Non-destructive testing of the metal-insulator-metal using miniature eddy current transducers

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Abstract. The paper puts forward a modified eddy current testing method based on the use of miniature eddy current transducers within a localized controlled area of the material surface of up to 50 µm². Measurement results are provided for a model composite material made up of alternating conducting and dielectric layers of system AI-PAPER -A1. Structural flaws are specified as changes in the number and position of layers in the sequence. Prospects of the proposed method and a measuring device operating on its basis for flaw detection in composite aluminum alloy materials are shown.

1. Introduction

Despite our great experience in using vortex-current transducers/transformers (VCT) in the sphere of nondestructive control, several important aspects still need to be studied nowadays. In particular, the most vital problems are: carrying out local contactless measurements combined with controlled object scanning; price reduction in sensor engineering; making the control locality more accurate and the quick allocation of the frequency range, the most proper to scan the controlled object.

The worked out conception of the virtualized measuring device (transformer) enables a researcher to make a great number of measurements in different spheres with the help of one sensor only. To these spheres belong fault detection of conducting materials and stratified composites, thickness measuring, profilometry, tension measuring of permanent and variable magnetic fields and conductivity measuring of unferromagnetic materials and some others. In the past there were several attempts to use highly sophisticated magnetic field sensors like SQUID and Fluxgate sensors for sensitive low frequency eddy current testing to detect deep defects in metal parts [1–3]. Although very good results could be achieved such testing systems can hardly be used in real industrial applications because of their complexity, prices and insufficient robustness [4]. To make the price lower the authors came to the conclusion that one should replace the expensive hardware blocks with the software for personal computers (PC). As a result, developed device consists of a vortex-current transformer (VCT) only, which is connected to the sound card of the PC, managed with the special software. The software manages the voltage given to the generative transformer winding, it also reads out the values of the voltage from the measuring winding in conventional units. Later these units are transferred into the values of conductivity taking into account the preliminary calibration. A very promising sensor performance could be obtained by using highly sensitive inductive coils. The problem is that such sensors have to be produced by skillful specially trained operators; it results in low reproducibility and low productivity [4]. To solve these problems the VCT is often provided with an extra magnetic conductor [4].
One of its terminals has a shape of a truncated cone. This solution of the problem has only one disadvantage. Despite the increased localization of the magnetic flux, the construction of the magnetic conductor has become considerably more complicated. It makes the measuring accuracy worse, because the output signal of the VCT depends to a great extent on the interaction between two magnetic conductors, which can influence the intensification of the vortex-current field in a rather unpredictable way.

There are different well-known constructions of superimposed VCTs, whose working surface has either a plane or hemispherical form. Such kind of a surface provides a satisfactory contact of the VCT with the surface under control, but the tension quantity, sent to the VCT, greatly depends on the curvature of the controlled surface. The edge effect influences the work of the VCT considerably. This effect makes it impossible to control the details of a complicated configuration and of small sizes. If the size of the sample is small, the measurement error is unavoidable. The results show that the relative errors increase with the decrease of the size of the sample [6]. The small size of the cores (starting with 1 millimeter), used in the virtualized VCT, gives an opportunity to improve the control locality, without applying additional complication of the construction. Due to that the influence of hindrances on the VCT is considerably reduced.

The core, shaped either as a cone or pyramid, supports a high degree of localization of the magnetic field that is why the influence of the edge effects and the surface curvature is practically avoided. The existence and shape of a defect can be recognized by observing the difference in variation of the equivalent impedance. Magnetic systems with various interior deep defects are numerically analyzed by finite element method and their data are compared with those of the experimental systems. The measured data of the impedance variation are distinguishable enough to be used to estimate the existence and shape of defects in the steel structure [7]. In the laid on VCTs theory the most general objective is the study about the distribution of the electromagnetic field, created by the circular wind with the alternating current, in the multilayer media [8]. Let us consider that the turn of the radius R1 is placed above the multilayer medium in the plane, parallel with the ambit (boundary) of the section layers. Taking into account the resulting ratios, we have made hodographs, illustrating the influence of different parameters of the medium and the sensor on the values of the applied voltage. Defects in welding joints of the LSMP may significantly reduce the material strength. Eddy Current Testing (ECT) is considered as a powerful NDT tool for the detection and sizing of defects [9]. Earlier the eddy current control method could be used to investigate only surface defects (such as cracks, cuts and other examples of metal surface discontinuity), now, due to using subminiature VCTs and special software, it is getting possible to localize the magnetic field in a small zone of the controlled object and to achieve a high degree of the (magnetic) field penetration depth into the investigated object. The only condition is to choose a proper field frequency, created by the actuating winding.

2. Materials and methods

In general the scheme of the sensor is presented in Figure 1. In this scheme there are actuating (AW) and measuring (MW) windings, placed in the VCT.

A digital signal comes from the virtual generator to the input of the digital analog transformer (DAT) of the sound card and then it is transformed into the analog one. After passing though the power-amplifier (PA) the analog signal is sent to the actuating winding (AW) of the transformer. While passing through the actuating winding of the VCT, the sinewave signal makes the electromagnetic field, that creates EMF in the measuring winding (MW) of the VCT. The tension is received by the microphone input of the sound card and, after coming though the preamplifier (PA), it goes to the input of the analog digital transformer (ADT) sound card. The analog signal is transformed into the digital one and is sent to the treatment and operation unit of the software. The treatment and control unit fixes the level of the digital signal in conventional units that correspond to the voltage values in the measuring winding.
This level is accepted as a zero one that corresponds to the voltage level on the measuring winding without the control object. Without the control object the indicator shows zero, it corresponds to the zero value of conductivity.

Along with the considerable price reduction of the device, the virtualization of the generator and signal receiver makes it possible to mark out the frequency range, at which the process of scanning of the control object gets very effective. The effectiveness is reached due to the quick varying of the current frequency, given by the virtual generator to the VCT. Thus, researchers can define the frequency, at which changing the amplitude of the signal on the measuring winding (when it is passing through the imperfect area) is at a maximum. Besides, frequency varying enables us to find the depth of the defect hiding, because the depth of the electromagnetic field distribution of the VCT directly depends on the frequency of the field sent to the actuating winding [1].

The principle of operation of the VCT is based on the alternating magnetic field, localized in the controlled object with the help of the oxide pyramid shaped core. The shape of the core is conditioned with the necessity to localize the magnetic flux from the actuating (generator) coil. The core of this model was made of a midrange metadiscipline ferrite NM3, chosen according to the value of the maximum initial magnetic conductivity 500. The actuating winding of the subminiature transformer consists of 10 wounds 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 subtract the tension 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 scheme of the subminiature VCT is represented on the Figure 2.

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**Figure 1.** The scheme of sensor operation.

**Figure 2.** The scheme of the SMVCT.
The VCT is a transformer. It has 1) an actuating 2) a compensation windings 3) and a magnetic conductor 4) which is placed inside the cylindrical platform 5) with the tracks for the windings, cut on the outer side 6) which is impregnated with a compound at 200 degrees centigrade in order to prevent the windings from destruction while the ferrite screen is being put on 7) which is meant for the magnetic field localization on the controlled object. From the outside the sensor is covered with a corundum washer 8 that protects the core 4 from contacting with the controlled object.

The electromagnetic field of the generating winding gives an impulse to eddy currents in the electroconductive controlled object. Eddy current density in the object depends on the geometric and electromagnetic values of the object and on the back-to-back location of the measuring VCT and the object. The magnetic field of the eddy currents is opposed to the primary magnetic field of the generating winding, as a consequence the resulting field depends on the electromagnetic characteristics of the controlled object and on the distance between the VCT and the object, as the distribution of the eddy current density depends on these factors. There is EMF in the measuring winding of the VCT; it serves as a signal, hands over the information about the object into the measuring unit.

In this case EMF of the measuring winding decreases due to the opposite magnetic field produced by the eddy currents.

3. Experimental results
The worked out VCT enables the researchers to investigate the defects effectively. These defects may be found in the places of metal-insulator transition in the extra-small layered metal-polymeric composite objects. Such composites can contain several metal layers, separated with thin polymeric dielectric interlayers. To typical defects of such materials refer, for instance, the disturbance of layer continuity, the formation of crossbars between the layers. To investigate layered structures of the metal-dielectric-metal type we used the MNME – 5FA device (the Meter of Nonferromagnetic Material Electroconductivity), constructed earlier. A modified Fourier analyzer was used in a very special way to measure the decibel-log frequency characteristic. To demonstrate the operational capability of the suggested method we used the structure that was based on the alternation of the aluminum foil and paper, both of which were 100 micrometers thick. A hollow parallelepiped was placed between the layers as a model defect. Its sides were 300 micrometers thick.

In Figure 3 there is a spectral picture, observed when the sensor is moved above the layered medium, inside of which there is a 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) mW. Area 1 and area 2 on the diagram, where the voltage level falls up to 115 mW, correspond to the walls of the parallelepiped. These changes in the signal amplitude make 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 4mW, it makes 3 percent from the signal level, corresponding to the nondefective zone of the sample.

Judging by the diagrams in Figure 4, 5 one can notice the amplitude changes when the transformer is being tested at other frequencies. These changes, in case when the frequency is increased, are determined by the lesser penetration depth of the eddy currents into the depth of the layered structure and by the increasing influence of different small cracks on the surface of the layered structure. If the frequency decreases the eddy current field goes much deeper into the investigated object. Thus, the influence of the model defect practically cannot be traced. At the frequency of 6000 Hz (Figure5) the model defect is found as before but now the amplitude fluctuations in the nondefective zone of the sample exceed the signal level that corresponds to the nondefective zone of the sample, by 7 per cent. When the controlled object is investigated with unknown defects, such amplitude changes can be interpreted as defects by mistake. At the probing frequency at 500 Hz (Figure 6), the amplitude fluctuations in the nondefective zone are insignificant but the amplitude changes in the defective area do not exceed 3 per cent from the signal level, corresponding to the nondefective zone of the sample.
When laboratory or production measurements are carried out such amplitude fluctuations can be caused by external influence and not by defects.

**Figure 3.** A spectral picture, observed when the sensor is moved along the layered medium with a defect. The transformer frequency – 1000 Hz. 1, 2 – the sides of the parallelepiped, 3 – a nondefective zone of the sample.

**Figure 4.** A spectral picture, observed when the sensor is moved along the layered medium with a defect. The transformer frequency – 6000 Hz.

When the operating frequency of the device exceeds the pointed limits the results of the measurements will be skewed by the amplitude fluctuations, caused by microcracks on the surface of the sample or by decreasing the localization of the field that is inside the layered structure. The amplitude changes, caused, in this case, by the microcracks on the sample surface, are much higher than the amplitude changes, caused by the defect directly.
Figure 5. A spectral picture, observed when the sensor is moved along the layered medium with a defect. The transformer frequency – 500 Hz.

The defect was 600 micrometers from the sensor in the depth of the layered structure. Right up to the depth of the defect location that was 1400 micrometers we could trace a direct dependence between the response of the transformer and its position above the defect. Stating the amplitude changes of the transformer response, determined by the defect, it is possible to change the current frequency in the actuating winding so that eddy currents could concentrate in the composite layers above the defect. The inverse problem solution enables us to define the occurrence depth of the defect. After the typical defect calibration of Fourier analyzer we can use the MNME – 5FA device to diagnose multi-layer composite materials which are from 1 up to 1400 micrometers thick.

4. Conclusion

Therefore, the results of the experiment demonstrate the wide range of possibilities provided by the eddy-current method in the study of defects concealed in metal-insulator-metal type structures. Earlier the eddy current control method could be used to investigate only surface defects (such as cracks, cuts and other examples of metal surface discontinuity), now, due to using subminiature VCTs and special software, it is getting possible to localize the magnetic field in a small zone of the controlled object and to achieve a high degree of the (magnetic) field penetration depth into the investigated object. The only condition is to choose a proper field frequency, created by the actuating winding.

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