DOI: https://doi.org/10.37434/tpwj2023.04.07

TECHNICAL-ECONOMIC INDICES OF OPERATION OF AC STEEL-MAKING FURNACE WITH APPLICATION OF CORED ELECTRODES

A.G. Bogachenko[1], **L.A. Sidorenko**[1], **I.O. Goncharov**[1], **I.A. Neylo**[1], **S.G. Kiyko**[2], **I.N. Logozinskyi**[2], **B.A. Levin**[2], **K.N. Gorban**[2]

[1]E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine
[2]PJSC Dneprospetsstal
81 Pivdenne Shose, 69000, Zaporizhzhia, Ukraine

ABSTRACT

For the first time in the world practice, several series of experimental melts (more than 60) were performed, during which graphitized composite (cored) electrodes of EGC (C) type were used, designed by the E.O. Paton Electric Welding Institute. It is shown that a "cored" arc is fundamentally different in geometrical and power parameters from the arc of a monolithic electrode. A "cored" arc is dispersed, spatially stable and has a high stability in a wide range of lengths and electrical modes. This is especially important during the formation of wells and charge melting. A cored electrode (depending on the composition) provides a 2–5 times decrease in time from the first short circuit to a stable arc burning as compared to a monolithic electrode; 2–4 times reduction in harmonic factor; 6–16 % saving of electric power; 12–23 % growth of furnace output, etc. Cored electrodes improve almost all technical and economic indices of the furnace operation, providing the ability to control high-current arcs and their high stability.

KEYWORDS: electric arc, short circuit, saving of electric power

INTRODUCTION

In recent decades, the world metallurgy has been characterized by a continuous growth in steel production. Thus, in 2012, the total steel production amounted to 1517 bln t, in 2017 it was 1691 bln t and in 2019 it reached already 187 bln t, in 2021 it was 1950 bln t. At the same time, about a third of its total amount is electric steel. The share of electric steel is also constantly growing and currently amounts in Europe to about 42 %, in the USA it exceeds 60 %, in China and Asia it is about 20 %. In countries where ferrous metallurgy appeared relatively recently (Luxembourg, Indonesia, Saudi Arabia), steel is produced only in electric arc furnaces of alternating current (EAF) and of direct current (EAF DC). It is also important to note that in metallurgical production in order to solve problems of environmental safety, the advantage is given to electrometallurgical technologies.

The growth in the production of electric steel occurs simultaneously with the continuous improvement in the design of furnaces, power sources, preparation of charge, melting modes, out-of-furnace steel processing, heat treatment, etc. At the same time, manufacturers of graphitized electrodes are effectively working to improve the electrical and mechanical characteristics of electrodes, provide uniformity of properties in the volume of electrodes, increase their length, etc. Electrodes with protective coatings that reduce the intensity of lateral oxidation are used quite successfully.

Some successful research works are known, in which the properties of electrodes were improved by applying functional layers on their surface. However, such electrodes were not used in industry because of their high cost.

Quite a lot of attention is paid to studying properties of arcs, possibilities of their stabilization in order to effectively improve technical and economic indices of operation of arc furnaces. Thus, hollow electrodes were successfully tested, which provided arc stabilization, increase in furnace output and cos φ, saving of electric power, etc. However, cavity in the electrode causes a sharp increase in its loss (by 20–25 %) as compared to conventional monolithic electrodes. For this reason, hollow electrodes are not widely used in industry.

EXPERIMENTAL

At the E.O. Paton Electric Welding Institute for EAF and EAF DC, fundamentally new — graphitized composite (cored) electrodes (EGC (C)) were designed and investigated. The concept of the work consists in creating favorable thermodynamic conditions in the near-cathode region of a graphitized electrode to ionize gases in the arc column. Based on that, for manufacture of a cored electrode, a standard (monolithic) electrode is used, in which one or more vertical holes are made, which are filled with different functional materials, incl. those, containing elements of the Periodic Table with a low electronic work function, forming a solid insert (core) [1].

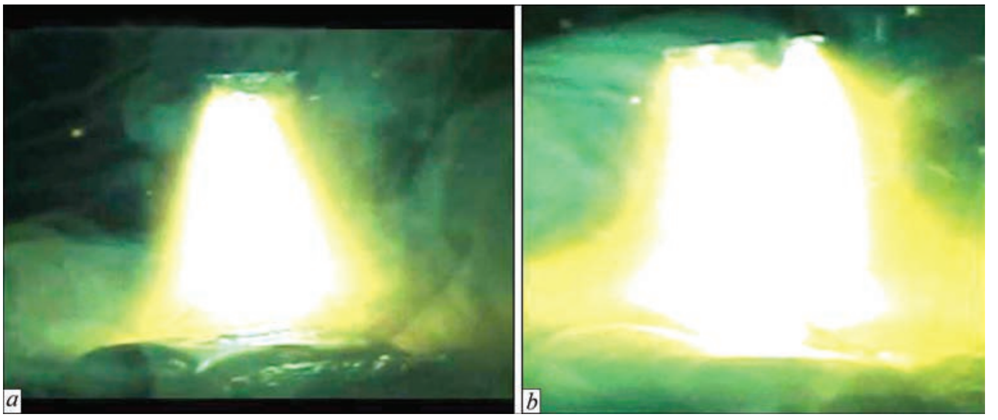

Figure 1. General appearance of the arc of a graphitized monolithic electrode (*a*) and a cored electrode (*b*) (U_A = 60 V, I_A = 700 A; d_C; d_{AN}; L_A, mm: ≈2.5; ≈10; ≈ 11 (*a*) and ≈8.5; ≈16.5; ≈16.5 (*b*) respectively)

The investigations of temperature dependence of electric resistance of cores of different composition, volt-ampere characteristics and cathode processes were carried out in the specialized laboratory units developed at the E.O. Paton Electric Welding Institute with the use of modern software, photo recording and computer equipment. At this stage of works, graphitized electrodes of 50 mm diameter were used. In the industrial furnace, electrodes of 300 mm diameter with the cores of different composition (F_{16}, F_{18}, F_{19}, F_{20} and F_{21}) and control devices showing voltage, current and melting capacity were used. To record current and voltage, the registering "REKON-09MA" archiver was used.

Comprehensive industrial tests of cored electrodes were first carried out in 12 ton EAF DC with the use of different charge, melting modes, core compositions, etc. It was found that the arc of a cored electrode is always maintained on the core, does not migrate along the end of the electrode and fundamentally differs from the arc of a monolithic electrode (at equal voltages and arc currents) in geometrical and energy parameters, Figure 1.

Thus, the volume of the arc of a cored electrode is 3–7 times higher than that of a monolithic electrode, and, accordingly, all parameters referred to a unit surface or volume of the arc of a cored electrode are significantly lower than those of a monolithic electrode. It is very important that the voltage drop in the near-cathode region of the arc of a cored electrode is 2–3 times lower than that of a monolithic electrode. At the same parameters, the arc length of a cored electrode (L_{AC}/L_{AM}) is 1.3–1.5 times longer. Due to the operation of emitters, the same current is provided at a voltage of 1.5–2.0 times lower on a cored electrode than on a monolithic one. At the same voltages, the arc current of a cored electrode, respectively, is 1.5–2.0 times higher, etc.

Due to the mentioned features, the arc of a cored electrode is distinguished, first of all, by a high stability – the main technological and energy factor in a wide range of lengths and electrical modes. A high stability of the electrical mode also determines a high stability of the thermal mode of the furnace, the thermal field of the electrodes, a complete running of physicochemical processes, and as a result, the improvement of all technical and economic indices of the furnace. Such an arc is also characterized by a high spatial stability, it is dispersed and elastic, i.e. it more rarely breaks off under the action of external factors (for example, charge downslide, etc.). The arc of a cored electrode also poorly reacts to "magnetic blow". Due to the noted features and advantages, cored electrodes in EAF DC-12 industrial furnaces provided 7–10 % saving of active electric power; 20–23 % reduction in reactive power; increase in cos φ from 0.48 to 0.74; 15–20 % increase in furnace output; 12–15 % decrease in loss of alloying elements; 8–12 % reduction in noise of the operating furnace; 2–3 times reduction in dust and gas emissions [2].

Currently, about 1200 electric arc furnaces are operating in the world, incl. about 200 DC furnaces and, accordingly, 1000 AC furnaces. AC furnaces with a capacity of 100–180 t are widely used in Europe, America and Asia. Actually, such furnaces represent high-speed aggregates for melting a steel semi-product, alloying, degassing and finishing of which according to other parameters is carried out in a ladle furnace and a vacuum degasser.

Such furnaces require electrodes of a high quality, large diameter and length with a low electrical resistivity (at the level of 5 μOhm·m). The production of electrodes with a diameter of 810 mm and a length of up to 3500 mm has already been mastered, and the admissible current density reached the level of 40 A/cm^2. For manufacture of large-sized electrodes, expensive oil needle coke and unique equipment are used. The cost of such electrodes can reach 30 % of the cost of the produced steel. Therefore, the possibility of using cored electrodes in AC furnaces was of undoubted interest for us.

RESULTS AND DISCUSSION

The first industrial experimental melts were carried out in 2018–2019 in a 6-ton three-phase EAF of the type DS-6N1. The graphitized electrodes of 300 mm diameter were used. Five compositions of cores were

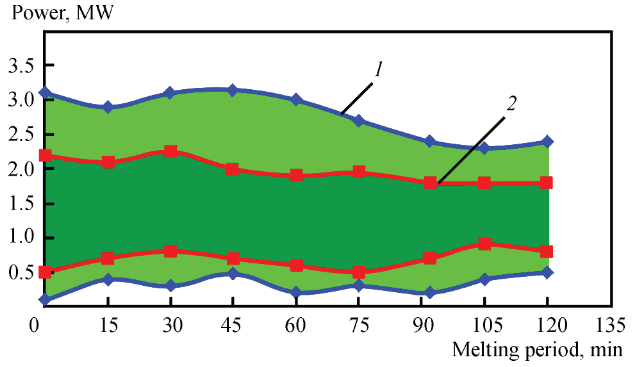

Figure 2. Range of power spread in the DS-6N1 furnace with the use of monolithic (*1*) and cored (*2*) electrodes (average statistical data on power are given with an interval of 15 min)

tested. More than 60 melts were carried out, on which practically the same type of charge — compact lumpy scrap with up to 30 % additives of the total weight of charging chips of power grinding of high-speed steels (HSS) was used. The melts were carried out with different combinations of cored and monolithic electrodes operating simultaneously in the furnace: three cored, 2 cored and one monolithic, one cored and two monolithic electrodes. For an adequate comparison of the results, the melts were carried out on standard electrical modes with the fixation of current and arc voltage signals.

As in the case of DC furnaces, first, a high stability of the electric mode in the DS-6N1 furnace was noted. Figure 2 shows, that in all periods of melting (arc stabilization, formation of wells, charge melting, finishing of liquid metal), the power fluctuation on cored electrodes is 20–30 % lower than on monolithic electrodes. A stable electrical mode is provided by a high current stability and lower distortions of sinusoidal voltage curves (Figure 3). Records of oscillograms of the main energy indices of melts are given in Table 1.

From Table 1, it follows that depending on the composition of cores:

● time of frequent arc breaks in cored electrodes is 3–10 times shorter than in monolithic ones;

● time of arc stabilization from the first interphase short circuit to a continuous burning in cored electrodes is 1.75–5.4 times lower than in monolithic ones.

These factors determine a rapid stabilization of the electric melting mode, a rapid formation of wells and the efficient melting of charge. It also results in decreased frequency and strength of current rushes into the primary network, which improves the quality of electric power, providing more stable operation of such powerful consumers of electric power as neighboring furnaces, units for secondary treatment, rolling mills, etc.:

● cored electrodes provide a higher cos φ and, as a result, a decrease in reactive power and power losses, which leads to a decrease in power consumption and the possibility of stable operation of the furnace at low currents;

● cored electrodes provide low harmonic factors, which also contributes to an improved quality of electric power.

It was found that during melting in a standard mode with the use of monolithic electrodes, the arc length is 50–70 mm, on cored electrodes it is 70–105 mm (1.4–1.5 times more), while maintaining the stability of the electrical and technological parameters of melting.

On cored electrodes, modes with an increased arc voltage "unloading mode" (from 150–160 V to 180–190 V) and reduced current (from 8.0–8.5 kA to 6.5–7.0 kA) were also tested. At the same time, the length of the arcs increased, cos φ increased and stabilized at the level of 0.92–0.94, the harmonic factors decreased to 0.28–0.08. This corresponds to modern concepts and the feasibility of operation of electric arc furnaces on long arcs and lowered currents. First of all, the noted features of cored electrodes provide their effective use on long arcs in furnaces of an old design, where the possibilities of the power source for the secondary voltage are limited and, secondly, they can expand the power and technological capabilities of modern ultra-high-power furnaces.

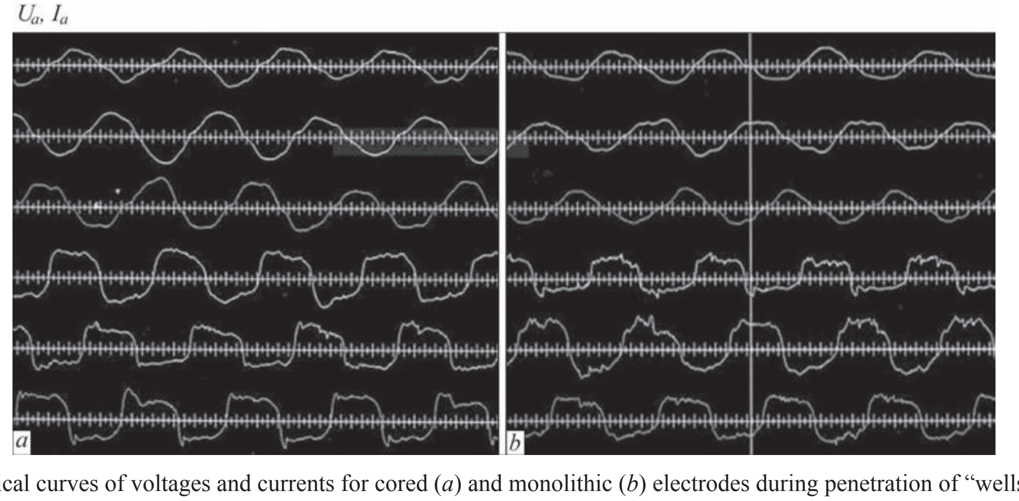

Figure 3. Typical curves of voltages and currents for cored (*a*) and monolithic (*b*) electrodes during penetration of "wells" and charge melting

Table 1. The main energy parameters of melts on AC furnace with monolithic and cored electrodes

Parameter	Type of electrodes				
	Monolithic	F_{16}	F_{18}	F_{19}	F_{20}
Time of frequent arc breaks from the furnace switching, s	Standard electrical mode				
	Up to 30	Up to 10	Not more than 3	Not more than 3	Not more than 3
Time of continuous arc burning, s	Up to 70	Up to 40	Not more than 13	Not more than 13	Not more than 13
cos φ	0.81–0.86	0.90–0.93	0.91–0.94	0.91–0.94	0.91–0.94
Factors of harmonic	0.65–0.59	0.58–0.28	0.36–0.09	0.36–0.09	0.36–0.09

On cored electrodes the forced melting modes (150–160 V and the current increased to 9–10 kA) were also tested. In this case, the length of the arcs decreased to 20–25 mm, an increased end loss of the electrodes, overheating of metal and slag under the electrodes and increased loss of alloying elements were observed. This mode is not recommended for melts on cored electrodes.

The characteristic feature of the cored electrode is the formation of a depression on its working end, which is always formed around the core. In the case of direct current, this depression has the shape of a hemisphere with rather thin walls in the lower part (Figure 4, *a*). In the case of alternating current, this hemisphere always has thicker walls (Figure 4, *b*).

The shape and depth of the hemisphere can be adjusted, since it depends on the composition of the core, electrical modes and has a significant effect on at least two important technological factors. First, the edges of the hemisphere shield the arc, having a significant effect on the degree of radiation of walls and roof of the furnace, i.e. on the life of the lining and, secondly, on the intensity of the end oxidation of the electrode (electrode consumption). At a sufficiently large depth of the hemisphere, up to 40–50 % of the arc power can be concentrated in it. In this case, the life of the lining can be increased by 30–40 %, but there will be an increased end consumption of the electrode. Thus, as a control object, the hemisphere at the working end of the electrode should have optimal dimensions, taking into account the type of current, diameter of electrodes, composition of cores, etc. In addition, the presence of a hemisphere provides an effective operation on long arcs and lowered currents, which contributes, as noted above, to a decrease in the heating intensity of the cored electrode body and, as a consequence, to a decrease in the intensity of its lateral oxidation. Our studies showed that with the use of cores, the resistance of which is lower than the resistance of the electrode body, it is possible to redistribute the current over the cross-section of the electrode in such a way that its density in the core can be increased to 100–160 A/cm^2. Naturally, this factor also contributes to a decrease in the temperature of the electrode body and the rate of its lateral oxidation. Visually, this is confirmed by the fact that a lower, most heated part of the electrode (400–700 mm) has a shape close to a cylinder and not to a cone. In other words, on cored electrodes, in contrast to monolithic ones, the lateral oxidation rate is lower, and the lateral oxidation can be adjusted. However, the overall rate of oxidation of a cored electrode (electrode consumption) is lower than that of a monolithic one. This can provide saving of cored electrodes in AC furnaces. To prove this statement, a series of melts was carried out on standard modes, during which one cored electrode of the composition (F_{21}) and two monolithic electrodes were used. The consumption of electrodes was determined by weighing each electrode assembly before melting. The results of this

Figure 4. Macrostructure of the end of a cored electrode on direct current (*a*) and a general view of the ends of electrodes on three-phase alternating current (*b*); diameter of all electrodes is 200–210 mm

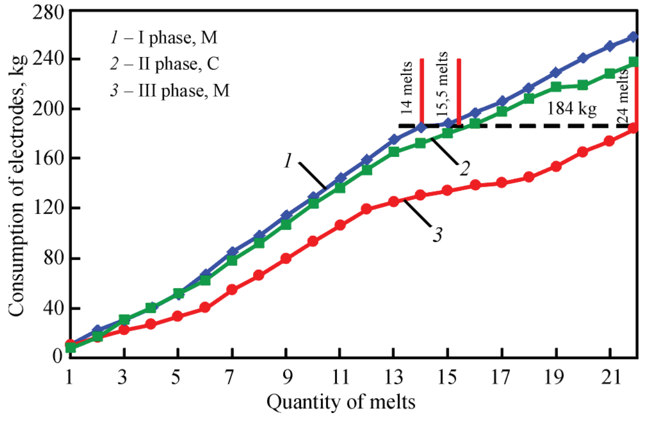

Figure 5. Dynamics of oxidation (burning loss) of electrodes in the furnace DS-6N1, determined by weighing electrode assemblies

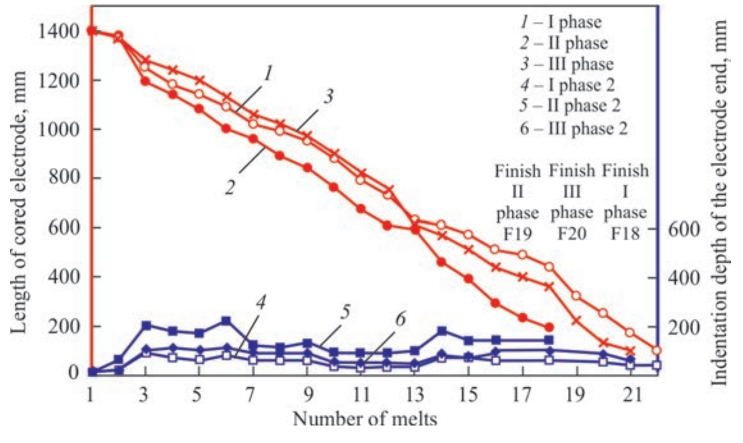

Figure 6. Dynamics of oxidation of cored electrodes of the III series (left diagram) and change in the indentation depth on the ends of the electrode (right diagram)

work are shown in Figure 5. From the mentioned data, it follows that monolithic electrodes (M) provided 14 and 15.5 melts, and cored electrodes (C) provided 22 melts. Therefore, an increase in the durability of a cored electrode by 25 % is observed. As was noted above, the composition of cores has a greater influence on the ratio of core resistances, electrode temperature, etc., which ultimately determines the cost of an electrode. A series of melts with the use of cores of three compositions (F_{18}, F_{19}, and F_{20}) clearly confirmed this statement, Figure 6. The consumption of electrodes was controlled by measuring their length before melting. The core of the composition F_{19} with a low electrical resistance worked out 18 melts, and the electrodes with the cores F_{18} and F_{20} (with a higher electrical resistance) worked out 22 and 21 melts, respectively.

It is known that as a result of the action of the skin effect, a central part of a graphitized electrode with 450 mm diameter or more does not conduct electric current, i.e. an inactive zone exists, the diameter of which naturally increases with an increase in the diameter of the electrode. The calculated averaged diameters of the inactive zone depending on the diameter of the electrode at a frequency of 50 Hz, are given in Table 2 [3].

From the Table 2, it is seen that the electrodes of large diameters used in the industry in AC furnaces have a rather large inactive zone. Making a central hole in the electrode for a core (hollow electrode) already determines the flow of a current of a certain density along the walls of the hole by itself, i.e. a part of the current from the peripheral zones of the electrode goes into its central zone. Moreover, a core with a specific electrical resistivity, which is higher or lower than the electrical resistivity of the electrode body, can enhance or weaken the effect of current redistribution to the walls of the hole, regulating the rate of lateral oxidation of the electrode in such a way.

The production and operation of cored electrodes is featured by the fact that after the manufacture of the core, the electrode is not subjected to heat treatment, i.e. the core is put to the furnace in a “raw” state. Consequently, all processes associated with the formation of its structure and properties occur in the furnace in the process of heating and operation of the electrode. Natu-

Table 2. Relationship between electrode diameter (*D*), mm and diameter (*d*), mm of inactive zone for AC furnaces

D	400	450	500	550	600	650	700	750	800
d	0	45	80	110	180	220	270	328	385

rally, in this case, diffusion of the core components into the electrode body takes place, which form interlayer compounds, providing a significant increase in electrical conductivity (decrease in electrical resistance of the electrode body) [4]. Therefore, it is quite probably that for manufacture of cored electrodes, monolithic electrodes with a higher specific electrical resistivity can be used than it is common for a particular arc furnace. We also assume that it is possible to use cored electrodes with a smaller cross-section than in monolithic ones. Naturally, both of these factors are a significant case in saving graphitized electrodes. At the same time, the use of electrodes of a smaller diameter (mass) will reduce dynamic loads on the mechanical units and short mains of the furnace, which is very important at the beginning of melting in the period of charge melting.

Our experience of using electric arc with oxide cathodes [5], calculated data on the temperature of high-current arcs in ladle furnaces [6] and our data on the specific distribution of current and power in the arc of a cored electrode indicate that the temperature along the axis of the column of a cored electrode can be 12000–13000 K, i.e. by 15–20 % lower than on monolithic electrodes. This feature of cored electrodes can open up new opportunities for technologists in terms of optimizing melting modes, saving lining, extension of the furnace campaign, etc. In our opinion, a lower arc temperature of a cored electrode on a long arc will also significantly reduce the thermal load on the melt, reducing its overheating and contributing to reduce the loss of alloying elements and ferroalloys.

CONCLUSIONS

1. For the first time in the world practice, several series (more than 60 melts) of experimental melts with the use of cored electrodes of different composition were successfully carried out in a three-phase electric arc furnace of the DS-6N1 type.

2. It has been established that the arc of cored electrode is highly stable and provides, in particular, a 20–30 % lower power spread during melting.

3. It was found that depending on the composition of cores and melting mode, cored electrodes provide: 1.75–5.4 times reduction in time from the first short circuit to a stable arc burning as compared to monolithic electrodes; increase in cos φ from 0.81–0.86 to 0.91–0.94; reduction of harmonic factor from 0.65–0.59 for monolithic electrodes to 0.36–0.09 for cored electrodes; 6–16 % saving of active electric power; 12–23 % increase in furnace output; decrease in consumption of electrodes by 20–25 %.

4. We consider it necessary to continue these works on furnaces of a larger capacity, for example, 50 tons or more, as well as in order to determine the durability of the lining, saving of alloying, ferroalloys, further optimization of cores composition, a deeper understanding of power, technological and metallurgical features of melting with the use of cored electrodes as a means of efficient control of high-current arcs operation.

5. It is shown that the best energy performance on cored electrodes is provided by running on long arcs.

6. It has been established that it is not recommended to carry out melting in forced modes (short arcs) in relation to AC furnaces with cored electrodes.

7. The cost of materials and works for the manufacture of cored electrodes did not exceed 0.5 % from the value of the obtained economic effect.

Acknowledgement. *Authors would like to thank to specialists of E.O. Paton Electric Welding Institute of the NASU and PJSC Dneprospetsstal for help in this work.*

REFERENCES

1. Paton, B.E., Lakomsky, V.I., Galinich, V.I., Mishchenko, D.D. (2011) Cored electrodes of electric arc furnaces. *Chyornye Metally,* **5**, 13–15 [in Russian].
2. Bogachenko, A.G., Mishchenko, D.D., Braginets, V.I. et al. (2016) Saving of electric power at the arc steel melting furnaces of direct current with graphitized cored electrodes. *Sovrem. Elektrometall*., **1**, 58–64 [in Russian].
3. Okorokov, N.V., Nikolsky, L.E., Egorov, A.V. (1962) Influence of tubular electrodes on thermal operation of arc electric steel furnace. News of higher educational institutions. *Ferrous Metallurgy*, **9**, 105–110.
4. Fialkov, A.S. (1977) *Carbon, interlayer compounds and composite on its base.* Moscow, Aspekt press [in Russian].
5. Lakomsky, V.I. (1997) *Oxide cathodes of electric arc.* Zaporozhie, Internal [in Russian].
6. Krikent, I.V., Krivtsun, I.V., Demchenko, V.F. et al. (2018) Numerical modeling of high-current arc discharge in DC ladle–furnace installation. In: *Physical processes in welding and metal working: Collect. of articles and reports.* Kiev, 135–140 [in Russian].

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

A.G. Bogachenko
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.
E-mail: stemet@ukr.net

SUGGESTED CITATION

A.G. Bogachenko, L.A. Sidorenko, I.O. Goncharov, I.A. Neylo, S.G. Kiyko, I.N. Logozinskyi, B.A. Levin, K.N. Gorban (2023) Technical-economic indices of operation of ac steel-making furnace with application of cored electrodes. *The Paton Welding J.*, **4**, 54–59.

JOURNAL HOME PAGE

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

Received: 03.03.2023
Accepted: 25.05.2023

SUBSCRIPTION–2023

«The Paton Welding Journal» is Published Monthly Since 2000 in English, ISSN 0957-798X, doi.org/10.37434/tpwj.

«The Paton Welding Journal» can be also subscribed worldwide from catalogues subscription agency EBSCO.

If You are interested in making subscription directly via Editorial Board, fill, please, the coupon and send application by Fax or E-mail.

12 issues per year, back issues available.

$384, subscriptions for the printed (hard copy) version, air postage and packaging included.

$312, subscriptions for the electronic version (sending issues of Journal in pdf format or providing access to IP addresses).

Institutions with current subscriptions on printed version can purchase online access to the electronic versions of any back issues that they have not subscribed to. Issues of the Journal (more than two years old) are available at a substantially reduced price.

Subscription Coupon			
Address for Journal Delivery			
Term of Subscription Since	**20**	**Till**	**20**
Name, Initials			
Affiliation			
Position			
Tel., Fax, E-mail			

The archives for 2009–2021 are free of charge on www://patonpublishinghouse.com/eng/journals/tpwj

ADVERTISING
in «The Paton Welding Journal»

External cover, fully-colored:
First page of cover
(200×200 mm) — $700
Second page of cover
(200×290 mm) — $550
Third page of cover
(200×290 mm) — $500
Fourth page of cover
(200×290 mm) — $600

Internal cover, fully-colored:
First/second/third/fourth page
(200×290 mm) — $400

Internal insert:
(200×290 mm) — $340
(400×290 mm) — $500

- Article in the form of advertising is 50 % of the cost of advertising area
- When the sum of advertising contracts exceeds $1001, a flexible system of discounts is envisaged
- Size of Journal after cutting is 200Í290 mm

Address

11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine
Tel./Fax: (38044) 205 23 90
E-mail: journal@paton.kiev.ua
www://patonpublishinghouse.com/eng/journals/tpwj