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Improving the accuracy of thin metal film research using the eddy current method

Danil Shmykov[1*], *Vladimir* Malikov[1], *Alexander* Katasonov[1], *Sergey* Voinash[2], *Irina* Vornacheva[3], *Oleg* Larin[3], and *Anton* Tansura[3]

[1]Altai State University, Barnaul, Russia
[2]Kazan Federal University, Kazan, Russia
[3]South-West State University, Kursk, Russia

Abstract. Based on the review of the current state and literature in the field of non-destructive examination of thin metal films, it has been established that the optimal method for studying thin-film structures in terms of the performance/quality ratio is the non-destructive eddy current method. The main principles of constructing eddy current transducers are considered, the design of the developed overhead transformer miniature eddy current transducer with a ferrite core for studying the electrical conductivity of thin metal films is described. The structural diagram is given and the algorithm of operation of the hardware and software complex is described, the characteristics of the main components of the hardware of the hardware and software complex are given. The algorithm of operation of the software that controls the operation of the hardware and software complex and is responsible for processing and visualizing the results in a form convenient for the operator is described. A method for analyzing the rate of change of the eddy current transducer signal has been developed, allowing measurements of the sizes of defects and inhomogeneities of a thin metal film. The proposed method was used to study a thin metal film and showed a significantly increased accuracy in determining the boundaries and sizes of defects as a result of analyzing the rate of change of the ECT signal. The increase in accuracy was up to 7% compared to the analysis of the direct change in the amplitude of the ECT signal.

1 Introduction

Thin metal films are gaining recognition for their unique properties and variety of applications in fields such as aerospace, electronics, healthcare, and renewable energy.

One of the key advantages of thin metal films is their high surface area-to-volume ratio, which allows for improved electrical conductivity, increased catalytic activity, and enhanced sensitivity in sensors. These properties make them valuable materials for use in electronic devices, such as touch screens, solar cells, and flexible electronics.

The production of thin metal films involves advanced techniques such as physical vapor deposition, sputtering, and chemical vapor deposition, which require precise control over

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[*] Corresponding author: osys11@gmail.com

thickness, composition, and structure. Researchers are constantly exploring new methods to fabricate thin metal films with tailored properties for specific applications.

In the healthcare sector, thin metal films are used for biomedical implants, drug delivery systems, and diagnostic devices. Their biocompatibility, corrosion resistance, and ability to interact with biological molecules make them ideal for medical applications.

Furthermore, in the field of renewable energy, thin metal films play a crucial role in the development of efficient and cost-effective solar cells, fuel cells, and batteries. Their transparency, conductivity, and stability make them essential components in energy storage and harvesting devices.

As the demand for advanced materials continues to grow, the scientific and technical expertise in the production and application of thin metal films will be essential for driving innovation and progress in various industries. Collaborations between researchers, industry partners, and government agencies will be crucial for accelerating the development and commercialization of thin metal film technologies. Of particular interest are biocompatible pressure sensors used in hip prostheses. When developing such sensors, the requirements for wear resistance, corrosion resistance and electrical conductivity are also taken into account [2]. At present, the possibility of using coatings based on titanium and aluminum intermetallics has been studied.

One of the key properties of thin films is their high surface-to-volume ratio, which can lead to enhanced catalytic activity, improved sensing capabilities, and increased efficiency in energy storage and conversion devices. Additionally, thin films can be designed to have specific optical, electrical, thermal, and mechanical properties, allowing for tailored applications in various industries such as electronics, optoelectronics, and biotechnology.

Furthermore, thin films can be deposited on a wide range of substrates, including flexible materials such as polymers, enabling the integration of thin film-based devices into flexible and bendable electronics. This opens up new possibilities for wearable technologies, flexible displays, and other innovative applications that require lightweight and conformable materials.

Overall, the study and application of thin films offer a wealth of opportunities for researchers and engineers to explore and exploit the unique properties of these materials for the development of advanced technologies that can have a significant impact on various industries and society as a whole.

For the full use of thin films in various areas of electronics, it is necessary to control the thickness and electrical conductivity of the film, to determine the degree of its defectiveness [3]. Such data are important for ensuring the accuracy and reliability of various electronic devices, and also allow saving materials and reducing production costs. Therefore, the issue of choosing a method for searching for defects in thin films is an urgent task. Traditional testing methods based on creating electrical contact with the film surface can change its properties, so innovative approaches and testing techniques are required. One of the most promising are contactless non-destructive testing methods.

Some of them are: electron microscopy, ultrasonic spectroscopy, scanning electron microscopy, magnetic spectroscopy, X-ray diffractometry, optical spectroscopy [5-8].

Other techniques include machine learning algorithms such as support vector machines or convolutional neural networks, which have been successfully applied to classify different types of defects in thin films [4, 9, 10, 11]. These automated image analysis methods offer a fast and reliable way to detect and quantify defects in thin films, allowing for efficient quality control and optimization of manufacturing processes.

Overall, rapid optical non-destructive testing combined with automated image analysis provides a powerful tool for characterizing thin films and identifying defects that may affect their performance. By using these techniques, researchers and manufacturers can ensure the quality and reliability of thin films in various applications, from microelectronics to photovoltaics [12, 7].

These methods have common disadvantages such as high cost and bulky equipment. The advantages include high measurement accuracy. But the choice of research method also depends on the specific task and measurement requirements.

Compared to the methods listed above, the eddy current method is simpler, does not require direct contact and a high degree of automation.

The integration of machine learning algorithms can further enhance the capabilities of the eddy current method by allowing for pattern recognition and classification of defects in metal films. Overall, the continued advancement of technology and automation in the eddy current method of materials research holds great potential for improving our understanding and control of thin film growth processes.

2 Materials and methods

An eddy current transducer is used to generate and detect eddy currents within the material being tested. The transducer consists of a coil or probe that is connected to a high frequency alternating current (AC) source. When the probe is placed near a conductive material, the alternating current generates eddy currents within the material.

The eddy currents interact with the material's properties, such as its conductivity and permeability, and produce changes in the impedance of the coil. These changes are then converted into an electrical signal that can be analyzed to determine the material's properties, such as its thickness and conductivity.

Overall, the eddy current transducer plays a crucial role in eddy current testing, as it is responsible for generating and detecting the eddy currents that provide valuable information about the material being tested. In the case of testing defects of thin metal films, the use of a clamp-on transformer eddy current transducer is effective [13]. Figure 1 shows the design of the developed clamp-on transformer transducer with a conical ferrite core. This transducer includes three windings: excitation, measuring and compensation windings.

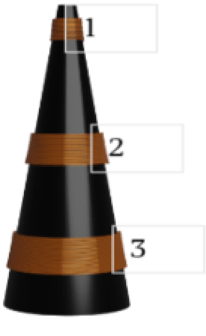

Fig. 1. Construction of the ECT: 1 – measuring winding; 2 – generator winding; 3 – compensation winding.

The core of the eddy current transducer has the shape of a truncated cone with a height of 4.3 mm, a base diameter of 1.5 mm and a top diameter of 0.1 mm. The measuring winding, consisting of 50 turns, is placed on the tip of the cone, while the generator winding, also consisting of 50 turns, is located in the center. When winding the generator winding, the radius was taken into account in order to minimize its value and achieve maximum localization of the magnetic field. Both windings are made of copper wire with a diameter of 15 µm.

During the measurements using this eddy current transducer, certain difficulties were identified. For example, manually compensating the measuring winding turned out to be quite difficult due to the need for mechanical adjustment and the large amount of time spent on eliminating the influence of the generator winding. In this regard, we decided to apply electronic compensation using a generator connected to an analog-to-digital converter.

Figure 2 shows the relative position of the eddy current transducer (ECT) and the object to be tested. When placing the transducer, special attention is paid to such a position that the measuring winding is at a minimum distance from the test object, while avoiding direct contact with it. In order to protect against possible mechanical damage, the eddy current transducer is covered with a layer of epoxy resin and placed in a plastic case.

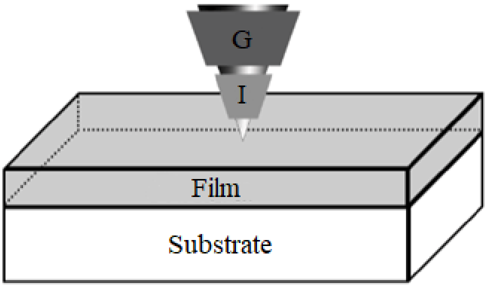

Fig. 2. Location of the ECT and the control object.

Taking into account the set goals, the main principles of hardware development were compactness and the ability to work in conjunction with a personal computer (PC). The diagram of the software and hardware complex developed within the framework of this project is presented in Figure 3.

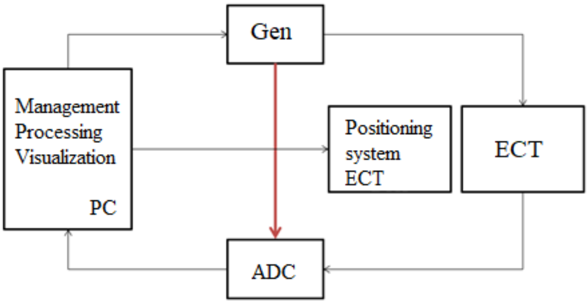

Fig. 3. Block diagram of the measuring system.

The control unit (PC) generates and sends commands to the generator (GEN) and the ECT positioning system. The generator, having received the control signal, generates alternating electric current of a given frequency. The voltage from the measuring coil passes through the analog-to-digital converter, from where it enters the processing and visualization unit as a digital signal. The channel through which the compensation signal is transmitted is shown by the red line. To move the eddy current transducer (ECT) over the test object, a positioning system based on Cartesian kinematics (Figure 4) was developed, which uses a three-axis coordinate system (X, Y, Z). The platform intended for fixing the test object can move along the Y axis, the sensor holder moves along the X axis, and can also change its height along the Z axis. Each axis is controlled by a corresponding motor: the Y and X axes are equipped with belt drives, and the Z axis is controlled by a screw system consisting of a stepper motor, a flexible coupling, and a screw with a certain pitch.

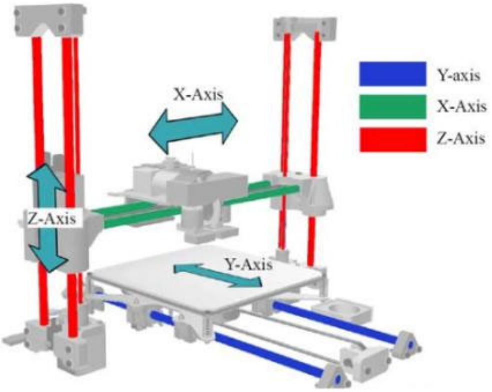

Fig. 4. Cartesian kinematics diagram.

The maximum scanning area size is 22 × 22 cm, the maximum movement speed is 180 mm/s, and the positioning accuracy is 100 µm. Stepper motors are controlled by a motherboard with a 32-bit processor. The motherboard has a USB port for connecting to a PC and receiving control commands. The motherboard software is based on Marlin firmware and is controlled using G-code commands. The sensor, which is an eddy current transducer, is placed on the positioning system in a special holder. It interacts with the control object using the generated electromagnetic field.

To control and process system data, as well as to visualize the results, software was developed in Python using a graphical shell created in Qt Designer.

The choice of Python is due to its simplicity, versatility, relevance and the presence of a large number of open libraries for processing and visualizing data. The following libraries were used in the software development process: NumPy, Serial, Sys, PyQt5, QThread, Time, RtlSdr, Interpolation, Plotly, pylab.

3 Experimental results

To convert the measurement results from conventional units to electrical conductivity, the dependence of the system response on the standards was constructed. The calibration line consists of three points. The first point corresponds to zero electrical conductivity (without the test object), the second point is the electrical conductivity of aluminum, and the third is the electrical conductivity of copper. The measurements were carried out at a height of 0.5 cm. In order to evaluate the resolution of the developed measuring complex when detecting defects on the film, an artificial defect was created. Figure 5 shows images of a defect on films obtained using an optical microscope.

Fig. 5. Image of a film defect obtained using an optical microscope.

Based on the findings of [13], the rate of change of the signal in the defective area was analyzed. Figure 6 shows the results of the analysis of the rate of change of the ECP signal when scanning a film with a defect; the highlighted area corresponds to the image obtained using an optical microscope. The electrical conductivity along the section line is shown in Figure 7.

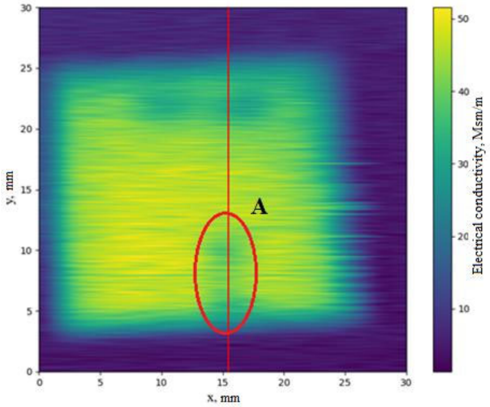

Fig. 6. Result of measuring a film with a defect using the eddy current method.

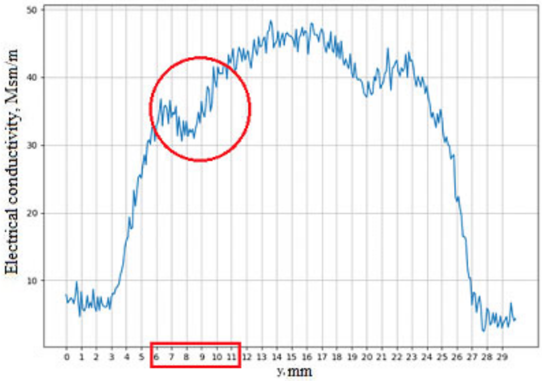

Fig. 7. The result of measuring the electrical conductivity of a film with a defect using the eddy current method.

We can draw a conclusion about the size of the defects. Defect A is 5 mm in size, the drop in electrical conductivity was from 38 Msm/m to 31 Msm/m.

4 Conclusion

A design of an eddy current transducer was developed, allowing local scanning of thin metal films and measurements of defect and heterogeneity sizes, and a hardware and software complex was designed for experimental study of heterogeneities and defects of thin metal films with a thickness of 100 nm and specific electrical conductivity of 14 Msm/m. The method involves recording the signal from the eddy current transducer while scanning the thin metal film. The rate of change of the signal is then calculated by taking the derivative of the signal with respect to distance. This rate of change can be used to identify regions of the film where defects or heterogeneities are present.

To analyze the defect or heterogeneity sizes, the rate of change of the signal can be plotted as a function of distance along the film. Peaks in the plot indicate regions where the signal is changing rapidly, which may correspond to defects or heterogeneities. The width and height of these peaks can be used to estimate the size and severity of the defects or heterogeneities.

In addition to analyzing the signal itself, the amplitude and phase of the signal can also be analyzed to provide further information about the defects or heterogeneities. By combining information from the rate of change, amplitude, and phase of the eddy current signal, a more comprehensive analysis of the thin metal film can be performed.

Overall, this method provides a powerful tool for non-destructive testing of thin metal films, allowing for the detection and characterization of defects and heterogeneities with high sensitivity and resolution.

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