -$$
$$-\left(\frac{859}{T} - 0.487\right)[\mathrm{Al}\,\%].$$

In keeping with the conducted calculations, standard solubility of nitrogen in steels at melt temperature of 1873 K was equal to 0.49 and 0.57 %, respectively for melt 1 and melts 2 and 3. It was determined that with melt temperature increase by 100 K the standard solubility of nitrogen in the metal decreases by 17 % on average, and at increase of nitrogen partial pressure in furnace atmosphere by 100 kPa it grows by 40 %.

Calculated data on nitrogen solubility were used at optimization of technological modes of PASM of Kh-21G17N2 steel with super equilibrium nitrogen content. Experimental melts were conducted in UPG-1L furnace, using a plasma-forming mixture of nitrogen and argon gases. Gas flow rate was equal to 80 l/min. Metal melting and soaking were performed at plasmatron current of 280–300 A and 70 V voltage. According to the data in Table 2, the required working pressure of gases was maintained in the furnace chamber, and the specified partial pressure of nitrogen was provided.

Table 2. Parameters of pressure and composition of plasma-forming gas mixture

Melt	Working pressure in the chamber, kPa	Nitrogen content in the gas mixture, vol.%	Partial pressure of nitrogen during melting, kPa
1	185	85–86	160
2	200	–»–	170
3	210	–»–	180

PRODUCING CASTINGS FROM AUSTENITIC Kh21G17AN2 STEEL WITH SUPER EQUILIBRIUM CONTENT OF NITROGEN

The method of conducting the melting at excess pressure of nitrogen allows treating the metal not only during its melting, soaking and pouring, but also during its solidification. It greatly widens the possibility of controlling the gas-shrinkage, liquation and other processes at formation of the casting structure to improve the density and other physical-mechanical properties of the metal.

The main problem of producing the ingots and castings from steels with super equilibrium nitrogen content is related to the high probability of formation of gas porosity in the metal at its hardening. It is known that the limit concentration of nitrogen at plasma-arc treatment of the melt is determined by nitrogen boiling of the metal pool, from the viewpoint of technology, which is indicative of reaching the dynamic equilibrium of the sorption process at these thermodynamic conditions [8, 15]. Its value is determined by the conditions of existence of gas bubbles in the melt volume, and it is in equilibrium with the total pressure of gases in the furnace, and not with partial pressure of nitrogen. Further increase of partial pressure of nitrogen does not influence its content in the metal. The start of nitrogen boiling of the pool depends on nitrogen absorption rate, convection conditions, standard solubility of nitrogen in the melt and total gas pressure in the melting chamber.

Application of such a technological measure as gas pressure increase in the furnace chamber during metal pouring into the mould allows inhibiting the dissolved nitrogen desorption in the metal and preventing gas porosity formation. In work [11], devoted to PASM of critical castings from 0Kh20N5AG2 steel with super equilibrium nitrogen content, a nomogram was proposed for determination of limit pressure of gas in the plasma-arc furnace, which should be maintained at pouring to produce porefree castings. Guided by the theoretical principles of this work, the respective nomogram was plotted for the studied Kh21G17AN2 steel (Figure 3). The nomogram contains two dependencies, one of which corresponds to limit concentration of nitrogen in steel in the mode of nitrogen boiling of the pool, depending on total gas pressure in the furnace (curve *1*) and the second corresponds to nitrogen content in steel, depending on nitrogen partial pressure (curve *2*). Proceeding from nitrogen content in Kh21G17AN2 steel which should be achieved a horizontal line is drawn up to intersection with dependencies 1 and 2. The abscissas of the points of their intersection indicate the limit pressure of gases in the furnace chamber at metal pouring to ensure solid cast products and the partial pressure of nitrogen, required to produce metal with the specified nitrogen content.

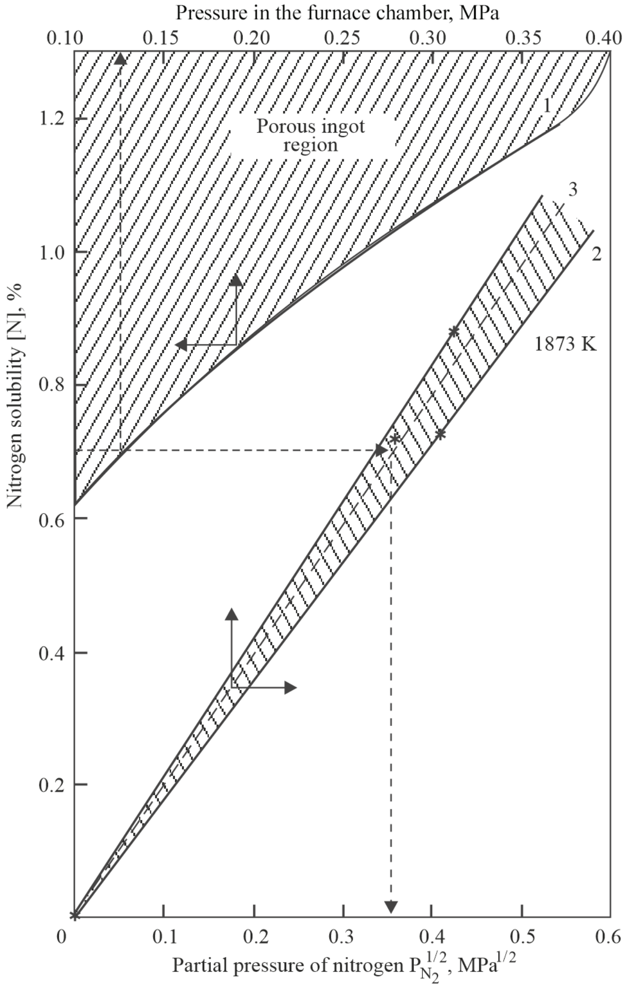

Figure 3. Nomogram for determination of limit pressure at pouring under the conditions of PASM of nitrogen-alloyed steels: *1* — nitrogen solubility calculated under the conditions of metal pool boiling using equation $[N] = S_N\sqrt{P_\Sigma}$, where S_N is the standard nitrogen solubility, %; P_Σ is the total pressure of gases, at; *2* — dependence of nitrogen content in steel on nitrogen partial pressure; *3* — isotherm of nitrogen solubility in steel at 1873 K

Used as a mould in the experiments was a detachable steel mould (Figure 4), which as a result of one-time pouring ensured metal crystallization in the form of cylindrical rods (18 pcs) of 12 mm diameter and 180 mm length (Figure 5). After metal melting and inducing the pool, the melt was soaked for 10–15 min under the conditions of plasma-arc heating at the specified partial pressure of nitrogen, eliminating the possibility of its nitrogen boiling, and then the treated metal was poured into the mould. During metal melting the pressure of gases in the furnace and the composition of plasma-forming mixture were maintained in keeping with the data given in Table 2.

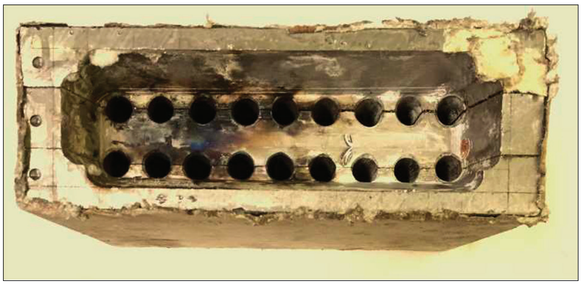

Figure 4. Detachable steel mould

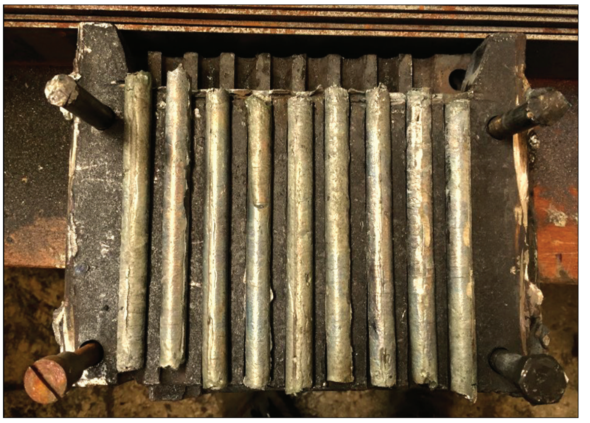

Figure 5. Appearance of the mould with cast rods

Produced castings were used to prepare longitudinal macrosections to study the cast structure of the rods and to take samples for chemical and gas analysis.

INVESTIGATIONS OF TIG WELDING OF SAMPLES FROM NITROGEN-ALLOYED AUSTENITIC STEEL Kh21G17AN2

Weldability of high-nitrogen Kh21G17AN2 steel was studied in the case of manual nonconsumable tungsten electrode argon-arc welding. With this purpose 6 and 3 mm plates were produced from the rods by rolling. Rectangular samples were directly made from 6 mm plates for optimization of the welding technology. Milling of the edges was performed from the welding side on the adjacent faces of the samples on both sides. The 3 mm plates were used to produce filler material in the form of the so-called "noodles". Thus, filler electrodes of the same steel grade were applied for TIG welding of samples of Kh21G17AN2 steel. Butt welding of the samples was performed, conducting it in two passes from both sides, in keeping with the welding modes, given in Table 3.

The produced welded joint samples were used to prepare transverse macrosections to study the metal structure in the joint zone. Mechanical properties of the welded joints and their nitrogen and oxygen content were additionally studied.

Figure 6. Macrostructure of the longitudinal section of rods with different nitrogen content, %: *1* — 0.73; *2* — 0.74; *3* — 0.9

Table 3. Modes of manual argon-arc welding

Sample	Voltage, V	Current, A	Gas composition, %		Gas flow rate, l/min	Welding speed, cm/s	Number of passes
			Ar	N_2			
1	20	100	80	20	10	0.20	2 from each side
2	18	80	90	10	–»–	0.15	–»–

Table 4. Mechanical properties of the welded joint

Sampling area	$\sigma_{0.2}$, MPa	σ_t, MPa	δ, %	ψ, %	*KC*, MJ/mm²	Fracture site
Base metal	841	933.0	25.9	42.7	1.45	–
Weld	540	860.0	28.0	41.2	1.58	Weld

Table 5. Content of gas admixtures in the metal of the weld of Kh21G17AN2 steel welded joint

Gas admixtures	Base metal	Weld metal				
		1	2	3	4	5
[O]	0.042	0.033	0.028	0.032	0.036	0.034
[N]	0.74	0.74	0.73	0.74	0.73	0.74

Note. 1–5 are samples taken every 25 mm along the weld length.

DISCUSSION OF THE RESULTS

As a result of the conducted experiments, technological modes of alloying Kh21G17N2 steel of austenitic-ferritic grade by nitrogen from the gas phase in plasma-arc skull melting and its pouring into a steel mould. Castings from high-nitrogen steel were produced in the form of small diameter rods. The results of gas analysis of the rods by Kjeldahl, given in Table 1, show that nitrogen content in the rods of all the three batches exceeds the standard nitrogen solubility by more than 1.3 times, being equal to 0.73, 0.74 and 0.9 % for melts 1, 2, and 3, respectively. Comparing the derived concentrations with the calculated values of equilibrium nitrogen content at 1873 K, it was found that the nitriding mode, followed during melts 1 and 3, ensures such a nitrogen concentration in the castings, which is by 7 and 15 % higher than the equilibrium one, respectively. Investigations of the cast structure of the rods showed that the rods of the first and second melt are solid, without visible pores or nonmetallic inclusions in the macrosection field of vision (Figure 6). In both the cases metal pouring into the mould was performed at the total gas pressure in the furnace higher than the limit gas pressure determined by the nomogram (Figure 3). Coarse pores of 0.5 to 2.0 mm diameter were found in the entire thin section field in the body of the rods of the third melt. Despite the fact that metal pouring was conducted at the pressure exactly corresponding to the limit value (Figure 4), it turned out to be insufficient to prevent gas porosity for this concentration of nitrogen,. Thus, in order to inhibit development of this process, it is necessary to maintain a pressure during pouring with a certain excess over the one determined by the nomogram.

Performed weldability studies of high-nitrogen Kh21G17AN2 steel showed that the mechanical properties of the weld and base metal are within the expectations (Table 4). Somewhat lower ultimate strength (σ_t), yield limit ($\sigma_{0.2}$) of weld metal, but higher relative elongation (δ) and impact toughness (*KC*) are noted.

Analysis of gas admixtures content in the welded joint showed that compared to base metal a certain lowering of oxygen is found, while nitrogen concentration practically does not change (Table 5). The proposed welding modes ensure formation of a joint with a pool of limited dimensions and short time of its existence, which, probably does not allow development

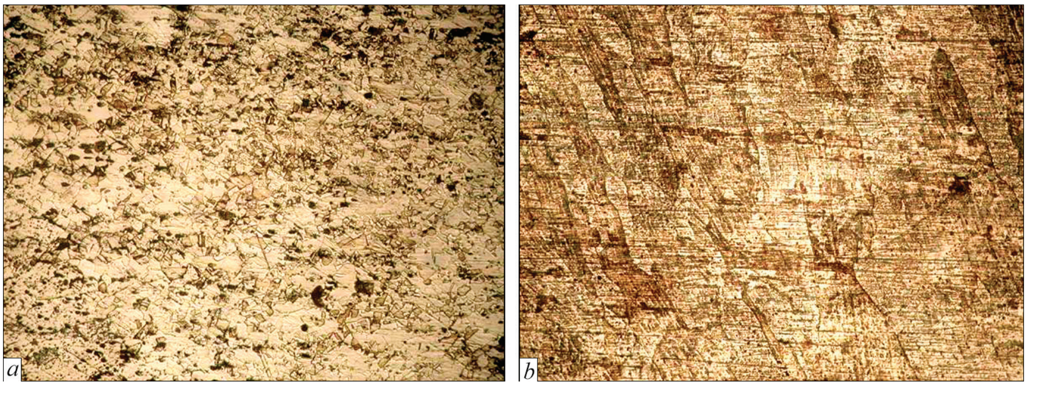

Figure 7. Microstructure (×100) of base (wrought) metal (*a*) and weld (*b*)

of the reaction of nitrogen desorption from the weld metal or porosity formation.

Metallographic studies of the weld and base metal (Figure 7) showed that their microstructure is completely austenitic. No pores, cracks or other defects were detected in the joint. Considering the above data, one can state weldability of high-nitrogen Kh21G17AN2 steel is satisfactory.

CONCLUSIONS

1. Conducted investigations showed that the PASM technology allows actively conducting alloying by nitrogen from the gas phase of Kh21G17AN2 steel sparsely-alloyed by nickel, producing castings with a super-equilibrium nitrogen content and austenitic structure.

2. It is found that in order to produce castings without defects in the form of pores, it is necessary to conduct pouring of Kh21G17AN2 steel at total gas pressure in the plasma furnace, exceeding the limit pressure of gases, determined using a nomogram.

3. Experiments on weldability of Kh21G17AN2 steel show that the proposed modes of argon-arc welding ensure satisfactory mechanical characteristics of the welded joint, without porosity or cracks in the HAZ or weld metal.

REFERENCES

1. Uggowitzer, P.J., Magdowski, R., Speidel, M.O. (1996) Nickel free high nitrogen austenitic steels. *ISIJ Inter.*, 36(**7**), 901–908. DOI: https://doi.org/10.2355/isijinternational.36.901
2. Gavriljuk, V., Petrov, Y., Shanina, B. (2006) Effect of nitrogen on the electron structure and stacking fault energy in austenitic steels. *Scr. Mater*., **55**, 537–540. DOI: https://doi.org/10.1016/j.scriptamat.2006.05.025
3. *Nithi* Saenarjhan, Jee-Hyun Kang, Sung-Joon Kim (2019) Effects of carbon and nitrogen on austenite stability and tensile deformation behavior of 15Cr–15Mn–4Ni based austenitic stainless steels. *Materials Sci. and Eng.*, *A*, **742**, 608–616. DOI: https://doi.org/10.1016/j.msea.2018.11.048
4. Patnaik, L., Maity, S.R., Kumar, S. (2020) Status of nickel free stainless steel in biomedical field: A review of last 10 years and what else can be done. *Mater. Today Proc*., **26**, 638–643. DOI: https://doi.org/10.1016/j.matpr.2019.12.205
5. Chail, G., Kangas, P. (2016) Super and hyper duplex stainless steels: Structures, properties and applications. *Procedia Structural Integrity*, **2**, 1755–1762. DOI: https://doi.org/10.1016/j.prostr.2016.06.221
6. Mohammed, R., Madhusudhan Reddy, G., Srinivasa Rao, K. (2017) Welding of nickel free high nitrogen stainless steel: Microstructure and mechanical properties. *Defence Technology*, 13(**2**), 59–71. DOI: https://doi.org/10.1016/j.dt.2016.06.003
7. Sheiko, I.V., Grigorenko, G.M., Shapovalov, V.A. (2016) Alloying of steels and alloys with nitrogen from the arc plasma. Theory and practice (Review. Pt 1). *Sovrem. Elektrometall.,* **1**, 32–37 [in Russian].
8. Paton, B.E., Grigorenko, G.M., Sheiko, I.V. et al. (2013) *Plasma technologies and equipment in metallurgy and foundry.* Kyiv, Naukova Dumka [in Russian].
9. *Nabil* Ghali, S., Eissaб M., El-Faramawy, H. et al. (2013) Production and application of advanced high nitrogen steel. In: *Proc. of Inter. Conf. on Sci. and Technology of Ironmaking and Steelmaking* At. Jamshedpur, India, 1. DOI: https://www.researchgate.net/publication/262698868_Production_and_Application_of_Advanced_High_Nitrogen_steel
10. 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 Elektrometal.,* **2**, 23–26 [in Ukrainian]. DOI: https://doi.org/ 10.37434/sem2020.02.04
11. Granovsky, V.K. (1982) *Study of physical-chemical processes and development of technology of plasma-arc skull melting of high-nitrogen steels and alloys*: Syn. of Thesis for Cand. of Tech. Sci. Degree. Kyiv [in Russian].
12. Burnashev, V.R., Zhadkevich, M.L., Shapovalov, V.A. (2002) Plasma-arc skull melting and casting of refractory metals and alloys. *Advances in Electrometallurgy,* **2**, 30–33.
13. Zeng, Liu, Chenglei, Fan, Chunli, Yang et al. (2022) *Dissimilar welding of high nitrogen stainless steel and low alloy high strength steel under different shielding gas composition: Process, microstructure and mechanical properties. Defence Technology*. DOI: https://doi.org/10.1016/j.dt.2022.10.010
14. Yushchenko, K.A., Solokha, A.M., Kazennov, N.P. (1989) Technological peculiarities of welding of high-nitrogen steels. In: *Proc. of Inter. Conf. on High-Nitrogen Steels 89 (1–3 October, 1989, Varna, Bulgaria)*, Vol. 2, 12–15 [in Russian].
15. Erokhin, A.A. (1975) *Plasma-arc melting of metals and alloys.* Moscow, Nauka [in Russian].

ORCID

V.O. Shapovalov: 0000-0003-1339-3088
V.P. Burnashev: 0000-0001-6807-3810,
T.I. Grishchenko: 0000-0001-7840-9832,
V.V. Yakusha: 0000-0001-5962-9194,
Yu.O. Nikitenko: 0000-0002-3603-2333

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

V.O. Shapovalov
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.
E-mail: vash52@ukr.net

SUGGESTED CITATION

V.O. Shapovalov, V.P. Burnashev, T.I. Grishchenko, V.V. Yakusha, Yu.O. Nikitenko (2024) Plasma-arc skull melting and casting of austenitic steel with super equilibrium nitrogen content. *The Paton Welding J*., **2**, 27–32.

JOURNAL HOME PAGE

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

Received: 12.06.2023
Received in revised form: 07.12.2023
Accepted: 14.02.2024