Examination of the junctures of aluminium and dielectric structures using subminiature eddy-current transducers

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Abstract. The article presents the structure of a subminiature eddy-current transducer of a transformer type, which is based on the pyramid-shaped core providing the localization of the magnetic field on the area of 2500 μm². It also describes the major transducer parameters, which provide such localization of the magnetic field. The article describes the structure of the measuring system and the measurement procedure, which allows determining the thickness of different objects depending on the signal. The measuring system includes two subminiaturized eddy-current transducers controlled by software. The output signal of the transducers is processed in the hardware filtration systems. The article contains data demonstrating dependency of the amplitude part of the signal on the different thickness of objects, and states the objects experimentally determined size limits that precondition the practicability of these measurements. Such objects as conductive coatings, laminated structures (metal-polyethylene), solid conductive objects (aluminium) and non-conductive dielectric coatings were examined. The article demonstrates the change of the signal amplitude of the eddy-current transducer depending on the type of the monitored material. The pattern of this change allows determining a type of the studying object and its thickness on a small area of the monitored item.

1. Introduction

Conductive coatings find wide application in some branches of industry, such as pipelines, spacecraft and aircraft, through their advantages in corrosion protection, electrical contact, wearing resistance and thermal isolation [1]. The thermal barrier coatings are applied in the surface construction of the airplane engine; it effectively protects the substrate metal of the blades from high temperature [2]. In any case, inhomogeneous distribution in thickness is supposed to be the problem that influence coating performance [3]. In addition, there is a problem in the incongruity of the parameters between the substrate metal and the coating, and in the corrosion under the coatings. The thickness of the coating influences on the coating term of the work, surface stress and consumption of the material. Therefore, a smart method of measuring the coating thickness is required for both process control and checking up of the key conductive structures.

Nowadays thermal, microwave, ultrasonic and eddy current (or EC) inspection techniques are applied in the measurements of coating thickness [4,5]. EC has many advantages over the other ones: it has high resistance to harsh conditions, measurements can be carried out in a noncontact way, and its cost is low [6]. To estimate the thickness of a coating with determined conductivity Takashi et al. [7]
conversed about the possibility of estimating the thickness of the alloy with the Ni-based coating sprayed on stainless steels of austenitic type 304 applying test with a measured EC frequency (SFEC). The coating thickness was estimated within an accuracy of 22 μm with inverse modeling methods. Barbosa [8] proposed a formula that obtains the coating thickness of galvanized steel from the impedance of a solenoid containing a sample of wires. Tai et al., Yang [5,9] and Tai [10] applied pulsed EC and SFEC techniques, trying to determine the conductivity and thickness of coating on a metallic substrate in conditions of either the coating or the substrate is magnetic.

Mandache and Lefebvre [11] explored the behaviour of the lift-off point of intersection (LOI) in different test conditions. LOI is used for measuring the thickness of conductive layers over the ferromagnetic substrates.

Thickness gauges based on the eddy-current method are applied to study the thickness of the electrically conductive sheets, plates, films and coatings; cylindrical and spherical gas cartridges; pipe walls. It also determines the air-gap distance between the plates made from the identical material. The purpose of the work was to assess the possibility of the amplitude eddy-current method in order to find the thickness of the conductive or dielectric coating, placed on the conductive base, as well as to estimate the error of such measurement. The research of the conduction demonstrated the possibility of the amplitude eddy-current technique application to determine the local thickness of the conductive objects, represented by several alternating conductive and non-conductive layers and solid conductive objects. An eddy-current transducer (ECT) is intended for on-site studies of the various coatings thickness, and to bring out the effect of different coatings on the output low frequencies.

2. Specifications, material choices and design
A subminiaturized eddy-current transducer [12, 13] is designed for the local examination of the different coatings thickness in experiments and to determine how different coatings influence the output signal value.

The actuating winding of the subminiature transducer consists of 10 winds and its diameter is 0.12-0.13 mm. The measuring winding includes 130 winds and its diameter is 0.05-0.08 mm. The compensation winding is included into the scheme to minimize the influence of the actuating winding on the received signal. The compensation winding is connected with the measuring winding so that the researcher could deduct the voltage of the actuating winding. It consists of 20 winds. A copper wire, that is 0.005 mm thick, is used to reel the winds. The windings are wound round the pyramid shaped core. The proposed shape of the core is favourable for the area of the magnetic field. The core is made of ferrite with initial magnetic conductivity equal to H/m.

The characteristics of the constructed transducers allow one to efficiently localize the magnetic field within 2500 μm² and larger and ensure a large (up to 5 mm) depth of penetration into the investigated object in operation at relatively low frequencies.
The eddy-current transducer (figure 1) is a transformer with measuring (1), exciting (2), and compensation (3) windings and a magnetic circuit 4, which is located inside the cylindrical platform 5 with tracks that are cut on the external side for windings. The platform is impregnated with a compound 6 at a temperature of 200 °C to prevent the disintegration of the windings in the process of application of the ferrite screen 7, which is used to locate the electromagnetic field in the monitored object. Outside the transducer, there is a corundum washer 8, which protects the core 4 from contacting the tested object.

The core consists of a tetrahedral pyramid (height 1 mm), with a square base (sides of 0.2 mm). The measuring winding is situated on the top of the pyramid, which improves the localization of the magnetic field. Such transducer permit effective localization of the magnetic field, so that defects as small as 250 μm may be detected. In addition, the magnetic field penetrates into the sample to a considerable depth when working at relatively low frequencies.

The pyramid shape of the core was received with the help of two main methods. The first one is as follows: thin triangles (0.1 mm) were cut of the alloy 81NMA [14]. After that the plates were put together and their upper parts were ground off. Such kind of an approach has its disadvantages: the upper parts turned out to be uneven which resulted in the creation of a weak the magnetic field.

The second way to make a pyramid shaped core was grinding off the thin triangles and their matching into a pyramid.

Wire coils were placed on the pyramid shaped cores. The coils were impregnated with compound. The temperature of impregnation was 200 °C, the diameter of the wire was 1.5×10⁻⁶ meters. The measuring winding was placed at the end of the top of the pyramid, the diameter of the winding was 0.05 mm., the number of winds varied from 100 up to 200. In the middle of the pyramid there was an actuating winding that consisted of one wind. The compensating winding was situated on the mobile frame and included 100 wires. The mobile frame enables it to move freely along the oxide core from the bottom up to the actuating winding.

On the whole, 10 ECTs were made and their calibration was carried out in order to deduct the voltage induced in the measuring winding from the actuating winding. ECTs of different types were made in order to get the magnetic field of different voltage. Therefore, the cores of different sizes were created. The interrelation between the diagonal of the bottom and the edge of the pyramid varied from 1:1 to 1:10 (figure 2).
The ECTs constructed on the basis of the cores, having similar interrelation between the diagonal of the base (400 μm) and the length of the rib (4 mm), have been calibrated on semi-conductors with the certain conductivity. Thus, the ECTs have identical geometric parameters of the cores and the same number of the winds of the actuating (1 wind), measuring (200 winds) and compensation (200±40) windings.

The developed measuring system is used in the following way. The software of the PC supervises the operation of the generator, which produces a chain of rectangular voltage pulses with the repetition rate “f” - it is necessary for the functioning of eddy-current transducers. The voltage pulses are transmitted from the generator output to two series integrators. Then they are going further to the input of the power amplifier. At the output of the amplifier, the pulses are applied to the exciting inductance coils of the ECT. The signal passes through two rows of high-quality low-pass filters, then - two-series selective amplifiers and reaches the amplitude detector. Then the signal goes via an analog-to-digital converter to a PC. Through the contemporaneous control of the generated signal frequency on the exciter coil, the filtration system frequency, and selective amplification, the signal contains either the information on the distribution of electrical conductivity within the object and the data about the probable defects of the object. The program allows changing the operational frequency of the measuring system, so that the received signal can be reliably registered.

3. Experimental results
In order to test the measuring system, an aluminum coating of various thickness located on a 3 mm thick copper base was scanned. Figure 3 demonstrates the dependence of the signal magnitude on the thickness of the aluminum coating on a non-ferromagnetic substrate. If the coating thickness is increased to 1200 μm, a decrease in the signal magnitude from 28.2 to 22 mV is observed. In the range from 750 to 1500 μm the signal magnitude is much smaller than the signal magnitude from the solid unit. It can be explained by the insufficient thickness of the coating. Nevertheless, when the thickness of the coating is between 1500 and 2500 μm, the magnitude of the signal is stable. The next experiment illustrates the change in signal from the thickness of a laminated coating with alternating foil and polyethylene layers placed on a copper substrate.
Figure 3. Dependency of the signal value on the aluminium coating on the copper base.

The next experiment illustrates the change of the signal depending on the thickness of the laminated coating with alternating foil and polyethylene layers placed on a copper substrate. Figure 4 presents the dependency of the intensity of the signal on the thickness of laminated coating. If the thickness is within the range of 0 to 100 μm, the signal value from the base falls from 29 to 26 mV; whereas if the thickness is within the range of 100 to 240 μm, the signal change pattern is flatter. In the range of 240 to 400 μm, the signal changes from 26 to 23 mV; this is possible due to the contribution of the laminated coating signal and decrease of the copper base signal contribution.

Figure 4. Dependency of the signal intensity, while scanning a laminated structure.
The final experiment considered a copper plate and a dielectric coating as the studied objects. As a dielectric coating, the varnish coating was used. A copper sample consisted of a unitary copper block.

Figure 5. Dependency of the eddy-current transducer response on the thickness of the dielectric coating.

A set of experiments with copper-samples and a varnish coating were conducted. A layer of varnish was put on pre-cut samples of copper. As can be seen from the dependence of the signal amplitude on the dielectric coating thickness on figure 5, the output signal value decreases rapidly in parallel with increasing coating thickness. This dependency can be fit as an exponential function:

\[ y = A_1 e^{-\frac{x}{t}} + y_0 \]  

To demonstrate the operational capability of the suggested method, a structure consisting of the alternating aluminum foil and paper layers (100 µm thick) was used. A hollow parallelepiped was placed between the layers as a model defect. Its walls were 300 µm thick.

In figure 6, there is a spectral picture, observed when the sensor is moved above the layered medium, which has an inner defect. The signal level from the measuring winding characterizes the values of conductivity on the survey plot. For the fundamental frequency at 1000 Hz the level of the voltage, sent to the measuring winding, was (130±2) mV. Area 1 and area 2 on the diagram where the voltage level falls to 115 mV, correspond to the walls of the parallelepiped. These changes in the signal amplitude account for 11 percent from the signal level corresponding to the nondefective zone of the sample. Thus the signal amplitude in the nondefective zone does not exceed 4 mV, it accounts for 3 percent from the signal level corresponding to the nondefective zone of the sample.
Figure 6. Dependency of the eddy-current transducer response, observed as the sensor is used to examine the layered medium with a defect. 1, 2 – the sides of the parallelepiped, 3 – a nondefective zone of the sample.

4. Conclusions

On the basis of the eddy-current transducer of the transformer type, a measuring system was developed. It allows estimating the possibility of the eddy-current method application to measure the thickness of the conductive and dielectric coatings located on the conductive base. The developed measuring system was applied to examine the objects (conductive and non-conductive coatings) located on the conductive base, as well as to measure the thickness of the solid conductive objects. It was determined that the thickness of the coating influences the signal of the eddy-current transducer. In perspective, this will allow using the amplitude control method of such class of objects for exact local measurements of the thickness of conductive and non-conductive coatings as well as other objects. Owing to the received dependencies of the eddy-current transducer signal on various coatings, it becomes possible to use the developed system in the process of diagnostic testing of composite hardening coatings. Therefore, the results of the experiment demonstrate the wide range of possibilities provided by the eddy-current method in the process of the examination of defects concealed in metal-dielectric-metal structures.

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