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EDDY-CURRENT METHODS

Flaw Detection of Alloys Using the Eddy-Current Method

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Abstract—A subminiature transformer eddy-current transducer (ECT) that is intended for the study of different nonuniform materials, alloys, miniature parts, printed-circuit boards, and microscopic defects has been designed. A block diagram of the transducer is given and its basic technical characteristics ensuring localization of the magnetic field on areas of approximately 50 × 50 μm are stated. 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 designed measuring system eliminates the main drawback of eddy-current transducers (the small area of the electromagnetic field), simultaneously significantly reducing the noise level due to the use of high-quality amplifiers and filters, and searches for defects in printed circuit boards, metal–dielectric–metal-junctions, and alloys of different metals. A measurement procedure that allows one to perform high-accuracy monitoring of flaws in different alloys is described. The eddy-current transducer was successfully tested on several objects, e.g., a 5.5-μm thick Al–Mg alloy and welded seams of 5-mm thick titanium plates, as well as other objects. The dependences of the ECT signal on the flaws in these structures are given.

Keywords: flaw detection, eddy-current transducer, titanium, aluminum–magnesium, localization of the electromagnetic field, filtering

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INTRODUCTION

Titanium and its compounds are applied in large volumes in aeronautical engineering, shipbuilding, the chemical industry, in critical assemblies of different mechanisms, and for manufacturing products that are intended for operation in aggressive conditions. Low-quality welded seams can lead to the destruction of products that are made of this material. Due to a good combination of strength and lightness, Al–Mg alloys are used as structural materials in aviation and cosmonautics, during the production of high-speed trains (e.g., Shinkansen trains (Japan)), in other machine-building sectors, and in the electrical, chemical, and food industries.

The quality control of these alloys and their products is an urgent problem; investigations are making progress in this direction [1–7]; for example, L. Barbato et al. [2] scanned two aluminum plates with a model flaw in the center and tested cracks between the plates. The diameter of the measuring winding was 7 mm. The scanning was performed at 1 and 5 kHz. In this case, the penetration depth of eddy currents into the studied plates at the above-mentioned frequencies was 3.82 and 1.71 mm.

Experimental methods based on two eddy-current transducers that operate in the differential mode have been developed [3]. Similar connection circuits significantly decrease parasitic noise that arises during high-speed scanning in real time.

The analysis of a recent investigations points to the miniaturization tendency for eddy-current transducers. Transducers with a size of 5 × 5-mm and a 0.15-mm diameter of the wire have been designed [5]. However, they do not provide the required penetration depth and localization of the magnetic field that are necessary for local measurements in different nonuniform media. Ferrite magnetic-field concentrators are often used to increase the area of the magnetic field. A similar design provides an advantage that is related to the absence of the scatter of eddy currents [6]. In addition, a 2.5-mm penetration depth is attained.

In this connection, the challenge is to design subminiature eddy-current transducers that provide a penetration depth of up to 5 mm and an area of 2500 μm^2. Since the eddy-current inspection method is insensitive to non-conducting paint layers, it can also be used for diagnosing parts with paint coats [7].

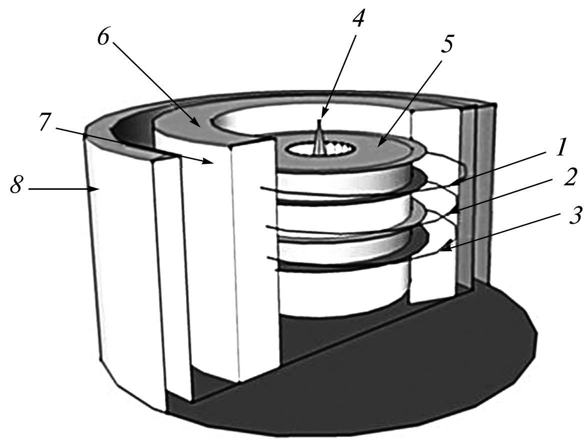

Fig. 1. A block diagram of the eddy-current transducer.

THE DESIGN OF A SUBMINIATURE EDDY-CURRENT TRANSDUCER AND MEASURING SYSTEM

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 μm^2 and provide penetration of the magnetic field into the studied object at a depth of up to 5 mm [8–10].

The eddy-current transducer (Fig. 1) is a transformer with measuring (*1*), exciting (*2*), and compensation (*3*) windings and a magnetic circuit *4*, which is located inside the cylindrical platform *5* with tracks that are cut on the external side for windings. The platform is impregnated with a compound *6* at a temperature of 200°C to prevent the disintegration of the windings when the ferrite screen *7*, which is intended for the localization of the electromagnetic field on the tested object, is put in place. From the outside the transducer is contained in a corundum washer *8*, which protects the core *4* from contacting the tested object.

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_1 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. Due to the simultaneous control of the generated signal frequency at the exciting coil and the cutoff frequency of the filtering system and the selective amplification, the useful signal, which contains information on the electric conductivity distribution inside the object, in particular, on possible flaws of the object, is detected. 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.

SCANNING THE WELDED SEAMS OF TITANIUM ALLOYS

A set of measurements was performed on VT1-0 technical titanium plates that were connected by welded seams to demonstrate the appropriateness of the proposed unit for the determination of the quality of welded seams. The plate thickness was 5 mm and the width of the welded seam was 5 mm. Before the measurements were started, the transducer was calibrated. The calibration consisted of the determination of the induced voltage from the flaw-free sector. 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 titanium plate. The calibration was performed at different frequencies. The frequency was varied from 500 to 2000 Hz with a 100-Hz step. The subsequent scanning was carried out by displacing the transducer along or across the welded seam or across the flaw area. During the experiments it was determined that the optimal frequency range of the electromagnetic field of the exciting winding for studying titanium is approximately 1500 Hz. To determine the uniformity of welded seams, the samples were scanned along the surface of the welded seam. In this case, any substantial amplitude changes of the signal were not detected. The experimental data indicate that the structure of the welded seam is relatively uniform, while there is no information on the seam quality, i.e., on the uniform distribution of flaws of the welded seam or on its lack of defects.

In the next experiment the scanning was carried out across the welded seam. The length of the welded seam was 150 mm. The seam was divided into 30 regions and the length of each region was 5 mm in order to read the signal from both the seam itself and directly from the plates. The obtained dependences were averaged (Figs. 2a and 2b).

In sample no. 1 the influence of the poorly welded seam on the induced voltage is clearly seen via the substantial drop of the signal amplitude in the area of the welded seam, as compared with the plate area. The poor quality of the welding was also confirmed when the welded seam was cut. The scanning of sample no. 2 found no deviation of the signal amplitude within the welded seam. Cutting the welded seam of sample no. 2 demonstrated the high quality of the welding.

SCANNING AN ALUMINUM–MAGNESIUM ALLOY WITH MODEL FLAWS

For the evaluation of the maximum depth of occurrence and linear sizes of flaws, for which it is expedient to use the eddy-current inspection method, samples with model flaws were prepared.

The samples were Al–Mg alloy plates (Al is 94% and Mg is 3%). The thickness of the first plate was 5.5 mm. It contained three flaws in the form of a 1-mm thick slot at depths of 1, 3, and 4 mm. The thickness of the second plate was 5.5 mm. It contained six flaws in the form of a 0.25-mm thick slot, at depths of 1, 2, 3, 4, 5, and 5.3 mm.

Scanning from the flaw-free side of the sample was carried out in order to determine the sensitivity of the transducer to flaws in the metal depth.

During the experiments with the first plate the induced voltage on the exciting plate of the transducer was 2 V.

The results from the first plate with flaws with a thickness of 1 mm allowed us to explicitly detect all three slots from the drop in the signal amplitude at 500 Hz and signal amplitude of 2 V (Fig. 3). This was approximately 0.75 V at the first flaw; 0.2 V at the second flaw, and 0.1 V at the third flaw.

The results of the second plate at 500 Hz and a signal amplitude of 3 V allowed us to detect five flaws (Fig. 4a). The signal amplitude drop at the first flaw was 2.5 V. At the second flaw the signal amplitude drop was 1 V, at the third flaw it was 0.4 V, at the fourth flaw it was 0.2 V, and at the fifth flaw, 0.1 V. A change of the signal response during transmission over the sixth flaw was not detected due to its low value. The value of using a system of amplifiers and band-pass filters in search for deep-occurrence flaws is shown in Fig. 4b. The flaws at depths of 3 mm and more are virtually unnoticeable on the background of the noise.

The experimental results show the efficiency of the designed measuring system for searching for flaws with a thickness from 0.25 mm that lie at depths of up to 5 mm.

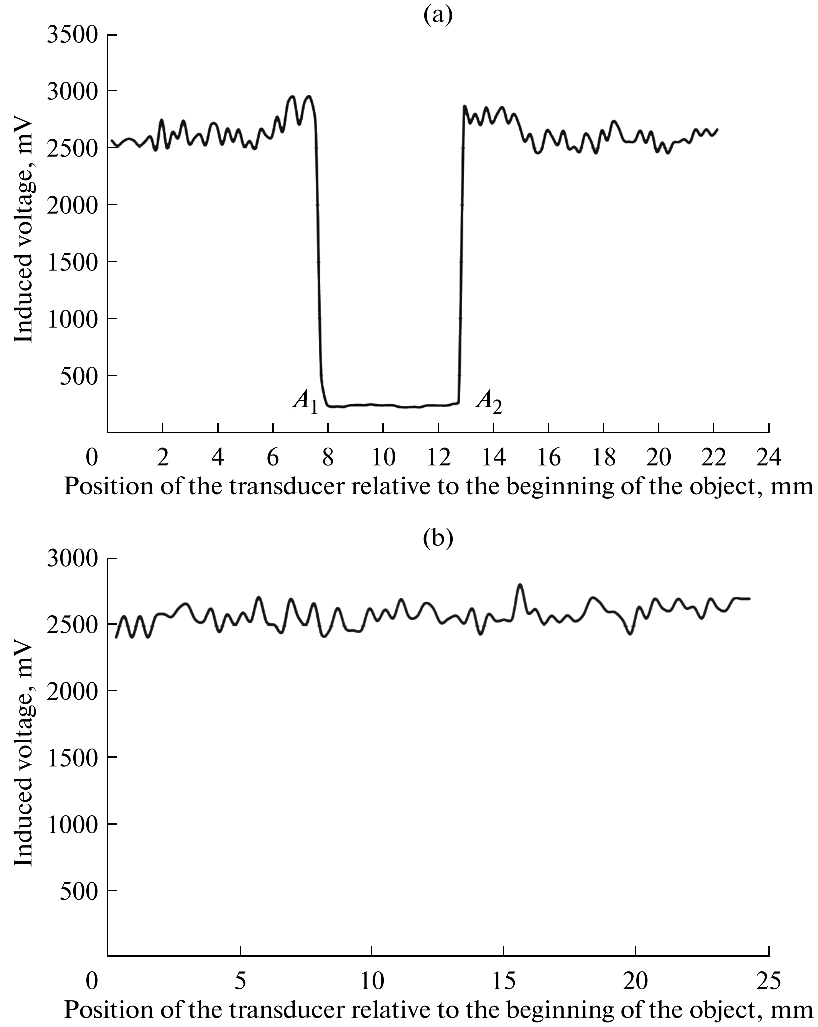

Fig. 2. The response value during the scanning of the welded seam: (a) sample no. 1, A_1–A_2 are the boundaries of the welded seam, and (b) sample no. 2.

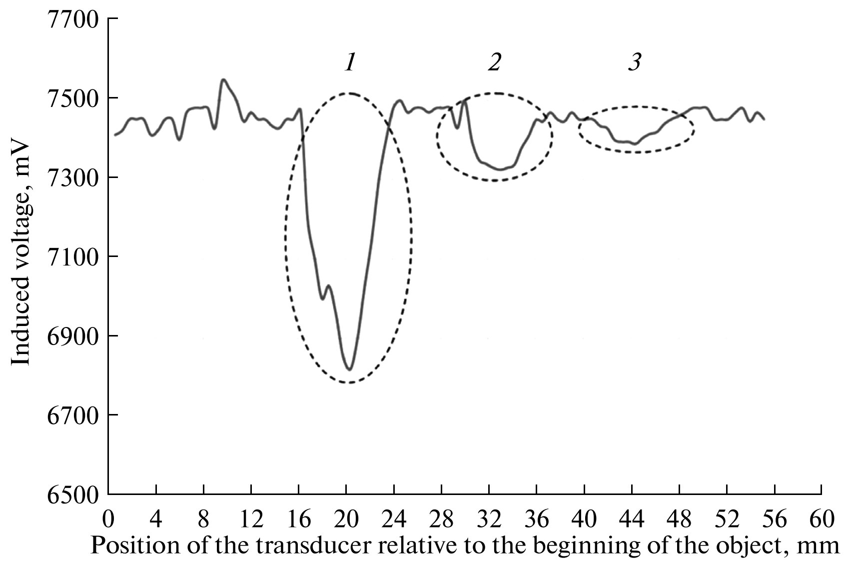

Fig. 3. The scanning results of plate no. 1: (*1*–*3*) numbers of flaws.

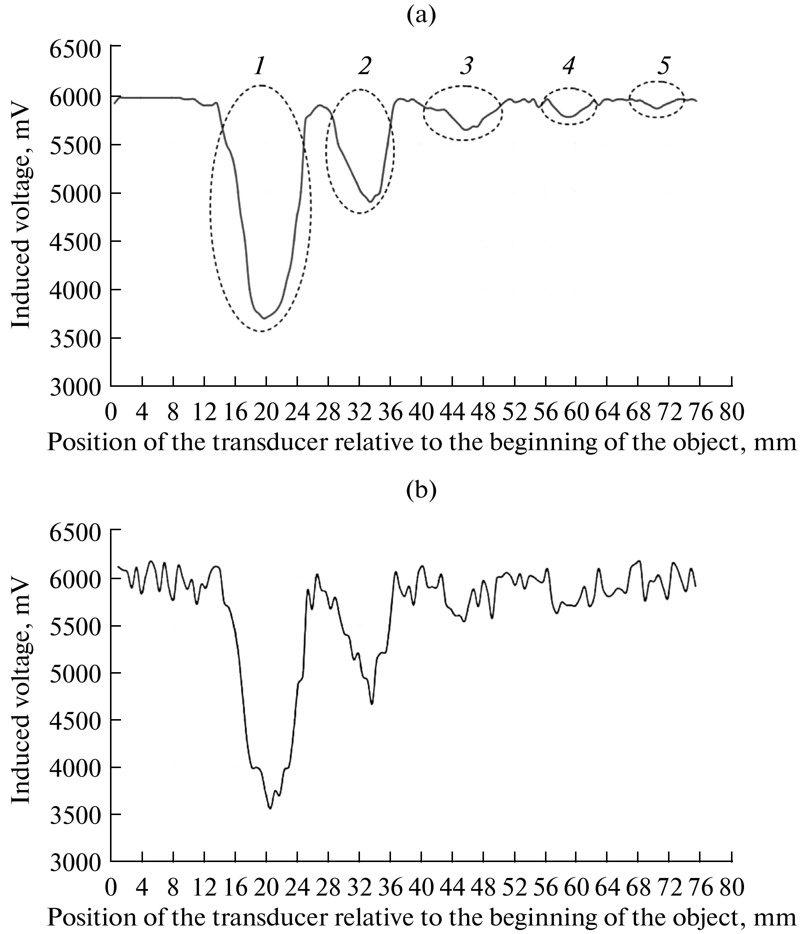

Fig. 4. Scanning results of plate no. 2: (a) with the filtering and selective amplification system; and (b) without the filtering and selective amplification system.

CONCLUSIONS

The designed measuring system based on subminiature eddy-current transducers allows one to attain stronger localization of the electromagnetic field compared with similar well-known systems.

The pyramidal shape of the core, band-pass filter system, and the selective amplification substantially decreased the noise level and significantly increased the penetration depth of eddy currents into the studied object. The designed ECTs allow one to efficiently scan welded seams of titanium alloys and analyze their quality. The scanning of flaws in aluminum alloys allows one to detect flaws with linear sizes of approximately 100 μm at depths of up to 5 mm. The designed software allows one to automatize measurements and quickly change the operating frequency of the device.

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