Subminiature Eddy-Current Transducers for Conductive Materials and Layered Composites Research

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Abstract

The measuring system based on subminiature eddy-current transducers has been developed to carry out local investigations of aluminum-magnesium alloy plates, titanium and layered metal-insulator-metal composites for flaws. The Delianna filter has been modified to allow the significant increase of signal-to-noise ratio. A scheme that uses a computer as a generator and receiver of signals from windings is proposed. It is capable of automatically changing the filtering cutoff frequency and operating frequency of the device. The transducer has been tested on a number of aluminum-magnesium alloy plates, titanium and layered metal-insulator-metal composites with flaws. The article presents data on the relationship of eddy-current transducer re-sponse to the presence of flaws in alloys as hidden holes at signal frequencies comprised between 300÷700 Hz on an exciting winding.

1 Introduction

Non-destructive testing of a number of structures occupies a special place in modern materials science. Layered composite metal-insulator-metal, aluminum alloy (aluminium-magnesium and duraluminium), titanium alloys welds are among these objects. Layered metal-polymer composites of metal - insulator – metal type are widely used as sound and thermal insulation of aircraft, surfaces of equipment and devices reflecting the radiation, materials for manufacturing of printed circuit boards. Such composites contain one, two or more metallic layers separated by dielectric layers. Titanium and its compounds are largely used in aviation equipment, shipbuilding, chemical industry, important units of machines. Technical titanium is used for the production of products intended for the use in aggressive environments. However bad-quality titanium welds can lead to the destruction of the products made from this material. Aluminum-magnesium (AMG) alloys are the main structural materials in aircraft and astronautics, thanks to good combination of strength and lightness. Duralumin is used in the electrical engineering, chemical and food industries. They are also used in manufacturing of ventilation systems, in radio engineering, in construction. For example, the D16AM alloy brand is used in extreme cold environments. D16T duralumin is flexible and therefore it is used in shipbuilding.

Despite our great experience in using vortex-current transducers (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 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 compos, thickness measuring, profilometry, tension measuring of permanent and variable magnetic fields and conductivity measuring of un ferromagnetic 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 cur-rent 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. 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 [5].

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]. 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].

With the development of computer equipment, numerical methods have become a frequent practice for solving tasks in non-destructive testing based on the interaction of electromagnetic fields with defects.

Rigorous numerical methods were mainly used for solving two-dimensional tasks with the application of integral equations and finite elements.

V.E. Shaternikov [10] suggested generalizing theoretical calculation models for complex shapes products. Based on these models, the solutions for the method of quasi-conformal mappings were made and the algorithms for calculating the output parameters of ECP with arbitrary section windings were designed.

V.F. Muzhitskiy [11] proposed a three-dimensional mathematical model based on the representation of secondary charges by the surface currents, flowing along the side edges of the defect. The surface current density was linked to the magnitude of the initial magnetic field. V.F. Muzhitskiy analyzed the basic interaction laws of the defects under normal magnetization of the controlled objects and under the longitudinal magnetization at an angle to the side edge of the defect [12].

An approximate calculation method of the attachable ECP was suggested by K. Shkarlet [13] in order to control flat-shaped conductive items (the model is a round coil with alternating current over a flat two-layer conductive object). It allowed to disclose the basic laws of the electromagnetic field distribution of the model under study and to find effective signal processing methods.

The efforts of Russian and foreign scholars led to the development of a large number of other methods for signal processing in addition to the above mentioned amplitude and phase, phase and amplitude, in order to separate the information about the measured parameter and the detuning from confounding factors - autogenous, variable frequency, multifrequency, modulation and etc [14-16].

The development of eddy-current measuring system used for detecting defects in layered composites, aluminum alloys, able to assess the quality of titanium alloy welds is an urgent task. Since eddy-current testing method is insensitive to non-conductive layers of paint, it can be used to diagnose the details with varnish-and-paint cover.

2 Materials And Methods

One of the well-known drawbacks of eddy-current flaw detection is the ability to control the quality of a relatively thin surface layer of a conductive material. Up-graded design of the measuring system includes two differentially included subminiature transducers. Such a construction allows to detect defects at the depth up to 5 mm due to its small size and the special shape of the cores.

Eddy-current measuring system has been developed on the basis of super small eddy-current transducer [17-21]. Controlled parameter is the value of electrical conductivity of the material and its distribution over the surface and the thickness of the tested object. Eddy-current transducer is connected to a series of bandpass filters and amplifiers, managed using a PC working on the bases of special software. The soft-ware controls voltage supply to transducer generator winding, and also reads voltage values from measuring winding in conventional units, which are then converted into electrical conductivity values, given the preliminary calibration.

Exciting subminiature transmitter winding consists of 10 turns, and its diameter is 0.13-0.12 mm. Measuring winding consists of 130 turns and its diameter is 0.05-0.08 mm.

In order to minimize the influence of the exciting windings on the received signal, compensating winding is included into the circuit. The compensating winding is connected to the measuring winding so that the voltage of the exciting windings can be subtracted. The compensating winding consists of 20 turns. Copper wire 5 μm thick is used to the wind the turns. The windings are wound on pyramidal shape core. The core is made of HM3 2000 ferrite with initial magnetic permeability of the value of μ_{max}=500. The scheme of the subminiature eddy-current transducer (ECT) is shown in figure 1.

Specifications of developed transducers allow to efficiently localize magnetic field within the limits of 2500 μm^2 and to provide considerable depth of its penetration into the object under study.

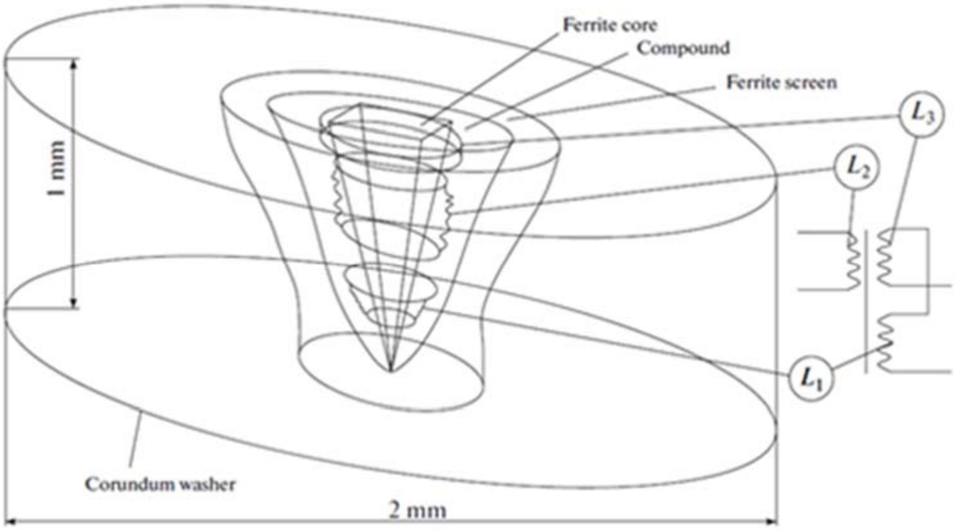

Figure 1: Scheme of eddy-current transducer. L1 - measuring winding L2 - the exciting winding L3 - compensation winding.

Digital signal from the virtual oscillator is fed to analog-to-digital transducer (ADC) input of sound card, after which the analog signal through the power amplifier is fed to the exciting winding transducers. Passing through the excitation windings, sine wave signal creates electromagnetic field which induces voltage in the measuring windings of eddy-current transducer. The voltage depends on the parameters of the object under control. The transducers are included counter-currently, whereby the resultant signal represents the difference between two values of voltage. This signal is fed to a series of amplifiers and bandpass filters, and then supplied to the micro-phone input of the sound card and then through the preamplifier - to the input of an analog-to-digital transducer (ADC) of sound card. The analog signal is converted to the digital one and transferred to software processing and control unit. The processing and control unit records the level of the digital signal in conventional units corresponding to the difference between the voltages on the measuring windings.

This level is assumed to be zero, it corresponds to the signal that takes place when both transducers are situated over the defect-free sections the object under control.

Using computer sound card makes it possible to carry out scanning of electromagnetic field frequency variation which is generated by transducer excitating winding in the range of 20Hz to 2kHz. The developed measuring system allows effective investigate the metal-insulator transitions in miniature metal-polymer composite objects. Similar composites may include several metal layers separated by thin dielectric layers of polymer.

The typical defects of such materials are, for example, the disturbance of layers continuity and the formation of link between the layers.

3 Materials And Methods

3.1 Layered Composites

To demonstrate the proposed method operability the structure of alternating aluminum foil of 100 µm thick and paper of 100 µm thick has been used. As a defect model between the layers a hollow parallelepiped with a wall of 300 µm thick has been placed. The defect was at a distance of 600 µm from the sensor in the depth of the layered structure. In figure 2. there is a spectral picture, observed when the sensor is moved above the layered medium, inside of which there is a defect.

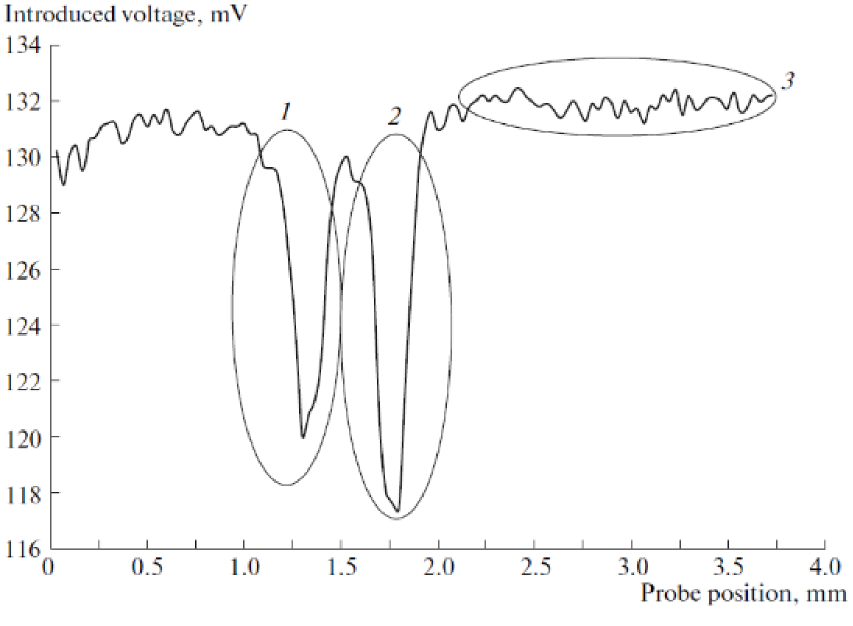

Figure 2: Picture observed when the probe moves along the layered medium with a defect. The frequency of the transducer is 1000 Hz: (1, 2) walls of the parallelepiped, (3) defect-free part of the sample

The signal level from the measuring winding characterizes conductivity values on the survey section. For fundamental operating frequency of 1000 Hz the voltage level included in the measuring winding was 130 ± 2 mV. Areas 1 and 2 on the graph where in voltage level drop is up to 115 mV correspond to the walls of the parallelepiped. This change in the signal amplitude is equal to 11% of the signal level, corresponding to the defect-free section of the sample. At the same time the fluctuations of signal amplitude at the defect-free section does not exceed 4mV, representing 3% of the signal corresponding to the defect-free region of the sample.

When operating frequency of the device is beyond the given limits the results of the measurements will be distorted by amplitude fluctuations caused by microcracks on the surface of the sample or by the decreasing of field localization inside the layered structure. As seen from the graph, 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. Right up to the depth of the defect, equal to 1400 µm, there is a clear dependence of the response of transducer, on the position of the transducer over the defect. By fixing change in amplitude response in the converter caused by a defect, it is possible to change the frequency of the current in the exciting winding so that the eddy-currents are concentrated in the layers of composite placed above the defect.

The solution of the inverse problem allows to determine the depth of the defect. After calibration, The Fourier analyzer for typical defects, can use the "IENM-5FA" for the diagnosis of composite laminates with a thickness of 1 to 1400 µm.

3.2 Welds in titanium alloys scanning

In order to demonstrate the performance of the device to determine the quality of titanium alloys welds a series of measurements. The samples were titanium plates, combined by means of welds. The thickness of the plates equaled 5 mm. The weld width equaled 5 mm.

The tested feature is the voltage induced by the eddy-current field developing in the object under control. The sensor calibration was performed before the beginning of measuring operations. It consisted in the detection of the inserted voltage from the defect-free section. In the experiment the calibration section was chosen on the titanium defect-free plate similar to the tested one. The calibration was performed at different frequencies. At the same time the variation of the frequency in the 500 – 2000 Hz range at the pitch of 100 Hz was performed. The further scanning was con-ducted by means of the sensor moving through the length or breadth of the weld or crosswise the defective section. During the experiments, it was found out that the optimum frequency range of the induction winding electromagnetic field for titanium study equaled to 1500 – 1700 Hz.

In the experiment scanning was conducted crosswise the weld. The length of the weld was 150 mm. The seam was divided into 30 sections, 5 mm each, so that the signal from both the weld and directly from the plate could be read. The dependences received were averaged. The results of the experiment are presented in figure 3. (a)., 3.(b). (A1 – A2 correspond to the edges of the weld seam).

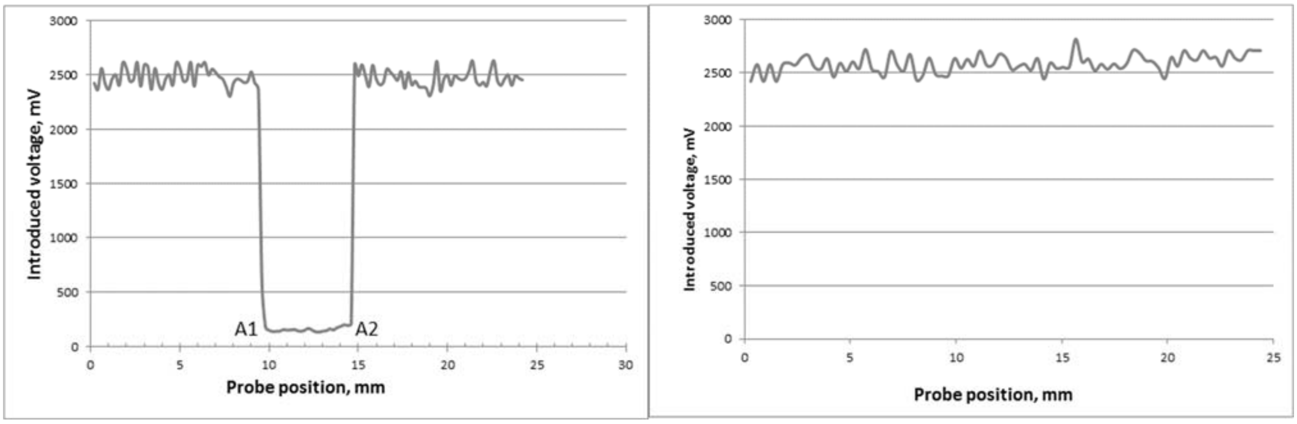

Figure 3: (a) Results of scanning Sample №1. b) Results of scanning Sample№2.

In the given sample the influence of a deficient weld on the inserted voltage is clearly traced by the significant drop in the signal amplitude in the weld area in comparison with the plate area.

On the bases of the experiment the conclusion about the low quality of Sample 1 weld was made. The low quality of welding was confirmed directly by the weld cut-ting. Sample 2 scanning showed the absence of the signal amplitude deflection within the weld seam. The weld of Sample 2 cutting showed the high quality of welding

3.3 Plates linking without welding

In order to simulate such amplitude drop an additional experiment was conducted. During the experiment, two titanium plates of the same thickness were linked tightly, the area of the junction being scanned afterwards. The results of the experiment are presented in figure 4

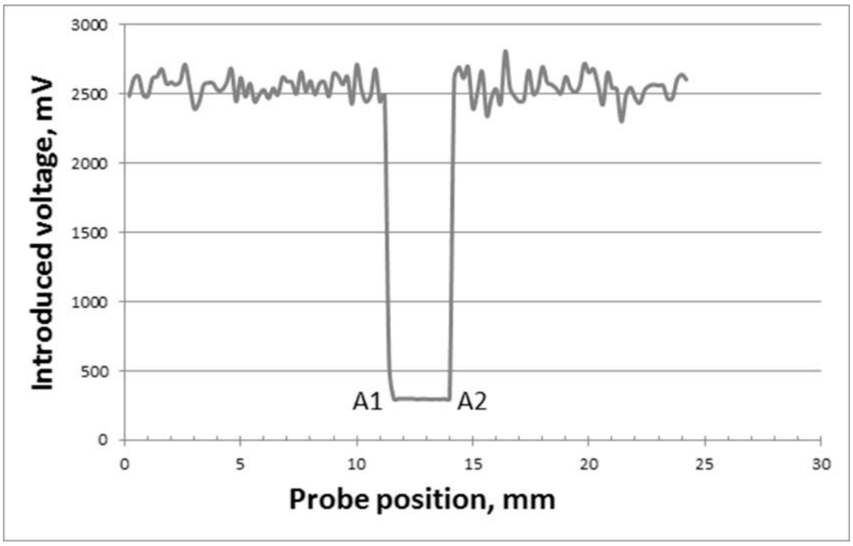

Figure 4: Voltage value to the measuring winding of the transducer, while scanning in the area of two plates junction. Scanning frequency is 1600 Hz. A1 – A2 correspond to the edges of the area where the junction influences the inserted voltage.

The dependence analogous to that observed in Picture 3.b. in the Sample weld section was received in the experiment. The signal amplitude in the area of the junction changed by times in comparison with the signal amplitude from the plates them-selves

3.4 Aluminum-magnesium alloy with model defects scanning

Samples with model defects were prepared in order to assess the maximum depth and the linear dimensions of the defects, for the detection of them it is advisable to use the eddy-current inspection method.

The samples were plates of Al-Mg alloy. The thickness of the first plate was 5.5 mm. The plate contained three defect in the form of slits 1 mm thick at the depths of 1, 3 and 4 mm. The thickness of the second plate was 5.5 mm. The plate contained six defects in the form of slits of 0.25 mm thick at the depths of 1, 2, 3, 4, 5 and 5.3 mm.

In order to determine the sensitivity of the sensor to the defects at the depth of the metal, scanning of defect-free side of the sample was performed. During the experiments with the first plate the magnitude of the inserted voltage to the exciting winding of the transducer was 2 V.

The results of the defectoscopy of the first plate, with the defects of 1 mm thick at the frequency of 500 Hz and 2 V signal amplitude allowed to detect all three slits by means of signal amplitude drop figure 5

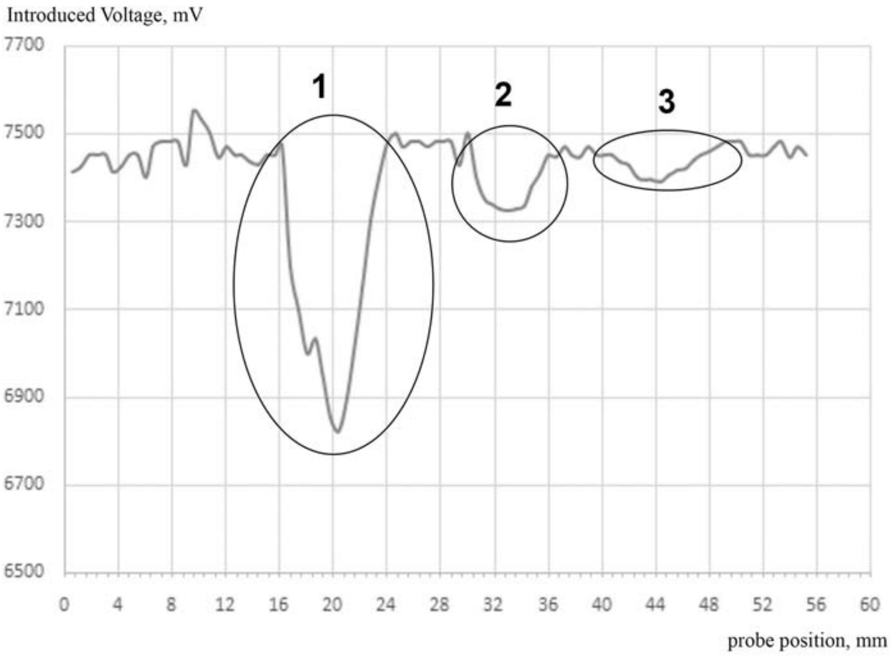

Figure 4: Results of the plates №1. 1, 2 and 3 scanning - the defects numbers.

Signal amplitude drop in the first defect was 0.75 V, in the second one - 0.2 V, in the third one - 0.1 V.

With increase in amplitude of the signal at the exciting winding, the output signal from the measuring system will be exceeded and the results will be significantly distorted. To improve the localization of the magnetic field, the measuring system must be significantly modernized. To increase the power of the electromagnetic field by increasing the voltage U_e at the exciting winding from 2 to 3.5 V, a second eddy-current transformer is introduced in the system. The results of defectoscopy at the frequency of 500 Hz and 3 V signal amplitude allowed to reveal five defects figure 6.

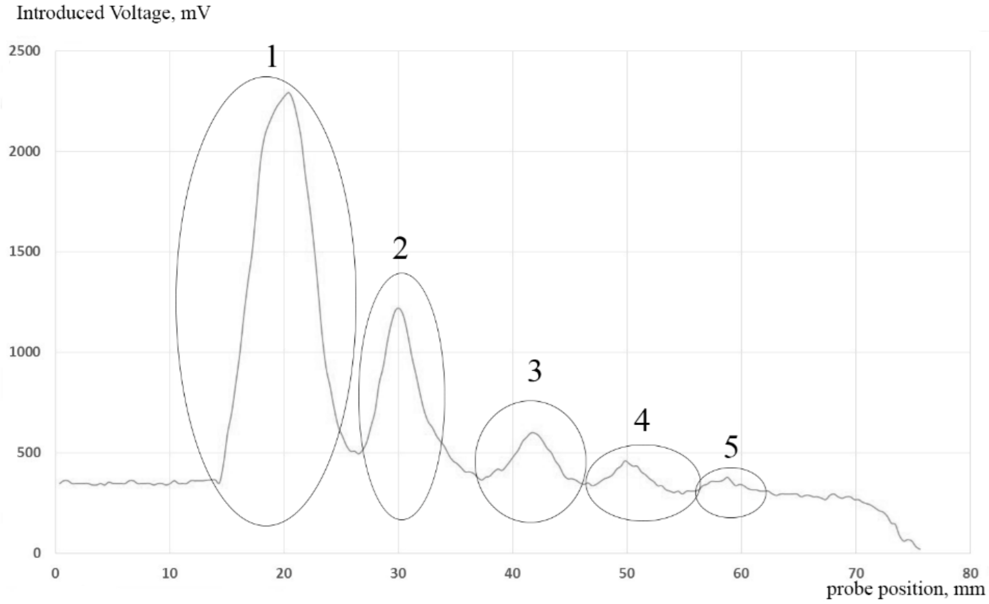

Figure 4: Results of plate №2 scanning.

The signal amplitude drop at the first defect was 2.5 V, at the second defect – 1 V, at the third one - 0.4 V, at the fourth one - 0.2 V, at the fifth defect - 0.1 V. The changes in the response signal when passing over the sixth defect were not fixed.

The experimental results show the effectiveness of the developed measuring system to find defects of the thickness from 0.25 mm at the depth of 5 mm.

4 Conclusions

The developed measurement system based on eddy-current subminiature transducers, allows greater localization of electromagnetic field in comparison with previously known similar systems. The pyramidal shape of the core, the system of band pass filters and selective amplification allow to reduce interference and achieve significant penetration depth of eddy currents in the object under study. The developed eddy-current transducers can effectively produce scanning of titanium alloys welds and analyze their quality. Defects scanning in aluminum alloys can detect defects with linear dimensions of the order of 100 microns at the depth of 5 mm. The developed software allows to automate measurements and make rapid changes in the operating frequency of the device.

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