Acoustic and Eddy Current Methods of Nondestructive Testing of Thermally Expanded Graphite Sheets

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Abstract. The paper presents noncontact methods for testing the density of thermally expanded graphite (TEG) sheets: acoustic shadow method, based on the evaluation of the transmission coefficient of the acoustic wave in high frequency range, and eddy current method, based on the evaluation of the complex resistance of parametric surface-mounted eddy-current transducer. Results of investigation of the sensitivity curves for the sheets and mats of TEG in a wide range of their density variations. According to the results of the experiment, there is a decrease in the amplitude parameter U in the implementation of the acoustic shadow method with an increase in the density of TEG sheets. Increasing the density of TEG sheets also leads to a linear decrease in the complex resistance of eddy current transducer.

1. Introduction

The safety of pipeline transport in difficult operating conditions under the influence of high pressures, temperatures and aggressive media is determined, in particular, by the degree of tightness of its junctions. One of the new promising materials for seals is thermally expanded graphite (TEG), which is a low-density carbonaceous material that has the ability to be pressed without a binder, the resistance to aggressive media, high elastic characteristics, low thermal conductivity, wide operating temperature ranges, etc. [1–5]. The main application of TEG is found in the oil and gas industries, nuclear industry, chemical engineering, etc., as sealing gaskets of branch joints of various types, packing rings, braided packings, thermal insulation materials, upholstery materials for protection against electromagnetic radiation, membranes, filters, etc. [6–8].

The use of TEG in especially dangerous fields of industry requires reliable testing not only of finished products made of it, but also testing of properties and detection of defects at the stage of sheets-blanks. One of the main defects in the production of TEG is a deviation in the density distribution (density difference), which is a result of uneven distribution of the mass of expanded graphite on the width of the sheet in the manufacturing process and variation in the thickness of the sheet. Deviation in the density distribution can lead, for example, to uneven compression of the sealing connection and, as a consequence, the loss of tightness of the pipeline transport element [8]. TEG density is one of the main physical characteristics of the material used in the calculations of most other physical and mechanical characteristics, in particular, dynamic modulus of elasticity, acoustic impedance, porosity, etc.

The number of methods for testing the density of TEG sheets is extremely limited and includes a weight method that does not provide local density evaluation, as well as radio frequency and radiation using Cherenkov radiation methods that have insufficient sensitivity and require the use of special protection and safety measures for storage, operation and disposal of radionuclides [9–10]. According to foregoing, there is a need to develop new safe physical methods of testing the density of sheets-blanks and finished products made of TEG, which have a higher sensitivity and resolution.
Because of the use of waves of elastic nature and unambiguous connection of their parameters (velocity and amplitude) with the elastic moduli and the medium density, acoustic methods are successfully used in the problems of structurescopy and stress-strain state assessment of a wide class of materials and products [11-17], including porous media [18–22].

The paper presents noncontact methods for testing the density of TEG sheets: acoustic shadow method, based on the evaluation of the transmission coefficient of the acoustic wave in high frequency range, and eddy current method, based on the evaluation of the complex resistance of parametric surface-mounted eddy-current transducer, and results of investigation of the sensitivity curves for the sheets and mats of TEG in a wide range of their density variations.

2. Contactless acoustic shadow method

The basis of the contactless shadow acoustic method of testing the density is a decrease in the amplitude of the acoustic signal passing through the studied TEG sheet in the frequency range of 7–15 kHz. The block diagram of the experimental setup implementing the amplitude-shadow acoustic method is presented in Figure 1.

![Block diagram of experimental setup for testing the density of TEG sheets by acoustic amplitude-shadow method](image)

The generator of probing pulses, controlled by a microcontroller, delivers an electric signal to the radiant acoustic transducer exciting an acoustic wave in the air. The emitted acoustic wave passes through the object made of the TEG, located in the air, and enters the receiving acoustic transducer, located coaxially to the radiant one and identical to it in principle. The acoustic signal converted to electrical signal is further amplified and digitized. The value of the amplitude parameter $U$ of the registered signal is displayed on a computer with specialized software. The main informative parameter is the amplitude $U$ of the pulse [23] passing through the TEG sheet, the value of which depends on the density of the TEG sheet.

The coefficient $D$ of acoustic wave transmission through the interface of two semi-infinite media is determined by the formula:

$$D = \frac{2\rho_1 C_2}{\rho_2 C_2 + \rho_1 C_1},$$

where $\rho_1, \rho_2$ are the densities of the first and second media, $C_1, C_2$ are the velocities of sound in the first and second media.

In the case of passage through a layer of limited thickness, the transmission coefficient is also determined by the layer thickness and the acoustic wave frequency. Under the conditions of constancy of these values, the transmission coefficient is directly related to the density of the medium, and the lower the density, the greater it is.

The density $\rho$ of TEG can be determined by the formula:

$$\rho = \frac{U}{K_U},$$

where $K_U$ is the sensitivity of the amplitude-shadow method [V·m²/kg].
Sensitivity shows how much the amplitude of the transmitted signal will change when the density of the TEG sheet (mat) changes by 1 kg/m$^3$ and is defined as:

$$K_U = \frac{U_{\text{max}} - U_{\text{min}}}{\rho_{\text{max}} - \rho_{\text{min}}},$$

where $U_{\text{max}}$ and $U_{\text{min}}$ are the maximum and minimum values of the amplitude of transmitted signals corresponding to the maximum $\rho_{\text{max}}$ and minimum $\rho_{\text{min}}$ densities of TEG sheets.

The sensitivity of $K_U$ is determined on the basis of previously studied correlation dependences of the amplitude parameter for the TEG objects with known densities measured by the weight method under the condition of sheet thickness constancy.

To increase the reliability of TEG density testing by acoustical amplitude-shadow method [19], the experimental setup is acoustically isolated to protect it against mechanical and acoustic noise and interferences, as well as preliminary calibrated according to the reference sample with passport data of density and thickness in order to minimize the influence of time drifts in properties of the emitter and receiver, electronic components and other factors that can affect the amplitude parameter of the signal.

3. Contactless eddy current method of TEG density testing

The basis of the contactless eddy current density testing method is the change in the complex resistance of the overhead parametric eddy current transducer, conditioned by the occurrence of eddy currents in the near-surface layer of the conductive TEG sheet. At the same time, the density of the material, which determines its electrical properties, changes its complex resistance.

The block diagram of the experimental setup, implementing the eddy current method of testing of density is presented in Figure 2.

![Block diagram of the experimental setup for testing the density of TEG by eddy current method](image)

Eddy current transducer of special design, optimized for the measurement of TEG parameters, is an overhead parametric absolute transducer. The RLC meter excites electromagnetic oscillations in the eddy current transducer with frequency of 1 MHz, resulting in an electromagnetic field interacting with the tested object. During this interaction, eddy currents are induced on the surface of the electrically conductive tested object, leading to a change in the complex resistance $Z$ of the eddy current transducer, which is registered by the RLC meter.

The transducer impedance $Z$ is dependent on the electromagnetic field penetration depth $\delta$, which is determined by properties of the tested object and the frequency of the excitation current:

$$\delta = \sqrt{\frac{1}{\pi f \cdot \sigma \cdot \mu \cdot \mu_0}},$$

where $\mu_0$ is the permeability of free space.
where \( f \) – frequency of excitation current in the eddy current transducer, Hz; \( \sigma \) – the electrical conductivity, S/m (for TEG \( \sigma = 1.1\cdot10^{-5} \) S/m); \( \mu \) – magnetic permeability, H/m; \( \mu_0 \) – magnetic permeability of vacuum, \( 4\pi \cdot 10^{-7} \) H/m.

According to the formula (4), the penetration depth \( \delta \) of eddy currents in the TEG sheet is 1.5 mm at an excitation current frequency \( f \) of 1 MHz.

The transducer impedance \( Z \) is affected by the surface roughness, thickness of the tested object, the gap. Depending on the degree of rolling between the graphite particles in the volume of the TEG sheet, the free space in the form of cavities, channels, pores increases or decreases, which affects the electrical conductivity, and, consequently, the complex resistance of the transducer.

An informative parameter of testing is the measured value of the complex resistance \( |Z| \) of eddy current transducer. The density \( \rho \) of an object made of TEG can be determined by the formula (1) by substituting the value \( K_U \) (sensitivity of amplitude-shadow method, V·m³/kg) with the value \( K_Z \) (sensitivity of eddy current method, Ω·m³/kg). The sensitivity of the eddy current method is determined by the formula:

\[
K_Z = \frac{|Z_{\text{max}}| - |Z_{\text{min}}|}{\rho_{\text{max}} - \rho_{\text{min}}},
\]

where \( |Z_{\text{max}}| \) and \( |Z_{\text{min}}| \) are the maximum and minimum values of the eddy current transducer impedance corresponding to the maximum \( \rho_{\text{max}} \) and minimum \( \rho_{\text{min}} \) densities of the TEG sheets.

The sensitivity \( K_Z \) is determined on the basis of previously studied correlation dependences of the complex resistance parameter \( |Z| \) for TEG objects with known densities measured by the weight method under conditions of constant sheet thickness.

4. Results and discussion

Sheets-blanks of TEG, manufactured at the company “Silur” (Perm, Russia) by rolling (milling) on special equipment, with thickness of 1.5 mm, linear dimensions of 200×200 mm were used as tested objects. The values of the average density of the sheet, determined by measuring their linear dimensions and mass, are represented by the following set: 675 kg/m³, 750 kg/m³, 877 kg/m³, 1023 kg/m³, 1042 kg/m³, 1108 kg/m³, 1205 kg/m³, 1299 kg/m³, 1316 kg/m³, 1377 kg/m³. Physical characteristics of the studied samples of TEG are summarized in Table 1.

| Parameter                                      | Value          |
|------------------------------------------------|----------------|
| Shore hardness                                 | 30             |
| Friction ratio on steel (in wet atmosphere)    | 0.08 ± 0.02    |
| Specific surface area, m²/g                    | 10–35          |
| Young's modulus under compression (at 20 °C), depending on density, MPa | 100–195 |
| Coefficient of linear thermal expansion, relative to the rolling surface, 10⁻⁶/°C | along 1.1; across 28.7 |
| Thermal conductivity ratio (at 20 °C), relative to the rolling surface, depending on density, W/(m K) | along 95–310; across 8.1–3.5 |
| Electric conductivity, 105.1/(Ω m)             | 1.1 ± 0.1      |
| Specific electric resistance (at 20 °C), depending on density, relative to the rolling surface, Ω·mm²/m | along 12.2–7.4; across 570–690 |

Measurements of the amplitude parameter \( U \) of the passed acoustic signal and the complex resistance \( |Z| \) of the eddy current transducer were carried out in the same zone in the center of the raw sheet of TEG. Graphs of the amplitude parameter \( U \) of the transmitted acoustic signal and the complex resistance \( |Z| \) of the eddy current transducers dependences on the density \( \rho \) of the TEG sheet are presented in Figure 3. There is a decrease in the amplitude parameter \( U \) in the implementation of the acoustic shadow method with an increase in the density of TEG sheets. Increasing the density of TEG sheets also leads to a linear decrease in the complex resistance \( |Z| \) of eddy current transducer. Note that both presented dependences are close to linear in nature, and the deviations of the points are caused, first of all, by the inaccuracy of density measurement by an alternative method (weighing) in the local area due to the possible uneven
distribution of density and thickness over the area of the sheet. It should also be noted that the steepness of the calibration curve characterizing the sensitivity of the method is most expressed for the acoustic shadow method.

![Graph](image)

**Figure 3.** Graphs of the dependences of the amplitude parameter $U$ of the passed acoustic signal and the complex resistance $|Z|$ of the eddy current transducer (calibration curves) on the density $\rho$ of TEG sheets.

Calculation of the sensitivity of developed methods for testing the density of TEG sheets showed that the sensitivity of the contactless acoustic shadow method was 0.39 rel. units·m$^3$/kg, and the sensitivity of the contactless eddy current method was 0.06 Ω·m$^3$/kg. The sensitivity appears to be fairly uniform over the entire range of TEG sheet densities. Hence it can be concluded that the acoustic method is four times more sensitive to changes in the density of TEG at 1 kg/m$^3$.

The degree of change in the complex resistance is affected by the size of the gap between the tested object and the transducer, therefore a prerequisite is to ensure its constancy. The complex resistance $|Z|$ of the eddy current transducer of special design in the absence of the tested object is equal to 300 Ω. The increase in the gap between the tested object and the transducer leads to an increase in the value of the recorded complex resistance $|Z|$, and, as a consequence, to a decrease in the sensitivity of the method. Thus, when the gap increases from 0 to 500 µm, the sensitivity drops by about 20%.

Along with the heterogeneity of TEG sheets in density, one of the unacceptable defects are local thinning, including through defects. The possibility of defect detection on the example of through holes of different diameters $D$ is investigated using acoustic shadow method. The dependence of the amplitude parameter $U$ on the diameter $D$ of the through hole is shown in Figure 4. The measurements are performed for a TEG sheet of 1.5 mm in thickness with a density of 1110 kg/m$^3$. The increase in the diameter of the through holes leads to a nonlinear increase in the amplitude parameter $U$. In the presence of a through hole with a diameter $D = 1.2$ mm, the amplitude parameter $U$ increased almost twice (from 430 rel. units in the absence of defect up to 700 rel. units in its presence). Herewith, the sensitivity to the through hole diameter is $K_D = 256$ rel. units/mm. The sensitivity of the contactless eddy current method is insufficient for revealing through holes of the studied diameters.
Figure 4. Graphs of the dependence of the amplitude parameter $U$ of the transmitted acoustic signal on the diameter $D$ of the through hole in TEG sheet

5. Conclusions
The developed methods of acoustic and eddy current testing of TRG sheets density are quite simple to implement and can be reproduced using simple laboratory equipment, which provide a relatively low cost and ease of maintenance of the equipment. The main advantages of the developed methods include contactless, high sensitivity and locality of testing, the absence of harmful factors inherent in alternative methods.

It should be noted that the contactless acoustic shadow method of testing the density requires additional noise isolation from external acoustic and mechanical noise and interference; the eddy current method is free of these disadvantages, but it has less sensitivity, while there is a need to tune out from influence of the gap between the transducer coil and the surface of the tested object.

The use of two complementary methods will improve the reliability of testing in the workshop conditions of acoustic noise and electromagnetic interference with the possibility of detecting not only deviations in the density of the TEG sheets, but also technological defects, including through ones.

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