DOI: https://doi.org/10.37434/tpwj2025.01.04

MASTERING THE TECHNOLOGY OF PRODUCING INGOTS FROM HEAT-RESISTANT ALLOYS KhN38VT AND KhN60VT BY THE ELECTRON BEAM MELTING METHOD

S.V. Akhonin[1], V.O. Berezos[1], M.I. Medvedev[2], O.S. Bobukh[2], D.S. Ivanov[3], O.G. Yerokhin[1]

[1]E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine
[2]Ukrainian State University of Science and Technologies
2 Lazaryan Str., 49010, Dnipro, Ukraine
[3]Zaporizhzhia Casting-Mechanical Plant
72 Pivdenne Prosp., 69008, Zaporizhzhia, Ukraine

ABSTRACT

In order to optimize the technology of production of nickel- and iron-based heat-resistant alloys, the E.O. Paton Electric Welding Institute conducted melting of a batch of ingots of Kh38VT and Kh60VT grades. The ingots were produced using the technology of cold hearth electron beam melting and portioned feed of liquid metal to a water-cooled crucible. The conducted work showed that the electron beam melting method allows producing high-quality defect-free ingots of nickel-based heat-resistant alloys that meet the requirements of the standards, and it can be used instead of secondary vacuum-arc remelting. When using ingots of primary induction remelting as the initial charge billet, it is not necessary to add alloying elements with high vapor pressure to ensure a chemical composition that meets GOST 5632–72. In addition, the level of mechanical properties of KhN60VT alloy bars almost completely satisfies the requirements of TU 14-3-571–2004 on “Seamless cold-deformed pipes from the KhN60VT (EI868) alloy and KhN60VT-VD alloy for the aviation industry”.

KEYWORDS: heat-resistant alloy, charge billet, ingot, electron beam melting, cold hearth, refining, impurities, metal quality

INTRODUCTION

Development of new technological processes, ensuring removal of impurities, nonmetallic inclusions and the production of physically and chemically homogeneous ingots, is of great importance in improving the service and technological properties of heat-resistant steels [1].

Vacuum metallurgy has a prominent place among the metallurgical methods of improvement of the quality of steels and alloys [2, 3]. Vacuum melting of the metal, on the one hand, prevents its interaction with atmospheric gases, and on the other hand, intensifies the degassing and evaporation reactions. Moreover, remelting in a vacuum environment enables additional cleaning of the metal from nonmetallic inclusions, producing ingots and finished products with a homogeneous dense structure without any macrodefects [4].

New processes of electron beam melting (EBM) allow producing metal of an even higher quality [5, 6].

Electron beam melting, which combines the best features of vacuum-induction and vacuum-arc melting, is an efficient method of furnace vacuum metallurgy. At EBM the liquid metal contact with fire-resistant materials is absent, and the heating and melting processes are controlled independently of each other, that allows varying the liquid metal temperature and vacuuming time in a broad range [7]. These advantages in combination with continuous metal feed ensure producing ingots of maximally high purity with defect-free structure during EBW.

Application of EMB technology to improve the quality of special steels and complex alloys based on iron and nickel allows practically completely removing many of the low-melting impurities (lead, zinc, bismuth, tin, etc.) and even lowering the nonmetallic inclusion content simultaneously with an abrupt lowering of the content of hydrogen, nitrogen, and oxygen at remelting of these materials. Owing to a high degree of refining and formation of ingots with a more homogeneous structure and chemical composition, EBM results in an essential improvement of the physical-mechanical properties of the metals and alloys [8]. Their technological plasticity is increased, particularly at pressure treatment. So, remelting of tool and bearing steels provides: an improvement in hot deformability; lowering of the required degree of forging reduction and cracking sensitivity at heat treatment; improvement of polishedness and ductile properties [9].

MATERIALS AND EXPERIMENTAL PROCEDURE

In order to determine the degree of refining of heat-resistant nickel-based alloys and to optimize the technology of their production, PWI performed melting

Figure 1. Charge billets: *a* — KhN60VT; *b* — KhN38VT

of ingots of KhN38VT and KhN60VT grades. Nickel-based KhN60VT alloy is widely used in the aircraft industry. Ingots were produced by the technology of cold hearth EBM with portioned feed of liquid metal into a water-cooled crucible.

Test melts were conducted in UE5812 electron beam unit fitted with a cold hearth [10].

The technological sequence of melting the ingots consisted of the following stages: taking samples for control chemical analysis of the initial charge, preparation of the equipment and technological fixture for melting; forming the consumable billet; melting process; taking samples for chemical and gas analysis of the produced ingot.

SE "STC "Titan" of the E.O. Paton Electric Welding Institute of the NAS of Ukraine" performed melting of a batch of ingots of KhN60VT and KhN38VT grades.

Charge billets for producing ingots of KhN60VT and KhN38VT grades were ingots of primary induction remelting (Figure 1).

The head parts of the initial billets had a certain amount of crystallized slag in their composition (Figure 2).

Figure 2. Appearance of the head part of the initial charge billet

Compared to a VAR ingot, an EBM ingot does not require any additional surface treatment (cutter turning or surface melting by an arc), or removal of the ingot crop part.

Experience of producing nickel-based heat-resistant alloys by cold hearth EBM showed that at a sufficiently large amount of slag in the initial charge it penetrates into the cold health. When slag accumulates in the cold hearth, the drain spout is blocked, thus creating the conditions which make pouring of the liquid melt into the crucible more complicated. Moreover, the cold hearth is not capable of holding up the all the liquid slag accumulated during melting, and its certain amount penetrates into the liquid metal melt in the crucible. At pouring of the next melt portion into the crucible, slag entrapment in the liquid melt at the cold walls of the crucible may occur, thus impairing the ingot surface quality.

Thus, in order to prevent ingress of a large amount of slag into the ingot melting and crystallization zone, the initial billets are loaded into the unit so that remelting occurred from the bottom part at the start of melting to the head part at the end of melting.

The consumable billet was loaded into the electron beam unit box by the shop crane.

After loading in the charge billet and preparation of the unit for melting, it was sealed and pumped down. Upon reaching the working pressure in the melting chamber of $1.33\cdot10^{-2}$–$6.66\cdot10^{-3}$ Pa, leakage into the chamber working volume was determined. The admissible leakage value is not higher than 30 μm·l/s.

The essence of the process (Figure 3) consisted in the horizontal feed of consumable billet *6*, at a set speed into the melting zone, its melting by the electron beams above cold hearth *7*. As the cold hearth was filled, the liquid metal was poured into crucible *8*, where ingot *9* of the required length was formed.

Deposition of a new layer of the skull in the cold hearth was performed for each ingot (Figure 4).

During melting, the initial charge was continuously fed into the working area above the cold hearth,

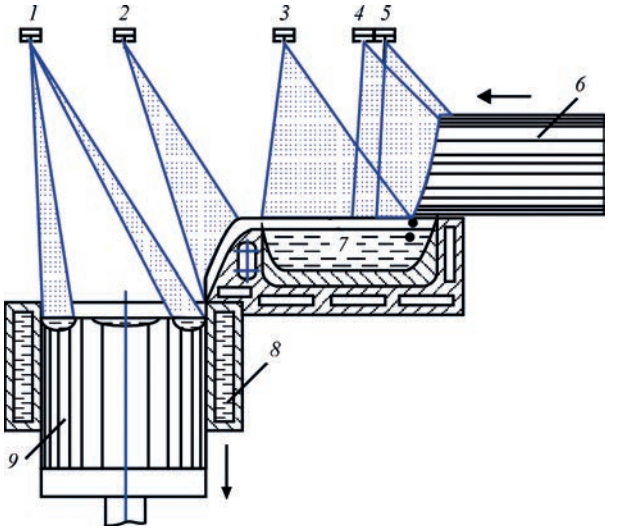

Figure 3. Schematic of cold hearth electron beam melting: *1–5* — electron beam guns; *6* — consumable charge billet; *7* — cold hearth; *8* — crucible; *9* — ingot

where its smelting occurred under the effect of electron beam heating. The melting process was stable, however, precipitation of a considerable amount of slag was observed, which stayed in the cold hearth in the melting zone. Slag penetration into the liquid melt in the crucible in small amounts was also observed (Figure 5).

In order to improve the processes of refining from impurities and inclusions at melting of ingots of nickel-based heat-resistant alloys, the time of liquid metal soaking in the cold hearth and the crucible was extended, due to lowering the melting productivity from 280 to 240 kg/h.

During melting, in keeping with the conducted calculations for determination of optimal melting modes, the following technological parameters were kept constant: melting rate, time between portion pouring, and portion height in the crucible. Ingot heating in the crucible was conducted by scanning over the surface with the beam of electron beam guns. During melting the electron beam moved over the upper end face of the formed ingot in the zone of the melt contact with the working surface of the crucible inner part, providing deeper penetration of the ingot surface, melting up of the present casting defects and compensation of heat removal into the crucible that had a positive impact on the structure. Numerical values of the technological parameters for ingots of 400 mm diameter are given below.

Technological parameters of melting 400 mm diameter ingots

Melting rate, kg/h	240
Time between pouring the portions, s	60
Height of portions in crucible simultaneously, mm	4
Power of the 1st gun, kW	90
Power of the 2nd gun, kW	90
Power of the 3rd gun, kW	90
Power of the 4th gun, kW	150
Power of the 5th gun, kW	150

Figure 4. Appearance of skull

Rate and power of metal deposition into the cold hearth and crucible were kept constant. The process of smelting the initial charge billets was continued up to approaching the zone of the head part melting. This moment was clearly observed at penetration of slag into the melting zone, located in the head part of the initial billet. Here, intensive metal sputtering and bright glowing of the melting slag were observed (Figure 6). At that moment the process of melting of the initial charge billet stopped.

At the end of melting, removal of the shrinkage cavity was performed by gradually lowering the power of heating the ingot upper end face in the crucible.

Ingots of nickel-based heat-resistant KhN60VT and KhN38VT alloys with outer diameter of 400 mm

Figure 5. Process of EBM of nickel-based heat-resistant KhN60VT alloy

Figure 6. Melting of slag contained in the initial charge billet

and up to 2000 mm length were produced as a result of the conducted melting operations (Figure 7).

The ingot surface quality as regards the presence of pores, cavities, nonmetallic inclusions and cracks was determined visually, without application of magnifying instruments. The side surface of the produced ingots after cooling for 6 h in vacuum was clean, without traces of tarnishing colours. The depth of surface defects of casting origin did not exceed 6 mm, defects in the form of tears, cracks or lacks-of-fusion were absent. Individual slag embedments were observed in the ingot surface layer (Figure 8).

Ingot facing was performed on a band saw.

The surface of the produced ingots was machined to remove casting defects. The ingots were stripped on DIP-500 lathe (Figure 9).

Thus, a technology of melting high-quality ingots of nickel-based heat-resistant alloys by the method of electron beam melting was optimized, which allows producing ingots with a satisfactory surface quality. The possibility of EBM application instead of VAR for remelting ingots of open induction melting is shown.

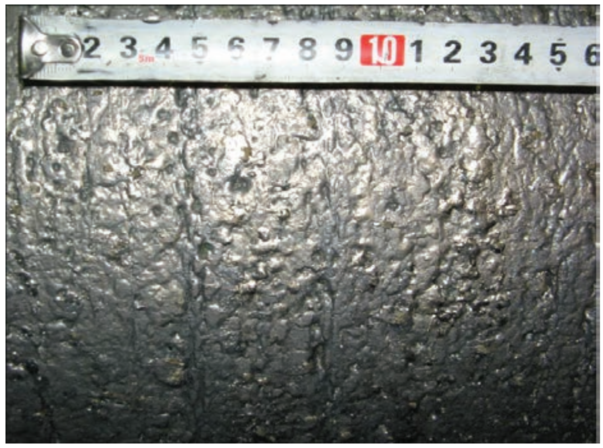

Figure 8. Quality of the cast surface of 400 mm dia ingot from heat-resistant KhN60VT alloy

Samples for ICP analysis were taken from the head, middle and bottom parts of the produced ingots. Samples were taken from the ingot side surface at its machining as follows: preliminary drilling to 2–3 mm depth, surface layer chips were thrown away. The sample was taken at further turning to the depth of 7–10 mm. Chip overheating when taking the samples was not allowed. No lubricating-cooling liquids were used when taking the samples. The selected samples were placed into paper bags with indication of melt number and sampling area. The weight of each sample was at least 20–30 g. Element content in the ingots was taken to be equal to mean arithmetic values of the results of measurements for all the samples.

The same procedure was used to select one point in the central part of each initial charge billet.

Chemical element content was determined by the method of inductively-coupled plasma-optical emission spectrometry (ICP-OES) in ICP-spectrometer ICAP 6500 DUO.

Figure 7. Finished ingots of 400 mm diameter from heat-resistant alloys: *a* — KhN60VT; *b* — KhN38VT

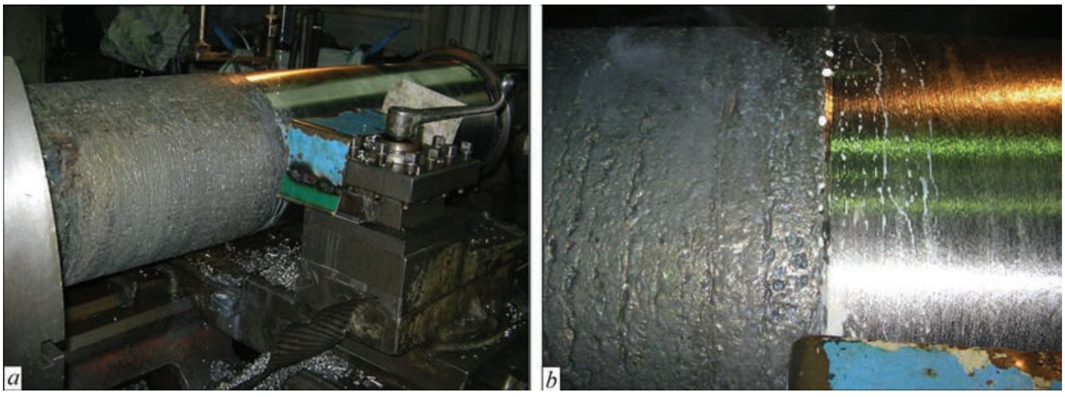

Figure 9. Machining of 400 mm dia. ingot from heat-resistant KhN60VT alloy

Table 1 shows the results of measurement of chemical composition of the initial charge billets and finished ingots by the main elements and impurities to GOST 5632–71.
In addition, measurements of the content of other impurities and modifiers were conducted (Table 2).

Analysis of the obtained results showed that at EBM of the initial billets manganese content decreases by 35 % for KhN38VT alloy and by 57 % for KhN-60VT alloy. A significant lowering of the content of magnesium by 95 % and of silicon by 50 % also takes place in KhN60VT alloy. A certain increase of phosphorus content in KhN38VT alloy should be noted. As to the content of other chemical elements, there is no significant change in ingots of KhN60VT and KhN38VT alloys after electron beam remelting.

MI-99 samples of a cylindrical shape, in 4 mm diameter and length were prepared to determine the content of oxygen and nitrogen. Samples were made from blanks, cut out of the ingot end face chamfer.

Nitrogen and oxygen content in KhN60VT and KhN38VT ingots was determined in TC-500 analyzer. The principle of operation of the analyzer for nitrogen/oxygen determination consists in melting the analyzed sample in the graphite crucible of the furnace in a helium flow. Reaction of the released oxygen with

Table 1. Chemical composition of EBM ingots from KhN60VT, KhN38VT steels, wt.%

Grade	Sampling location	Fe	C	Si	Mn	Ni	Cr
KhN38VT	Initial	34.209	0.07	0.343	0.674	36.351	21.521
After EBM	1	34.709	0.11	0.357	0.435	35.802	21.131
	2	34.358	0.09	0.361	0.462	35.757	21.068
–	GOST 5632–72	31.08–41.44	0.06–0.12	<0.80	<0.70	35.0–39.0	20.0–23.0
KhN60VT	Initial	0.214	0.08	0.393	0.455	58.83	23.526
After EBM	1	0.218	0.09	0.198	0.194	59.13	23.363
	2	0.207	0.10	0.177	0.189	59.25	23.417
–	GOST 5632–72	<4.00	<0.10	<0.80	<0.50	50.874–63.200	23.50–26.50

Table 1 (Cont.)

Grade	Sampling location	W	Ti	Al	Ce	S	P
KhN38VT	Initial	3.450	0.856	0.460	<0.03	0.001	0.0065
After EBM	1	3.490	0.891	0.464	–»–	–»–	0.010
	2	3.370	0.926	0.461	–»–	–»–	0.013
–	GOST 5632–72	2.80–3.50	0.70–1.20	<0.50	–»–	<0.020	<0.030
KhN60VT	Initial	14.670	0.488	0.356	–»–	0.010	0.0081
After EBM	1	14.460	0.429	0.379	–»–	0.003	0.0050
	2	14.980	0.433	0.400	–»–	–»–	0.0060
–	GOST 5632–72	13.0–16.0	0.30–0.70	<0.50	–»–	<0.013	<0.013

Table 2. Content of impurities and modifiers in EBM ingots of KhN60VT, KhN38VT steels, wt.%

Grade	Sampling location	As	Ca	Cd	Ce	Co	Cu
KhN38VT	Initial	<0.001	0.010	<0.001	<0.03	0.020	0.047
After EBM	1	–»–	0.013	–»–	–»–	0.019	0.039
	2	–»–	0.011	–»–	–»–	–»–	0.040
KhN60VT	Initial	–»–	0.032	–»–	–»–	0.003	0.002
After EBM	1	–»–	0.009	–»–	–»–	0.002	–»–
	2	–»–	0.012	–»–	–»–	–»–	–»–

Table 2 (Cont.)

Grade	Sampling location	Mg	Mo	Nb	Pb	Sb	V
KhN38VT	Initial	0.005	0.155	0.013	0.003	0.017	0.010
After EBM	1	0.004	0.158	0.012	0.002	0.015	0.011
	2	–»–	0.160	0.016	0.003	–»–	–»–
KhN60VT	Initial	0.344	0.003	<0.001	0.004	0.013	<0.001
After EBM	1	0.014	0.006	0.002	0.003	0.017	–»–
	2	–»–	0.007	0.004	–»–	0.013	–»–

graphite results in formation of CO and partially CO_2. These gases, together with helium, are carried away and pass through a catalyst (CuO-based), where CO is oxidized to CO_2. The mixture passes through an infrared cell, which measures the lowering of the intensity of infrared radiation caused by CO_2 absorption that is proportional to oxygen content being determined.

The gas flow from the IR cell passes through "Lecosorb" catalyst, where CO_2 and H_2O are retained, while the remaining nitrogen is carried out in the helium flow to the thermoconductometric cell, where nitrogen content is determined by the principle of different conductivity of the two gases (detected mixture of nitrogen and helium against pure helium).

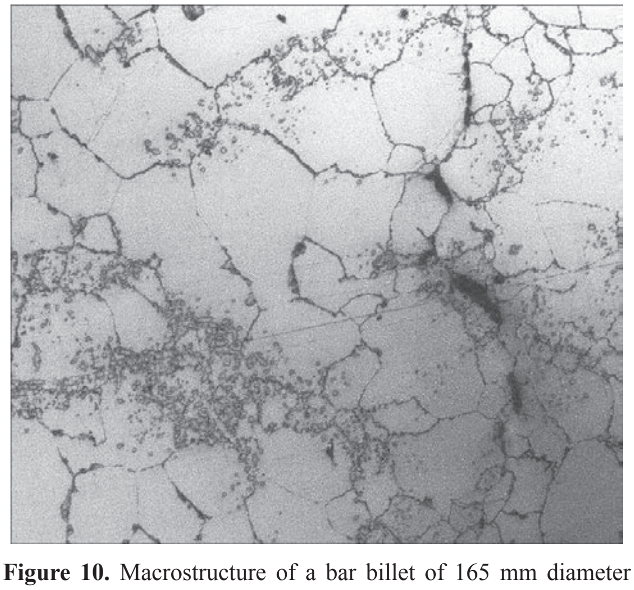

Figure 10. Macrostructure of a bar billet of 165 mm diameter from KhN60VT alloy (×100)

Table 3 shows the results of measuring oxygen and nitrogen content in KhN60VT and KhN38VT alloys.

As one can see from the Table, oxygen content decreases by 10–14 % for KhN38VT and KhN60VT alloys. Nitrogen content decreases by 8 % for KhN-38VT metal and by 42 % for KhN60VT metal.

Research on fabrication of semi-finished products in the form of KhN60VT bars was conducted with the purpose of further study of metal quality.

Bars of 165 mm diameter were produced by forging from 400 mm dia ingots. Deformation processing of the ingots was conducted in the temperature range of 1170–900 °C.

Investigations of the produced bar billet of 165 mm diameter from KhN60VT alloy showed that the microstructure is austenitic, with grain size corresponding to 1–2 number of DERZHSTANDART 5639 (Figure 10).

Studies of mechanical properties of the produced metal were conducted by tensile testing of samples at

Table 3. Gas content in EBM ingots of KhN60VT, KhN38VT steels, wt.%

Grade	State	[O]	[N]
KhN38VT	Initial	0.0048	0.0084
	After EBM	0.0043	0.0078
KhN60VT	Initial	0.0048	0.026
	After EBM	0.0041	0.015

Table 4. Mechanical properties of 165 mm bars from KhN60VT alloy produced by EBM

Sample number	δ, %	ψ, %	σ_y, MPa	σ_t, MPa
1	68.4	70.2	311	749
2	67.4	65.9	323	756
3	67.6	70.9	303	745
TU 14-1-286–72	45–60	52–60	295–390	740–880

T = 20 °C. Results of the conducted tests (see Table 1) show that the metal of semi-finished products in the form of bars, obtained as a result of the performed work, meets the standard requirements. The bars are characterized by higher ductility. This may be related to the fact that the EBM process provides deeper removal of nonmetallic inclusions and lower values of gas content.

Performed work showed that the electron beam melting method allows producing sound defect-free ingots of nickel-based heat-resistant alloys that meet the standard requirements, and it can be used instead of secondary vacuum-arc remelting. At application of ingots of primary induction remelting as the initial charge billet, there is no need for adding to the charge the alloying elements with a high vapour pressure to ensure the chemical composition, meeting the requirements of GOST 5632–72. It should be further emphasized that the level of mechanical properties of the bars from KhN60VT alloy practically completely meets the requirements of TU 14-3-571–2004 for "Seamless cold-deformed pipes from the KhN60VT (EI868) alloy and KhN60VT-VD alloy for the aviation industry".

REFERENCES

1. Bratkovsky, E.V., Zavodany, A.V. (2008) *Electrometallurgy of steel and special electrometallurgy*. Novotroitsk, NF MISiS [in Russian].
2. Zhouhua, J., Yanwu, D., Kuangdi, X. (2023) Vacuum Metallurgy. In: *The ECPH Encyclopedia of mining and metallurgy.* Ed. by Xu, K. Springer, Singapore. DOI: https://doi.org/10.1007/978-981-19-0740-1_1388-1
3. Voskoboynikov, V.G., Kudrin, V.A., Yakushev, A.M. (2002) *General metallurgy*: Textbook for universities. 6th Ed. Moscow, ICC Akademkniga [in Russian].
4. Kudrin, V.A. (2003) *Theory and technology of steel production*. Moscow, Mir [in Russian].
5. Paton, B.E., Trigub, N.P., Kozlitin, D.A. et al. (1997) *Electron beam melting*. Kyiv, Naukova Dumka [in Russian].
6. Ladokhin, S.V., Levitskyi, M.I., Chernyavskyi, V.B. et al. (2007) *Electron beam melting in foundry production*. Kyiv, Stal [in Russian].
7. Paton, B.E., Trigub, N.P., Akhonin, S.V. (2008) *Electron beam melting of refractory and highly reactive metals*. Kyiv, Naukova Dumka [in Russian].
8. Trigub, N.P., Akhonin, S.V. (1996) Optimization of smelting of steel and alloy ingots in an electron beam installation with an cold hearth. *Problemy Spets. Elektrometallurgii*, **2**, 12–17 [in Russian].
9. Movchan, B.A., Trigub, N.P., Gromov, V.I. et al. (1975) Purity and properties of SH15, 18H2N4VA and H18N10T steels, premelted in an electron beam furnace with an cold hearth. *Problemy Spets. Elektrometallurgii*, **1**, 48–50 [in Russian].
10. Trigub, N.P., Zhuk, G.V., Kornejchuk, V.D. et al. (2007) Industrial electron beam installation UE-5812. *Sovrem. Elektrometall.*, **1**, 11–14 [in Russian].

ORCID

S.V. Akhonin: 0000-0002-7746-2946,
V.O. Berezos: 0000-0002-5026-7366,
M.I. Medvedev: 0000-0002-1230-420X,
O.S. Bobukh: 0000-0001-7254-3854,
D.S. Ivanov: 0009-0000-6916-8109,
O.G. Yerokhin: 0000-0003-2105-5783

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

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

SUGGESTED CITATION

S.V. Akhonin, V.O. Berezos, M.I. Medvedev, O.S. Bobukh, D.S. Ivanov, O.G. Yerokhin (2025) Mastering the technology of producing ingots from heat-resistant alloys KhN38VT and KhN60VT by the electron beam melting method. *The Paton Welding J.*, **1**, 21–27.
DOI: https://doi.org/10.37434/tpwj2025.01.04

JOURNAL HOME PAGE

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

Received: 06.08.2024
Received in revised form: 11.09.2024
Accepted: 23.01.2025