Development of technology and methods for detecting metal inclusions in composite materials

A Kuznetsov

JSC “Central Research Institute for Special Machinery”, Khotkovo, Moscow Region
National Research University of MPEI
kuznetsov.anton.93@gmail.com

Abstract. In complex multilayer structures made from PCM, metal inclusions of small sizes (from 0.1 ÷ 0.2 to 15 mm) randomly distributed throughout the material (at depths up to 100 mm), are unacceptable for normal operation, as they can penetrate into the material structure of a finished product. This paper is aimed at developing a device that provides a small error in determining the coordinates of small-sized metal inclusions in PCM when they are detected in real conditions of production and operation. Some devices capable of detecting the content of small particles in fluids or capable of detecting metal objects in various environments are known. The disadvantages of these devices are that they can only detect magnetically active particles, or large objects – more than 3–6 mm, while the location accuracy is recorded with a big error, insufficient for the detection process of small metal inclusions in PCM – from 30 mm and higher. This determines the urgency of developing a device for detecting small metal inclusions in finished products from PCM and in the technological cycle of their production. In this paper, the basic principles of the developed device are described, a block diagram of the device is presented, including the configuration of the eddy current transducer and the main processing units of the signals coming from the transducer. As confirmation of the operation of the developed device, photos of experimental studies and their results are presented in the form of the obtained dependences of the value of metal inclusions on the depth of their occurrence, from which it can be seen that the error in determining the depth of small-sized metal inclusions by the developed device did not exceed 10% and unchanged for all small-sized metal inclusions.

1. Introduction

Small-sized inclusions in multilayer products made of polymer composite materials (PCM), for example metal particles that are not included in the design of products, are not allowed, due to the specifics of their operation.

However, in production there is a probability of such metal particles entering the PCM (sizes from 0.1 ÷ 0.2 to 15 mm) randomly distributed throughout the material (at a depth of up to 100 mm), which is unacceptable by technical conditions.

Thus, the urgent need for the detection of small metallic inclusions in PCM products is in the development of a diagnostic device for a wide range of PCM products.

As studies have shown, this problem is currently not completely solved due to a small size, shape uncertainty and physical characteristics of the particles, their random location in the material [1–5].
2. Methods

The process of testing and implementing the control technology includes the following steps: modeling the control process, choosing the optimal modes, creating equipment, testing and implementing the control methodology.

Due to the complexity of the experimental process of testing the technology for detecting metallic inclusions in PCM (installation of defects in it, etc.), studies using modern 3-D models reliably simulate real research on the basis of modern mathematical apparatus and powerful computing technology play an important role.

Figure 1 shows a generalized structural diagram of a mathematical model of the process of non-destructive testing (detection of defects in the material) based on the analysis of the distortion of the physical field after its interaction with the controlled material and inclusions (defects) [6-8].

Here:

\( U_{in} \) is the input function of the magnetic field depending on the magnitude and frequency \( (f_V) \) of the excitation current \( (I_V) \) of the exciting coil of the eddy current transducer;

\( W_{mat}, W_{incl} \) are transfer functions of the material and inclusions, respectively, depending on the characteristics vectors \( \Theta_M, \Theta_{VC} \) of the material and inclusions, respectively;

\( U_{out} \) is the output function of the magnetic field depending on the transfer functions of the material \( (W_{mat}) \) and inclusions \( (W_{incl}) \), as well as \( f_V \).

This device detects metallic inclusions and marks the coordinates of each of them (if the small-sized metallic inclusions are not too close to one another).

A device [9] for determining the content of small particles in fluids is known. Its disadvantage is that it is capable of detecting only magnetic particles.

A more universal device [10] is designed to detect metal objects in various environments, but it only detects the presence of large objects (more than 3-6 mm). The accuracy of the location is recorded with a large error, insufficient for the process of detecting small metal inclusions in PCM.

A decrease in the error in determining the location of small-sized metal inclusions in the PCM became possible with the advent of new technologies in the field of electronics, control, and informatics [11] and the development of the corresponding software for mathematical modeling and microprocessor data processing in real time [12].

This problem can be fundamentally solved by other non-destructive testing (ND) methods, for example, X-ray, thermal or ultrasound. However, this did not give the desired results [2].

In the present study, a device that provides a small error in determining the coordinates of small-sized metal inclusions in PCM in real production and operation conditions is described.

The technical result achieved by using the developed device is to increase the reliability of detection of small metallic inclusions by introducing several measuring inductors in the induction transducer and, as a result, rejecting the resonant circuits used in known devices. This is due to the fact that the induction converter system, which includes the use of resonant circuits, is not able to solve the problem due to the influence of temperature changes, noise and interference [13–716].

The device (Figure 2) contains a generator 1, the signal of which is amplified by an amplifier 2 and fed to an exciting coil 11.1 with a diameter 2Rv of an eddy current transducer. The radius \( R_V \) is selected taking into account the maximum thickness of the product from composite material.
where $T_{OT}$ is the maximum thickness of the object under study, and measuring coils (11.2, 11.3, 11.4, .., 11.N), coaxially located in the same plane with the exciting coil, the outputs of which are connected to the inputs of the switch.

**Figure 2.** Block diagram of the device: 1 – generator; 2, 4, 5 – amplifiers; 3 - signal switch; 6, 7 – synchronous detectors; 8 – two-channel analog-to-digital converter; 9 – block signal processing and synchronization; 10 – indicator; 11 – eddy current transducer; 11.1 – exciting inductor of the eddy current transducer; 11.2, 11.3, 11.4 – the first, second and third measuring inductor, respectively; N – “N-th” measuring coil; 12 – object of control.
The signals of the measuring coils through the switch 3 are fed to amplifiers 4, 5 and then to the synchronous detectors 6, 7 (which also receive the reference signal from the generator through a two-channel analog-to-digital converter (ADC) 8), the outputs of which are connected to the synchronization and signal processing unit 9, indicator 10 is connected to the output of block 9.

The number of measuring coils of the eddy current transducer and their radii are determined using the estimated depth and size of the metal inclusions and the necessary error in determining their location.

In terms of design, generator 1 is combined with block 9, the harmonic oscillation generator frequency $\omega$ is selected from the condition $R \sqrt{\omega \mu_0 \sigma_{OT_{min}}} = 20 \pm 25$, where $\sigma_{OT_{min}}$ is the minimum possible conductivity of the supposed metal inclusions in a composite material under study ($\mu_0$ is the magnetic constant of the vacuum).

Experimental studies were carried out on PCM samples (Figure 3) with artificial metal inclusions of different sizes located at different depths relative to the control surface.

![PCM sample](image)

**Figure 3.** PCM sample: 1 – PCM sample with artificially embedded small metal inclusions; 2, 3, 4 – small metal inclusions with a size of 0.1, 0.3, 0.5 mm, respectively.

### 3. Results and discussion

Figure 4 shows the dependence of the device readings on the size of metal inclusion in the PCM. The experiment was carried out in accordance with [17].

As can be seen from Figure 4 the proposed device can detect small inclusions up to 2 mm in size at a depth of 30 mm, which is several times smaller than the known devices.
Figure 4. Dependence of detection depth on inclusion size.

Figure 5 shows the results of experiments on the error in determining the location and size of metal inclusions in PCMs (modeled in the ANSYS Maxwell software environment [18-22]) depending on the number of measuring coils. It can be seen that with an increase in the number of coils, the error decreases.

Figure 5. Graph of the error in determining the location and size of metal inclusion.
Figure 5 shows that the error in determining the depth of small-sized metal inclusions by the developed device does not exceed 10% and is constant for all small-sized metal inclusions. For prototype devices, the error in determining the depth is approximately 1.5-2.2 times greater and reaches 20%.

4. Conclusion
The developed device is capable of detecting small-sized metal inclusions with sizes from 0.1 ÷ 0.2 to 2 mm at a depth of up to 30 mm in PCM products with an error of less than 10% and, thereby, improves the quality of PCM structures due to timely and reliable location detection metal inclusions.

References
[1] Kuznetsov A O, Chernov L A and Budadin O N (2018) Proc. Int. 24th Conf. Radioelektronika elektrotekhnika i energetika [Radioelectronics, Electrical Engineering and Power Engineering] (15-16 March 2018 Moscow) (Moscow: National Research University MEI) p 345
[2] Kuznetsov A O (2018) Proc. All-Russ. Conf. Osnovnyye tendentsii, napravleniya i perspektivy razvitiya metodov nerazrushayushcheho kontrolya v aerokosmicheskoj otрасли [Trends, Directions and Prospects for Non-Destructive Testing Methods in Aerospace Industry] (9 February 2018 Moscow) (Moscow) p 162–166
[3] Kuznetsov A O, Chernov L A and Budadin O N (2018) Proc. Res. Conf. Pribory i metody Nerazrushayushcheho kontrolya kachestva izdelii i konstruktsiy iz kompozitsionnykh i neodnorodnykh materialov [Devices and Methods of Non-Destructive Testing of Products and Structures from Composite and Inhomogeneous Materials] (11-13 December 2018 St. Petersburg) (St. Petersburg) p 49-50
[4] Kuznetsov A O, Chernov L A and Budadin O N (2019) Voprosy oboronnoy tekhniki. Seriya 15. Kompozitsionnyye nemetallicheskiye materialy v mashinostroyenii [Defense technology issues. Series 15. Composite non-metallic materials in mechanical engineering] (M: NTTS “Informtekhnika” - filial FGUP “VNII “Tsentr”) vol 2(193) 96 p
[5] Barynin V A, Budadin O N and Kulkov A A (2013) Sovremennyye tehnologii nerazrushayushcheho kontrolya kachestva izdelii i konstruktsiy iz kompozitsionnykh materialov [Modern technologies non-destructive testing of structures made of polymer composite materials] (Moscow: ID Spektr) p 308
[6] Gerasimov V G, Pokrovskiy A D and Sukhorukov V V (1992) Nerazrushayushchiy kontrol’ [Nondestructive testing] (Elektromagnitnyy kontrol’ [Electromagnetic testing] vol 3) (Moskva -Vysshaya shkola) p 308
[7] Klyuyev V V, Muzhitskiy V F, Gorkunov E S and Shcherbinin V Y (2006) Magnetnyye metody kontrolya [Magnetic testing methods vol 1]. Nerazrushayushchiy kontrol’: Spravochnik: V8 t. [Non-destructive testing: Reference in 8 vol] ed V Klyuyev 848 p
[8] Gerasimov V G, Klyuev V V and Shaternikov V E (2010) Metody i pribory elektromagnitnogo kontrolya [Methods and devices of electromagnetic testing] ed V E Shaternikov (Moscow: ID Spektr) 256 p.
[9] Sandulyak A A, Yershova V A, Sandulyak D A, Sandulyak A V, Yershov D V, Sandulyak L P (2016) RF patent No. 2593155, IPC B03C 1/00 (2006.01). Sposob magnitnogo kontrolya ferroprimesey melkozernistoy sypuchey sredy [The method of magnetic control of impurities of fine-grained granular medium] (Moscow: Moscow Technological University)
[10] Lubov V P, Zlygostev I N, Gruzov V M and Titov B G (2008) RF patent No. 2366982, IPC G01V 3/11 (2006.01). Metalloiskatel’ [Metal detector] (Institute of Petroleum Geology and Geophysics)
[11] Proc. Int. 27th Conf. Sovremennyye tehnologii v zadachakh upravleniya, avtomatiki i obrabotki informatsii [Modern technologies in the tasks of control, automation and information processing] (September 14-20, 2018, Alushta). (Tambov: Publishing House TGTU, 2018 280 p
[12] Proc. Int. 14th Conf. Vysokoproizvoditel'nye parallel'nyye vychisleniya na klasternykh sistemakh [High-performance parallel computing on cluster systems] (10–12 November 2014 Perm) (Perm: Publishing house Perm National Research Polytechnic University), 2014

[13] Potapov A I, Syasyako V A, Solomenchuk P V et al (2014) Elektromagnitnyye i magnetnyye metody nerazrushayushchego kontrolya materialov i izdeliy [Electromagnetic and magnetic methods of non-destructive testing of materials and products] (Elektromagnitnyye i magnetnyye metody kontrolya tolschchiny pokrytiy i stenok vol 1 [ Electromagnetic and magnetic methods for controlling the thickness of coatings and walls] (St. Petersburg: Nestor Istorya) 480 p

[14] Dorofeev A L and Kazamanov Y G (1980) Elektromagnitnaya defektoskopiya [Electromagnetic defectoscopy] (M.: Mashinostroyeniye) 232 p

[15] Fedosenko Y K, Shkatov P N and Efimov A G (2014) Vikhretokovy kontrol’ [Eddy Current Testing] ed V V Klyuev (Moscow: ID Spektr) vol 2 224 p

[16] Horowitz P and Hill W (2015) The Art of Electronics (Cambridge University Press).

[17] GOST 24026-80. Issledovatel'skiye ispytaniya. Planirovaniye eksperimenta. Terminy I opredeleniya [Research trials. Experiment planning Terms and Definitions]. (Moskva Gosudarstvennyy komitet SSSR po upravleniyu kachestvom produktsii i standartam) 06.03.80 No 1035.GOST 24026-80

[18] Borovkov A I, Burdakov S F, Klyavin O I, Melnikova M P, Mikhailov A A, Nemov A S, Palmov V A and Silina E N (2012) Komp'yuternyy inzhiniring: ucheb. posobiye [Computer engineering: textbook] (SPb.: Izd-vo Politekhn. un-ta) 93 p