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ELECTROMAGNETIC NON-DESTRUCTIVE EVALUATION OF CONDUCTING OBJECTS

The paper deals with the overview of non-destructive methods of investigation of materials as a tool for decreasing of costs of industrial equipment and increasing of safety of sophisticated and environment threatening facilities. The special attention is devoted to the method utilising eddy currents induced in a surface layer of conducting samples by means of small flat coil. The eddy current testing (ECT) method is theoretically described and results of its concrete application are presented.

1. Introduction

The present period is characteristic with a fast development of sophisticated technologies, which influence not only industry but also global living surroundings. Due to their price and possible consequences of their breakdown a permanent inspection of their proper state and function is more and more important part of their running. This inspection has many aspects and methods. One group of inspection methods consists of non-destructive methods of material investigation. They are precious because of a possibility to check properties of new produced construction parts of equipment or to check their proper function during their operation period without their damage and often without need to disassemble the equipment. The proper inspection methods are important because of preventing the accidents and of effective utilisation or safe prolongation the life-time period of economically demanding equipment, like nuclear reactors, dams, space

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devices, aircrafts, submarines, sophisticated medical devices, information databases etc. The significance of the perfect and errorless function of modern technical means consists in preventing huge economic losses, saving lives and health of people, sparing of energy and natural resources or ensuring powerful and safe industrial processes.

The most often task of the non-destructive evaluation consists in discovering of different defects arisen during the production of the equipment or during the operation due to a fatigue, overloading or influence of extreme conditions. Special part of non-destructive evaluation represents non-destructive defectoscopy. The defectoscopic methods depend on the character of the material and the character and position of the defect. They differ mainly in a resolution and in a sensibility to various kinds of defects (e.g. surface or volume). The methods of non-destructive evaluation can be divided into several main groups:

- *Mechanical wave techniques* consist in the evaluation mechanical vibrations of the inspected body, propagation of surface or volume mechanical waves in the sample or emission of acoustic waves from the body. Resolution of mechanical wave methods is limited by a wavelength or a frequency of the wave.
  - Ultrasonic defectoscopy.
  - Acoustic emission.
  - Investigation of resonance spectra of mechanical vibrations.
- *Electromagnetic wave techniques* consist in evaluation of electromagnetic wave interaction with the inspected body, mainly propagation, reflection and scattering of the electromagnetic wave caused by shape and inhomogeneities of the sample.
  - Optical methods of investigation of the sample surface (e.g. microscopic investigation, holographic and interferometric methods) are very effective mainly in the case of investigation of sample deformation or changes of quality of its surface.

  - Infra-red thermography uses the investigation of non-homogeneous thermal profile of the sample caused by electrical or mechanical losses (e.g. heating of bearing or breaks, heating of electric joints or electric devices).
  - X-ray investigation represents very effective and powerful means of defectoscopy. They are based on the influence of the structure on the propagation of X-rays through the sample. It is sensitive to the internal defects of conducting samples like welding joints, parts of motors, railway carriages wheels, organic samples, etc.
- *Nuclear methods*.
  - Radioactive sampling methods consist in addition of radioactive substance (liquid or gas) into flowing fluid and dosimetric evaluation of the fluid propagation thorough the investigated system or penetration into the investigated defects.
  - Nuclear magnetic resonance is a method, which is able to discover special atoms in the sample, e.g. hydrogen atoms of the water. The method is effectively used for living structures investigation (plants or animals).
- *Computer tomography methods* represent modern methods developed in connection with construction of powerful computers. Tomography imaging consists in computer aided processing of a huge amount of data obtained by successive detection of radiation emitted by investigated body. The source of signal should be X-rays, nuclear magnetic resonance signal, radioactive emission etc. Computer tomography is a tool for 3D-imaging of the internal structure of the sample.
- *Electromagnetic inductive methods* are based on the principle of interaction of the alternating electromagnetic field and an electro-dynamic structure of a conducting material.
  - Electromagnetic field can generate in a surface layer of a conducting material acoustic wave, which propagates through the sample. The special generating and detecting probe is known as EMAT (Electromagnetic-Acoustic Transducer). The advantage of the method consists in

combination of advantage of the ultrasonic investigation of the sample and contact-less inductive method of the ultrasound generation and detection. Detailed description of the method together with some results of its development has been published in [1 – 5].

- External electromagnetic field generates strongly damped electromagnetic wave known as skin effect in the surface layer of a conducting sample. It is connected with existence of induced eddy currents. Non-destructive method ECT (Eddy Current Testing) is utilized for contact-less investigation of conducting bodies. This method is described in detail in [6 – 11] and in the present paper.

2. Eddy Current Testing

Principle of ECT method is based on the interaction of eddy currents with the structure of the examined body. Alternating electromagnetic field generated by a proper coil penetrates into the surface layer of an effective depth given by an expression

$$\delta = \sqrt{\frac{2}{\omega \mu \sigma}} \, ,$$

where ω is angular frequency, μ and σ are permeability and conductivity of the material.

Eddy currents (EC) are influenced by defects and other inhomogeneities of the tested sample. Electromagnetic field generated by EC is detected by the probe coil and can be evaluated as the change of its impedance. This impedance is influenced not only by the sample properties but also with the structure of the probe coil and its lift-off distance from the sample. One of the main problems of the method consists in the obtained signal evaluation. The connection between the detected change of the impedance of the coil and details of the tested sample is very complex and has to be evaluated by means of special transformation procedures provided by corresponding computer programs, developed by means of ECT simulations.

Due to the exponential decrease of the amplitude of EC with increasing of the depth from the surface, the ECT method is effectively used for surface defects testing. The target layer goes from several decimals of mm (100 kHz range) up to several mm (kHz range). The chosen frequency depends on the estimated character and depths of the detected defects. On the other hand the resolution of the method is limited by EM wavelength, which is comparable with the effective skin depths $\lambda = 2\pi\delta$. The ECT method uses three near different frequencies for the sample profile determination.

The input impedance and thus primary current of circuit are affected by material properties of a specimen, geometrical arrangement of a probe itself and a lift-off distance. Hence, the measured ECT signal depends on the changes of material properties in general, material properties in damaged area and provides the information about crack location, shape and proportions.

The main advantages of ECT method are [9]:

- Sensitivity to small cracks and structural inhomogeneities;
- High resolution and possibility to identify very small defects;
- Inspection gives immediate results;
- Portable equipment;
- Contactless measurement;
- It inspects complex shapes and sizes of conductive materials.

In the other hand, ECT has some limitations rising from its own physical principles. The primary limitation is applicability only to conductive materials inspection. Depth of penetration is constraint by skin effect so the method is usable only for detection of surface and near surface defects or for thin materials. Intergranular defects lying parallel to the probe coil winding and probe scan direction are undetectable. In addition, surface roughness may interfere with the measured data and disable to recognize the crack presence, parameters and shape. However, because of advantages listed above, ECT is used in many fields of industry for structural and material properties measurements and defectoscopy. The main appliance of ECT is for finding of material inhomogeneities and cracks in case of well-understood defects' nature. For thin materials, ECT is used to measure the thickness of the material. For example, it can be used in evaluation of wall thinning due to corrosion or measurement of conductive materials' coating or painting thickness. ECT is widely used for control measurement of material properties in manufacturing process as well.

3. Measurement of conductivity by using ECT

This section deals with one of practical applications of ECT; a measurement of conductivity is concerned here.

A welded specimen, shown in Fig. 1, is inspected in the study and its conductivity is estimated based on measured values. A base material of the specimen is Alloy 600. The material is frequently used in structural components of nuclear power plants where ECT is applied for the non-destructive testing. The electromagnetic parameters, i.e. conductivity and relative permeability of the base material are given. However, one of the basic elements of such components is weld. The conductivity variation in the weld is unknown while the relative permeability is the same as the one of the base material, i.e. $\mu_r = 1$. To be able to deal with such configuration in numerical simulations using finite element method, a numerical model of the specimen with known parameters has to be built.

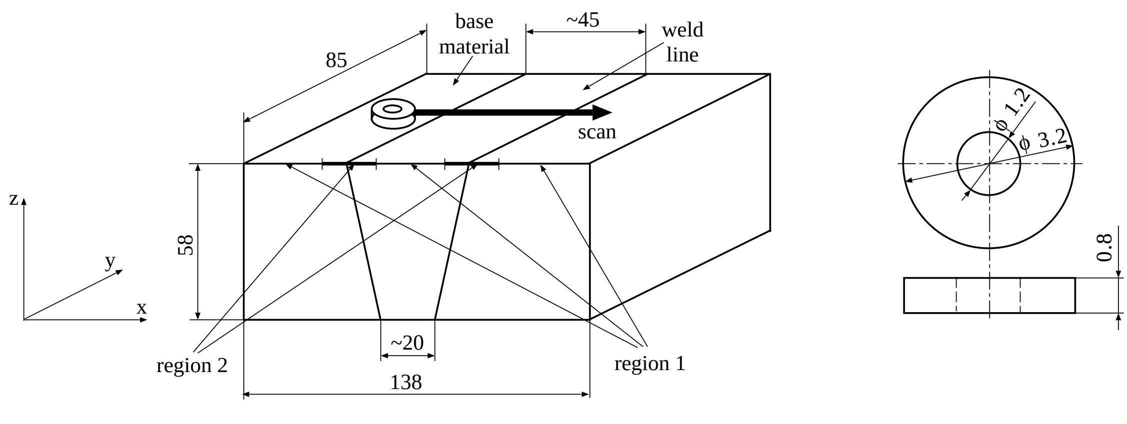

Fig. 1. Configuration and dimensions of the specimen and pancake coil.

A circular coil so called self-inductance pancake probe, shown in Fig. 1, is used for this study. The probe scanned over the surface of the specimen as depicted in Fig. 1 across the weld line. A professional ECT instrument ASWAN was used to drive the probe and at the same time to pick-up the signal. The length of the scanning line was 90 mm and the probe moved with a lift-off of 0.25 mm. The signals for three frequencies of 200, 300 and 400 kHz were gained at the same time and they were stored in a PC for further analysis. The real part and the imaginary part of the detected signal for the frequency of 200 kHz are shown in Fig. 2.

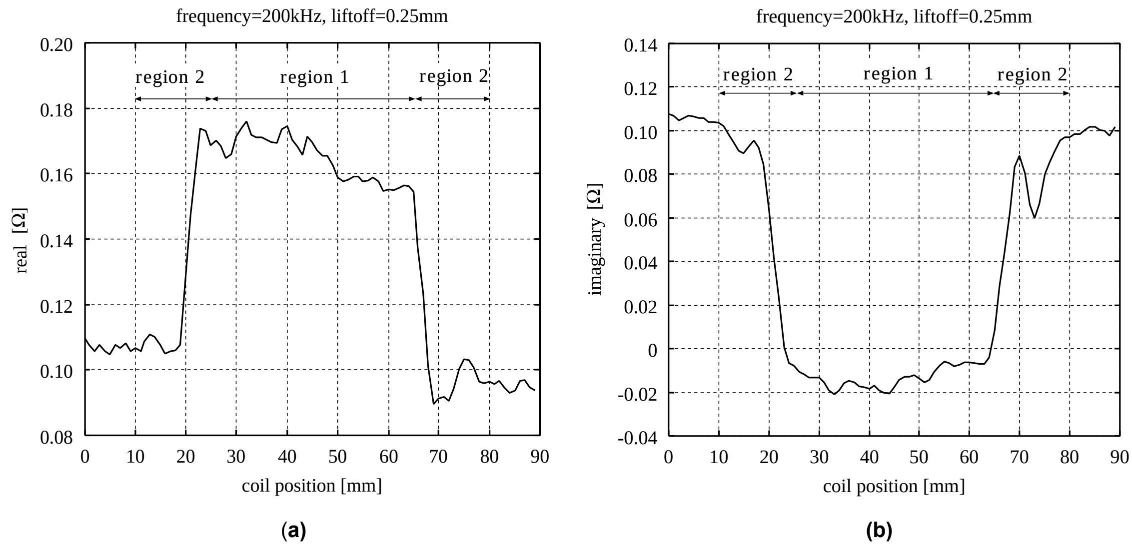

Fig. 2. Detected signal across the weld line: (a) real part, (b) imaginary part.

Two assumptions are made to reconstruct the conductivity variation across the weld line:

- The surface of welded specimen is divided into two regions.
  The first (Fig. 1 – region 1, part of the base material, middle part of the weld) is quasi stable one, where the signal variation is small.
  The second, transient one (Fig. 1 – region 2) covers heat affected zone and the boundary of weld, where the signal variation is large.

- The conductivity is supposed to vary just in a direction *x* perpendicular to the weld line.

According to these assumptions, two different prediction methods have been proposed for the two regions separately [12]. The conductivity distribution along the quasi stable regions is estimated based on the relationships derived from a uniform model. It was proved, that such method can deal also with no uniform distribution of the conductivity if its variation is limited. A neural network approach is utilized to tackle the conductivity profile recognition along the transient regions. More description about the methods can be found in [12]. All the input data for both the approaches were acquired by numerical simulations using finite element method.

The reconstructed profile of conductivity across the weld line is shown in Fig. 3. The conductivity in the quasi stable regions (region 1) was estimated based on the uniform model (UM) for all three frequencies. As it can be seen, the weld has approximately 7-8 % lower conductivity than the one of the base metal. In the transient regions (region 2), the conductivity profile was estimated by using the neural network (NN) for the frequency of 200 kHz. The conductivity changes sharply at the border of the weld line.

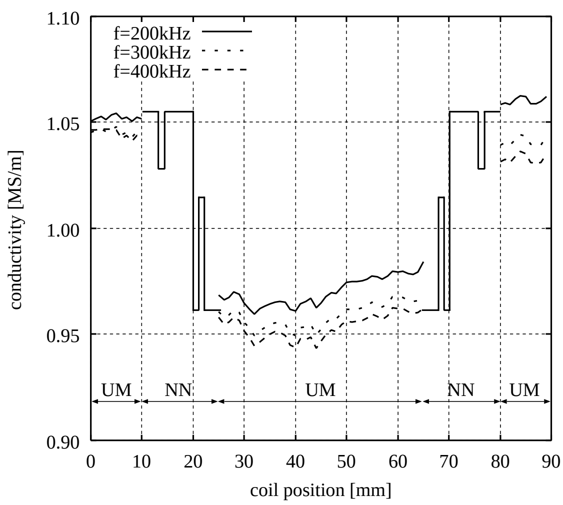

Fig. 3. The reconstructed conductivity profile

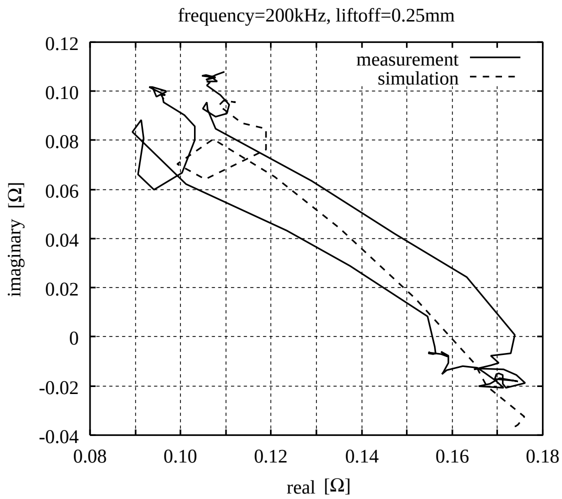

Fig. 4. Lissajous plot, comparison between the measured and simulated signals.

To prove the results of the conductivity profile reconstruction a finite element model of the target with taking into account the estimated profile of conductivity was build and the probe signal for the same scanning as used in experiment was simulated. Both the signals, i.e. experimental and simulated ones, are shown in Fig. 4. The numerical results well coincide with the measured ones.

Conclusion

The importance of non-destructive testing (NDT) of materials was emphasized in the paper. Different NDT methods were described with the main aim to introduce the eddy currents use in non-destructive evaluation of conductive objects. The fundamentals of the method were explained and the possible application areas were shown. The welded structure prepared of Alloy 600 was inspected by means of eddy currents NDT. The conductivity profile in the base material as well as in the weld was reconstructed based on the measured data. It was found out that the conductivity of the weld is approximately 8 % lower than the one of the base material. The consecutive numerical simulations of the signal using the finite elements method and the comparison with the measured signal confirmed the validity of the gained results.

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