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Study of conductive materials by means of a multi-frequency measurement system based on microminiature eddy current transformers

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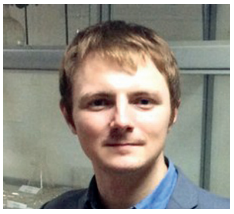
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Abstract. *A measurement system has been developed that is based on an eddy current transformer and allows evaluating the applicability of the eddy current method for detecting local defects of products made of an aluminium-magnesium alloy. The paper describes the design of a microminiature eddy current transformer (ECT) with an excitation, measurement and compensation windings that uses a pyramidal core that enables localization of the magnetic field within an area about 2500 square мм. The distinctive feature of the measurement system consists in the ability to detect deep defects (up to 5 mm). The paper sets forth the primary parameters of the transformer that enable the magnetic field localization (shape, material and size of the core, number of the windings and number of loops). It also describes the process of preparation and application of several ECTs with different core and winding parameters. That allowed the ETCs generating different electromagnetic fields and reacting to the changes in that field with varied efficiency. Optimal ECT size for identifying defects in aluminium-magnesium alloys was established (pyramidal shape of the core, base 400 мм in diagonal, edge 4 mm long, 20 loops of the excitation winding, 200 loops of the measurement winding, 200±40 loops of the compensation winding). The paper describes the design of the measurement system and the measurement method that allows finding defects with the linear size of 0.25 mm situated 5 mm below the surface or more depending on the signal received from the eddy current transformer. The measurement system includes two microminiature transformers controlled by special C++ software. Voltage to the excitation winding was applied by an integrated rectangular wave generator. This setup allowed creating a magnetic field with minimal noise. The voltage of the excitation winding varied from 2 to 3V. The transformers output signal was processed in a hardware filtering system described in this paper. The distinctive feature of the measurement system is the synchronous change of the measurement signal generation frequency and filtration frequency. That enables efficient extraction of the useful signal that carries information on the defects of the tested object. The paper sets forth data that demonstrate the dependence of the amplitude part of the signal from the defects of various sizes and experimentally establishes the limit defect sizes under which such measurements are possible. The research covered objects in the form of aluminium-magnesium plates (94% Al, 3% Mg). Amplitude changes due to the linear sizes of the defects and the depth of their situation. The nature of such changes allows identifying the defects' parameters. Depending on the size and depth of the defects, the change of the amplitude associated with the transformer passing above the defect were from 2.5V (for a defect 0.25 mm wide situated 1 mm from the surface) to 0.1V (for a defect 0.25 mm wide situated 5 mm from the surface).*

Keywords: *eddy current transformer, aluminium-magnesium, core, defect, alloys.*

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Introduction

Methods and means of non-destructive eddy current testing are used for detecting defects in products made of any conductive materials. Such measurement allows – if necessary – testing each manufactured product at the factory.

The duraluminium and aluminium-magnesium alloys are widely used in today’s production, most widely in the aerospace and other industries. Due to the combination of their strength and light weight, those alloys are also widely used in the production of high-speed trains including Shinkansen, as well as a number of other machine construction industries. Duraluminium is also frequently used in the electrical, chemical and food industries, as well as radio engineering and construction. The D16AM alloy is used in extreme conditions of low temperatures, the D16T duraluminium is highly ductile, which is the reason of its widespread application in shipbuilding.

Quality control of such alloys and products made out of them becomes a relevant matter. Research in this area is in constant development.

The analysis of current research shows a trend to size reduction (miniaturization) of eddy current transformers (ECT) used in quality control of alloys [1-6]. One of the methods allows developing 5*5 mm transformers with the wire diameter of 0.15 mm. However, such transformers do not enable the required depth of magnetic field penetration and localization for local measurement in heterogeneous conductive media. Ferrite cores are often used in order to increase the magnetic field localization. This design solution ensures a significant reduction of eddy current scattering. It also enables the depth of field penetration of 2.5 mm.

There are several known designs of laid-on eddy current transformers, of which the working surface is made in the form of a plain surface or a hemisphere. This surface ensures satisfactory contact between the transformer and the tested surface, yet the voltage applied to the transformer significantly depends on the curvature of the tested surface. Additionally, the transformer’s operation is significantly affected by the edge effect, which prevents testing parts of complex shape and small size. In order to solve this problem, ECT is often equipped with an additional core, one of the ends of which is shaped as a truncated cone. The disadvantage of this solution is that despite the higher magnetic field localization the core design is significantly more complex. That decreases the measurement accuracy of the controlled parameter due to the fact that the transformer’s input signal significantly depends on the interaction between the two cores that can unpredictably affect the enhancement of the eddy current field that carries the information on the tested objects [7].

Manufacturing such instruments requires the deployment of special production lines, which causes a significant growth of the price of the final product. In order to reduce the instrument’s price it has been suggested to substitute the expensive hardware units with PC software.

Sensor design

A microminiature eddy current transformer has been developed for local testing of physical parameters as part of research of the properties of aluminium alloy plates and welds. The advantage of this transformer (that the comparable devices do not have) is the capability to perform local measurements within areas of about hundreds of мms and about 5 mm deep. The measurement parameter is the conductivity of the material and its distribution over the surface and depth of the tested object [8].

The excitation winding with the diameter D_1 = 0.12ч0.13 mm of the microminiature transformer consists of 10 loops of copper wire with the cross-section area of 5 $мm^2$. The measurement winding with the diameter of 0.05ч0.08 mm consists of 130 loops of copper wire with the cross-section area of 20 $мm^2$. In order to minimize the effect of the excitation winding on the resulting signal, the design includes a compensation winding with the cross-section area of 5 $мm^2$ that is connected to the measurement winding in such a way that the voltage of the excitation winding is calculated based on the result. The winding is placed around the pyramidal core made of ferrite 2000 NMZ with the relative magnetic permeability of $\mu_{max= 500}$ or (if higher magnetic field localization is required) of 81NMA alloy annealed using a special technique. The core is a four-face pyramid 1 mm high and 0.2 mm-long base edges. The measurement winding is at the tip of the pyramid, which improves the magnetic field localization. The performance characteristics of the developed transformers enable efficient magnetic field localization and applicability for analysis of defects 250 мm or larger in size. The transformers also ensure significant depth of penetration into the tested object when operating at sufficiently low frequencies.

A laid-on ECT consists of a pyramidal core. The pyramidal cores are covered with wire windings. The windings are treated with a compound at the infiltration temperature of 200 degrees Celsius; the wire diameter is $1.5Ч10^{-6}$ m. The measurement winding is at the tip of the pyramid; the winding diameter is 0.05 mm; the number of loops varies between 100 and 200. In the middle of the pyramid is the excitation winding that consists of one loop. The compensating winding is on a movable frame and consists of 100 loops. 10 ECTs were created and tuned in order to subtract the voltage induced by the generator winding to the measurement winding. The aim of creating various ECTs is obtaining a magnetic field of different strengths, hence the

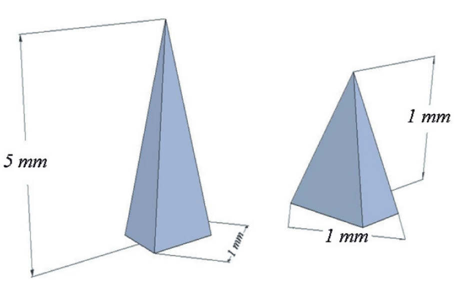


Figure 1. Cores of different sizes

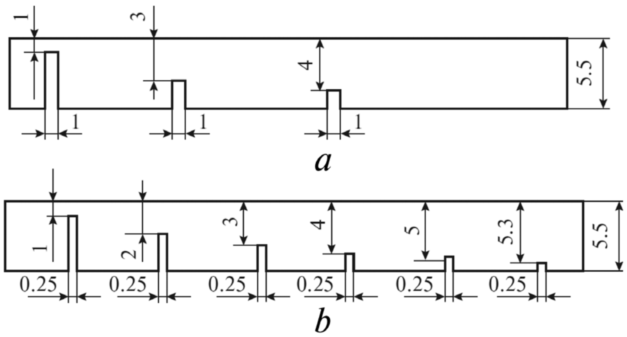


Figure 2. Plates nos 1 and 2 (side views)

size differences from core to core. The correlation between the base diagonal and edge of the pyramid varies from 1:1 to 1:10 (Fig. 1).

The ECTs designed using cores having identical correlations between the base diagonal (400 мm) and edge length (4 mm) were calibrated using semiconductors with known conductivity. Thus, the ECTs have identical geometrical parameters of the cores and identical loop counts of the excitation (20 loops), measurement (200 loops) and compensating (200±40 loops) windings.

The measurement system based on a microminiature eddy current transformer operates in the following manner. The computer software operates the generator that generates a series of rectangular voltage pulses with the repetition frequency f1 required for the operation of the eddy current transformers. The voltage pulses from the generator outputs are transmitted to two integrators connected in series and then to the input of the power amplifier. From the amplifier outputs the pulses are sent to the excitation windings of the eddy current transformers. The difference between the output voltages of the measurement windings of the transformers carries the information on structural heterogeneity of the tested object that falls within the coverage of the eddy current transformers. It is identified and amplified in a special microphone amplifier. The signal, having passed two serially connected quality low-frequency filters and two serially connected selective amplifiers, arrives to an amplitude detector. Then the signal is transmitted to the computer via an analog-to-digital amplifier. Owing to simultaneous control of the frequency of the generated signal at the excitation winding and cut-off frequency of the filtration system, as well as selective amplification the useful signal is extracted. The latter carries information on the distribution of conductivity within the object, including its defects [9-10]. Software control allows changing the operation frequency of the measurement system in such a way as to enable reliable recording of the signal received from the measurement winding.

Experimental results

In order to evaluate the maximum depth of situation and linear dimensions of defects that justify the use of eddy current test method, samples with model defects were prepared.

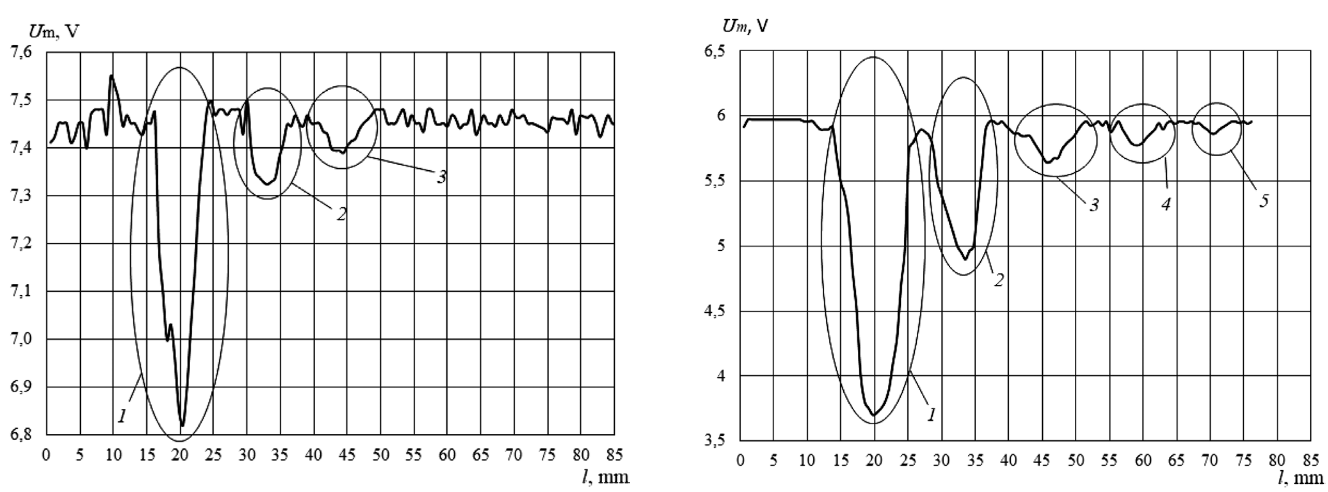
The samples were Al-Mg alloy plates (94% Al, 3% Mg). The thickness of the first plate was 5.5 mm, it contained three defects in the form of 1 mm thick cuts 1, 3 and 4 mm deep (Fig. 2.a). The thickness of the second plate was 5.5 mm, it contained six defects in the form of 0.25 mm thick cuts 1, 2, 3, 4, 5 and 5.3 mm deep (Fig. 2.b).

In order to identify the sensor's sensitivity to defects inside metal, the scanning was performed from the defect-free side of the sample.

During the experimentation with the first plate, the amount of induced voltage at the excitation winding of the transformer was 2V.

The research results of the first plate with 1 mm defects under signal frequency of 500 Hz and amplitude of 2V ensured evident detection of all three cuts based on the drop of signal amplitude (Fig. 3.a): for the first defect it was about 0.75V, for the second one it was 0.2V, and 0.1V for the third one.

The research results of the second plate under signal frequency of 500 Hz and amplitude of 3V ensured the detection of five defects (Fig. 3.b.). The drop of signal amplitude



a) b)

Figure 3. Scanning results of plates no. 1 (a) and no. 2 (b). U is the voltage applied to the measurement winding of the voltage transformer, l is the coordinate of the transformer relative to the beginning of the tested object

for the first defect was about 2.5V, 1V for the second one, 0.4V for the third one, 0.2V for the forth one and 0.1V for the fifth one. No signal response change was registered for the sixth defect due to its small value.

The results of the experiment show the efficiency of the developed measurement system for detection of defects 0.25 mm wide or higher situated up to 5 mm below the surface.

Conclusion

The developed measurement system based on micro-miniature eddy current transformers enables higher electromagnetic field localization compared to the previously available systems.

The pyramidal shape of the core, a system of bandpass filters and selective amplification enabled a significant reduction of the noise level and significant penetration depth of eddy currents into the object under examination. The developed eddy current transformers enable efficient scanning of welds of titanium alloys and quality analysis. Scanning of defects in aluminium alloys allows detecting defects with linear size of about 100 мм situated up to 5 mm deep from the surface. The developed software automates the measurements and provides for real-time modification of the device's operation frequency.

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