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APPLICATION OF CORED GRAPHITIZED ELECTRODES IN ELECTRIC ARC FURNACES OF DIRECT CURRENT (EAF DC)

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ABSTRACT

An effective means for improvement of technical and economic indicators of EAF DC are graphitized cored electrodes, designed at the E.O. Paton Electric Welding Institute of the NAS of Ukraine. The research works carried out in the industrial furnaces of the type EAF DC-12 showed that the arc of the cored electrode is always maintained in the center of the electrode, which provides a stable electric mode of melting on long arcs and low voltages of the power source. It was established that the voltage in the near cathode area, as well as the range of current and voltage pulsation of the cored electrode arc is significantly lower than in the standard (monolithic) graphitized electrode. The cored electrodes in EAF DC provide saving of active energy, reduction of reactive power losses, increase in cos φ and efficiency, reduction in the burning loss of alloying elements and the furnace noise level.

KEYWORDS: cored graphitized electrodes, EAF DC, electric power, volt-ampere characteristics, current and voltage pulsations, furnace efficiency

INTRODUCTION

In [1–3] it was noted that a characteristic feature of the world metallurgy industry in the last decades has been a year by year growing of steel production. Thus, from the middle of 70s of the XX century the steel production increased by 2.8 times and in 2021 it amounted to 1.950 bln tons.

More than 30 % of steel from the mentioned volume is melted in the electric arc furnaces of alternating (EAF AC) and direct (EAF DC) current. The total volume of electric steel is also continuously growing and by 2050 may reach 43 % [4, 5].

The growth of steel production occurred in highly competitive conditions at the metal products market and this predetermined the rapid development of different technologies and the proper equipment for melting steel, its ladle treatment, pouring, processing, etc. All these developments are aimed at improvement of such important technical and economic indicators of melting as consumption of electric power, refractory materials and graphitized electrodes, improvement of efficiency of furnaces under the condition of providing the high-quality of metal and meeting the requirements to the environmental protection.

A very important stage in the development of electric steel production, providing substantial improvement of technical and economic indicators and environmental problems of this production, was the creation and a wide implementation of EAF DC into industry.

The indisputable advantages of EAF DC are the following: efficient stirring of metal and slag; high stability of arc burning and its higher temperature; comparatively low electric power consumption; low burning loss of metal and alloying elements; very low consumption of electrodes and refractory materials; high and stable quality and satisfactory cost of metal. A stable low noise level of the operating furnaces (by 15–20 %); a significant reduction (by 6–10 times) of dust and gas emissions and reduction of interference level into supplying the mains are also noted.

The main disadvantages of EAF DC are the following: presence of one or more bottom electrodes; arc deflection in the direction opposite to the power source; need in using electrodes of the limited sizes — 700, 750 and even 810 mm [5–9].

While choosing the type of furnace it is naturally to pay attention not only to the abovementioned factors, but also to the condition and characteristics of supplying mains, charge provision, peculiarities of infrastructure, type and purpose of products, etc. Nevertheless, a number of EAF DC supporters grow and some of them believe that the indisputable advantages of EAF DC were already proved [10–14]. A number of EAF DC is continuously growing and about 1000 EAF AC and 200 EAF DC are currently operated in the world [2, 5, 15, 16].

RESEARCH PROCEDURE AND RESULT DISCUSSION

The steelmakers were always seeking and trying to reveal the potential opportunities of electrodes in order to use them as a universal instrument to control the melting parameters, and ultimately, to improve the technical and economic indicators of furnace operation [17].

As-applied to EAF DC, at the PWI, such multifunctional electrodes were designed, having a solid active insert or core. These electrodes were called the cored electrodes. The core in the electrode is made by drilling of one or more vertical holes in the standard (monolithic) electrode, which are filled with different components, including those containing elements of I and II groups of the Mendeleyev's Periodic Table with a low electron work function. Due to that, in the near cathode area of the electrode, the favorable thermodynamic conditions are created for ionization of gases of the arc column.

As a result, geometric and power parameters of the arc change dramatically. In particular, its volt-ampere characteristics (VACh), shape of the working end of the electrode and other characteristics are fundamentally changed, causing the possibility of efficient optimization of technological and electrical melting modes and, as a consequence, improvement of technical and economic indicators of furnace operation. This is evidenced by the results of laboratory and industrial investigations presented in [18]. As an example, Figure 1 shows VACh of arcs of the monolithic and cored electrodes. It is seen that at the same voltages of the arcs (40 V), in the cored electrodes the current is 1.8 times higher than in the monolithic electrode (respectively 900 A and 500 A). The core can be produced in the electrode of any quality and sizes. As the object of our investigations, the EAF DC were initially selected, where the arc repolarization is absent and, consequently, the cored electrode properties are revealed most completely.

In the process of investigations and tests of the cored electrodes, over 100 industrial experimental melts were carried out, 10 compositions of cores and 8 experimental electrical modes were tested.

The works were carried out in the 12-ton EAF DC with padded acid lining using graphitized electrodes of 350 mm diameter based on remelting of FeSiMn wastes. It is important to note that when using cored electrodes, the design of the furnace remains unchanged. The unstable charge quality (large variation in chemical and fractional composition, as well as in CaO content) causes a considerable variation of values of electric power consumption if it is attributed to one ton of a suitable ferroalloy.

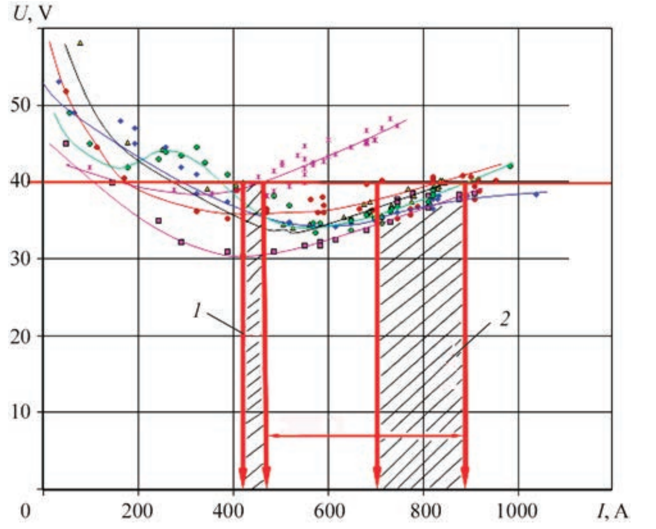

Figure 1. VACh of arcs of monolithic (*1*) and cored (*2*) electrodes of 50 mm diameter: × — monolith; ♦ — C1; ■ — C2; ▲ — C3; ○ — C4; ● — C5; L_a = 15 mm, anode — core

Therefore, the specific active electric power consumption in the specified conditions of production is accepted as the consumption for melting (on the original mass of the charge, *p*, kW·h/melt) and saving of electric power, where the compared indicators are taken as average as to the maximum number of identical melts.

The program of works envisaged: carrying out the comparative tests of the cored electrodes of different composition and monolithic electrodes at the serial modes (Figure 2); evaluation of influence of short and long arcs on power consumption, as compared to the serial mode (Figures 3, 4); evaluation of influence of reduced voltage of the power source on long arcs for the cored electrodes and nipples (Figure 5); evaluation of change in reactive power and cos φ for the cored and monolithic electrodes (Figure 6).

It follows from Figure 2 that the cored electrodes (C1, C2 and C6) at the serial modes provide a reduc-

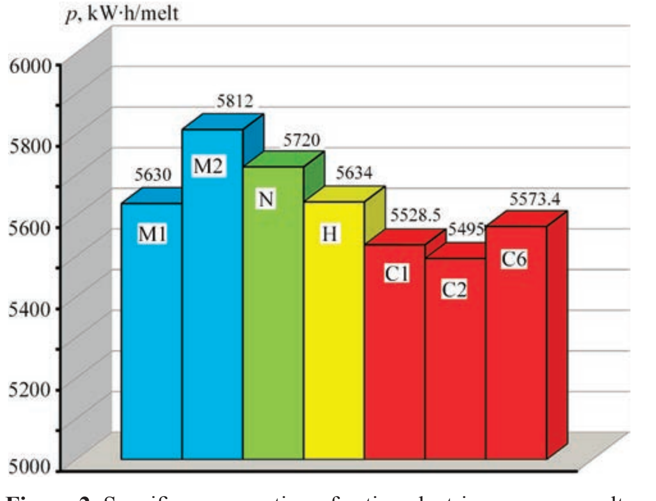

Figure 2. Specific consumption of active electric power on melts according to serial mode with the use of monolithic (M1, M2), hollow nipple (N) and cored electrodes (C1, C2, C6) (8 voltage level)

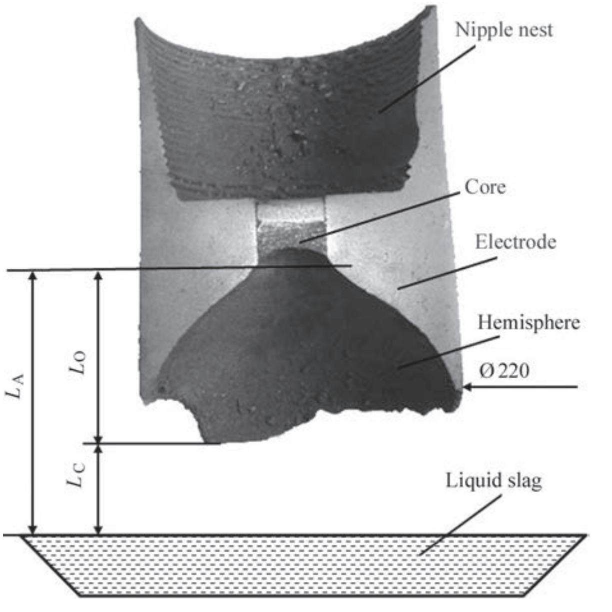

Figure 3. Macrotemplate of cored electrode with initial 350 mm dia and components of arc length of cored electrode (L_A, L_C and L_O)

tion in the active power consumption by 2.4–5.3 % as compared to the monolithic ones (M1 and M2), nipples (N) and hollow electrodes (H).

It is known that the effective means of saving the electric power is the operation of furnace on long arcs [19]. Speaking about the length of the arc as-applied to the cored electrode, it should be taken into account that the end of the cored electrode has always the shape of a concave hemisphere that essentially distinguishes it from the monolithic electrode. Therefore, the arc length of the cored electrode (L_A) consists of the length of its open (L_O) and closed (L_C) part (Figure 3). At the same time, L_A of the cored electrode is always 1.3–1.5 times longer than L_A of the monolithic electrode at the equal parameters of electric mode, which is caused by the presence of the core and its composition. In this paper, as the initial condition, the practical equality of arc length of the monolithic electrode (L_M) and the open part of the arc of the cored electrode (L_C) in a serial electric mode was taken. An increase (or decrease) in the arc length L_O at the experimental modes was carried out by the corresponding adjustment of arc voltage and current in the second half of melting (after the second charge loading). The comparative results of these investigations are shown in Figure 4. It is seen that operation on the long arcs provides a decrease in the specific consumption of electric power on the cored electrodes, on average, by 3.2 and by 8.35 % as compared to the monolithic electrodes (Figure 2). It should be noted that due to a low resistance of padded acid lining used for remelting of FeSiMn wastes, even at a comparatively low increase in the arc length (by 10–15 %) it turned to be impossible to reveal adequately the influence of the long arc factor of the cored electrodes on saving of the electric power. Here, a certain resource exists in the part of saving the electric power, which, in our opinion, will be significant in melting the steel scrap in the furnace with a basic lining. As another factor providing saving of active electric power on the cored electrodes, a stable operation of furnace at lower voltages of the furnace transformer became (Figure 5). This Figure shows that melting with the electrode C2 on the long arc and at the 9 level provided saving of electric power by 2–4 % as compared to the operation on the long arc at the 8 level (Figures 5 *a*, *b*) (serial mode on the monolithic electrodes is not stable at the 9 voltage level). The same dependence is observed on other cored electrodes and nipples (Figure 5, *c*). It is important to note that operation of the furnace on the long arcs provided also the highest efficiency determined by an average melting time of 2.11 h both at the 8 (531 V) as well as 9 (467 V) voltage level without the loss of the metal temperature before pouring. In the experimental modes, envisaging short arcs, the melting time increased in average to 2.28 h, i.e. by 7.5 %. Moreover, the cored electrodes provide also a

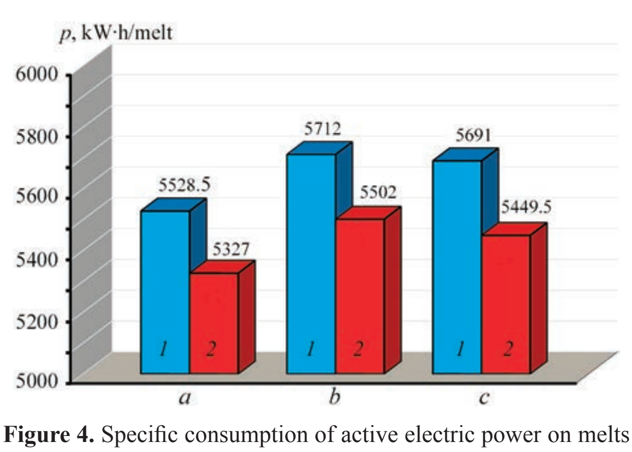

Figure 4. Specific consumption of active electric power on melts with cored electrodes on short (*1*) and long (*2*) arcs: *a* — serial (*1*) and long (*2*) arcs, core C1; *b* — core C2; *c* — core C5

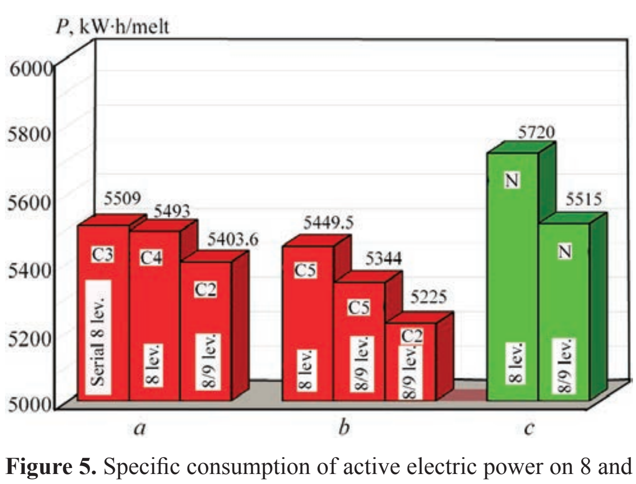

Figure 5. Specific consumption of active electric power on 8 and 9 voltage levels: *a* — cored electrodes C2 (V series), C3 and C4 (IV series) (composition F2); *b* — cored electrode C5 (IV series) (composition F3); *c* — nipples (serial mode)

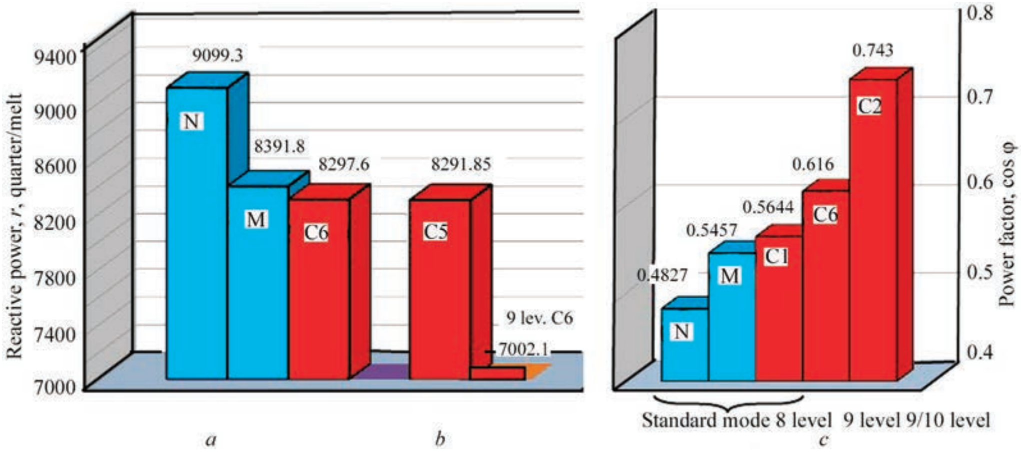

Figure 6. Comparative indicators of reducing reactive power and cos φ: *a* — standard mode, nipple No. 5 (N), monolithic electrodes (M) (melt 3485–3487 according to Batovsky) and cored electrode C6 (melt 3732–3735); *b* — standard mode, C5 and experimental mode, Nos 8 and 9 voltage levels, C6; *c* — cos φ at the standard mode of the 8 level, on experimental mode of the 9 level, on experimental mode of the 9/10 level

stable operation of the furnace and saving the electric power by 2.5 % also at the 10 (394 V) level. These data clearly indicate a high arc stability of the cored electrodes and experimental electric modes, which is provided by the effective operation of the core components. Thus, the cored graphitized electrodes when operating on the long arcs and low voltage levels of the power source can provide up to 8.35 % of saving the active electric power and an increase in the furnace efficiency by 7.5 %.

The cored electrodes provide also a significant reduction in reactive electric power, Figure 6. Already in melting at the standard mode, a reduction in reactive electric power consumption, respectively, by 8.8 and 1.1 %, occurs with the cored electrodes as compared to the nipples and monolithic electrodes (Figure 6, *a*). The consumption of reactive electric power reduced even more when using cored electrodes at a low voltage of the transformer (9 level) and with the long arc as compared to the cored electrode at the standard mode (Figure 6, *b*). And as compared to the nipples at the standard mode, this value is reduced by 23 %.

The cored electrodes cause also an increase in the power factor (cos φ), (Figure 6, *c*). From Figure 6, *c* it follows that cos φ grows from 0.4827 (8 level) in melting with the nipples at a standard mode to 0.743 in melting with the cored electrodes at the experimental mode at the 10 level.

Thus, while operating with cored electrodes of optimal compositions in low transformer voltages and long arcs, saving of the active power to 8.35 % and reduction in reactive power by 23 % and increase in cos φ from 0.483 to 0.743 are provided.

To understand the facts of saving the reactive power and reduction in reactive power losses, let us consider the volt-ampere characteristics (VACh) of arcs of the monolithic and cored electrodes, Figure 7. The mentioned VAC were obtained on the model electrodes of 50 mm diameter for monolithic and five experimental compositions of cores.

In the industrial EAF DC-12, the melting processes are performed at the maximum current of 17.1–17.3 kA with the use of monolithic and cored graphitized electrodes with the initial diameter of 350 mm. In the installation (model) with the electrodes of 50 mm diameter, the mentioned current corresponds to the current of 345–350 A. As is seen from Figure 7, with the use of the cored electrodes (depending on their composition), the same current (400 A) is achieved at much lower voltage (32 V) than in the case with the monolithic electrode (62 V). Such reduction in voltage is provided due to the presence of substances in the cored material with a low electron work function. This explains a stable operation of the cored electrode arc at low transformer voltages (9 and

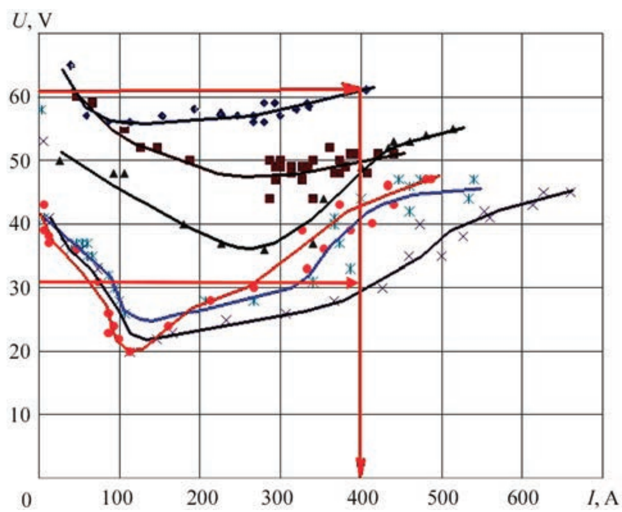

Figure 7. VACh of arcs, obtained on monolithic and cored electrodes, anode–copper: ♦ — M; ■ — C1; ▲ — C2; × — C3; ∗ C4; ● — C5

Table 1. Electric parameters of arcs at 15 mm length*

Parameters	Monolith		Core C3		Core C4		Core C5	
		% from P_a		% from P_a		% from P_a		% from P_a
Total voltage at arc U_a, V	52	–	36	–	41	–	39	–
Cathode voltage U_c, V	18	–	6	–	7.5	–	9	–
Arc column voltage U_{col}, V	20	–	20	–	20.5	–	19	–
Anode voltage U_A, V	14	–	10	–	13	–	11	–
Arc current I_a, A	300	–	420	–	320	–	313	–
Total power P_a, W	15608	–	15128	–	13120	–	12226	–
Cathode power P_c, W	5403	35	2521	17	2400	19	2821	23
Column power P_{col}, W	6003	38	8404	56	6560	51	5956	49
Anode power P_A, W	4202	27	4202	28	4160	30	3448	28

*Average data of three measurements are given.

10 level), as far as the current generated by the core elements (emitters current) takes place.

In Figure 1, this current is 400 A. One of the important consequences of the core components (emitters) operation is a considerable reduction in the voltage drop on the cathode spot of the cored electrodes (Table 1).

As it follows from the data of Table 1, there is one of the fundamental differences in the parameters of the arcs, i.e. the voltage drop at the cathode spot of the cored electrode is 2–3 times lower than on the arc of the monolithic electrode. The mentioned feature of the core arc is present both at equal arc lengths, as well as at equal arc voltages. This phenomenon causes a significant reduction in heat losses in the near cathode area of the cored electrode. In combination with a stable binding of the arc on the core and a stable electric melting mode, it causes the abovementioned saving of active electric power.

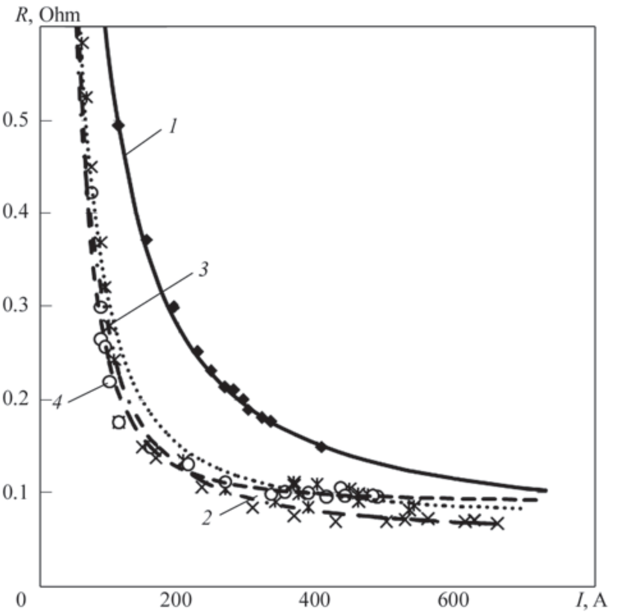

Figure 8. Dependence of arc resistance on current ($R = f(I)$) for monolithic and cored electrodes: *1* — M; *2* — C3; *3* — C4; *4* — C5

ABOUT REACTIVE POWER

At first sight, it looks weird that such high values of reactive power (commensurable with active power) are provided in the electric circuit of rectified current. At the same time, it is known that in the electric circuits, containing energy accumulators (throttle, capacitor) and a non-linear element, the self-oscillations or the so-called deterministic chaos can occur [20]. Such a circuit element in EAF DC is the electric arc possessing the properties of the non-linear active (non-reactive) energy accumulator. The studies of the voltage and current oscillograms, recorded in the industrial EAF DC-12 for the monolithic and cored electrodes at the standard modes showed that the amplitude of both current and voltage pulsations (especially voltage) is significantly larger in the case of monolithic electrode, right until repolanization of voltage. It was found that the range of voltage and current pulsation in the cored electrodes is respectively by 15 and 31 % lower than in the monolithic electrodes.

The reduction of amplitude of pulsations means the reduction of alternating component of current and, consequently, the reduction in reactive power by 23 %.

To explain the influence of activating components of the core on the level of pulsation of electric arc parameters, it is necessary to return to VACh of the arcs again. For better visualization, let us convert the dependencies $U = f(I)$ given in Figure 7 to the dependence of arc resistance on current $R = f(I)$. The experimental measurements were also processed with the help of the computer mathematics

Table 2. Results of mathematical processing of oscillograms of arcs on the model electrodes of 50 mm diameter

Electrode	Equation of dependence $R = f(I)$, Ohm	Equation of derivative dR/dI, Ohm/A	Value of dR/dI at I = 350 A, Ohm/A
Monolithic	$R(I) = 128.56 \cdot I^{-1.2} + 0.056$	$dR/dI = -154.274 \cdot I^{-2.2}$	$-3.903 \cdot 10^{-4}$
C3	$R(I) = 208.52 \cdot I^{-1.5} + 0.055$	$dR/dI = -312.777 \cdot I^{-2.5}$	$-1.365 \cdot 10^{-4}$
C4	$R(I) = 230.52 \cdot I^{-1.5} + 0.071$	$dR/dI = -345.783 \cdot I^{-2.5}$	$-1.509 \cdot 10^{-4}$
C5	$R(I) = 1512.84 \cdot I^{-2} + 0.090$	$dR/dI = -3025.671 \cdot I^{-3}$	$-0.706 \cdot 10^{-4}$

package Scilab and the mathematical dependences $R = f(I)$ were obtained for the each considered case. The results of mathematical processing of experimental measurements are presented in Figure 8. The currents of 345–350 A correspond to the range of rated current of melting in the industrial EAF DC-12 furnace (14.9–17.8 A) in the model conditions on the electrodes of 50 mm diameter. Table 2 gives some results of mathematical processing of oscillograms of arcs on model electrodes.

The indicator of the VACh nonlinearity for the preset value of current is a tilt angle to the curve of the dependence of the arc resistance on the current $R = f(I)$. The value of the tangent of this angle is equal to the first derivative dR/dI at this point. The linear dependence of VACh is characterized by a constancy of resistance, i.e. horizontal line of dependence of resistance on current.

The value of the derivative dR/dI for the current of 345–350 A can be considered as indicator of the VAC nonlinearity. The higher dR/dI from zero, the greater is the difference of VACh from the linear dependence and, as is seen from the given data, in the cores this value is closer to zero than in the monolithic electrode. In other words, the closer VACh of the arc to the linear dependence in the operating current range, the lower is the pulsation of current and voltage, which cause a decrease in reactive power losses during operation with the cored electrodes. Here the phenomenon of autooscillations in the electric circuit of EAF DC is least expressed.

The calculated, experimental and practical data mentioned above provide a strong evidence of clear power advantages of a "cored" arc. The presented data were obtained while remelting wastes of 30 % FeSiMn, i.e. a relatively simple and homogeneous charge. It gave a convincing reason to use cored electrodes for remelting more complex, multifractional and heavy charge. Such a charge was the catalyst — a product of oil refining. Its base is Al_2O_3. The catalyst also contains a large amount of nickel, molybdenum and vanadium. It is featured by a high content of sulphur, which amounts up to 4–6 %, and a high residual content of oil products. The basic purpose of remelting this material consisted in obtaining the maximum amount of molybdenum and nickel (ingots), as well as producing the slag with a high content of V_2O_5 (more than 12 %) for production of 50 % of FeV. Before melting, a preliminary preparation of the catalyst was not carried out, which caused extremely unstable electric and technological conditions and, as a consequence, technical and economic indicators of melting. Against the background of these circumstances, checking the efficiency of the cored electrodes work was of great interest. The work included three stages:

- Stage 1. Remelting of the catalyst itself with obtaining a vanadium-containing slag and a metal phase (ingots), containing Ni and Mo;
- Stage 2. Refining of ingots and obtaining a product with the maximum possible content of Ni and Mo;
- Stage 3. Producing ferrovanadium.

Technical and economic indicators (output rate, kg/h, output of a metal phase (reduction in burning loss), %, electric power consumption, kW·h/t) of the catalyst remelting by stages using the monolithic (M) and cored electrodes (C) are presented in Figure 9. The arrows show the comparable indicators.

First of all, the mentioned data indicate, that cored electrodes at all stages of remelting the catalyst and its products have essential advantages as compared to monolithic electrodes. These advantages have a large range of values (Figure 9, *a–c*), which is explained by two factors. The first is the lack of the charge (catalyst) preparation as required and, as a result, instability of electrical and technological conditions of melting. The second point, which has a major importance, is that compared indicators are largely determined by the composition of cores.

The data given in Figure 9, *a–c* show the following: the efficiency of the furnace during remelting of a catalyst is increased by 21.3–23.6 %. An increase in the output of the metallic phase (decrease in the burning loss of Ni, Mo, Fe) amounts to 1–9 %; a decrease in the specific power consumption is provided in the range of 16.6–30.0 %. Higher indicators were provided in the melts using cores of the composition C11.

During remelting of the metallic phase (of ingots), the following indicators are provided (Figure 9, *d–f*):

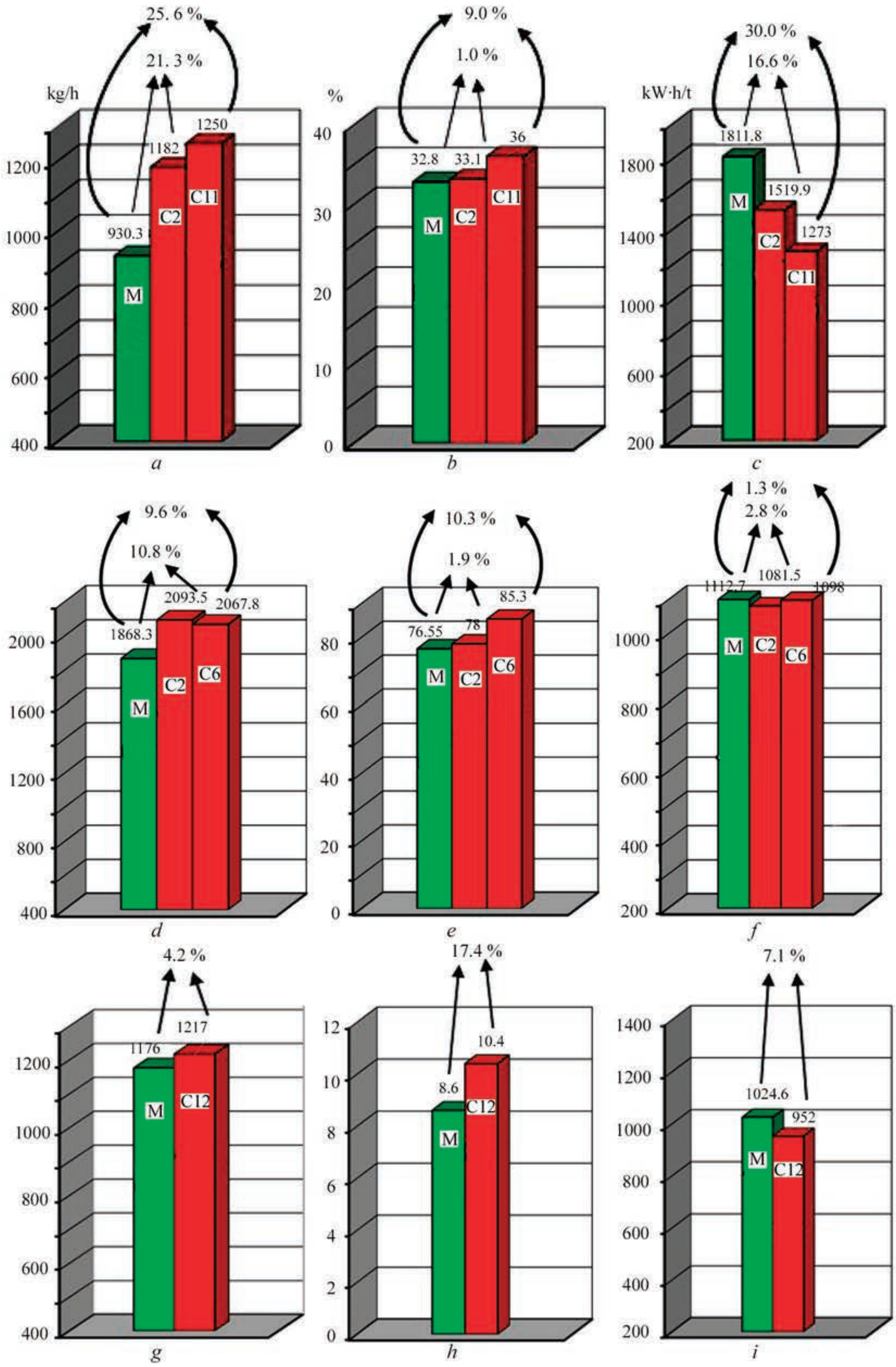

Figure 9. Efficiency of furnace (*a*, *d*, *h*), output of metallic phase (reduction of burning loss of Fe, Ni, Mo), (*b*, *e*, *h*) and consumption of electric power (*c*, *f*, *k*) during remelting of: catalyst with the use of monolithic (M) and cored (C2 and C11) electrodes (stage 1); of metallic phase (ingots) with the use of monolithic (M) and cored (C2 and C6) electrodes (stage 2); and melting of ferrovanadium while using monolithic (M) and cored (C12) electrodes (stage 3)

the efficiency of the furnace is increased by 96–108 %; the output of the metallic phase is increased by 1.9–10.3 % and the power saving is 1.3–2.8 % on the cored electrodes.

During melting of ferrovanadium with the use of cores C12 (Figure 9, *g*–*h*), the efficiency of the furnace is also increased by 4.2 %; a decrease in the burning loss of vanadium by 17 % is provided;

during melting of 50 % ferrovanadium, the power saving amounted to 7.1 %.

In the process of experimental melts in the EAF DC-12 furnace, it was found that an essential advantage of cored electrodes is the fact that during their use, the interval in melting time is 2.0–2.5 times reduced, i.e. a high stability of electrical and thermal conditions of the furnace operation, and a more full proceeding of physical and chemical processes are provided.

An important distinctive feature of cored electrodes consists in the fact that during melting, the working end of such an electrode always has a shape of a concave hemisphere, regardless of the core composition and the parameters of the electrical conditions. This hemisphere predetermines two main technological factors. First, it can concentrate of up to 50 % of the arc power. This, in combination with a high stability of long arcs on the cored electrodes should provide the effective melting of a large-sized charge and a smaller amount of arc breaks during melting of “wells”, etc. Therefore, it is expected that the consumption of refractory materials will be shortened by 20–30 %, a number of repairs of the furnace will decrease, and, therefore, its efficiency will increase.

It is also confirmed, that the cored arc also determines a 10–12 % reduction in the noise level during the operation of EAF DC-12.

The data presented in the article have fully substantiated the works on using cored electrodes in electric arc furnaces of alternating current.

CONCLUSIONS

1. It is noted that more than 30 % of steel from the world steel production is melted in arc furnaces of direct (EAF DC) and alternating current (EAF AC).

2. The effective means for improvement of the technical and economical indicators of EAF DC is the use of the cored graphitized electrodes, designed at the PWI. Cored electrodes are composed of components with a low electron work function, which creates favorable thermodynamic conditions for ionization of the arc column gases in the near cathode area.

3. It was found that the arc of the cored electrode is always maintained stable at the core and does not migrate along the end of the electrode, characterized by a high stability at a large length and at low voltages of the power source.

4. It was found that at equal voltages the arc current of a cored electrode is by 1.8 times higher than the current of a monolithic electrode.

5. It was found that the voltage drop in the near cathode area in the cored electrode is 2–3 times lower than in the monolithic electrode, which significantly reduces power (heat) losses in this part of the electrode.

6. It was shown that the amplitude of oscillations of voltage and current of the cored electrode arc is on average by 15 and 31 % lower, respectively, as compared to the arc of the monolithic electrode.

7. In accordance with the features and parameters of the arc of the cored electrodes, during remelting of FeSiMn wastes in the industrial EAF DC, the following parameters are provided: stable electric mode; up to 8.35 % saving of active electric power during operation on long arcs; reduction in reactive power to 23 %; increase in cos φ from 0.48 to 0.74; increase in the furnace efficiency by 7.5 %; reduction in interval between melting time by 2.0–2.5 times;

8. During remelting of the catalyst and its derivatives (ingots, vanadium-containing slag, melting of ferrovanadium), the cored electrodes depending on their composition, provide the following indicators: increase in the furnace efficiency by up to 25.6 %; reduction in burning loss of Ni and Mo during remelting and ingot refining by 10.3%; reduction in burning loss of vanadium by 17.4 % during melting of ferrovanadium; reduction in specific electric power consumption by 30 %.

9. The obtained results have fully substantiated the works on using cored electrodes in electric arc furnaces of alternating current.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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