Research of layered composites by using subminiature eddy-current probes

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Abstract. On the basis of subminiature eddy-current probes, a measuring system is designed that allows scanning of composite materials for detection of small defects. The results of the study of discontinuity defects simulated in metal-polymer layered composites of aluminum-polyethylene-aluminum systems up to 10-layer composite are described. Composites were made by alternating layers of aluminum or copper foil, 20...100 µm thick, with layers of a film, 20 µm thick. Defects in the structure of the material were modeled by skipping or increasing the number of separate layers, and defects in continuity and bridges were modeled by cutting a round or rectangular hole in the foil or dielectric layer. Visual images of model defects are obtained by Fourier-transformer of the IENM-5FA device. The dependence of the eddy current probe signal on the presence of a defect in the layered structure is established.

1. Introduction

The eddy-current method (ECM) together with ultrasonic scanning and fluoroscopy is one of the main methods to inspect defects for the purpose to control various materials and products in modern technology. The method is based on the analysis of an interaction of the electromagnetic field of a special sensor — the eddy-current probe (ECP) — and the object of control. The properties of the investigated object, the nature and topology of the defects detected by ECM, design of such probes and the principles taken as a basis for defects examination change depending on the goals.

At present, metal-polymer laminated composites (MPLC) hold a specific place among objects to non-destructive testing. Defects inspection of MPLC is performed to determine the following standard defects: defect of the metallic and (or) polymer layer uniformity, the number and thickness of the layers, conducting and non-conducting strips between layers, deformation of the metal layer surface, change in the state of boundary between the metal and polymer layers of the MPLC. One of the parameters sensitive to all the listed defects of MPLC is the local electrical conductivity of the material and its distribution over the surface, associated with the topology of the electromagnetic field in the material interacting with these defects.

According to the literature review, there are many types of inspections to evaluate composites and each of the proposed methods can be implemented in many ways [1-7]. Electromagnetic Testing (ET) methods use magnetism and electricity to detect and evaluate fractures, faults, corrosion or other conditions of materials. ET induces electric currents, magnetic fields, or both inside a test object and observes the electromagnetic response. Electromagnetic (EM) methods include Eddy Current Testing (EC) [8], Remote Field Testing, Magnetic Flux Leakage and Alternating Current Field Measurement. The physics behind each of these methods is different because various electromagnetic fields can be described by different equations. [9].

Nondestructive testing (NDT) measurements of realistic composite specimens have shown that material defects at the object surfaces and inside the material can be detected, e.g. [10]. Inner defects, which are not visible at the surface, can be found by time domain spectroscopy methods [11]. For technical composites, like laminated glass fiber reinforced plastics (GFRP), inner defects of the fiber rovings can be only in the dimensions of below 1 mm [12] but can also reduce the stability of the
entire specimen and may decrease its quality and the desired performance and safety targets [13]. Detecting these small material defects inside the woven fiber roving structure itself gets more difficult if the composite is built out of multiple fabric and matrix resin layers.

Earlier, we reported on the successful development and testing of a virtualized measuring instrument - a conductivity meter for non-ferromagnetic materials — CMNFM-5FA. The subminiature ECP [14, 15] of the original design is used as a sensor in this device, it is made according to a differential scheme of switching on of the coils of a transformer ECT and allowing to localize the control area up to 50 μm². Measurement of local electrical conductivity on the surface of a sample under investigation signal of the measuring coil of SMECT in real-time mode makes it possible to use this device as the defectoscope, comparing the data obtained at the object under investigation with the image of the defect previously obtained on the material model.

Timeliness is subject to the need to assess and predict safe operation life of products manufactured using metal-polymer laminated composites.

The purpose of this work was to investigate the possibility of detecting defects such as discontinuity of MPLC based on aluminum and LDPE type A1-(LDPE-Me)p-A1, as well as to visualize such defects by means of CMNFM-5FA.

**Materials and methods**

Developed a measuring system based on subminiaturized eddy-current probes aimed at examining locally the defects of metal-polymer laminated composites. A subminiature surface eddy-current transducer of the transformer type developed, and the optimum shape and size of the core and number of inductance coils and turns in them were defined, this provides efficient localization of electromagnetic field. On the basis of eddy-current transducer, a software and hardware complex was developed to control the eddy-current transducer (to generate alternating current of various frequencies, to provide its supply to the eddy-current transducer, to receive a useful signal from transducers to ensure its convenient visualization). To conduct the research, the CMNFM-5FA was used, equipped with a wireless hand-held SMECT with a locality of 0.1-0.5 mm².

The excitation parameters of ECP: the amperage is 30-35 mA, the voltage is 3.5-4.5 V, the operating frequency is 0.3-300 kHz. Absolute calibration of the device and the communication line with the sensor was carried out on the standard copper sample with the certified conductivity of 415±2 MS/m.

A set of measurements was performed on metal-polymer laminated composites.

MPLC and models of their defects were made by interchanging layers of aluminum foil with thickness of 100 μm and with layers of polyethylene film with thickness of 20 μm. Samples were cut out of these materials with a size of 20x50 mm, a package of the given structure was formed, a foil layer or dielectric with a defect was inserted. Defects in the MPLC structure were simulated by skipping or increasing the number of separate layers.

A superminiature ECP (SMECP) is designed to control the parameters of aluminum alloy products in small areas [16-18]. The defined parameter is the electrical conductivity of the material and its distribution on the surface and thickness of the object of control. The ECP is connected to the Arduino board, controlled by a personal computer with special software developed in C++ for the Windows operating system. The software controls the supply voltage to the exciting coil of the ECP and reads the voltage values (in conventional units) from the measuring coil of the ECP, and then, considering the pre-calibration converts the data into electrical conductivity values.

Information exchange between Arduino and the computer is performed via virtual COM-port. The developed software controls the frequency of the signal on the Arduino board, which generates a sinusoidal signal of a given frequency. The signal passes through a gain-controlled amplifier, thereby achieving the desired signal amplitude. After amplification, the signal enters the exciting coil of the ECP, inducing eddy currents in the object of control. The composite field of the exciting coil and eddy currents induces EMF in the measuring coil, carrying information about the object of control. This EMF is the output signal of the ECP. The output signal is amplified and filtered using a modified Delyann filter combined with a selective signal amplifier, and then is received by the Arduino ADC,
where it is converted into a digital signal, which is transmitted to a personal computer and displayed in a convenient form for processing.

ECP winding coils consist of a copper wire with the thickness of 5 \( \mu \)m. The core is made of ferrite 2000NM3 with an initial magnetic permittivity value of 2000 and has a pyramidal shape. Characteristics of the developed transducer make it possible to achieve high localization of the control. The characteristics of these ECPs allow for the localization of the magnetic field within the areas of 2500 \( \mu \)m\(^2\) and, when using sufficiently low (100-700 Hz) frequencies on the exciting coil, allow to achieve a significant depth of its penetration into the object of control. The software coded in C++ for Windows allows controlling the signal on the energizing winding and receiving the signal from the measuring winding. With the help of the software it is possible to effectively control the signal, which is applied directly to the energizing winding. This software makes it also possible to receive a signal directly from the measuring winding.

2. Experimental results and discussion
The main characteristic of MPLC sensitive to investigated defects is the electrical conductivity of the material of the metal layer.

As it is shown in [18], the contribution to the value of the voltage introduced into the measuring winding of the SMECP with high locality and the ratio of the radii of the measuring and transmitting coils is not less than 0.2-0.4 from each new layer will be from 10 to 25% which is enough to record it by any measuring instrument with an absolute permissible error not exceeding 3.5%.

The measurements carried out by us for model defects of the type of violation of the number and order of layers for multilayer MPLC systems aluminium-polyethylene showed a change in the reference electrical conductivity up to 3-7 mV in the defect area, with an absolute error of 0.1-0.1-0.3 conventional units, i.e. 20-30-time excess of the defect signal over the noise. The appearance of any of these defects in the study area causes a sudden change in the field topology and relative device readings.

The defect may also be represented by amplitude-time dependence of the readings, that has been already implemented in CMNFM-5FA, with manual or automatic scanning of the object's surface. Diagnostics of MPLC continuity defects is possible with direct contact scanning of the sample surface by a sensor. Therein, time is converted into the position of the sensor relative to the starting point of the movement, taking into account the speed of the sensor. Before the measurements were started, the sensor was been calibrated. The measured characteristic was the voltage that is induced by the field of eddy currents that arise in the tested object. In this experiment a sector for calibration was selected on
an intentionally flaw-free plate that was manufactured from an identical MPLC. In this case the dependence of the amplitude of the sensor signal on the sensor position in real time, displayed by CMNFM-5FA, can serve as a defect image.

In this case, the main frequency and amplitude of the signal are displayed on the left screen, and the probe coordinate — along the X axis.

The results of the experiment are presented in Fig. 2,3.

Figure 2 shows typical images of some MPLC model defects of layer discontinuity type, obtained with a device, when a sample of MPLC was placed on a dielectric base.

![Figure 2](image1.png)

**Figure 2.** Signal amplitude obtained when scanning a defect of layer discontinuity type, hidden in a 2-layer MPLC

![Figure 3](image2.png)

**Figure 3.** Signal amplitude obtained from the visible defect

It can be seen from Fig. 3 that the signal amplitude obtained when scanning a defect of layer discontinuity type, hidden in a 2-layer MPLC, as per selected control mode identical to that to the signal amplitude obtained from the visible defect (Fig. 2).
When obtaining a signal from such a defect, the device displays the dependence of the amplitude of its signal on the probe position. This allows to perform initial adjustment of the device and provides the operator's training in the diagnosis of defects directly from their visual models, hidden between the layers of MPLC.

3. Conclusion
1. The readings of CMNFM-5FA when measuring the electrical conductivity of MPLC type aluminium-polyethylene using SMECP with locality up to 50 μm² do not depend on the gap in the range from 100 to 250 μm.
2. High locality of the sensor and the determined dependence of electrical conductivity of MPLC on model defects make it possible to carry out defects inspection of materials directly as per CMNFM-5FA readings.
3. Visual images of model defects are obtained by Fourier-transformer of the IENM-5FA device. The dependence of the eddy current probe signal on the presence of a defect in the layered structure is established.

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