Algorithms and features of diagnosing of electric furnaces electrodes based on electrical technologies

A V Myatezh¹, M V Grechneva², K Yu Zhigalov³

¹Novosibirsk State Technical University, 20, Karla Marksa Av., Novosibirsk, 630073, Russia
²Irkutsk National Research Technical University, 83, Lermontov str., Irkutsk, Russia, 664074
³V.A. Trapeznikov Institute of Control Sciences of Russian Academy of Sciences, 65 Profsoyuznaya street, Moscow 117997, Russia

E-mail: mbv5@mail.ru;

Abstract. The paper highlights methods of nondestructive testing and their use to diagnose solid media of graphite electrodes applied in steel furnaces for identification of different defects. The main focus of the paper is to consider the methods of eddy-current testing of graphite electrodes. Besides, it presents the possibility of increasing the sensitivity of the method and localization of the place of potential damage. The practical importance of the paper includes simulation modelling of electromagnetic processes with further description of detailed results and conclusions.

1. Introduction
Nondestructive testing of product quality and integrity is quite popular these days, nevertheless is it not sufficiently studied and applied. At the same time, there are various methods of nondestructive testing of materials. The following methods seems the most suitable to solve the research objective of integrity of materials that do not conduct electric current:

• acoustic diagnostics [1, 2, 5];
• radiation diagnostics [3];
• infrared diagnostics [1-3];
• radio-wave diagnostics [1, 2, 4];
• electron-optical (partial discharges) diagnostics [1, 2];
• liquid-penetrant testing [1];
• etc.

The following may also be used to study the materials that conduct current:

• magnetic diagnostics [1-3];
• eddy-current testing [1-3];
• electrospark diagnostics [1-3];
• thermoelectric testing [1-3].

Graphite used as an electrode in arc steel furnaces is a substance with high conductivity, which is almost 400 times lower compared to copper.
At present, ultrasonic (acoustic) testing is generally used to control the quality of electrodes in arc steel furnaces.

The disadvantage of this method is high attenuation coefficient of acoustic waves in graphite, which makes its application for electrodes quite complicated, especially if their diameter exceeds 1 meter. Besides, piezoacoustic sensors of the device are characterized by excessive wear.

When choosing the method of defectoscopy there is a need to consider the main properties of the test item. Graphite conducts electric current quite well, at the same time it is not transparent and has sufficient to control frequency and duration of acoustic resonance. Hence, it is suggested using eddy-current testing.

2. Theory

The eddy-current testing implies change of the penetration depth due to change of the test current frequency according to the following expression:

$$\delta = \sqrt{\frac{1}{\pi \cdot f \cdot \mu \cdot \sigma}},$$  \hspace{1cm} (1)

where,  
- $\delta$ – current penetration depth, m;
- $f$ – current frequency, Hz;
- $\mu = \mu_0 \cdot \mu_r$ – magnetic permeability, H/m;
- $\sigma$ – electric conductivity, S.m.

The study shows that in order for electric current to penetrate into graphite by 0.5 m, the frequency shall make 8 Hz.

If the material has voids or foreign nonconducting impurities in the test item at some depth, the equivalent conductivity of this area will change in proportion to the relation:

$$k_s = \frac{S - S_0}{S},$$  \hspace{1cm} (2)

where,  
- $S = \pi \cdot (D \cdot \delta - \delta^2)$ - cross-sectional area of graphite electrode conducting principal current;
- $D$ – external diameter of an electrode;
- $S_0$ – cross-sectional area of foreign impurities.

The formula (2) shows that if the defect is located close to the center of an electrode when $\delta \to D / 2$, the gain of conductivity with the reduction of current frequency will not be too different from similar gain of conductivity of the electrode without the corresponding defect.

The overall coefficient considering the influence on electric conductivity of graphite electrode and the length of defect along the electrode axis will be as follows:

$$k = \frac{\sigma_u}{\sigma_0} = \frac{k_s \cdot l + 1 \cdot (L - l)}{L} = \frac{L - (1 - k_s) \cdot l}{L},$$  \hspace{1cm} (3)

where,  
- $\sigma_u$ – equivalent electric conductivity of graphite electrode with defect;
- $\sigma_0$ – electric conductivity of graphite electrode;
- $L$ – length of graphite electrode;
- $l$ – length of defect along the axis of a graphite rod.

Thus, the defect as a nonconducting void of a cubic form with size $d = 0.1 \cdot D$ located in maximum proximity to graphite surface with the length $L = 3 \cdot D$ will change its resulting conductivity through eddy-current testing only by 0.11%:

$$k_s = \frac{\pi \cdot 0.09 \cdot D^2 - 0.01 \cdot D^2}{\pi \cdot 0.09 \cdot D^2} = 0.9646, \quad k = \frac{3 - (1 - 0.9646) \cdot 0.1}{3} = 0.99882.$$
The use of lengths of defective and unaffected areas of a rod as weight coefficients in the formula is quite reasonable since the distribution of currents before and after defect is almost leveled.

The prevention of lateral in relation to the defect redis redistribution of currents limited to a cylinder with internal diameter $D - 2 \cdot d$ and external diameter $D$ will may change electric conductivity according to (2).

It is known that besides the surface effect the proximity effect may also occur near conductors with opposite currents, which displaces currents to lateral surfaces. The combination of the proximity effect with eddy-current testing shall lead to displacement of current density in the section of a graphite rod by foreign conductors. This will allow using the combination of currents in metal rods located in close proximity with the studied object to define the diagnosed sector of a rod. This aspect provides for considerable increase of sensitivity of the eddy-current testing method and to legalize the place of defect in a graphite.

3. **Experiment**

In order to localize the place of internal damage and to strengthen the influence of a defect on electric conductivity of a graphite electrode 6 metal rods with small section separated from each other by angle $\pi/3$ were placed around it. The current in each N rod changes according to sine function with changing frequency $f$ and phase $\varphi_N$:

$$I_N = I_m \cdot \sin(2 \cdot \pi \cdot f \cdot t + \varphi_N).$$

(4)

The electric conductivity of a graphite electrode was measured at various current frequencies and combination of currents in metal rods setting desirable displacement of current in a graphite rod.

The proximity effect created by metal rods distorts the distribution of current density to the sector in cross section of a rod. Fig. 1 shows the distribution of current density in cross section of a graphite rod with defect at a frequency of 8 Hz.

![Figure 1. Distribution of current density in cross section of an electrode at a frequency of 8 Hz: a) vertical distribution of current density of; b) horizontal distribution of current density. 1 – Graphite rod. 2 – Place of defect. 3 – Metal rod for current displacement](image-url)
It is shown that by controlling the distribution of current in an electrode it is possible to direct electric current towards the required trajectory so that it crosses all areas of a graphite electrode one by one thus ensuring scanning.

The study revealed that the resistance of a graphite electrode equals 27.07 microohms if the current density is distributed vertically as it is shown in Fig. 1 (on the right) and corresponds to diagram on Fig. 2 (on the right). In case of horizontal distribution of current density (Fig. 1, b) and other equal conditions the resistance of an electrode will make 25.27 microohms. Thus, in case of the joint use of the eddy-current testing with the proximity effect at a frequency of 8 Hz taking into account (3) the change of active resistance or electric conductivity by $\frac{3 - (1 - 0.9335) \cdot 0.1}{3} = 0.99778$ times or by 0.22% is reached by the results of modeling.

Similarly, Fig. 2 shows the distribution of current density in cross section of a graphite rod with a defect at a frequency of 80 Hz.

The calculations showed that the resistance of a graphite electrode is equal 13.31 microohms if the current density is distributed vertically as it is shown in Fig. 2a. In case of horizontal distribution of current density (Fig. 4) and other equal conditions the resistance of an electrode will make 5.88 microohms. Thus, in case of the joint use of the eddy-current testing with the proximity effect at a frequency of 80 Hz the change of active resistance or electric conductivity by $\frac{3 - (1 - 0.4418) \cdot 0.1}{3} = 0.981$ times or by 1.86% is received.

4. Conclusions
Nondestructive testing is quite critical for some items. At present, besides traditional ultrasonic testing the eddy-current testing seems quite promising to control the quality of graphite rods. Their efficiency can be significantly increased due to parallel use of the proximity effect. Thus, it is possible to detect
defects and various impurities up to several percent in size of the linear size of an electrode. In comparison with currently used ultrasonic testing the application of the proposed method may considerably improve the quality control of graphite electrodes.

References
[1] Malozyomov B V, Babaeva O V, and Andreev A I 2014 Posteriori analysis of the reliability of transport systems. Scientific problems of transport in Siberia and the Far East. 1-2 93-95
[2] Malozyomov B V, Wilberger M E, and Kulekina A V 2015 The most typical damage and methods of diagnosing the traction motor. Transport: science, technology, management. 10 60-65
[3] Vorfolomeev G N, Evdokimov S A, Malozyomov B V, Schurov N I, and Shalnev V O 2004 Reliable sources of a feed of the direct current. In the collection: 8th Korea-Russia International Symposium on Science and Technology Proceedings: KORUS 2004. sponsors: Tomsk Polytechnic University, University of Ulsan, Novosibirsk State Technical University 316-320
[4] Daimer J 2005 Graphite electrode for electrothermal reduction furnaces, electrode column and method for making graphite electrodes. Patent for invention RUS 2374342 12.05
[5] Shabalina A V, Lapin I N, and Belova K A 2015 Graphite electrodes for electric arc furnaces. Black metals. 12 (1008) 20-21
[6] Nikolaev A A, Nikolaev A V, Kirpichev D E, and Tsvetkov Yu V 2008 Formation of a diffuse cathode spot on a graphite electrode with an arc discharge. Physics and chemistry of material processing 43-48
[7] Shchurov N I, Porsev E G, and Vil'berger M E 2009 Asymmetrical and nonsinusoidal operation modes of multipulse rectifiers. Russian Electrical Engineering. 80(12) 680-684
[8] Borisenkov S, Votintsev A, and Roth H 2003 Quality control: non-destructive testing of brazed joints using X-ray radiation. Components and technologies. 28 168-170
[9] Grosse K U 2012 Non-destructive testing and technology for monitoring the technical condition of structures for quality control and supervision of construction sites. ALITinform: Cement. Concrete. Dry mixes. 6 62-77
[10] I Yu Loshkarev, and A S Chernyshov 2013 Unbrakable control. Features of methods of nondestructive testing. In the collection: Actual problems of power engineering of agrarian and industrial complex Materials of IV International scientific and practical conference. Edited by A.V. Pavlova. 184-186
[11] Nazarov M N, Palaev A G 2017 Diagnostics and repair of centrifugal oil transfer pump rotor shaft. IOP Conference Series: Earth and Environmental Science 87 092016