

Bogachenko A.G.^{1*}, Mishchenko D.D.¹, Goncharov I.O.¹, Braginets V.I.¹, Neylo I.A.¹, Plevako Y.A.²

¹*E.O. Paton Electric Welding Institute of the NAS of Ukraine, 11 Kazymyr Malevych str., 03680, Kyiv, Ukraine*

²*PJSC "Feroks"59, Pivdenne shose, 69032, Zaporizhzhia, Ukraine*

**stemet@ukr.net*

EFFICIENCY OF USING CORED GRAPHITIZED ELECTRODES ON ELECTRIC ARC FURNACES OF DIRECT CURRENT

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. The research works of the first stage, 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, a stable electric mode of melting is provided 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. These factors determined the saving of active energy, reduction of reactive power losses, increase in $\cos \varphi$ and reduction of the furnace noise level

Keywords: *cored graphitized electrodes; active and reactive energy; volt-ampere characteristics; current and voltage pulsations*

INTRODUCTION

A characteristic feature of the world metallurgy industry in the past decade has been a year by year growing of steel production. For example, if in 1974 about 700 million tons of steel was melted in the world, than in 2012 its production grew by more than twice, reaching 1.517 billion tons [1, 2, 3]. In 2014, this value already amounted to 1.661 billion tons and, on the results of 2020, it reached 1.864 billion tons (data of the World Steel Association).

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 occurs 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, casting, 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 melting units 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 arc furnaces at direct current.

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 fumes of metal and alloys; very low consumption of electrodes and a low consumption of refractory materials; high and stable quality and satisfactory cost of metal. A stable low noise level of the operating furnaces (by 15...20%) is also noted; significant reduction (by 6 ... 10 times) of dust and gas emissions and reduction of interference level supplying the mains.

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, 6, 7, 8, 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 and many others. Nevertheless, the number of EAF DC supporters grows and some of them believe that the indisputable advantage of EAF DC was already proved [10, 11, 12, 13, 14]. The number of EAF DC is continuously growing and about 1000 EAF and about 200 EAF DC are currently operated in the world [2, 5, 6, 8, 15].

It is known that the technical and economic parameters of EAF DC and EAF AC operation are largely determined by technical characteristics and operational reliability of the graphitized electrodes. In the cost of electric steel the immense volume belongs to electrodes, which is up to 8....12% and more. Therefore, it is difficult to overestimate the importance of works, which are carried out by the manufacturers of electrodes, to provide the required specific electrical resistance, increase in density, providing of high mechanical characteristics of electrodes, etc. For this purpose, different raw materials are used, including a scarce acicular petroleum coke, the technologies of preparation and pressing of raw materials are improved, including calcination in the Castner furnaces (direct heating), impregnation of surface with different reagents, etc. to solve the main problem: decrease in the specific consumption of electrodes. 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. So, in 1962, the experiments on industrial application of hollow electrodes were carried out. Such electrodes provided a more stable burning of the arc and its binding to the hole, more stable melting mode and reducing in the electric power consumption [16]. The other researchers introduced active inert gases, pellets and master alloys through the hole in the electrode. In other case the wasted oil was introduced through a hole and the arc ionization effect was achieved. There are some works known on deposition of multiple layers of materials on the electrode, where each among them had a preset conductivity or heat resistance. The tests of these electrodes showed the acceptable results. However, none of these methods found a widespread application in industry. Thus, the through hole significantly increased the consumption of electrodes, the use of oil is associated with explosion safety and the deposition of layers caused a very high cost of electrodes.

EXPERIMENTAL

As-applied to EAF DC at the E.O. Paton Electric Welding Institute 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 this, in the near cathode area of the electrode the favorable thermodynamic conditions are created for ionization of gases of the arc column. The works were carried out in the special laboratory equipment with the use of monolithic and cored electrodes of 50 mm diameter. In addition, the experiments were carried out in the industrial 12-ton EAF DC. Over 100 industrial experimental melting processes were carried out, 10 compositions of cores and 7 experimental electrical conditions were tested.

RESULTS AND DISCUSSION

In the process of investigations and tests of cored electrodes it was found that the parameters of the arc, its volt-ampere characteristics (VAC), shape of the working end of the electrode and other characteristics are fundamentally changed, causing the possibility of optimization of technological and electrical 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, which allow speaking of the real possibility of creating industrial large-sized cored electrodes [17]. As the example Figure 1 shows VAC of arcs of monolithic and cored electrodes of several compositions.

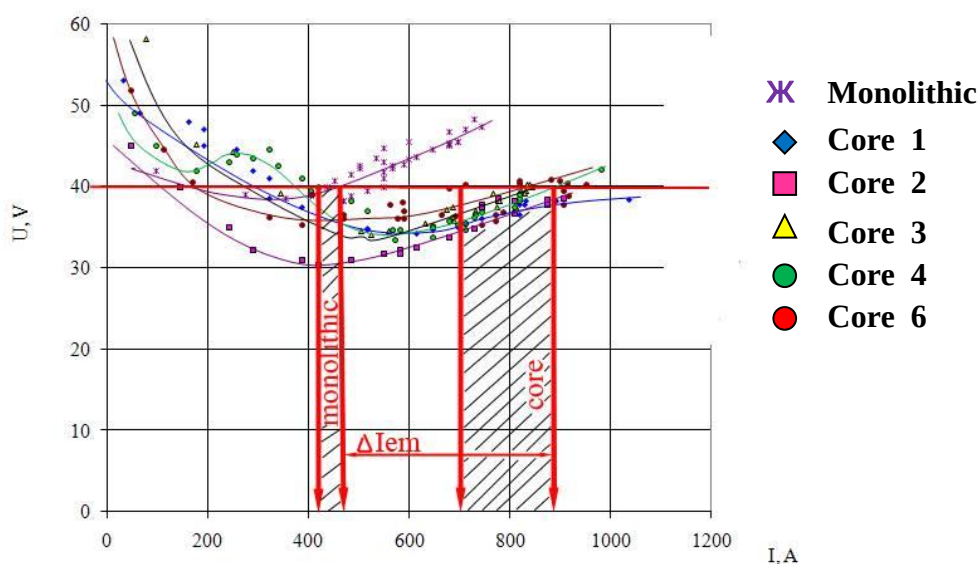


Fig. 1. Volt-ampere characteristics (VAC) of arcs obtained with the monolithic and cored electrodes.
Anode – graphite

It is seen that at the same voltage of arc (40 V), in the cored electrodes the current is provided in 1.8 times higher than on 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. It was clearly established that the saving of up to 10% of the active energy and, respectively, reduction in reactive power losses up to 23%, an increase in $\cos \varphi$ from 0.48 to 0.74 is observed depending on electrical conditions and composition of the core.

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 quality of charge (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 suitable ferroalloy. Therefore, the specific active electric power consumption in the specified conditions of production is accepted as consumption for melting (on the original mass of the charge) (p , kWh/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 different composition of core and solid 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 core electrodes and nipples (Figure 5).
- evaluation of change in reactive power and $\cos \varphi$ for 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 reduction in 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 operation of furnace on the long arcs [18]. 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 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_O) in a serial electric mode was taken. The increase (or decrease) in the arc length L_O 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 the low resistance of padded acidic 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 the electric power.

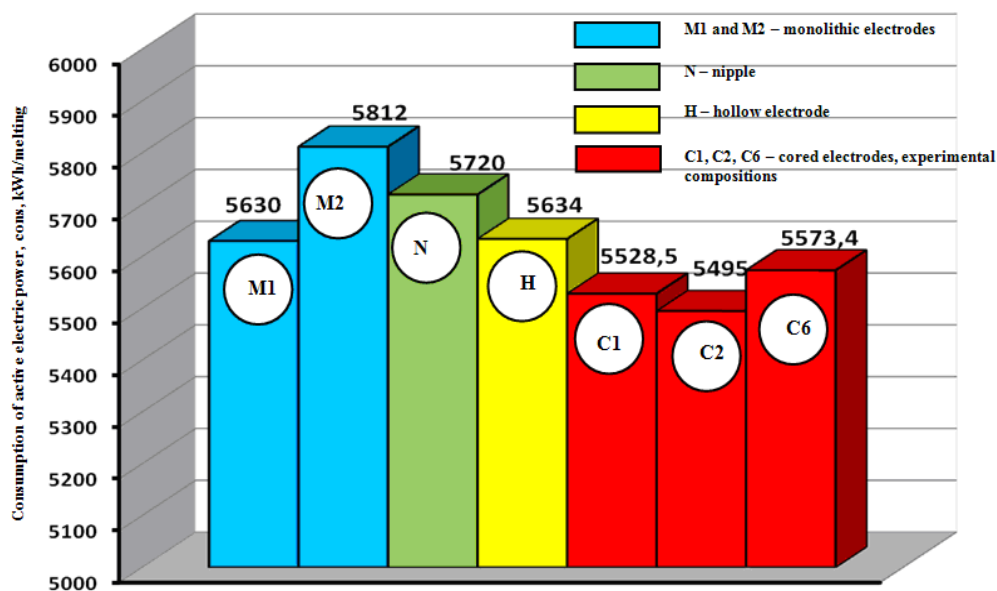


Fig. 2. Appearance of EAF DC-12 furnace during melting using cored electrode

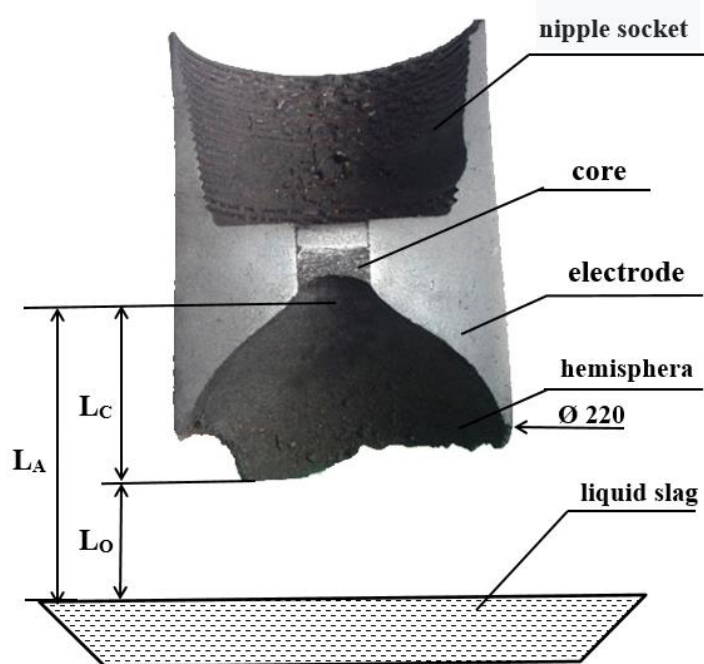


Fig. 3. Macrotemplates of cored electrode with initial 350 mm dia. And component of arc length of cored electrode: LA, LC and LO

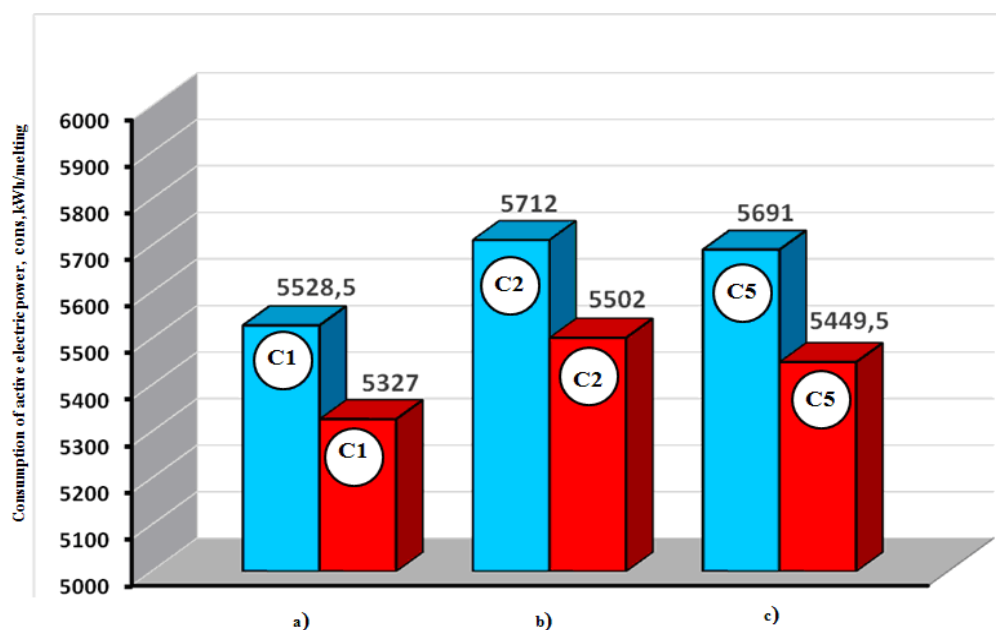


Fig. 4. Specific consumption of active electric power (kWh/melt) during melting using cored electrodes on the short and long arc, where: serial and long arc (electrode C1); short and long arc (electrode C2); short and long arc (electrode C5)

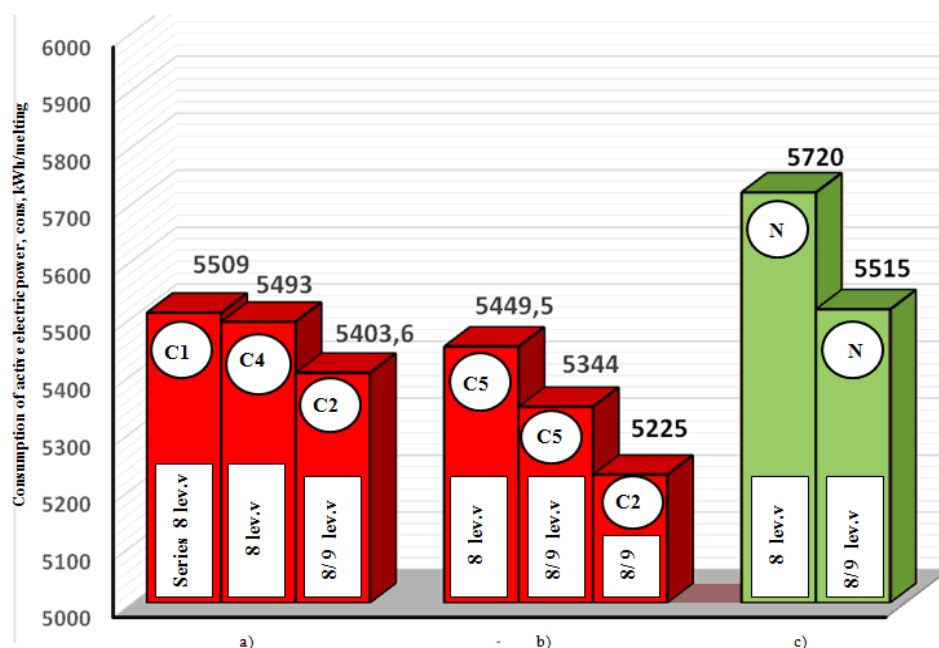


Fig. 5. Specific consumption of active electric power (kWh/melt) at 8 and 9 of voltage, where: a) cored electrodes C2 (V series), C1 and C4 (IV series) (composition F2); b) cored electrodes C5 (IV series) and C2 (composition F3); c) nipples (serial mode)

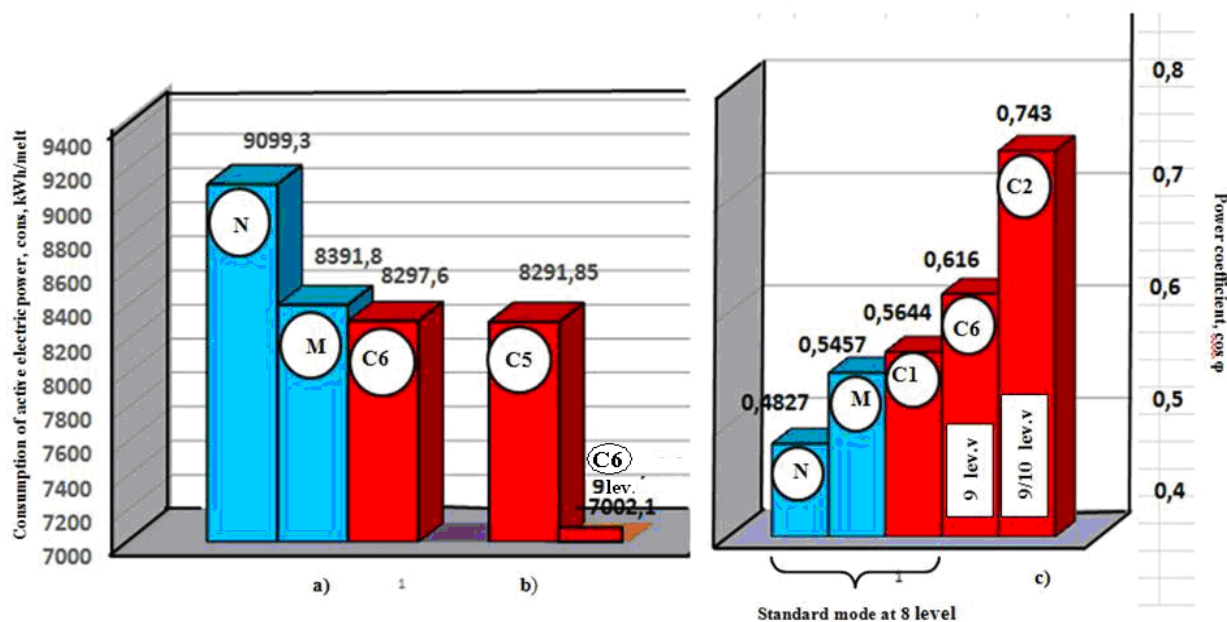


Fig. 6. Comparative values for reduction of reactive electric power and increase in $\cos \varphi$, where: a) nipple №5 (N), monolithic electrodes (M) (melting 3485...3487) and cored electrode C6 (melting 3732...3735); b) standard mode, C5 and experimental mode № 8 at 9 level, C6; c) $\cos \varphi$ at the standard mode 8 level; at the experimental mode on 9 level; at the experimental mode on 9/10 level

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 with the cored electrodes, a stable operation of furnace at the lower voltages of the furnace transformer became (Figure 5). This Figure shows that melting with the electrode C2 on the long arc and 9 level provided saving of electric power by 2...4% as compared to the operation on the long arc at the 8 level (Figures 5a and 5b) (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 5c).

It is important to note that operation of furnace on the long arcs provided also the highest productivity determined by melting time in average 2.11 h both at 8 and 9 voltage level without loss of the metal temperature at 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 stable operation of furnaces and saving the electric power by 2.5% also at 10 level. These data clearly indicate a high arc stability of the cored electrodes and the experimental electric modes, which is due to the effective operation of the components of the core. 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% saving of the active electric power and an increase in the furnace efficiency by 7.5%.

The cored electrodes provide 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 6a). The consumption of reactive electric power reduced even more when using cored electrodes at a low voltage of the transformer (9 level) and the long arc as compared to the cored electrode at the standard mode (Figure 6b). And as compared to the nipples at the standard mode this value is reduced by 23%.

The cored electrodes cause also increase in the power factor ($\cos \varphi$), Figure 6c. From Figure 6c it follows that $\cos \varphi$ grows from 0.4827 (8 level) in melting with the nipples at

standard mode to 0.743 in melting with the cored electrodes at the experimental mode at the 9/10 level.

To understand the facts of saving the active power and reduction in reactive power losses, let us consider the volt-ampere characteristics (VAC) of arcs of monolithic and cored electrodes, Figure 7. These 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 using monolithic and cored graphitized electrodes with the initial diameter of 350 mm. In the installation the models with the electrodes of 50 mm diameter the mentioned current corresponds to the current of 345...350 A. As is seen in Figure 7, using 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 monolithic electrode (62 V). Such reduction in voltage is provided due to the presence of substances in the core material with a low electron work function. Also, this fact explains the stable work of the cored electrode at low voltages of the source (9 and 10 level), as far as the emitter current occurs (I_{em}). In Fig. 1, I_{em} amounts to about 400 A. One of the consequences of presence of such substances is a significant reduction in voltage drop at the cathode spot.

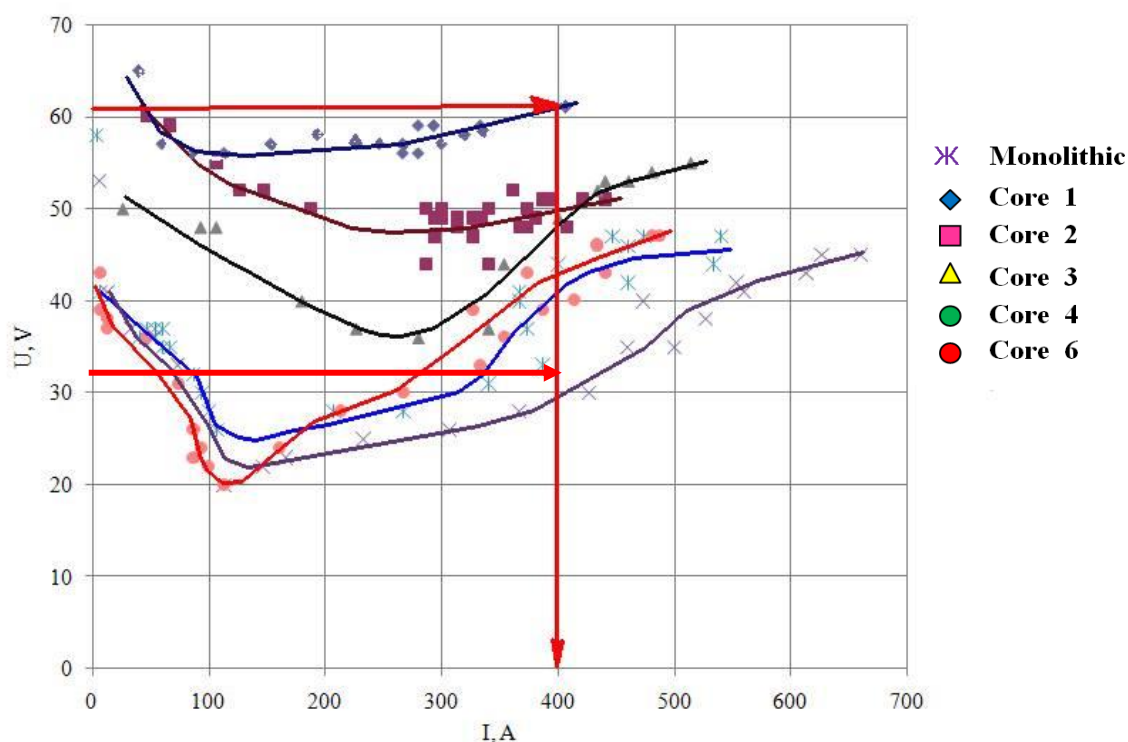


Fig. 7. VAC of arc monolithic and cored electrodes dia. 50 mm (long arc 15 mm). Anode – copper

The drop of voltage at the cathode spot and other areas of the arc was determined by measuring the potential at the end of the probe moved along the arc length. Basing on these data, the quantitative analysis of arc parameters (see Table 1) was carried out. The measurements were carried out on the arc length of 15 mm.

Table 1. Electric parameters of arcs at 15 mm length

Value	Monolith		Core C3		Core C4		Core C5	
		% от P _Д		% от P _Д		% от P _Д		% от P _Д
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 _c , 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 _c , 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

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

The situation over the reactive power is somewhat different. At the first sight the fact of such high values of reactive power (comparable with the active power) in the electric circuit of rectified current looks very strange. At the same time it is known that in the circuits containing energy accumulators (throttle, capacitor) and a non-linear element, the self-oscillations or so-called deterministic chaos can occur [19]. Such a circuit element in EAF DC is the electric arc possessing the properties of non-linear active (non-reactive) energy accumulator.

Below the oscillograms of voltage (upper window) and current (lower window) are given, which were recorded in the industrial EAF DC-12 for monolithic and cored electrodes at the standard modes (Figures 8, 9).

As is seen, the amplitude of pulsations of both current and voltage (especially voltage) is substantially higher than in the case of monolithic electrode, up to the repolarization of voltage. Here the range of oscillations of voltage at the arc amounted to +50...-350 V and the oscillations of voltage drop at the shunt amounted to 45...58 mV, which corresponds to the current oscillations in the range of 18.8 kA. For the case of cored electrode (Figure 9) these values amounted, respectively, to -10...-350 V and 14.9...17.8 kA. Thus, the range of voltage and current oscillations 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 additives of the core on the level of pulsation of electric arc parameters it is necessary to return to VAC 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 computer mathematics 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 10.

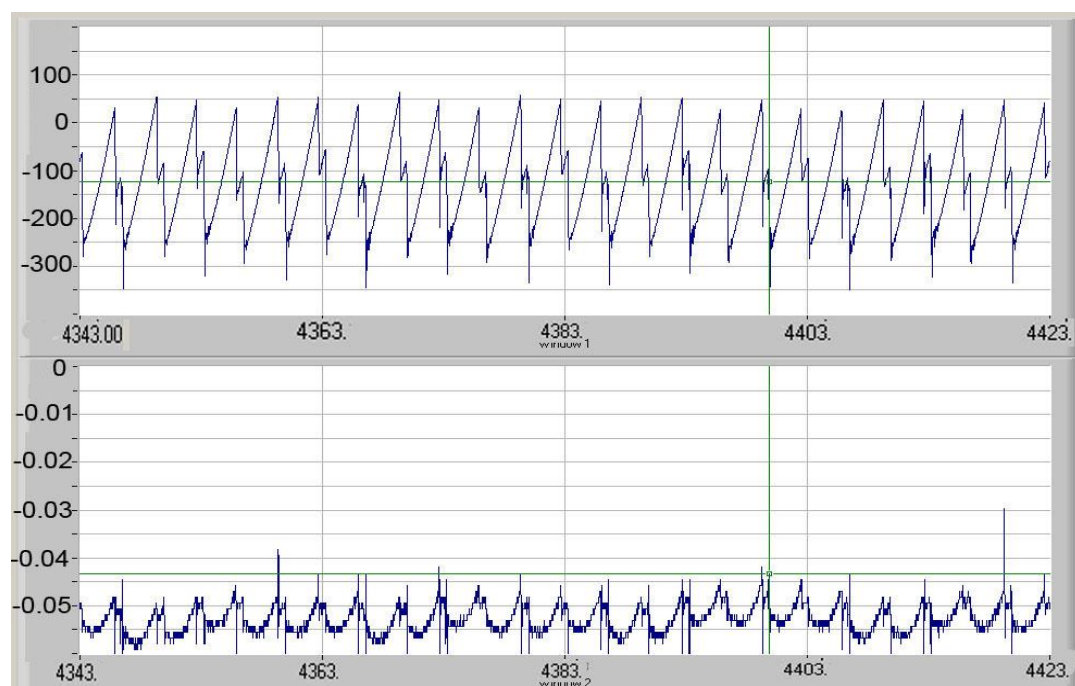


Fig. 8. Oscillogram of melting No. 3739. Monolithic electrode. Level 8. Standard mode (record 03.06.2014 13:58)

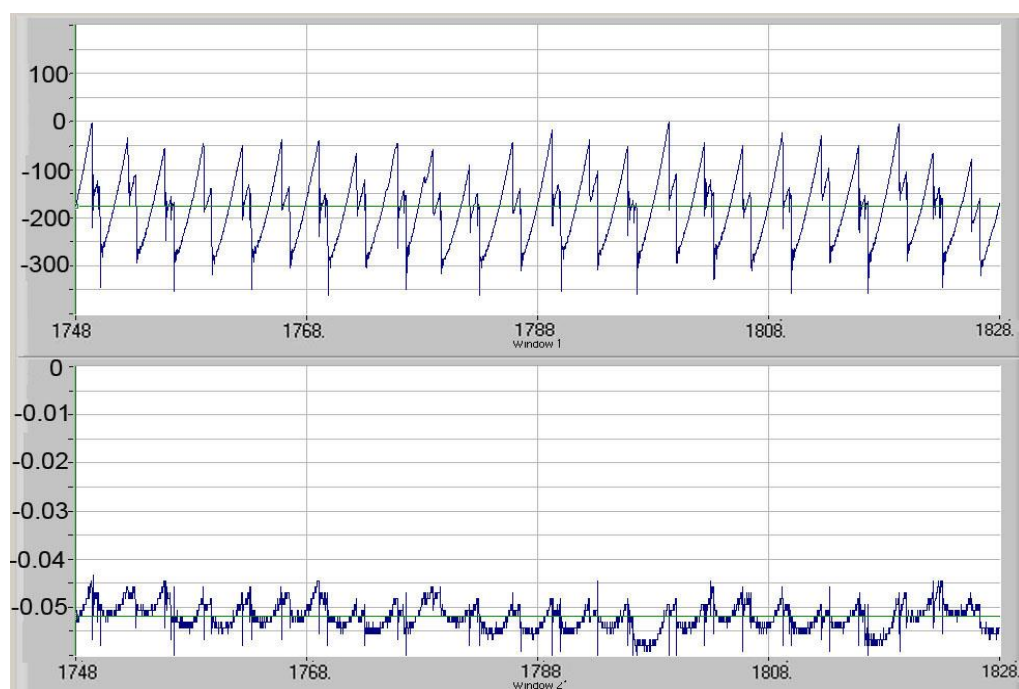


Fig. 9. Oscillogram of melting No. 3678. Cored electrode. Level 8. Standard mode

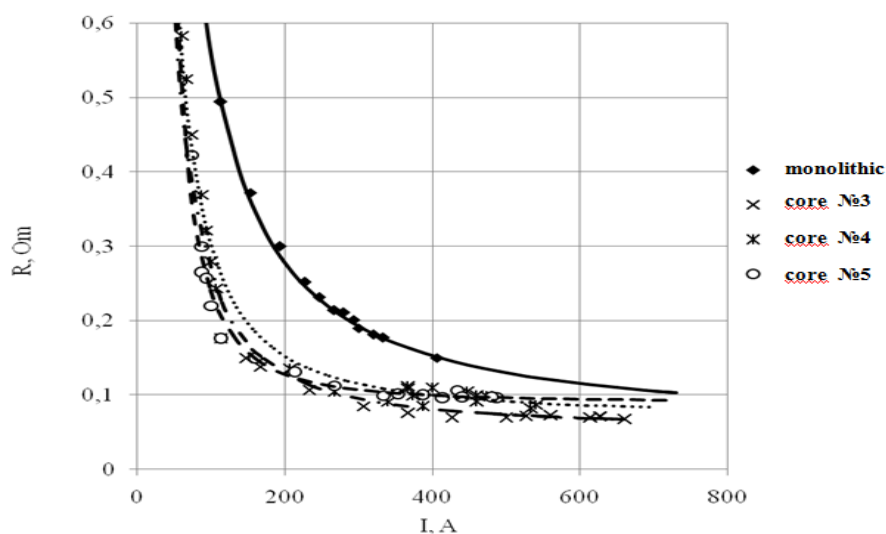


Fig. 10. Dependence of arc resistance on current ($R=f(I)$) for monolithic and cored electrodes

As was noted above, the currents of 345...350 A correspond to the range of rated currents of melting in the industrial furnace EAF DC-12 under the model conditions with the electrodes of 50 mm diameter. Table 2 shows some results of mathematical processing of oscillograms of arcs at the model electrodes.

The indicator of nonlinearity of VAC for the preset value of current is a tilt angle of the tangent to the curve of 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 VAC is characterized by a constancy of resistance, i.e. horizontal line of dependence of resistance on current.

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	$R(I)=128.56 \cdot I^{-1.2}+0.056$	$dR/dI= -154.274 \cdot I^{-2.2}$	$-3.903 \cdot 10^{-4}$
Core 3	$R(I)=208.52 \cdot I^{-1.5}+0.055$	$dR/dI= -312.777 \cdot I^{-2.5}$	$-1.365 \cdot 10^{-4}$
Core 4	$R(I)=230.52 \cdot I^{-1.5}+0.071$	$dR/dI= -345.783 \cdot I^{-2.5}$	$-1.509 \cdot 10^{-4}$
Core 5	$R(I)=1512.84 \cdot I^{-2}+0.090$	$dR/dI= -3025.671 \cdot I^{-3}$	$-0.706 \cdot 10^{-4}$

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 VAC from linear dependence and as is seen from the given data, in cored electrodes this value is close to zero unlike in a monolithic electrode. In other words, the closer VAC of the arc to the linear dependence in the operating current range, the lower is the pulsation of current and voltage, causing decrease in reactive power losses during operation with the cored electrodes. Here the phenomenon of autooscillations in the electric circuit 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 waste of 30% FeSiMn, i.e. a relatively simple and homogeneous, tiny 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, as well as ferrovanadium with the content of vanadium at the level of 50%. 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 work of cored electrodes 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 of a product with the maximum possible content of Ni and Mo;
- Stage 3. Obtaining of 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 monolithic (M) and cored electrodes (C) are presented in Fig. 11, 12 and 13, respectively. The arrows show the comparing indicators.

First of all, these data indicate, that cored electrodes at all stages of remelting the catalyst and its products have advantages as compared to monolithic electrodes. The data given in Fig. 11 show the following. The efficiency of the furnace during remelting of a catalyst is increased by 21.3...25.6%. An increase in the output of the metallic phase (decrease in the burning loss of Ni, Mo, Fe) amounted to 1...9% and 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 compositions F11.

During remelting of the metallic phase (ingots), the following indicators are provided (Figure 12). The efficiency of the furnace is increased to 9.6...10.8%; the output of the metallic phase is increased by 1.9...10.3% and the power consumption is 1.3...2.8% on the cored electrodes.

During melting of ferrovanadium with the use of the core Fe12, the efficiency of the furnace is also increased with the use of the core electrodes by 4.2%; a decrease in the burning loss of vanadium is provided to 17.4% during melting of 40...50% ferrovanadium. The power saving amounted to 7.1% (Fig. 13).

In the process of experimental melts in the EAD DC-12 furnace it was also found that an essential advantage of cored electrodes is the fact that during their use, the spread of melting time is 2...2.5 times reduced, i.e. a high stability of electrical conditions and furnace efficiency, a stability of heating conditions of the furnace, 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 (Figure 3), 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 cored electrodes, should provide the effective melting of a large-sized charge. Secondly, the edges of the hemisphere reliably shield a large part of the arc, protecting the lining of the walls and the furnace roof from overheating. 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.

The work on the cored arc also determines a 10...12% reduction in the noise level during the operation of EAF DC.

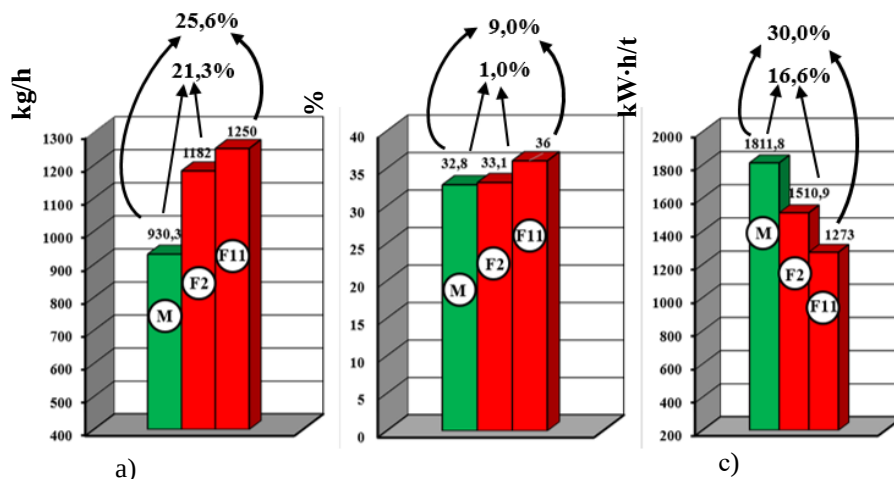


Fig. 11. Stage 1. Output rate (kg/h) of the furnace (a), output of a metal phase (reduction in burning loss, Fe, Ni, Mo), % (b) and electric power consumption (kW·h/t) (c) during remelting of the catalyst with the use of monolithic (M) and cored (F2 and F11) electrodes

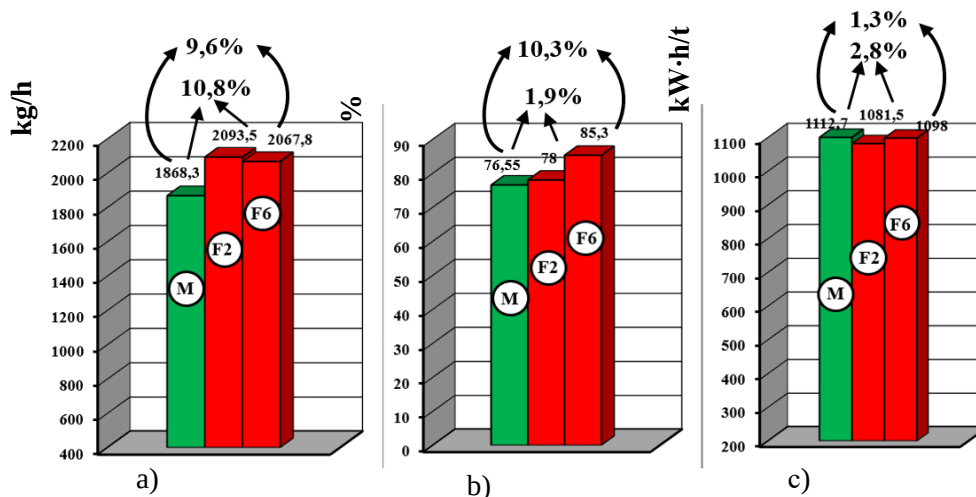


Fig. 12. Stage 2. Designations are the same as in Fig. 11. Remelting of a metal phase (ingots) with the use of monolithic (M) and cored (F2 and F6) electrodes

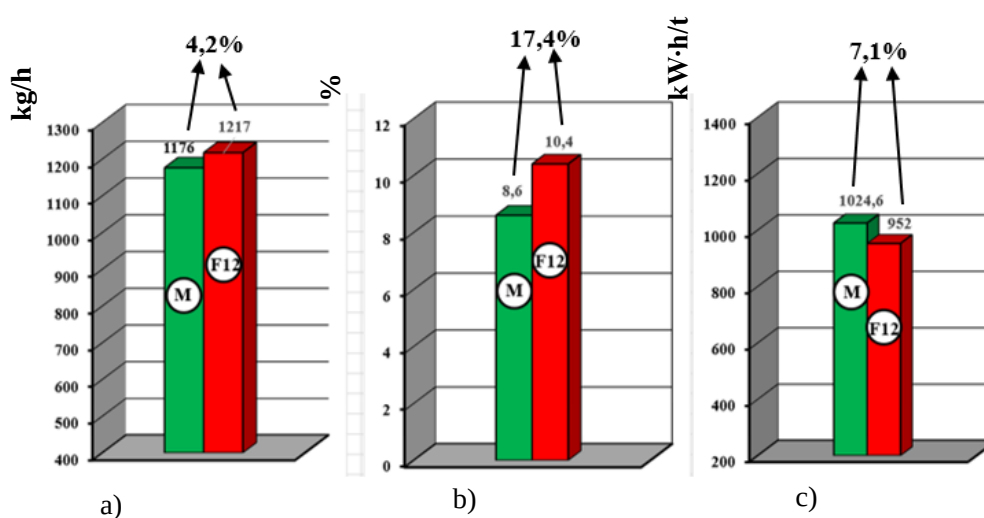


Fig. 13. Stage 3. Designations are the same as in Fig. 11. Melting of ferrovanadium using monolithic (M) and cored (F12) electrodes

CONCLUSIONS

- It is shown that the world metallurgical industry is characterized by a continuous growth in steel production. More than 30% of steel from the world steel production is melted in arc furnaces of direct (EAF AC) and alternating current (EAF DC).
- The effective means of improving the technical and economic indicators of EAF DC is the use of cored graphitized electrodes, designed at the E.O. Paton Electric Welding Institute of the NAS of Ukraine. Such electrodes are composed of components with a low electron work function, which creates favorable thermodynamic conditions for ionization of gases in the arc column in the near cathode area.
- It was found that at equal voltages, the arc current of the cored electrode is approximately by 1.8 times higher than the arc current of the monolithic electrode.
- It was established 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 the low voltages of the power source.
- It was shown 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.
- The amplitude of oscillations of arc voltage and current of the cored electrode is on average by 15% and 31% lower, respectively, as compared to the monolithic electrode.
- In accordance with the features and parameters of the arc of cored electrodes, during remelting of FeSiMn waste in the industrial EAF DC, the following parameters are provided:
 - stable electric conditions in a wide range of changes of electric parameters and arc lengths;
 - up to 8.35% saving of active electric power;
 - reduction in reactive power to 23%;
 - increase in $\cos \varphi$ from 0.4827 to 0.743;
 - increase in the furnace efficiency by 7.5%;
 - decrease in melts time scattering by 2...2.5 times;
 - reduction in noise level by 10...12%.
- During remelting of the catalyst (product of oil refining) and its derivatives, the cored electrodes provide the following indicators:
 - increase in furnace efficiency by up to 25.6%;
 - increase in the output of a metal phase (reduction in burning loss of Ni, Mo) by 10.3% during remelting of ingots;
 - reduction in burning loss of vanadium by 17.4% during remelting of ferrovanadium;
 - reduction in specific electric power consumption by up to 30%.
- A decrease in the noise level of the operating furnace by 10...12%.
- The results of using graphitized cored electrodes in the electric arc furnace (EAF DC) mentioned in the article have fully substantiated the start of works on using cored electrodes in electric arc furnaces of alternating current (EAF).

ACKNOWLEDGEMENT

Authors would like to thank to E.O.Paton Electric Welding Institute of the NASU, PJSC "Ferros" for supporting this work.

Conflicts of Interest

The authors declare that they have no competing financial interests or personal relationships that could have seem to influence the study reported in this paper.

REFERENCES

1. D.A. Dyudkin, V.V. Kisilenko, Production of steel, vol. 1. "Teplotekhnika", Moscow, 2008.
2. "Steeltime" - informational portal of ferrous and nonferrous metallurgy, May 2013.
3. A.G. Belkovsky, Ya.L. Kats, M.V. Krisnyansky: State-of-art and trends of development of technology of steel production in EAF and their designs (OJSC "VNIIMETMASH") UDK 669.187.2. Steelmaking production, newsletter "Black Metallurgy», 3(2013) 73-75.
4. Bogachenko A.G., Mischenko D.D., Braginets V.I., Galinich V.I., Neylo I.A.: Cored graphitized electrodes. Electric arc furnaces of direct current (EAF DC). Saving of electric power. Proc. Medovar Mevorial Symposium Kyiv, Ukraine, 2016 p.185-193.
5. Boom R.: Breakthrough development in ironmaking and steelmaking: collaboration or competition.Proc.2nd International Conference «Advanced in Metallurgical Processes and Materials». Kyiv, Ukraine, 2015 p.73-77.
6. D.A. Dyudkin, S.Yu. Bat et.al. Production of steel in the ladle. – furnace unit. LLC "Yugo-Vostok", Donetsk, 2003.
7. M. Ramires, I. Alexis, G. Trapage et al. : Stirring of melt in the arc furnace at direct current. News of ferrous metallurgy abroad, 3(2002) 54-57.
8. Classification of modern arc furnaces. Arc furnaces at alternating and direct current. The Ukrainian Association of Steelmakers. Informational portal. April 2015.
9. A. Savitsky: About the choice of rational design of EAF at direct current. Elektrometallurgia, 8(2000) 13-19
10. V.M. Soyfer: Response to the article of A.V. Rechkalov, I.Yu. Zinurov, M.G. Kuzmin et al. "The basic requirements to arc furnaces producing metal for production of castings" Elektrometallurgia, 12(2014) 9-12.
11. D.G. Egansky: Trends in the development of electric steel production. Elektrometallurgia, 5(2001) 3-18.
12. B.P. Platonov, O.I. Kotelnikov et al.: Investigation of dust and gas emissions of arc furnaces at direct and alternating current. Foundry production, 1(1996) 24-27.
13. A.M. Volodin, A.S. Bogdanovsky, V.S. Malinovsky: The results of operation of furnace at direct current EAF DC-20 vocational AT the JSC "Tyazhpessmash. Foundry production 9(2004) 31-35.
14. A.N. Makarov, M.B. Shimko, V.V. Ostriuk: Analysis of basic technical and economic indicators of operation of arc furnaces at direct and alternating current. Elektrometallurgia, 3(2004) 5-9.
15. A.F. Milyaev, S.V. Kadnikov: Selection of type and capacity of aggregates for melting pig iron and steel in the foundry shops. Elektrometallurgia 11 (2002) 21-24.
16. N.V. Okorokov, L.E. Nikolsky, A.V. Egorov.: Influence of tubular electrodes on thermal operation of arc electric steel furnace. News of higher educational institutions. Ferrous metallurgy, 9(1962) 105-110.

17. B.E. Paton, V.I. Lakomsky et al.: Cored electrodes of electric arc furnaces. *Ferrous metals*, 5(2011) 13-15.
18. E.A. Kazachkov, A.D. Chepurnoy: Ways of improvement of productivity of electric arc furnaces. *Newsletter of Pryazovskyi State Technical University*. 15 (2005) 1-5.
19. V.N. Sidorets, I.V. Pentegov, *Deterministic chaos in nonlinear circuits with electric arc*. International Association "Welding", Kyiv, 2013.