DOI: https://doi.org/10.37434/tpwj2024.08.04

COMPOSITE (CORED) GRAPHITIZED ELECTRODES FOR INDUSTRIAL DC AND AC STEEL-MELTING FURNACES

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ABSTRACT

The paper presents summary data based on the results of laboratory studies and comprehensive industrial trials of a fundamentally new type of product in electrometallurgy — cores of graphitized electrodes developed at PWI of the NAS of Ukraine for DC and AC arc steel-melting furnaces of up to 50 t capacity. It is shown that during the last decades, the world production of steel has increased continuously, getting very close to 2 bln t per year. Approximately 30 % of this volume is produced in arc furnaces, and by the end of this decade it will reach 40 %. It is shown that the cored electrode arc has much lower specific current and power values in all the sections (cathode, column, anode) than the monolithic electrode arc. It was found that voltage drop in the core cathode spot is 2.3–3.3 times smaller than in the monolithic electrode. Cored electrodes improve all the technical-economic characteristics of operation of DC and AC steel-melting furnaces.

KEYWORDS: arc furnaces, graphitized electrodes, geometrical and power parameters of the arc, electrode work function, specific power, specific electrical resistance

INTRODUCTION

Academician B.E. Paton in his program article "Duma of Metal" made a clear prediction that metal materials in general and, above all, materials based on iron (steels, alloys, cast irons) have been and will be the basic structural materials in the near future for our civilization for the various needs of modern engineering.

This forecast is clearly confirmed by the rapid development of production and consumption of steel in recent decades. It is sufficient to point out that steel production has increased from 700 mln t in 1974 to 1.950 bln t in 2021, that is, by 2.8 times, despite constantly growing requirements for environmental protection and cruel competition at the market of production and consumption of metal materials [1–4].

Modern metallurgy is actively developing also in terms of its quality. Much attention is now paid to the transition to "green" metallurgy, the development of production of metallic raw materials, etc. New processes combining steel smelting and casting, rolling and heat treatment of steel semi-finished products are emerging everywhere.

Smelting in the arc AC (EAF) and DC (EAF) furnaces occupies more than a third part in the world production of steel. These are first and foremost alloy steels and alloys with high standard and special properties for critical products. It is expected that the world's share of electric steel will grow to 40 % in the next decade. The production of electric steel in China will grow to 25 % compared to 10 % in 2020. Naturally, the production of electrodes will grow. In this case, the focus will be on the production of high-quality electrodes of the EGSP grade (UHP) with a diameter of 700 mm or more [5]. Ukraine is a well-known metallurgical state in the world and before the war of 2022 it had firmly occupied a position in the first ten world steel makers. The great contribution to the theory and development of electrical steel-making was made by such Ukrainian scientists and manufacturers as B.E. Paton, B.I. Medovar, M.M. Dobrokhotov, V.A. Efimov, V.I. Lakomsky, A.F. Tregubenko, V.V. Leporsky et al.

Large-scale works on the improvement of technology and equipment for smelting and redistribution of steel are carried out under conditions of rigid competition at the market of metal products. These works are aimed at improvement of such important technical and economic characteristics as consumption of electric power and graphitized electrodes, alloying elements and ferroalloys, output of furnaces, etc. under conditions of providing high quality of metal, satisfying rigid requirements for environmental protection and improving the working conditions of service personnel.

RESEARCH AND DISCUSSION OF RESULTS

It is known that technical and economic characteristics of arc furnace operation are largely determined by the operational reliability of graphitized electrodes. In the cost of electric steel, electrodes occupy a considerable share — up to 8–15 and sometimes

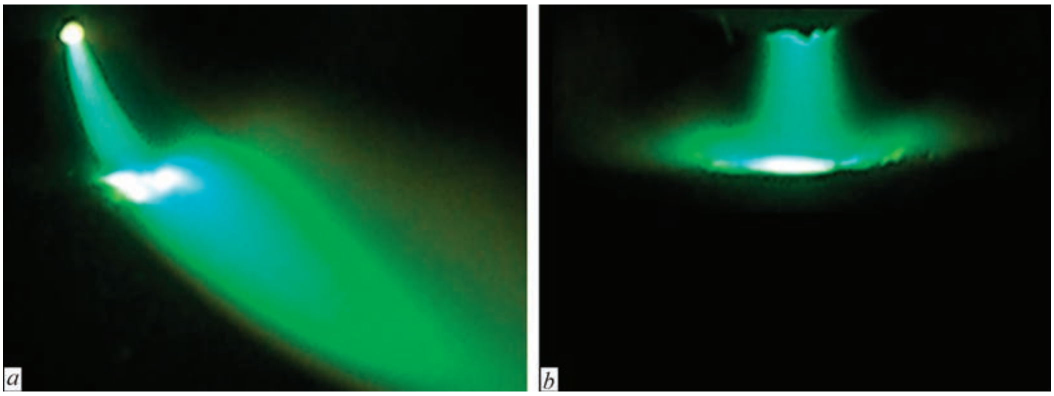

Figure 1. General appearance of the arc of graphitized monolithic (*a* — U_a = 62 V; I_a = 720 A; d_c = 2.5; d_a = 9.5 mm) and cored (*b* — U_a = 32 V; I_a = 720 A; d_c = 9.5 mm; d_a = 17 mm) electrodes at equal lengths of arcs (L_a = 15 mm)

up to 30 %. Therefore, it is difficult to overestimate the importance of the works conducted by electrode manufacturers to provide the required specific electrical resistance (SER), increase the density of electric current, ensure high mechanical characteristics of electrodes, etc. One of the modern world trends in improving the operation of arc furnaces is to increase the electric current to 80–100 kA. This requires a reduction in SER to 4–5 μOhm·m and an increase in the diameter and length of graphitized electrodes. Such famous Companies as SGL, Grafftech, Ukrgrafit, etc. have already mastered the production of electrodes with a diameter of 700, 750 and 800 mm. The length of the electrodes reached 3500 mm [5, 6]. The technical and economic assessment shows that a decrease in SER by 0.2 μOhm·m provides a reduction in power consumption by 6–8 % per a ton of metal.

At the PWI of NASU, a fundamentally new type of products for electrometallurgy — graphitized composite (cored) electrodes for arc steel-melting DC and AC furnaces was developed, which is studied and tested jointly with scientific centers and industrial enterprises.

PROCEDURE OF STUDIES

At the initial stage of works, the basic physical, chemical and power properties of the core and cored electrodes (Volt-ampere characteristics (VACh), current in the cathode-anode system, emission properties, power distribution over the arc sections, etc.) were investigated in the conditions of the PWI. For this purpose, specialized laboratory equipment was created, which used graphitized electrodes with a diameter of 50 mm. Industrial trials of cored electrodes were performed in 12-ton EAF DC-12 and three-phase DS-6N-1 and DSV-50 AC furnaces.

Cored electrodes are produced by drilling of one or more longitudinal holes in the serial monolithic electrode, which is stuffed with a mixture containing materials (components) to ensure the thermal stability of the core, regulation of its electrical conductivity and components with elements of the I and II groups of the Mendeleev table with low electron work function*. Due to these components with minimal power consumption, favorable thermodynamic conditions for the ionization of gases in the column of high-current electric arc in EAF and EAF DC are provided. The first comparative trials of cored and monolithic electrodes in laboratory equipment and in industrial furnaces showed that the cored electrode arc is fundamentally different by geometric and power parameters and very high stability compared to the monolithic electrode arc (Figure 1).

It was established that the diameter of the cathode spot on the cored electrode is approximately 4 times exceeds the analogue on the monolithic one. Diameters of anodes on the cored and monolithic electrodes differ in 2–3 times. The cored electrode arc is always maintained on the core and occupies almost the entire cross-sectional area of the electrode as a result of mutual diffusion of components in the core-electrode system. It does not migrate along the end of the electrode and does not come to its side surface, providing stable, soft heating of the melt and vertical position [7, 8]. At the same time, as a result of migration of the monolithic electrode arc, the plume of its plasma can amount to 7–8 lengths of the arc and reach the furnace lining, causing overheating and destruction of the lining. These and other features of the cored electrode arc are realized in improvement of almost all technical and economic indices of arc furnace operation.

The mentioned differences in geometric and electrical indices cause that all the cored electrode arc sections have significantly lower specific values of current density and power than the corresponding monolithic electrode arc sections. The calculations were performed according to the data of melts in a 12-ton DC furnace at equal voltages of arcs (220 V) and equal currents (11000 A) for monolithic and cored electrodes. Fifteen values were compared. It is enough to note that the spe-

*In the article, compositions of cores are not given. The cores are indicated by the letter C with indices 1, 2, 3 etc.

cific current, attributed to a unit of surface or a volume of the arc and specific power at the cored electrode cathode is 16.0 and 37.5 times lower, respectively, than at the monolithic electrode cathode [9].

RESEARCH RESULTS

SOME PROPERTIES AND FEATURES OF THE CORED ELECTRODE ARC

Studies of comparative voltage distribution over arc sections were performed in the laboratory equipment with the use of laboratory monolithic and cored electrodes with a diameter of 50 mm and a core of the composition C_4. The voltage drop on the arc sections and current under the conditions of the same voltage on the arcs (50 V), given in Table. 1, from which is follows that: the arc length L_a of the cored electrode was 23 mm, L_a of the monolithic electrode was 15 mm, i.e. more by 1.53 times; voltages on the anode spots of the arc U_{an} for these electrodes are close in values and equal to 15 and 13 V, respectively (average data by three dimensions); the emitter current I_{em} was 100 A, that is, the total current increased from 350 to 450 A, which was 28.5 %; the voltage drop on the arc column U_{col} of the core is 1.74 times higher than on the arc column of the monolithic electrode; the voltage gradients in the arc of cored and monolithic electrodes are close (1.0 and 1.1 V/mm); it is of particular interest that the cathode voltage U_c of the monolithic electrode (22.5 V) is 2.32 times higher than U_c of the cored electrode (9.7 V).

The voltage drops in the sections of the arcs at their equal lengths (15 mm) for compositions of the cores C_1–C_5 are presented in Table 2, from which it follows: the voltages U_{an} of the cored and monolithic electrodes are almost equal (10–13 V); the voltages on the arcs U_a of the monolithic and cored electrodes were 55 and 37.2 V (average values of 5 experiments), that is, the ratio is equal to 1.48 times. This index is close to the difference in arc lengths in case of equal voltages (1.53) (Table 1).

It is confirmed that equal currents can be ensured at the voltages of approximately 1.5 times lower in the case of the cored electrode compared to the monolithic one; the voltage drop on the arc column U_{col} of the monolithic and cored electrodes have close values — 25.5 and 20.8 V (average values from 5 experiments); as in the case of experiments with equal voltages (Table 2), the drop of voltages on the cathode spot of monolithic and cored electrodes: 18.0 and 5.5 V (average for 5 compositions), 18.0:5.5 = 3.3 times.

It is also important that the noted parameters have fairly clear stability at very large differences in the compositions of cores.

There were also experiments conducted to determine: the critical length of the arc at which its break occurs (L_{br}); the values of emitter currents (I_{em}); geometric parameters of the arc.

The obtained characteristics of the monolithic and cored electrodes are given in Table 3.

The VACh was investigated on the monolithic and cored electrodes of five core compositions (C_1–C_5). The results are presented in Figure 2.

As is seen from Figure 2, the current of the order of 400 A on the cored electrodes is provided at a voltage of 5–2.5 times lower than on the monolithic electrode, or at equal voltages on the arcs, the current on the cored electrodes is 1.5–2.0 times higher than the current of the monolithic electrode.

Table 1. Arc values in the sections of monolithic and cored electrodes at equal voltages of the arcs

Arc parameters	Electrode		Ratio of values
	Monolithic	Cored	
U_a, V	50.0	50.0	–
U_c, V	22.5	9.7	$\frac{U_{c.\,cored}}{U_{c.\,monol.}} = \frac{22.5}{9.7} = 2.32$
U_{an}, V	13.0	15.0	–
U_{col}, V	50–(22.5 + 13) = 14.5	50–(9.7 + 15) = 25.3	$\frac{U_{col.\,cored}}{U_{col.\,monol.}} = \frac{25.3}{14.5} = 1.74$
I, A	350	450	–
L_a, mm	15	23	$\frac{U_{arc\ cored}}{U_{arc\ monol.}} = \frac{23}{15} = 1.53$
b, V/mm	$\frac{14.5\ V}{15\ mm} \approx 1$ V/mm	$\frac{25.3\ V}{23\ mm} \approx 1.1$	–

Table 2. Values of voltage drop in the sections of the arcs at equal lengths of arcs and core compositions C_1–C_5

Arc parameters	Monolithic electrode	C_1	C_2	C_3	C_4	C_5
U_a, V	52–55 54.0	35–48 39.0	36–53 42.0	36–39 37.5	38–47 41.0	38–39 39.5
U_c, V	18–18 18.0	5–6 5.5	5–8 7.0	5–7 6.0	6–9 7.5	5–9 7.0
U_{col}, V	20–25.5 23.0	17–27 20.0	21–30 22.0	20–23 21.0	20–24 21.0	19–23 20.5
U_{an}, V	11.5–14 13.0	13–15 13.5	10–15 13.0	10–11 10.5	12–14 13.0	10–12 11.0
Current, A	300–307 304	300–360 354	300–350 350	313.5–420 367	320–387 350	310–320 313
b, V/mm	1.53	1.33	1.46	1.4	1.37	1.37

Table 3. Characteristics of monolithic and cored electrodes

Number	Mode parameters	Electrode		Note
		Monolithic	Cored	
1	U_a, V	64	64	–
2	I_a, A	400	500	I_{em} = 500 – 400 = 100 A; Δ = 25 %
3	P_a, W	25600	32000	32000:25600 = 1.25 due to I_{em}
4	L_a initial, mm	10	10	–
5	L_a break, mm	21	33	$\frac{33}{21} = 1.52$
6	Cathode diameter, mm	~5	~16	–
7	Arc column diameter, mm	~8	~20	–
8	Anode diameter, mm	~15	~35	–

It is known that one of the most important characteristics of graphitized electrodes for arc steelmaking furnaces is SER. This index is of some importance for each of the four grades of electrodes (EG, EGP, EGS, EGSP) used in all arc furnaces. Here, the higher the quality of the electrode (from EG to EGSP), the lower SER they have and, consequently, the higher the admissible current loads. For example, for electrodes with a diameter of 508 mm of EG grade used in 50-t furnaces, this index is 15–18 A/cm^2, and for EGSP grade it is 22–28 A/cm^2.

The core and the electrode create a single core-electrode system and are not isolated from each other. Therefore, SER of the cored electrode will be different from SER of the monolithic electrode-analogue.

The peculiarity of the production and operation of cored electrodes is that after stuffing of the cored mass into the electrode, it is not subjected to any heat treatment and is mounted on the furnace in the raw form. Therefore, all processes like removal of binding elements, physicochemical processes, formation of structure and properties of the core and electrode occur when the electrode is heated from a temperature of 20–30 °C (mounting in a set) on the furnace to the order of 4000 °C at the working end of the electrode in the near-arc part. At the same time, all the mentioned processes take place in the closed space of the furnace under conditions of lack of oxygen and excess of carbon.

In the mentioned conditions, there are no doubts regarding two factors: the first, in the core-electrode system there active processes of mutual diffusion of components occur; the second, given the constantly

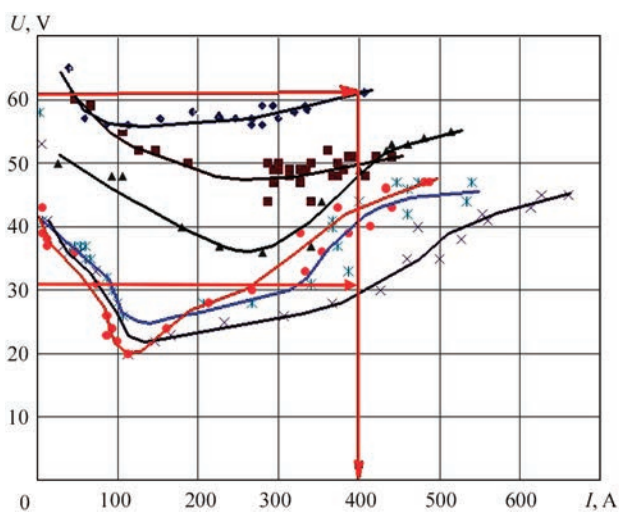

Figure 2. VACh of arcs of monolithic and cored electrodes: ✱ — monolithic electrode; ♦ — C_1; ■ — C_2; A — C_3; ● — C_4; ● — C_6

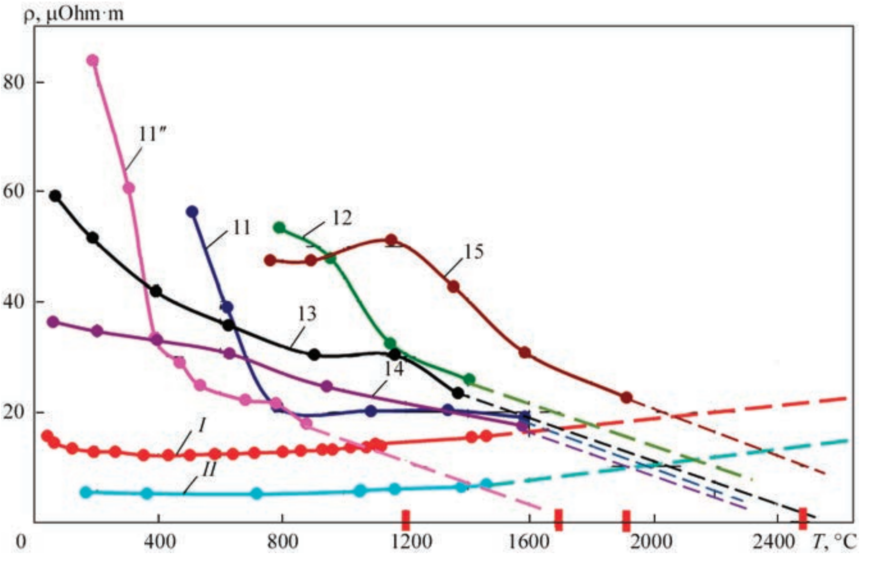

Figure 3. Dependence of specific electrical resistance of cores on temperature: 11–15 — core compositions, conditionally; *I* and *II* are monolithic electrodes

increasing temperature along the length of the electrode, all the above physicochemical processes in the core-electrode system are in a quasi-stationary state. Therefore, any analysis of the mentioned processes should be carried out in certain temperature zones along the length of the electrode.

The carried out studies and experiments indicate that SER of the cored graphitized electrode (core-electrode system) depends on many technological and power factors and processes being in a quasi-stationary state in an operating furnace. SER of the cored electrode is also in the same state, that is, it changes in time depending both on length as well as cross-section. As an example, Figures 3 and 4 show the results of studying the temperature dependence of SER on the composition of cores. In Figure 3, the results of trials of 5 core compositions (C_{11}–C_{15}) are given. As a criterion for evaluation of each composition, the temperature is accepted, at which curves of SER of cores intersect with SER of two initial monolithic electrodes (curves *I* and *II*). It is seen that SER of the core is equal to SER of the electrode and may further decrease in the temperature range of 1600–2500 °C, depending on the composition of the core and SER of initial monolithic electrodes. Even more clearly, the temperature dependence of SER of the core revealed itself when non-stoichiometric titanium nitride ($TiN_{0.8}$) was introduced into its composition. In this case, equalization of SER of the cores and electrodes has a clearly pronounced nature and occurs in the same temperature range (1400–2000 °C) relative to the initial monolithic electrode (*I*). With regard to the monolithic electrode with a low SER (*II*), the temperature interval of the SER lines intersection shifts to the right to approximately 1800–2500 °C.

Thus, the equality area of SER of the cores and electrodes is in the temperature range of 1200–2500 °C and is determined by the composition of the core and

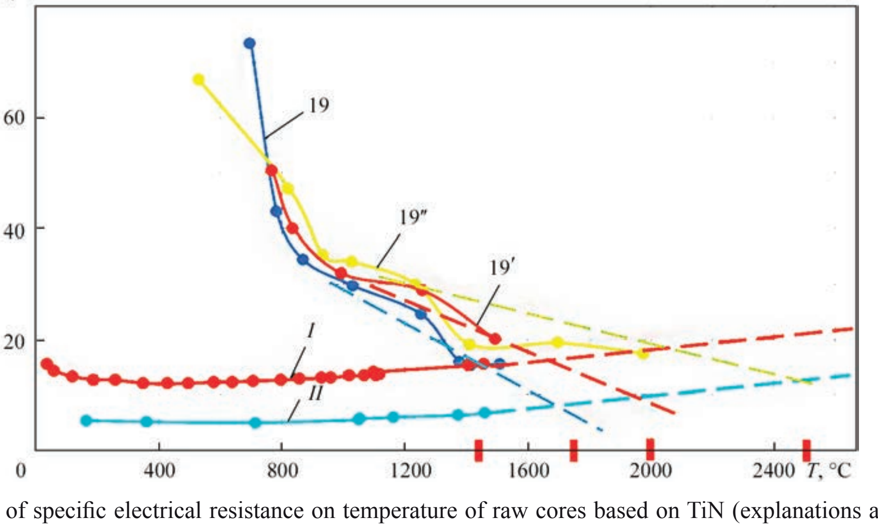

Figure 4. Dependence of specific electrical resistance on temperature of raw cores based on TiN (explanations are given in the text and in Table 2)

SER of the electrode. In turn, these indices are determined by the degree of completeness of diffusion processes in the core-electrode system and the actual state of creation (decomposition) of chemical compounds with semiconductor properties, that ultimately reduce SER of the core-electrode system.

The first studies of diffusion and determination of SER in the core-electrode system were conducted on full-scale samples from an industrial electrode with an initial diameter of 350 mm from the furnace EAF DC-12, which was heated from a temperature of 20–30 °C to the order of 3900–4000 °C (in the near-arc part) and exposure for 95 thou h.

In these melts, cores of the composition C_0^* were used. After 1.0–1.5 h from switching on the furnace, at the end of the electrode, a concave hemisphere was formed, predetermined by the presence of core in the center of the electrode. The shape of the hemisphere is determined by the electrical mode, the electrical resistance of the electrode body and core, the composition of metal and slag and other factors. The overall appearance of the working end of the electrode with the core, which was heated to 3900–4000 °C and natural cooling to room temperature, is presented in Figure 5. From the end of the electrode with the core, four samples were selected according to the scheme presented in Figure 6. The temperature dependence of SER of these samples was determined by specialized equipment. The test results are presented in Figure 7, from which it is seen that: SER of horizontal samples (1H and 2H) and extreme vertical (1V) are almost the same, which indices a high degree of isotropicity according to this indicator in the cored graphitized electrode; the vertical sample 2V has a significantly lower specific electrical resistance (in average by 12 %) and almost constant than the rest. This is explained by the fact that the elements with low electron work function, which transferred from the diffusion from the core into the electrode body, maintained in the central zone of the electrode in greater quantity than in the extreme sample 1V. Depletion of the sample 1V with the mentioned elements also occurred as a result of diffusion when the template was cooled to room temperature.

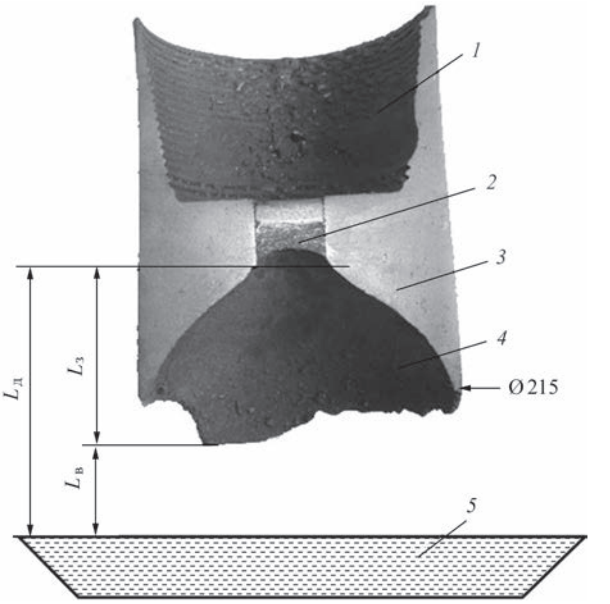

Figure 5. Macrostructure of working end of the graphitized electrode with an initial diameter of 350 mm (from EAF DC-12 furnace): *1* — nipple nest; *2* — core; *3* — electrode; *4* — hemisphere; *5* — liquid slag

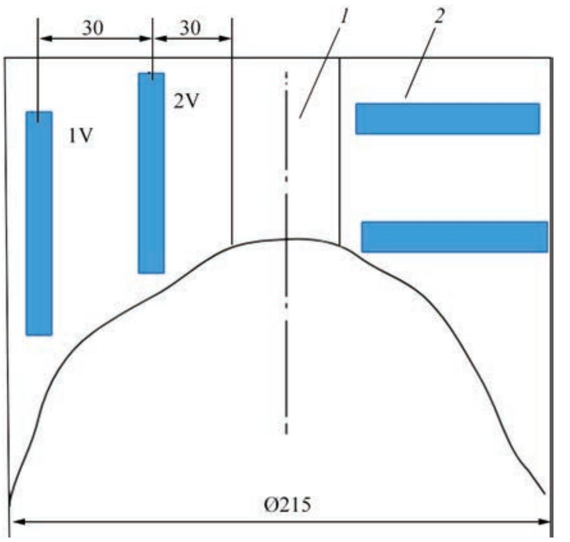

Figure 6. Scheme of cutting out samples: *1* — core; *2* — electrode

RESULTS OF USING CORED ELECTRODES IN INDUSTRIAL DC FURNACES

The above calculated, experimental and practical data convincingly testify the clear power and technological benefits of the cored arc.

The first industrial studies of cored electrodes were conducted in a 12-t EAF DC-12 furnace. 70FeSiMn wastes were used as a charge, i.e., a relatively simple and homogeneous charge. The tasks of these tests included: determination of technical and economic in-

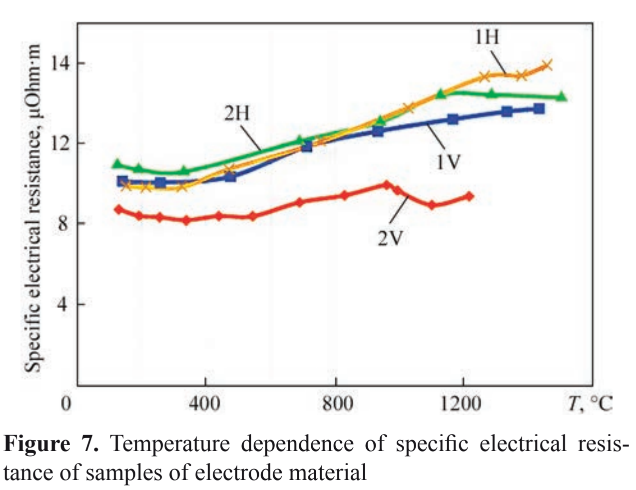

Figure 7. Temperature dependence of specific electrical resistance of samples of electrode material

*The composition of core and component distribution in electrode body is not given in the article.

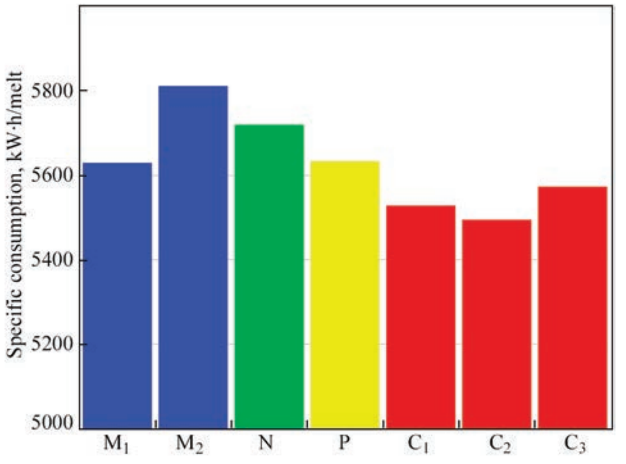

Figure 8. Specific consumption of active electric power during the melts on the serial mode using monolithic (M) electrodes, hollow (H) electrodes, nipple (N) and cored electrodes (C_1, C_2, C_6)

dicators during melts with monolithic and cored electrodes in regular modes, on short and long arcs, on reduced and increased voltages of arcs, determination of arc length before break, etc. As an example, Figure 8 shows generalized data on specific consumption of active electric power for monolithic (M_1 and M_2) electrodes, nipples (N), hollow electrode (H), cored electrodes (C_1, C_2 and C_6) in serial modes.

From Figure 8, it follows that regardless of the cores composition (C_1, C_2 and C_6), cored electrodes provide lower electric power consumption than monolithic, hollow electrodes and nipple.

The summary data on the use of cored electrodes compared to monolithic electrodes during remelting and refining of 70FeSiMn in a 12-t EAF DC are presented in [10, 11] and are the following: a stable arc in a wide range of changes in electrical modes and arc length; savings of active electric power to 10 %; reduction of reactive power to 23 %; increase in the furnace output to 12 %.

These results served as a convincing ground to use cored electrodes to remelt more complex, multifractional, heavy charge in the EAF DC-12 furnace. Such a charge was a catalyst — a product of oil refining. Its base is $A1_2O_3$. The catalyst also contains a large number of nickel, molybdenum (10–12 % of each element), vanadium. The peculiarity is the high content of sulfur (up to 4–6 %) and a high residual content of oil products. The main purpose of remelting of this material was to obtain the maximum content of molybdenum and nickel (ingots), as well as to produce a slag with a high content of V_2O_5 (more than 12 %) for the production of 50 % FeV. The preliminary preparation of the catalyst was not carried out before melting, which caused extremely unstable electrical and technological modes and, as a consequence, technical and economic indices of melting. Against this background, the testing of cored electrodes efficiency was of great interest. The work included three stages.

Stage 1. Remelting of the catalyst with the production of vanadium-containing slag and metal phase (ingots) containing Ni and Mo.

Stage 2. Refining of the ingots and obtaining a product with the highest possible content of Ni and Mo.

Stage 3. Obtaining of ferrovanadium.

As an example, Figure 9 shows the comparative results of the catalyst remelting on the monolithic and cored electrodes of the compositions C_2 and C_{11}.

From Figure 9 it follows that the furnace output when using cored electrodes grows by 25.6 %, a decrease in the burning loss of Ni, Mo and Fe is up to 9 %, savings of electric power are up to 30 % depending on the composition of cores.

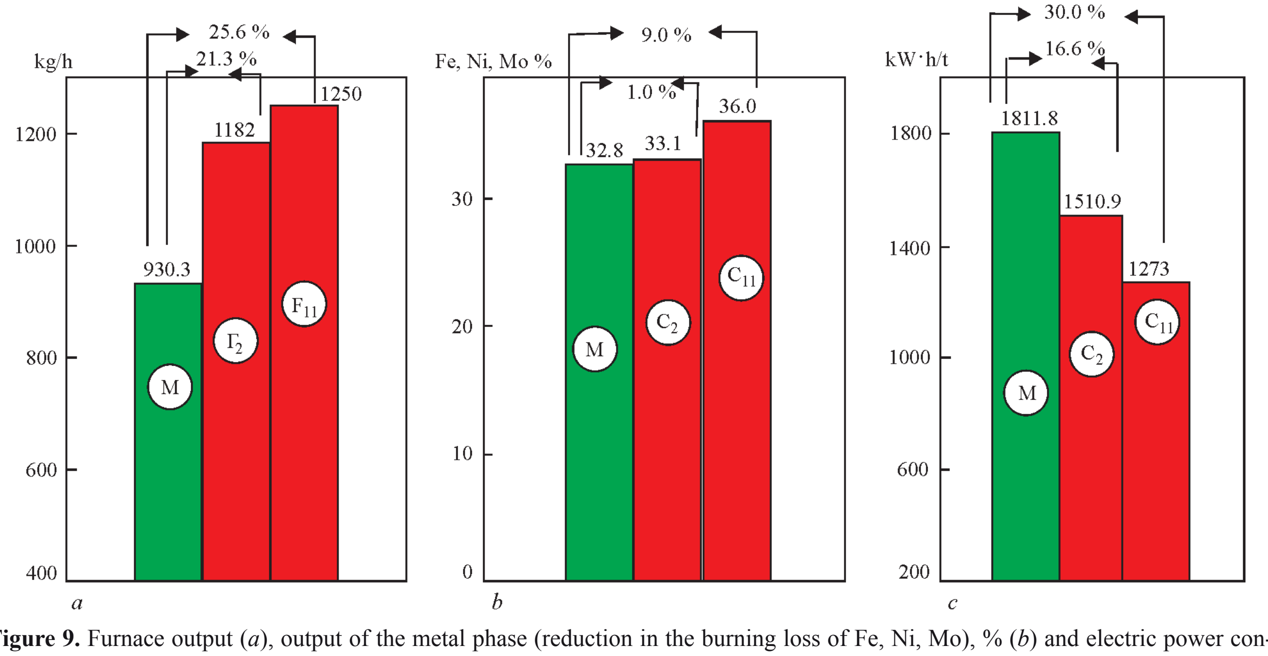

Figure 9. Furnace output (*a*), output of the metal phase (reduction in the burning loss of Fe, Ni, Mo), % (*b*) and electric power consumption (*c*) during remelting of the catalyst with the use of monolithic (M) and cored (C_2 and C_{11}) electrodes

Stage 2. During remelting of the metal phase, the use of the cored electrodes provided an increase in the furnace output by 9.6 %, a decrease in the burning loss of nickel and molybdenum by 10.3 % and saving of electric power by 2.8 %.

The similar results were obtained during smelting of 50 % FeV: the output increased by 4.2 %, the removal of vanadium form the slag increased by 17.4 % and saving of electric power were 7.1 %.

First of all, these data indicate that the electrode with a core at all stages of remelting the catalyst and its products have significant advantages compared to monolithic electrodes.

A significant advantage of cored electrodes is also the fact that when using time scattering, the melting decreases by 2.0–2.5 times, i.e., high stability of electrical modes and thermal conditions of the furnace output is provided.

As was noted, an important difference of cored electrodes is that during melting, the working end of such an electrode always has the shape of a concave hemisphere regardless of the core composition and electrical modes. This hemisphere causes the presence of close and open parts of the arc, the length of which can be adjusted. This causes two main technological factors. First, it can concentrate up to 50 % of the arc power. This in combination with the high stability of long arcs on the cored electrodes provides effective melting of a large-sized charge, a smaller number of arc breaks during penetration of wells, etc. Secondly, we assume that the consumption of refractories should be reduced

Table 4. Basic technical and economic parameters of operation of industrial EAF and EAF DC furnaces with cored electrodes*

	Melting parameters	12-ton EAF DC, electrode diameter of 350 mm	6-ton EAF, electrode diameter of 3×300 mm	50-ton EAF, electrode diameter of 3×508 mm
POWER	Arc stability	High	High	High
	Reactive power	Up to 23 %	–	–
	Increase in cosφ	From 0.88 to 0.94	From 0.81–0.86 to 0.91–0.94	–
	Reduction in time from the first short-circuit to a steady arc burning	By 2.4–4.8 times	By 2.75–5.4 times	–
	Reduction in time of arc stabilization on the wells and during charge melting	By 1.8–2.6 times	By 2.3–3.8 times	By 2.0–2.5 times
	Reduction in frequency and strength of surges into the primary mains	Significant	Significant	Significant
	Reduction in coefficients of current harmonics when penetrating wells and in liquid metal	–	From 0.65–0.59 to 0.28–0.09	From 0.9; 3.4; 1.1 to 0.3; 0.2; 0.3 respectively
	Reduction of the range of currents scattering by phases in the period of wells penetration and charge melting	–	By 25–40 %	By 30–50 %
	Distortion of sinusoidal curves of current and voltage in the basic periods of melting	–	Much lower	Much lower
	Reduction in the voltage and current fluctuations range	Voltage by 15 %, current by 31 %	–	–
TECHNOLOGY	Reduction in specific active electric power consumption (average), kW·h/t (%)	16.6–30.0 %	In average by 10 %	7–14 %
	Reduction in time of melt scattering (increase in stability)	2.0–2.5	1.5–2.0	2.0–2.5
	Increase in the furnace output, kg/h	Up to 25 %	By 23 %	By 18–22 %
	Reduction in burning loss of alloying elements (Mo, Ni, etc.)	Up to 10.3 %	–	–
	Reduction in overall burning loss of charge	Up to 3 %	Up to 2–3 %	Up to 3.5 %
	Reduction in specific consumption of cored electrodes of EG grade (in average), kg/t	–	By 18 %	By 16 %
METALLURGY	Reduction of nitrogen content in steel (in average)	–	By 15 %	By 19 %
ECOLOGY	Reduction in the noise level of furnace	By 7–10 %	By 8–10 %	By 7–10 %
	Reduction in the amount of dust and gas emissions	By 8–12 %	By 7–12 %	By 10–15 %

*Comparison is made with monolithic electrodes.

by 20–30 %, a number of furnace repairs should decrease and its overall output should grow.

It was also confirmed that the cored arc causes a reduction in the noise level during operation of EAF DC-12 by 10–12 %. More detailed results of using cores in DC furnaces are presented in [7, 8, 10, 11] and in the summary Table 4.

RESULTS OF USING CORED ELECTRODES IN INDUSTRIAL AC FURNACES

Currently, about 1200 electric arc furnaces are being operated in the world: 200 DC and 1000 AC furnaces, including the most common industrial furnaces with a capacity from 6 to 50 t (old furnaces) and 100–180 t furnaces of ultra-high capacity, which have been installed recently in different countries of Europe, Asia and America. Therefore, the possibility of using cored electrodes in AC furnaces is of great interest. The first melts of the kind were carried out in an industrial three-phase 6-ton EAF DS-6N1 furnace.

The wastes from abrasive cleaning of high-cut steels and heat-resistant alloys with large scraps of carbon and ball-bearing ShKh15 steels were exposed to remelting. In the process of works, the electrodes with cores of five compositions (C_{16}, C_{18}, C_{19}, C_{20} and C_{21}) were tested. The melts were carried out with different combinations of cored and monolithic electrodes operating in the furnace simultaneously: three cored; two cored and one monolithic; one cored and two monolithic.

For adequate comparison of the results, the melts were carried out on regular electrical modes with registration of current, arc voltage values and other parameters.

As in the case of DC furnaces, the high stability of all electrical mode parameters in the DS-6N1 furnace was immediately noted. It was found that: the time of arc stabilization from the first interfacial short-circuit to continuous burning in the cored electrodes is 1.75–5.40 times shorter than in the monolithic electrodes; the time of frequent arc breaks in the cored electrodes is 3–10 times shorter than in the monolithic electrodes.

These factors determine quick stabilization of the electrical melting mode, rapid formation of wells and efficient melting of the charge. This also results in a decrease in the frequency and strength of current surges into the primary mains, which improves the quality of electric power, providing more stable operation of such powerful electric power consumers as neighbooring furnaces, units for out-of-furnace treatment, mill rolls, etc.

In more detail, the results of experimental melts in the DS-6N1 furnace are outlined in [12, 13] and a summary Table 4.

Further, the experimental works were carried out in a 50-ton three-phase AC furnace of DSV-50 type, which uses graphitized electrodes with a diameter of 508 mm.

The works program included an assessment of the impact of a large-scale factor on the technical and economic indices of 6- and 50-t EAF, the operation of the furnace in continuous mode (melting by melting) for 8 days, the features of the furnace operation on long arcs, control of parameters of electric and technological modes of melting, etc. For this purpose, 24 electrodes of 508 mm diameter with cored inserts of four compositions (C_{18}, C_{22}, C_{23} and C_{27}) were made. For the correct comparison of the results, the melts were carried out on regular electrical modes. Also current and voltage oscillograms were recorded, some of which were made on long arcs and reduced currents. In total, with the use of cored electrodes, 1968 t of carbon, low-alloy high-strength structural and alloyed tool steels were smelted.

The obtained results convincingly indicate the high efficiency of using cored electrodes when smelting the entire assortment of structural and tool steels on both regular and experimental modes. These results are outlined in [9] and a summary Table 4.

CONCLUSIONS

1. It is stated that in recent decades, the world production of steel has increased continuously and is getting very close to 2 bln t in 2021. This is 2.86 times more than in 1970 (0.7 bln t). About 30 % of steel is produced in EAF AC and EAF DC arc furnaces. By the end of the decade, this index will grow to 40 %. Moreover, much attention is paid to green technologies and use of hydrogen instead of carbon.

2. It was established that equal lengths of the arcs of the cored and monolithic electrodes are ensured at a voltage on the arc of the cored electrodes approximately twice shorter than the arc of the monolithic electrodes at equal currents.

3. The arc of the cored electrode is always stable, disoriented, it does not migrate along the end of the electrode and has much larger sizes than the arc of the monolithic electrode. Therefore, all specific parameters (electric current density, power) of the cored electrode arc are much lower than in the monolithic electrode arc.

4. It has been shown for the first time that the voltage drop on the cathode spot of the cored electrode arc is 2–3 times lower than on the cathode spot of the monolithic electrode arc.

5. It was found that at equal voltages on the arcs (of the cored and monolithic electrodes), the length of the cored electrode arc is in average 1.5 times larger than of the monolithic electrode.

6. It was found that the voltage drop on the anode spots of the cored and monolithic electrodes is approximately the same.

7. The current of emitters contained in the core can amount to 25–43 % of the working melting current.

8. The specific electrical resistance of cores before a temperature of 1200–2500 °C is always higher than that of the electrode. After the range of 1200–2500 °C, SER of cores becomes equal or lower than that of the electrode body. This temperature range is purely indicative because SER depends on the core composition, the completion of mutual diffusion processes in the core-electrode system, the actual state of physicochemical processes in this system, etc.

9. It is shown that the mutual diffusion of components in the core-electrode system increases the isotropicity of SER of this system.

10. The cored graphitized electrodes provide high stability of the arc and improve all the main power, technological and metallurgical parameters of operation of steel-making arc furnaces.

11. The cored electrodes provide a reduction in the noise level by 7–10 % and emissions of dust and gases into the atmosphere by 7–15 %.

12. The efficiency of cored electrodes does not depend on the design of the arc furnace, the type of current (direct or alternating), as well as the capacity of the furnace.

13. The production of cored electrodes does not require significant capital costs and can be organized either at a steel-making enterprise or at an enterprise manufacturing graphitized electrodes.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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SUGGESTED CITATION

O.G. Bogachenko, D.D. Mishchenko, I.O. Goncharov, I.O. Neilo, M.M. Gasik, S.G. Kiiko, I.M. Logozinskyi, K.M. Gorban (2024) Composite (cored) graphitized electrodes for industrial DC and AC steel-melting furnaces. *The Paton Welding J*., **8**, 26–35.
DOI: https://doi.org/10.37434/tpwj2024.08.04

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Received: 29.04.2024
Received in revised form: 07.06.2024
Accepted: 22.08.2024