Superminiature Eddy-current Transducers for Thickness Studies

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Abstract. On the basis of the transformer type eddy-current transducer we created a measuring system which allows us to estimate the possibility of the eddy-current method application to measure the thickness of the conductive and dielectric coatings placed on the conductive base. We described the structure of the measuring system and the measurement procedure. A scheme that uses a computer as a generator and receiver of signals from windings is proposed. The article contains the data demonstrating the dependency of the amplitude part of the signal on the objects of different thickness and states the objects’ experimentally determined limits of the size that precondition the practicability of these measurements.

1. Introduction
Conductive coatings are widely used in industry (e.g., aircraft, spacecraft, and pipelines) due to their advantages in wear resistance, oxidation and corrosion protection, and electrical contact and thermal isolation [1]. For example, the thermal barrier coating on the surface of the airplane engine blades can efficiently protect the substrate metal of the blades at high operation temperature [2]. However, inhomogeneous distribution in thickness is one of the problems that impact coating performance, as well as the mismatch of physical parameters between the coating and the substrate metal, and the corrosion under the coatings [3]. The coating thickness has significant impact on the lifetime, surface stress, bonding strength, and material consumption of the substrates. Consequently, a fast approach to measure the coating thickness is necessary for both process control and in service inspection for the key conductive structures.

Presently, ultrasonic, thermal, eddy current (EC), and microwave inspection techniques are used in coating thickness measurement [4,5]. EC technique has many advantages over the other techniques, such as insensitivity to harsh environment, noncontacting measurement, and low cost [6].

For the estimation of coating thickness with known conductivity, Takahashi et al. [7] discussed the feasibility of thickness evaluation of Ni-based alloy coating sprayed on 304 austenitic stainless steels using swept frequency EC (SFEC) testing. The coating thicknesses were estimated within a maximum error of 22 fim through inverse modeling methods. Barbosa [8] presented a formula to obtain the coating thickness of galvanized steel wires from the impedance of a solenoid containing a sample of wires with the assumption that the skin depth of the ECs in the coating is much larger than the coating thickness. Tai et al. [5,9] and Yang and Tai [10] used pulsed EC and SFEC techniques to determine the thickness and conductivity of metallic coating on a metal substrate for the case when either the coating or the substrate is magnetic.
Sakran et al. [11] demonstrated a reflection mode EC technique to measure the thickness of conducting layers in a range from 0.1 to 1 μm with the spatial resolution of 1-2 mm at the microwave frequency. Lefebvre and Mandache [12] studied the behavior of the lift-off point of intersection (LOI) under various testing conditions, and LOI is presented to measure the thickness of conductive layers over the ferromagnetic substrates. Zhao et al. [13] experimentally demonstrated the feasibility of the nanometallic film thickness measurement by using the EC method.

Thickness gauges based on the eddy-current method are used to control the thickness of the electrically conductive sheets, films, plates, their coatings, pipe walls, cylindrical and spherical bulbs and to determine the air-gap distance between the plates made of the same material.

When conducting the eddy-current thickness gauging of the object, being by nature of a dielectric or conductive upper layer (coating), placed on the conductive base (substrate), often are used the control based on the measurements of the phase $\phi$ of the signal inserted into the transducer [14]. Judging by the phase changes in the scanning process, we determine the thickness of the upper layer $d$. An attachable transducer is usually a transformer type transducer with three windings. The exciting winding creates electromagnetic field, while measuring and compensation windings are designed for measurements. The phase is counted in relation to simple harmonic exciting current of the transducer. In order to increase the measurement accuracy, are used the EMF induced in the compensation winding of the transducer, as a reference signal in the work [15].

The advantage of the phase control method is the availability of a greater number of control parameters; while analyzing the locus function curves on the complex plane, it is possible to separate the impacts of the parameters under control from the nuisance ones. Its reverse side is the overload of the image with non-informative signals. The disadvantages of the phase control method are as follows: difficulty in detecting local inhomogeneities of the coatings due to the influence of the nuisance parameters; significant decrease in sensitivity due to the increase of the gap between the ECT and the monitored object, stipulated by the monitored object surface contamination; severe requirements to the operator qualification.

The purpose of this work was to estimate the application possibility of the amplitude eddy-current method alone in order to determine the thickness of the conductive or dielectric coating, placed on the conductive base, as well as to estimate such measurements inaccuracy. The conducted research showed the possibility of the amplitude eddy-current method application to detect the local thickness of the conductive objects, represented by several alternating conductive and non-conductive layers and solid conductive objects.

2. Specifications, material choices and design

A subminiaturized eddy-current transducer [16,17] is designed for the local examination of the different coatings thickness in experiments, as well as to reveal the influence of different coatings on the output signal quantity.

The design of the measuring system includes two differentially connected subminiature transducers, which provide a large area of the magnetic field.

The tested parameter is the electric conductivity of the material and its distribution over the studied object. The eddy-current transducer is connected to a set of the designed amplifiers and band-pass filters and is controlled by the sound map of a personal computer with special software, which applies a voltage to the generator winding of the transducer. This allows one to read the voltage values from the measuring winding initially in some arbitrary units, which are further translated into electric-conductivity values, taking the preliminary calibration into account.

The exciting winding of the transducer consists of ten turns; its diameter is 0.12—0.13 mm. The measuring winding consists of 130 turns and has a diameter of 0.05—0.08 mm. To minimize the influence of the exciting winding on the recording signal, the circuit contains a compensation winding that is connected to the measuring winding in accordance with the well-known differential circuit. This consists of 20 turns. A copper wire with a 5-μm thickness is used for winding turns. The turns are
wound around a pyramidal core. The proposed shape of the core is favorable for the area of the magnetic field. The core is made of ferrite with an initial magnetic permeability of 500.

Different transducers that are based on cores that have the same ratio of the base diagonal (400 µm) and edge length (1 mm) were calibrated using samples with a well-known electric conductivity.

The characteristics of the designed transducers allow one to efficiently localize the magnetic field within 2500 µm² and provide penetration of the magnetic field into the studied object at a depth of up to 5 mm [18-21].

The measuring system, which is based on a miniature eddy-current transducer, operates as follows. The software of the personal computer controls the operation of the generator, which produces a train of rectangular voltage pulses with the repetition rate f that is necessary for the operation of the eddy-current transducers. The voltage pulses are transmitted from the generator output to two series integrators. They are then directed to the input of the power amplifier. From the amplifier output the voltage pulses arrive at the exciting inductance coils of the eddy-current transducers. The difference of the output voltages of the measuring coils of the transducers contains information on the structural heterogeneities of the tested object that is located in the effective area of the eddy-current transducers.

It is detected and amplified in a special microphone amplifier. The signal arrives at the amplitude detector after the transmission through two series high-quality low-frequency filters and two series selective amplifiers. The signal is then transmitted through an analog-to-digital converter to a personal computer. The control program allows one to change the operating frequency of the measuring system so that the signal that is received from the measuring winding is reliably recorded. The developed software makes it possible to measure the thickness of conductive and dielectric non-ferromagnetic coatings and conductive materials.

3. Experimental results

In order to test the developed measuring system, we scanned the aluminium coating having different thickness and placed on the 3 mm thick copper base. Figure 1 presents the dependency of the signal quantity on the thickness of the aluminium coating on the non-ferromagnetic base. In case the thickness of the non-ferromagnetic coating is increased up to 1200 µm, we observe the signal quantity decrease from 28.2 to 22 mV. In the interval 750 to 1500 µm, the signal quantity is significantly less than the signal from the solid sample, which can be explained by the insufficient coating thickness. However, the coating thickness staying within the range of 1500 to 2500 µm, the signal quantity is stable and corresponds to the field size from the solid unit.

![Figure 1. Dependency of the signal quantity on the aluminium coating on the copper base.](image-url)
The next experiment demonstrates the dependencies illustrating the signal change from the thickness of the laminated coating with alternating foil and polyethylene layers, placed on the copper base. The object under study was represented by alternating aluminium foil (20 μm) and polyethylene (20 μm) layers.

Figure 2 demonstrates the dependency of the signal intensity on the thickness of the laminated coating with alternating foil and polyethylene layers, placed on the copper base. The thickness being within the range of 0 to 100 μm, the signal quantity from the base changes from 29 to 26 mV, while the thickness being 100 to 240 μm, the pattern of the signal change is flatter. In the range of 240 to 400 μm, the signal changes from 26 to 23 mV, which is stipulated by the contribution of the signal from the laminated coating and the decrease in the contribution of the signal from the copper base.

![Figure 2. Dependency of the signal intensity, while scanning a laminated structure.](image)

In the third test experiment, we conducted the scanning of a sample being by nature of a solid object made of aluminium having different thickness. Figure 3 shows the dependency of the signal quantity on the thickness of the aluminium sample. The contribution of the sample deeper layers to the signal amplitude rises with the increase in the sample thickness. The thickness being changed from 100 to 1200 μm, the signal quantity increases from 7 to 25 mV. If the thickness is changed from 1200 to 2200 μm, the signal quantity is stable and corresponds to the amplitude value from the solid unit (25.5mV).

![Figure 3. Dependency of the signal on the thickness of the aluminium sample.](image)
In the final experiment, the monitored object was represented by a copper plate and dielectric coating. The varnish coat served as dielectric coating. The copper sample was made of a unitary block of copper. We laid the dielectric coating layer onto the object under control.

![Image](image.jpg)

**Figure 4.** Dependency of the eddy-current transducer response on the thickness of the dielectric coating (fit as an exponential function).

We conducted a series of experiments with copper samples and varnish coating as well. We laid a layer of varnish coating onto the pre-cut out copper samples. As we can see from the dependency of the signal amplitude on the thickness of the dielectric coating (Figure 4), the quantity of the output signal decreases sharply with the increase in the coating thickness. This dependency can be fit as an exponential function:

\[ y = A e^{-\frac{x}{\tau}} + y_0 \]

This dependency graph is presented in Picture 4. As we can see from the picture, the signal decreases exponentially with the increase in the dielectric coating thickness.

4. **Conclusions**

We applied the developed measuring system to examine the objects being by nature of conductive and non-conductive coatings, placed on the conductive base, as well as to measure the thickness of the solid conductive objects. We determined that the thickness of the coating influences the eddy-current transducer signal. This allows us to prospectively use the amplitude control method of such object class for exact local measurements of the thickness of conductive and non-conductive coatings as well as of 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 diagnostic testing of composite hardening coatings.

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