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Investigation of aluminum alloys by using subminiature eddy current probes

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Abstract. On the basis of the eddy current probe(ECP) of a transformer type the measuring system that allows to search for defects in aluminum alloys is developed. The main technical data on the used eddy current probe and measuring system are given. The results of experiments obtained using different designs of the measuring system on two plates of duralumin D16T are presented. These dependences allow us to assess the quality of the alloys under study.

1. Introduction

Structures made from alloys based on aluminum are widespread in modern technology. The aluminum alloy (Al-Mg type) is widely used in structural applications, particularly in aerospace and automotive industry, due to the characteristics of good plasticity, good welding performance and corrosion resistance.

Conventional testing techniques such tension testing and micro-hardness testing, etc., are destructive measurement method. Some samples are taken from different parts of the object of control and are used for microstructure observation and property tests. However, microstructure and properties tested by the conventional approach just only present part of testing results of the component [1, 2]. In this regard, in modern industry, non-destructive methods are often used to test the object of control in the process of its control and operation [3,4]. On account of the fact that nondestructive testing doesn't damage the material performance, the change of physical parameters as ultrasonic sound velocity, attenuation coefficient and electrical conductivity are often used to deduce the variation of microstructure. Among many available non-destructive testing and evaluation (NDE) techniques ultrasonic test and eddy current test are widely studied to characterize the properties of the material. In recent decades, a number of studies of these methods have been carried out in order to evaluate properties of metals [4-6]. As a favorable method ultrasonic test has gained much attention in recent years, in investigating the relationship between the ultrasonic and the mechanical properties such as hardness, strength, impact strength, fracture toughness, etc. [7–10]. Eddy current testing is another important technique used to characterize materials, since eddy currents are influenced by microstructural alterations due to precipitates, cold work hardening, heat treatment, deformation, etc. Since Al-alloy is widely used for structural applications, therefore, extensive work has been conducted on characterizing properties by ultrasonic test and eddy current test. Therefore, the use of eddy current tests to study the properties of aluminum is relevant.

Eddy current (EC) testing is one of the most known and widely used NDE methods of conducting materials. The most common method to detect the presence of defects in conducting materials using EC

is indirect, by registering the coil impedance variation due to the interaction between the applied AC magnetic field and the magnetic moment generated by eddy currents [11, 12]. Firstly, EC testing does not require an acoustic couplant in contrast to ultrasonic inspection. Secondly, EC is more economical and less hazardous than radiography. In addition, EC testing boasts many advantages over conventional eddy current testing, including more extended detection depth and easier generation and control. EC testing can be widely used to measure the thickness and stress [13] and to characterize crack, metal loss, and corrosion of metal materials and carbon fiber-reinforced plastic [14].

EC systems have been proposed in the last years due to the high sensitivity and wide frequency response of this type of transducers. An eddy current testing technique in nonmagnetic metals using a EC sensor and a pancake-type excitation coil was proposed some years ago [15]. The authors proved the advantages of the proposed method using two different hybrid probes, where the high sensitivity of the EC sensor is exploited by using excitation coils of just a few turns. They introduced sensors as a viable EC testing system, but they did not establish a correlation between the EC output voltage and the dimension of the defect, which could help in estimating its dimension. However, the correlation of the EC output voltage with a set of defects (having different width, depth, and length) was not considered, see for example [16–18]. An EC system to detect and characterize cracks and holes by artificial neural networks, using the same probe configuration proposed in [19]. The EC sensor was magnetically biased with the use of an AlNiCo permanent magnet, and the system was able to estimate only the flaw width and the bore diameter [19]. The authors in [16] proposed a novel design of rotating magnetic field eddy-current probe for non-destructive evaluation of non-ferromagnetic and ferromagnetic tubes in nuclear power plants and they analysed the influence of the geometrical parameters of the excitation coils and EC sensor arrays in the sensitivity of the probe but not the detectability of the proposed system and the quantification of defects intended to be detected with such probe.

Even though EC testing is a well-known and established technique in the industry, there are still a lot of efforts to find efficient models in order to estimate the crack's dimension and also to find the depth profile of narrow cracks [20-22]. These models are advantageous over their predecessors but the computational time still poses a constraint when quick estimation of crack dimensions is a necessity. For instance, the rapid computation method proposed in [20] takes approximately 0.2 s per inversion step to obtain EC crack signals.

An inverse problem algorithm was developed to determine the spatial eddy current distribution in the aluminum plates in order to get relevant information about complex geometry of cracks [23]. As expected, the results show good characterization of the geometry of surface cracks that are not parallel to the current flow. In [23], the same kind of probe was used to evaluate a linear crack with a set of different probe angles to overcome this difficulty. However, the method was slow due to the requirement of several scans. Furthermore, small rotation errors were detected when measuring the magnetic field map due to mechanical misalignment of the probe. For this purpose, a faster excitation method and an improvement to the probe were made to induce parallel currents in the specimen in different directions without physical rotation of the probe during the scan in order to improve the accuracy of the measurements.

2. Materials and methods

A superminiature ECP is designed to control the parameters of aluminum alloy products in small areas [24-27]. The obtained parameter is the electrical conductivity of the material and its distribution on the surface and thickness of the object of control. The developed measuring system works as follows:
The sinusoidal signal is generated by a sinusoidal voltage generator and comes to the exciting coil of the eddy current probe. In addition to the exciting coil, the probe also uses measuring and stabilizing coils connected differentially. Due to the differential inclusion of the coils, the minimum value of the initial unbalance of the probe is provided when it is removed from the controlled product. The measuring coil of the probe is connected to the amplifier with automatic gain control (AGC). AGC acts effectively in the range of permissible changes in the gap between the probe and the object of control. The signal from the output of the amplifier comes to one of the inputs of the amplitude detector, then passes the

filter, the analog-to-digital converter and is transmitted to a personal computer. The personal computer processes the output signal of the analog-to-digital converter and displays the information.
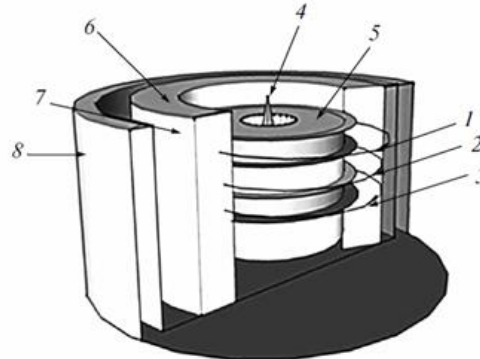
Figure 1. Eddy-current probe

The eddy current probe is a transformer with exciting, measuring and stabilizing coils placed on the core (Figure 1). The cores were made of ferrite 2000 NM3 with the value of initial magnetic permeability 500 and alloy 81NMA with the value of initial magnetic permeability 35000.

The characteristics of these ECPs allow for the localization of the magnetic field within the areas of 2500 μm^2 and, when using sufficiently low (100-700 Hz) frequencies on the exciting coil, allow to achieve a significant depth of its penetration into the object of control.

## 3. Experimental results and discussion

Experiments are conducted on D16T duralumin plates #1 and #2.

The first plate was 5.5 mm thick and contained three defects. The defects were slots imitating subsurface cracks. These slots were located at a depth of 1.3 and 4 mm. The width of slots was 1 mm. The second plate had a thickness of 5.5 mm and five slots with a width of 0.25 mm. The depth of slots was 1-5.3 mm.

In the study of the plate #1, the voltage on the exciting coil of the eddy current probe was 2 V.

In order to determine the sensitivity of the sensor to defects in the depth of the metal, scanning of the defect-free side of the sample was carried out.
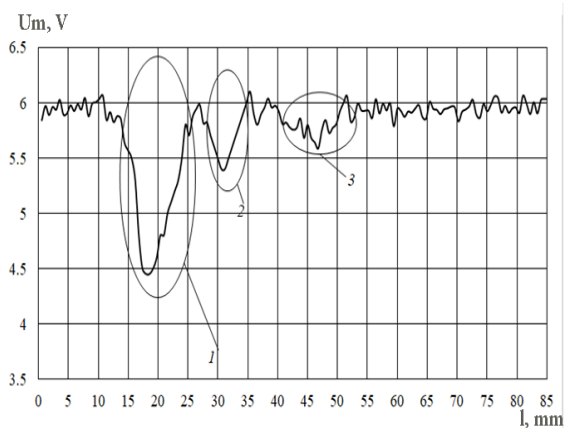
The results of the study of plates are shown in Figures 2-5, Um – voltage on the measuring coil, l – distance from the edge of the plate to the sensor.
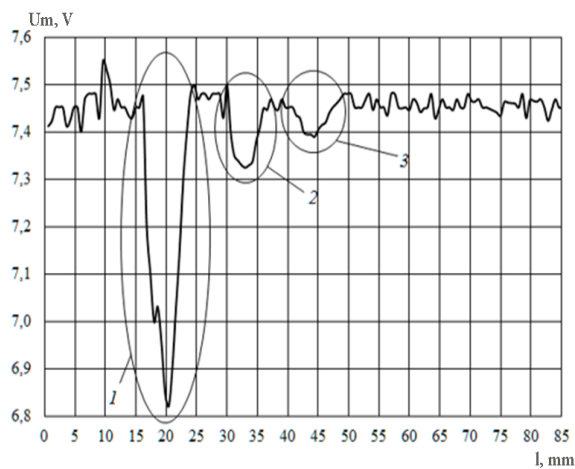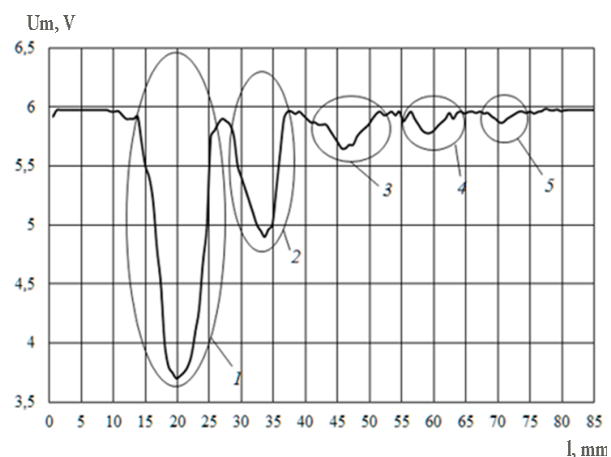
Figure 2. - Results of plates scanning #1 using a measuring system with one ECP (ferrite).
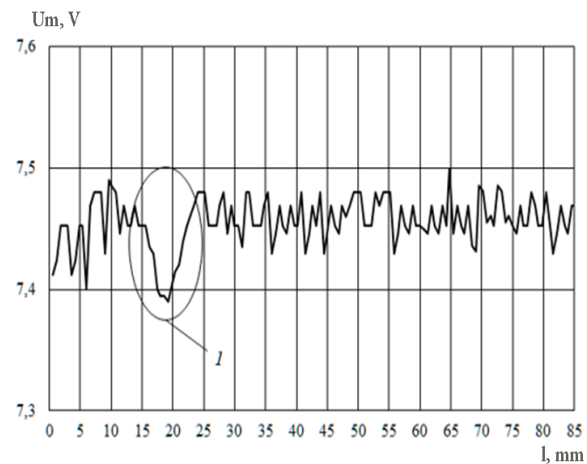
Figure 3. - Results of plates scanning #2 using a measuring system with one ECP (ferrite).

Figure 4. Results of plates scanning #2 using a system with two ECPs (ferrite).

Figure 5. Results of plates scanning #2 using a system with two ECPs (81NMA).

The results of defectoscopy of the plate #1 with defects with a width of 1 mm at a frequency of $\omega = 500$ Hz allowed to detect the slots to reduce the amplitude of the output signal Um. The decrease in the amplitude of the signal Um on the first defect was 0.75 V, on the second – 0.2 V, on the third – 0.1 V (Figure 2).

This study demonstrates the effectiveness of the developed eddy current sensor for finding defects of deep occurrence with a width of 1 mm and lying at a depth of 4 mm.

In order to determine the maximum localization of the magnetic field, the developed sensor was tested on the second plate with defects having a width of 0.25 mm, lying at a depth of 5.3 mm.

The measurements were carried out at a voltage of 2 V on the exciting coil. At the same time, it was managed to detect one of the defects occurring at a depth of 1 mm. The decrease in the amplitude of the output signal in this case was 0.1 V (Figure 3).

In order to improve the accuracy of measurements, an increase in the voltage on the exciting coil was made. In this case, there was an excess of the permissible value of the signal amplitude on the measuring coil and there was a significant distortion of the results.

In order to increase the localization of the magnetic field, the measuring system made on the basis of the subminiature eddy current probe was significantly upgraded as follows: the second eddy current probe was added to the developed hardware and software complex. At the same time, the first eddy

current probe was static and located above the defect-free part of the sample. The second probe was used to scan the sample for defects. The signal of the second probe was subtracted from the signal received from the first one. Thus, the output signal was the voltage difference obtained from the measuring coil of both ECPs.

Defectoscopy of the sample #2 was performed at a frequency of 500 Hz. At the same time, it was possible to detect three defects out of six (Figure 4).

To further increase of localization of the magnetic field, it was necessary to introduce a probe made on the basis of a core of annealed alloy 81NMA with a magnetic permeability value of 35000 as a scanning probe. With this upgrade, it was possible to detect five defects out of six.

The decrease of the output signal amplitude Um on the first defect was 2.5 V (position 1), on the second defect – 1 V (position 2), on the third defect – 0.4 V (position 3), on the fourth – 0.2 V (position 4), on the fifth – 0.1 V (position 5). Changes in signal response when passing over the sixth defect are not fixed (Figure 5).

4. Conclusion

As a result of theoretical and experimental studies the eddy current measuring system that allows to search for defects in the alloy duralumin D16T was developed. The developed methods of signal processing allowed to increase the signal/noise relation of the eddy current probe by several times and significantly reduce the measurement error. Subminiature eddy-current transducers with specially shaped ferrite cores and modified filters can be used to localize a magnetic field on a small segment of a test object and to make the field produced by the exciter winding penetrate more deeply into the test object at a suitable frequency.

References
[1]   Jobba M, Mishrab K and Niewczasa M Int J Plast. 2015 **65** 43
[2]   Mishina O, Godfrey A, Jensen D and Hansen K 2013 *Acta Mater.* **61** 6354.
[3]   Zergoug M, Lebaili S, Boudjelial H 2004 *NDT E Int.* **37** 65
[4]   Rajkumar V, Kumar A, Jayakumar T, Raj B and Ray K K 2014 *Metall Mater Trans.* **38A** 236.
[5]   Badodo A, Lebaili S and Benchaala A 2016 *NDT E Int.* **36(1)** 1
[6]   Vasudevan M and Palanichamy P 2002 *J Mater Eng Perform.* **11(2)** 169.
[7]   Li A, Roberts R and Frank J M 2001 *Rev Prog Quant Nondestruct Eval* **80(11)** 2469.
[8]   Lin L 2003 *Ultrasonic nondestructive characterization of microstructure of alloy steel* vol 1 (Dalian: Dalian University of Technology. Department of materials engineering). p 37.
[9]   Nanekar P P and Shah B K 2003 *BARC Newsl.* **249** 25
[10] Kwun S I, Hong S T, Choo W Y 2000 *J Mater Sci Lett.* **19** 1453
[11] He Y, Simm A and Jackson P 2012 *IEEE Sensors Journal* **12** 2113
[12] Fan M and Zhou Z 2009 *NDT & E International* **42** 376
[13] Morozov M and Withers P J 2010 *Journal of Applied Physics* **108** 024909
[14] Wu J and Wang J 2014 *Journal of Sensors* **727** 269
[15] Dogaru T and Smith S T 2001 *IEEE Trans Magn.* **37(5)** 3831
[16] Jen-Tzong J, Guan-Shiun L, Wen-Chu L and Chia-Lun S 2016 *J Magn Magn Mater.* **304(1)** 470.
[17] Nair N V, Malpudi V R, Jimenez H R, Liu X, Deng Y and Zeng Z 2006 *IEEE Trans Magn.* **42(10)** 3312.
[18] Cacciola M, Megali M, Pllicano´ D, Morabito F C 2011 *Sensors Actuators A: Phys.* **167(1)** 25
[19] Postolache O, Geirinhas Ramos H and Lopes R A 2011 *Comput Stand Interfaces* **33(2)** 191
[20] Theodoulidis T, Poulakis N and Dragogias A. 2010 *NDT&E Int.* **43(1)** 13
[21] Theodoulidis T 2010 *NDT&E Int.* **43(7)** 591
[22] Theodoulidis T, Haitao W and Tian G 2012 *NDT&E Int.* **47(4)** 144
[23] Pasadas D J and Ramos H G 2015 Proc. IEEE Int. Instrum. Meas. Technol. Conf. (Pisa) vol 1 (Pisa: IEEE Xplore) p 940
[24] Malikov V N and Dmitiev S F 2016 *Russ. Eng. Res.* **32** 626

[25]   Malikov V N and Dmitiev S F 2017 *Measurement Techniques* **60(4)** 372
[26]   Dmitriev S F, Katasonov A O and Sagalakov A M 2017 *Materials Science Forum.* **927** 161
[27]   Dmitriev S F, Katasonov A O, Sagalakov A M and Shevtsova L I 2015 *Journal of Physics: Conference Series* **643** 012058