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Non-destructive control of graphite electrodes with use of current displacement effect

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Abstract. The work is devoted to methods of nondestructive diagnostics and their use for solving the problem of diagnosing various defects in solid surface of graphite electrodes used in steelmaking furnaces. Various non-destructive control methods of materials are analyzed. In the article, methods of eddy-current defectoscopy of graphite electrodes are considered. Rationalization of the sensitivity increase of the method and localization of damage is described. Imitating modeling of electromagnetic processes was executed; results were made and conclusions were drawn.

1. Introduction

The problem of nondestructive quality control and integrity of graphite products is opened now. There are various methods of defectoscopy of materials. According to them, nonconducting electric current of materials is suitable for the researching of integrity: acoustic, radiation, infrared, radio wave, electron-optical (partial discharges), capillary defectoscopy, etc. For researching the current-conducting materials, magnetic [1], eddy-current [2], electrospark [3] and thermoelectric defectoscopy [4] can also be used.

The graphite, which is used as electrodes [5] in arc steel-smelting furnaces, is the substance having high conductivity, about $0.125 MS \cdot m$, but about 400 times smaller than that of copper.

Now ultrasonic (acoustic) defectoscopy is often used for quality control of electrodes of arc steel-smelting furnaces (figure 1) [6].

The disadvantage of the ultrasonic method is the high coefficient of attenuation of acoustic waves in the material, which is strongly complicating its application to electrodes, which diameter exceeds 1 meter, as well as increased wear of piezo-acoustic sensors of the control element [7].

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Figure 1. Electrodes for arc steel smelting furnaces.

In case of a choice of a method of defectoscopy, it is necessary to take the most characteristic properties of a controlled product into account [8]. Without having transparency for diagnostics of clearance and hardness for monitoring by frequency and duration of acoustic resonance, graphite conducts electric current well enough, which caused a choice of the offered eddy-current method [9].

2. Theory

Initially, the eddy-current method assumes a change in a penetration depth by a variation of frequency of test current according to expression [10]:

$$\delta = \sqrt{\frac{1}{\pi \cdot f \cdot \mu \cdot \sigma}}, \tag{1}$$

where δ - depth of current penetration, m;

f - current frequency, Hz;

$\mu = \mu_0 \cdot \mu_r$ - magnetic conductivity, H / m;

σ - electric conductance, S·m.

For electric current penetration into graphite by 0.5 m, characterizing current attenuation at specified depth of a current density of 2.71 times, the frequency of 8 Hz is required.

In presence of cavities or foreign nonconducting particulates in the sample of a product at some depth, the equivalent conductivity of this section will change proportionally to the relation:

$$k_S = \frac{S - S_0}{S}, \tag{2}$$

where $S = \pi \cdot (D \cdot \delta - \delta^2)$ - cross-sectional area of the graphite electrode, streamlined by the main current;

D - outer diameter of the electrode;

S_0 - cross-sectional area of the foreign inclusion.

From (2), it is visible that in case of occurrence of defect, close to the center of the electrode when $\delta \to D/2$, the conductance increment with a reduction in the frequency of current will differ poorly from a similar increment of conductance in the electrode which does not have defects.

The general coefficient, considering the influence on electric conductivity of a graphite electrode, as well as defect lengths along an electrode axis is:

$$k = \frac{\sigma_a}{\sigma_0} = \frac{k_S \cdot l + 1 \cdot (L - l)}{L} = \frac{L - (1 - k_S) \cdot l}{L}, \tag{3}$$

where σ_a - equivalent electrical conductivity of a graphite electrode in the presence of a defect;

σ_0 - electric conductivity of a graphite electrode;

L - length of a graphite electrode;

l - defect length along the axis of a graphite core.

So, for example, the defect in the form of a nonconducting cavity of a cubic form with size $d = 0.1 \cdot D$, located in the maximum proximity to a surface of graphite item with the length of $L = 3 \cdot D$, will change its resultant conductivity for diagnosis by the eddy-current method when $\delta = d$ only for 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 distribution of currents before and after defect is practically leveled. The application of lengths in the formula as weight coefficients of defective l and not struck sites of $L - l$ is reasonably true.

Prevention of redistribution of the currents, in relation to defect, limited to the cylinder with internal diameter $D - 2 \cdot d$ and external diameter D, will be able to strengthen the change of electric conductivity according to (2).

It is known that along with “skin-effect”, when arranged next to conductors with opposite directed currents, the effect of proximity takes place according to which the replacement of currents is on side surfaces. The use of this phenomenon in combination with the eddy-current method assumes current density shift in the section of graphite core third-party conductors with current. Thus, there is an opportunity of a special combination of currents in the metal cores located in close proximity with the studied object to define the diagnosed core sector that considerably increases sensitivity of an eddy-current method, as well as allows one to localize the defect place in graphite.

3. Experiment

For receiving a possibility of localization of the internal damage place, as well as gaining the influence of defect on electrical conductance of a graphitized electrode near it on a circle, there are 6 thin metal rods distant from each other at an angle $\pi / 3$. Current in each N-th rod changes by the function of a sine with the changing frequency f and a phase φ_N :

$$I_N = I_m \cdot \sin(2 \cdot \pi \cdot f \cdot t + \varphi_N) \qquad (4)$$

Measurements of electrical conductance of a graphitized electrode are executed with different frequencies of current in it and combinations of currents in the metal rods, setting desirable extrusion of current in the graphite rod.

Using the eddy-current method at a frequency of 8 Hz according to (1) sets the penetration depth of current of 0.5 m, and the effect of closeness, created by metal rods, distorts distribution of a current density to the sector in a transverse section of the rod. Figure 2 demonstrates distribution of a current density in a transverse section of the graphite rod with defect at a frequency of 8 Hz. Simulation is executed in a FEMM4.2. Current density distribution in a graphitized electrode depending on frequency and a phase of currents in rods is provided in fig. 2,a and fig. 2,b.

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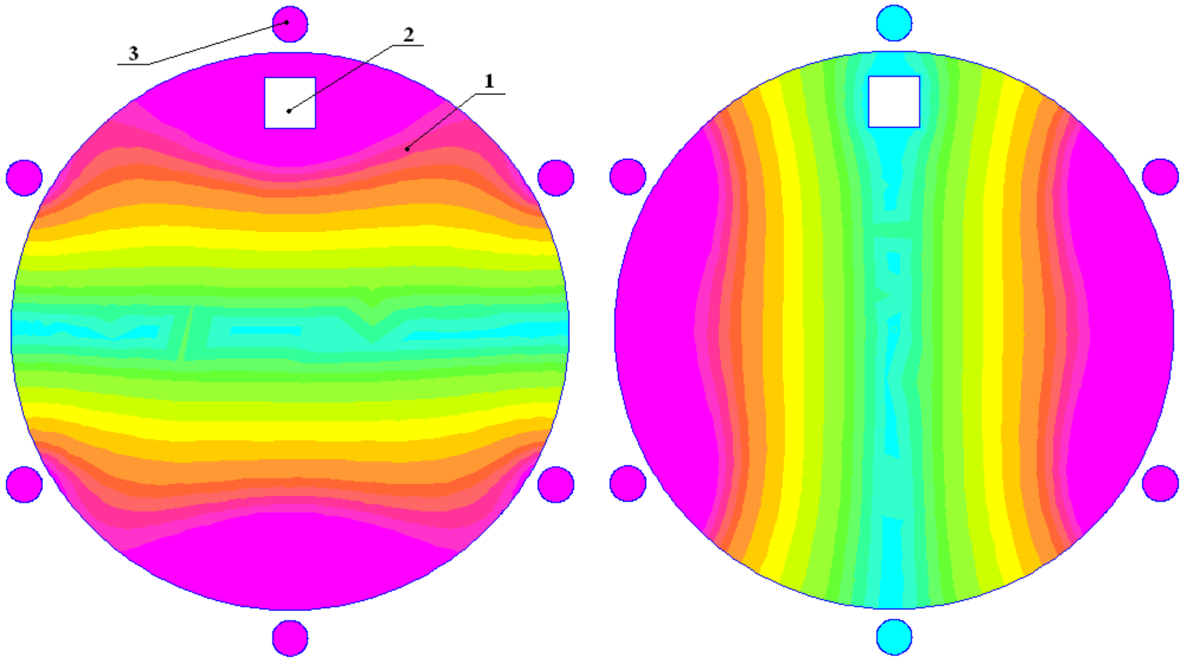

Figure 2. Current density distribution in a transverse section of an electrode with a frequency of 8 Hz: a) vertical current density distribution; b) horizontal current density distribution. 1 – graphite rod; 2 – place of defect; 3 – metal rod for current displacement.

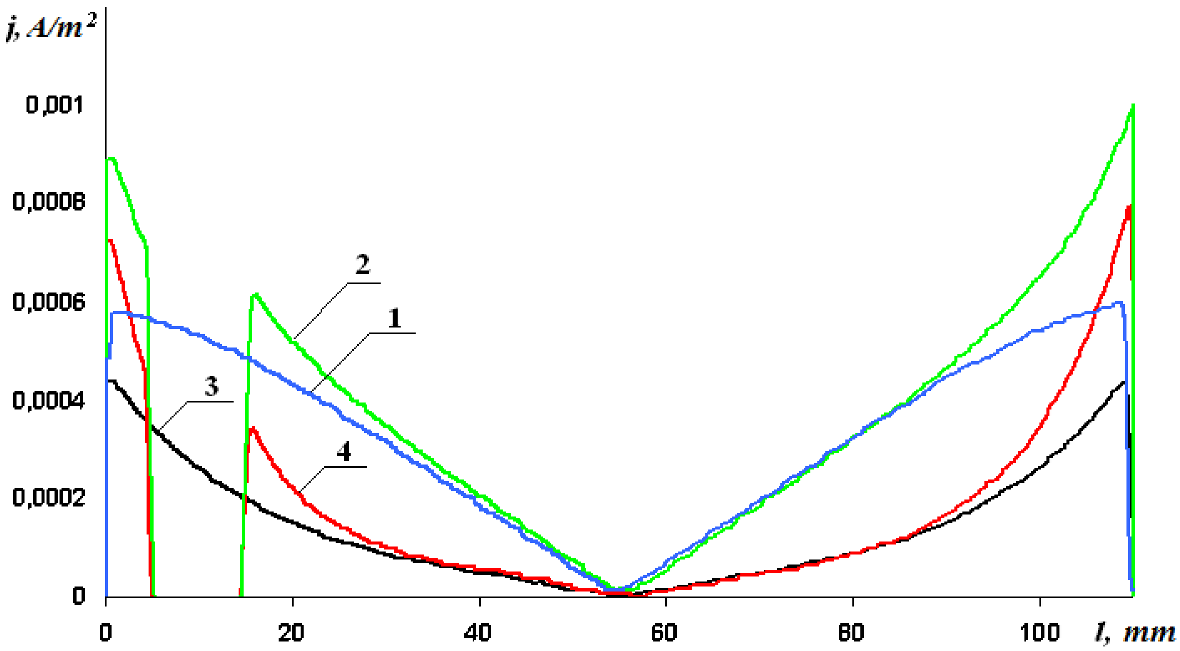

Figure 3. The diagram of current density distribution in a graphitized electrode: 1 – with a frequency of 8 Hz and horizontal current density distribution; 2 – with a frequency of 8 Hz and vertical current density distribution; 3 - with a frequency of 80 Hz and horizontal current density distribution; 4 - with a frequency of 80 Hz and vertical current density distribution.

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Operating current distribution in an electrode, it is possible to direct electric current by a desirable trajectory so that it crosses serially all areas of a graphite electrode, carrying out scanning. Comparing conductivity of a graphite core while finding the main electric current in various sectors, it is possible to localize the place of damage.

As a result of calculation, the authors came to a conclusion that resistance of a graphitized electrode is equal to 27.07 microohm if the current density was distributed vertically as it is shown in figure 2,a, and corresponds to the diagram of fig. 3. In case of horizontal current density distribution (figure 2,b) with the diagram of a current density fig. 3 and other equal conditions, electrode resistance will make up 25.27 microohm. Thus, when using the eddy-current method with the use of effect of closeness at a frequency of 8 Hz, taking into account (3), by the results of simulation, the change of the pure resistance or electrical conductance $\frac{3-(1-0.9335)\cdot 0.1}{3} = 0.99778$ times or by 0.22% is received.

Figure 4 similarly shows distribution of a current density in a transverse section of the graphite rod defect with a frequency of 80 Hz. Distribution density current in a graphitized electrode, depending on frequency and a phase of currents in rods, is shown in fig. 3.

As a result of calculation it is received that the graphitized electrode resistance is equal to 13.31 microohm if the current density was distributed vertically as it is shown in figure 4,a and corresponds to the diagram of fig. 3. In case of horizontal current density (distribution figure 4, b) with the diagram of a current density in fig. 3 and other equal conditions, the electrode resistance will make 5.88 microohm. Thus, when using the eddy-current method with use of the effect of closeness at a frequency of 80 Hz, one receives the change of the pure resistance or electrical conductance $\frac{3-(1-0.4418)\cdot 0.1}{3} = 0.981$ times or by 1.86%.

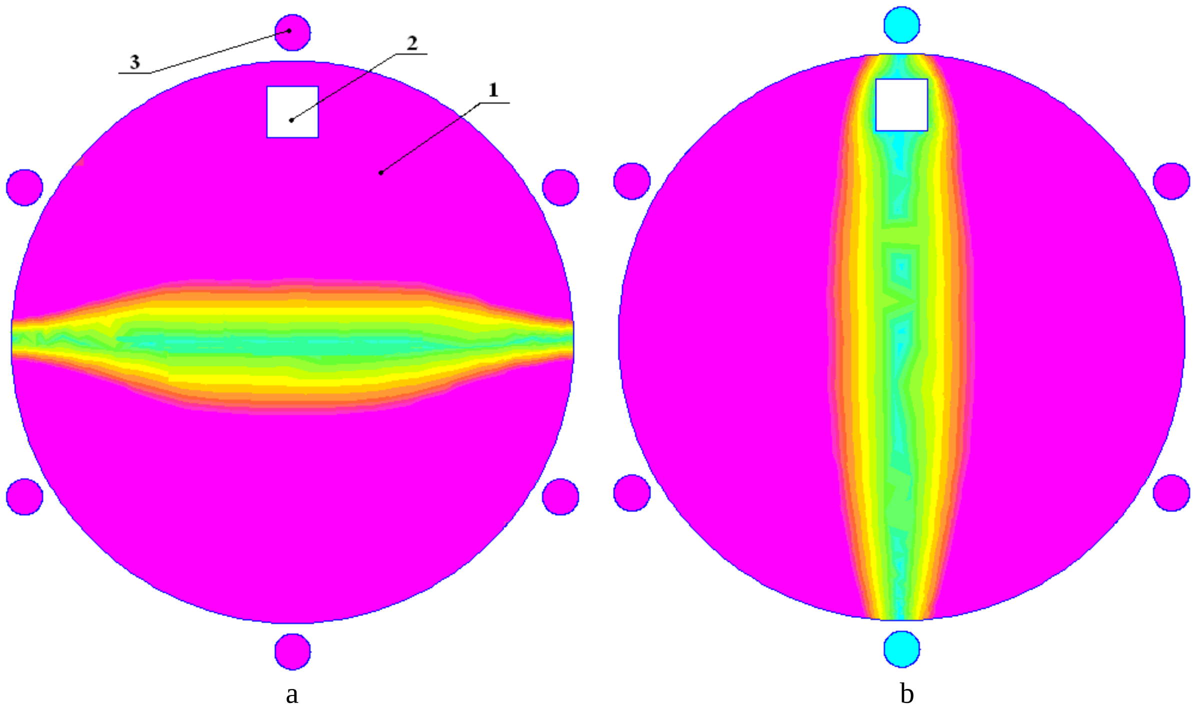

Figure 4. Current density distribution in a transverse section of an electrode with a frequency of 80 Hz: a) vertical current density distribution; b) horizontal current density distribution. 1 – graphite rod; 2 – place of defect; 3 –metal rod for current displacement

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4. Conclusions

For quality control of graphite cores, the use of the eddy-current methods has prospects (along with an ultrasonic one). An increase in sensitivity of means of registration and measurement is promoted by using the eddy-current method of the proximity effect. Thus, it is possible to detect defects and various inclusions up to several percent in size of the linear dimension of an electrode. In comparison with the method of ultrasonic diagnostics, assuming touch scanning of all surface, application of the offered method promotes acceleration of the process of quality control of graphite electrodes.

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