Досліджено питання можливості отримання сигналу про глибину залягання інтелектуальних датчиків, введених у полімерний композиційний матеріал, за допомогою використання електростатичного методу неруйнівного контролю. Здійснено моделювання розподілу електричного потенціалу у матеріалі, за допомогою якого визначено максимально можливу глибину введення датчика у полімерний матеріал

Ключові слова: інтелектуальні полімерні композиційні матеріали, інтелектуальні датчики, електростатичний метод неруйнівного контролю

Исследован вопрос возможности получения сигнала о глубине введения интеллектуальных датчиков, введенных в полимерный композиционный материал, с помощью использования электростатического метода неразрушающего контроля. Осуществлено моделирование распределения электрического потенциала в материале, с помощью которого определена максимально возможная глубина введения датчика в полимерный материал

Ключевые слова: интеллектуальные полимерные композиционные материалы, интеллектуальные датчики, электростатический метод неразрушающего контроля

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MODELING THE ELECTROSTATIC CONTROL OVER DEPTH OF THE INTRODUCTION OF INTELLIGENT SENSORS INTO A POLYMER COMPOSITE MATERIAL

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1. Introduction

One of the types of intelligent polymeric composite materials (PCM) is the materials that are capable of remote transmitting data on their properties, in particular the stressed-strained state (s.s.s.), for conducting online monitoring. This is achieved by the introduction into PCM of intelligent sensors that are miniature measuring devices. They have the form of a structural totality of one or more measuring transformers of the magnitude that is measured and controlled. Intelligent sensor produces an output signal suitable for the remote transmission, storage and usage in control systems, and possesses normalized characteristics.

The application of intelligent PCM is appropriate in such areas as:

– aerospace industry, to control the s.s.s. of aerial vehicles elements;

– medicine (to control elements of artificial heart valves, etc.);

– shipbuilding (to control wear on the most critical elements of submarines);

– automotive and machine building (to control stresses arising in responsible locations during operation).

A problem of obtaining data from the intelligent sensors in PCM is a multidisciplinary one. On one hand, the issue of technologies and equipment for the introduction of sensors onto PCM, interpretation of data on s.s.s. and other properties, received from sensors, is related to polymer machine engineering. On the other hand, the question of obtaining signals about the depth of the introduction of intelligent sensors and their further processing is related to nondestructive testing.

2. Literature review and problem statement

One of the characteristic features in the creation of intellectual PCM is the isolation and sidedness in the consideration of this problem in the literary sources. Papers that are devoted to the topic of intelligent PCM consider the issue only in terms of problems in materials science and the fabrication of PCM, paying little attention to the issues of receiving and processing electrical signals from the sensors.

Article [1] presents a broad review of structural polymer composite materials, including the intelligent ones. Much attention is paid to the types of intelligent PCM, general methods of receiving and processing information from them, but the review is quite superficial.

Papers [2, 3] examine the creation of intelligent polymeric systems based on electroactive sensors that allow control of the action of external factors on the product, which makes it possible to monitor in real time the responsible parts and nodes. Articles [4, 5] consider a possibility of using intelligent polymeric materials in medicine, in particular, for such critically important applications as the prosthesis of joints, artificial cardiac valves, etc. Work [6] carries out a general comparison of polymer compositions with and without intelligent sensors, drawing conclusions on the possibility of their application in different areas. The paper, however, did not put any emphasis on the technologies of receiving signals about the depth of the introduction of sensors.

Article [7] dealt with the required technological modes for the introduction of intelligent sensors into PCM. By means of numerical simulation of the flow of polymer melt [8, 9], dependences were obtained of the depth of introduction of sensor on the technological parameters of equipment, such as the angle of the sensor introduction into PCM and the relation of pressures in the processing equipment.

Paper [10] addresses methods, devices, and technical solutions for the introduction of intelligent sensors for the purpose of manufacturing the products from intelligent polymeric composite materials. However, the paper lacks a substantiation of the depth of introduction of sensors in terms of the possibility to obtain information about the depth of their placement.

One of the most acceptable means to receive signals about the depth of introduction of intelligent sensors is using the electrostatic method of nondestructive control [11]. Traditional electrostatic methods are based on electrostatic capacitive coupling between active pairs of electrodes and use electric field for probing.

Among capacitive sensors, the flat sensors (called as sensors of dielectrometry [12]) have been thoroughly explored. They require access to a sample only from one side due to coplanar electrodes and can provide for measuring the electrical properties of the sample in the immediate vicinity from the surface of the sensor [13–15]. In most cases, an impedance measuring circuit carries out the measurement with a certain frequency of excitation. The measured capacitance is then correlated with the measured properties by using mathematical models [16]. Databases are also utilized, which are created for the purpose of comparing characteristics of the signal to the measured properties [17].

Articles [18, 19] address the method of nondestructive control, which is capable of performing the visualization of a wide range of materials and structures, starting from insulators to metal conductors. This method, if further developed, may help to extend the scope of applying intelligent sensors in PCM.

Papers [20–22] examine a question of nondestructive testing for non-metallic materials, such as PCM, using the electrostatic method, and define the possibilities of finding defects in polymer materials. However, the papers are devoted only to questions of detecting defects in homogeneous materials while intelligent PCM have metallic inclusions (intelligent sensors).

Articles [23–25] address the design of a number of technical solutions aimed at improving the electrostatic method of nondestructive control, in particular, enhancing noise immunity for a wide range of materials and structures, goods made of dielectrics and conducting materials without using a contact fluid. A structural scheme is proposed for the instrument that implements this method for conducting nondestructive testing. However, the questions of controlling the depth of the introduction of metal objects, the intelligent sensors actually, were not dealt with. The following should be particularly noted. Despite the fact that the creation of PCM with the introduction into structure of the material of intelligent sensors, as well as the nondestructive control over PCM by the electrostatic method, were examined in the aforementioned studies, a comprehensive consideration of this issue in terms of polymer machine engineering and nondestructive testing is still missing. In particular, the question of relationship between the depth of the introduction of intelligent sensors into PCM and the possibility of obtaining reliable information on the value of this depth is not sufficiently investigated.

3. The aim and tasks of the study

The aim of present study is to establish a dependence of the accuracy of obtaining information about the value of depth of the introduction of intelligent sensors on the depth of their placement using the electrostatic method of measuring with coplanar electrodes.

To achieve the set aim, the following tasks were to be solved:

– to select and define optimal parameters of mathematical model (the size of the element of finite-element grid, properties of material and boundary conditions);

– to conduct a series of numerical simulations at different geometric parameters;

– to obtain the distribution of electric field, and the value of relative electrical capacitance for varying depth of the introduction of intelligent sensors into PCM;

– to determine maximum possible depth of the introduction of sensor into PCM that would provide for the reception of signals about the depth at a given accuracy.

4. Materials and methods for examining the electrostatic method of control at the introduction of intelligent sensor into PCM

To control the depth of the introduction of intelligent sensors into PCM, it is expedient to use the electrostatic amplitude-phase method of nondestructive testing using orthogonal reference signals and digital signal processing. This method makes it possible to register with great accuracy a change not in the phase shift of measuring signal only but a change in the amplitude of measuring signal as well. As it is known, in the course of orthogonal processing, phase shift of the signal will not depend on the amplitude of measuring signal.

Electromagnetic phenomena are governed by Maxwell's equations. In a general case, materials that possess both dielectric and conducting properties are described by the Maxwell-Ampere equations [26]

$$\nabla\times H = J + \frac{\partial D}{\partial t}, \quad (1)$$

where H is the voltage of magnetic field; J is the current density; D is the density of electrical flux.

To eliminate magnetic field intensity H, equation (1) transforms into the form

$$\nabla\left(J + \frac{\partial D}{\partial t}\right) = 0. \quad (2)$$

Given that the derivative of magnetic flux density B in time can be neglected, and, according to Faraday's law, electric field E is free to turn,

$$\nabla\times E = -\frac{\partial B}{\partial t} = 0.$$

Thus, electric field E can be described using scalar electric potential of distribution φ(x, y, z)

$$E = -\nabla\varphi(x,y,z),$$

using constitutive relations

$$J = \sigma(x,y,z)E,$$

$$D = \varepsilon(x,y,z)E.$$

Thus, expression (2) will take the form

$$\nabla\left[\sigma(x,y,z)\nabla\varphi(x,y,z)\right] + \\ +\nabla\left\{\frac{\partial}{\partial t}\left[\varepsilon(x,y,z)\nabla\varphi(x,y,z)\right]\right\} = 0, \quad (3)$$

where σ(x, y, z) is the distribution of conductivity; ε(x, y, z) is the distribution of dielectric permittivity.

If one knows the conductivity of electric field and the distribution of dielectric permittivity, then electric potential distribution σ(x, y, z) can be obtained by solving equation (3). In practice, however, because of the time derivative of connection between dielectric and conductive properties, equation (3) cannot be resolved [1]. Practical way of solving this problem is to consider the system as "predominantly dielectric" or "predominantly conducting". In the first case, equation (3) can be simplified to the Laplace equation

$$\nabla\left[\varepsilon(x,y,z)\nabla\varphi(x,y,z)\right] = 0.$$

In the latter case, the equation is written down as

$$\nabla\left[\sigma(x,y,z)\nabla\varphi(x,y,z)\right] = 0.$$

Using the above-mentioned quasistatic assumption, it is possible to apply the finite element method for solving the above-mentioned equations and to predict the distribution of potential φ(x, y, z), created by capacitive electrodes in a particular environment and for a certain geometry. Numerical model satisfies the Dirichlet boundary condition

$$\varphi(x,y,z) = \begin{cases} V \mid (x,y,z)\in\Gamma_1, \\ 0 \mid (x,y,z)\in\Gamma_2, \\ 0 \mid (x,y,z)\in\Gamma_3, \end{cases}$$

where Γ_1 is the surface of reference electrode, Γ_2 is the surface of measuring electrode, Γ_3 is the outer surface of computed areas, V is the voltage applied to the reference electrode.

Upon solving equation (3), the Gauss law can be applied in numerical form of the integral over the surface of measured electrode for the calculation of induced charge on the electrode by the estimated distribution of electric potential. The Gauss law can be written down in the form

$$q = -\oiint_s \varepsilon(x,y,z)\nabla\varphi(x,y,z)ds,$$

where s is the surrounding surface of sensing electrode.

5. Results of examining the electrostatic method at the introduction of intelligent sensor into PCM

When modeling, we used electrodes in the shape of rectangles with zero thickness. It was assumed that the length of rectangular electrode is much larger than the width, so the electric field distribution along the length can be considered constant and it will not depend on the ends' fields. With this in mind, a 3D-geometry of the problem can be reduced to a 2D model, which can be used for the representation of the problem. In connection with this, the simulation was carried out in a two-dimensional planar setting.

To unify the calculations, we introduced relative magnitude "H"; all geometric dimensions were assigned relative to this magnitude:

– electrodes – width 2H, distance between the electrodes 2H;

– product made of PCM – width 25H, height – 100H;

– intelligent sensor in the shape of a material point in the center of the product at depth from 1H to 100H.

Geometry of a 2D model of PCM with the introduced intelligent sensor is shown in Fig. 1.

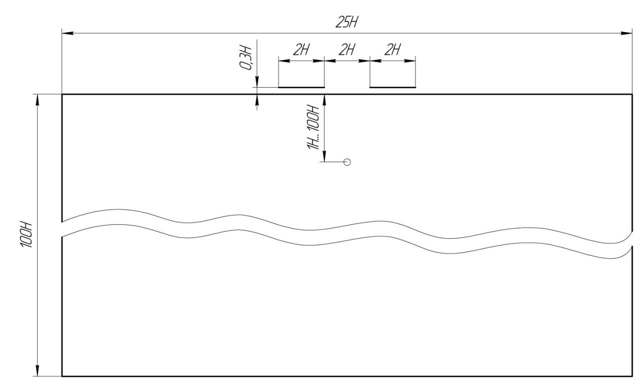


Fig. 1. Geometric dimensions of the PCM model with the introduced intelligent sensor

In the course of modeling, we used the following materials:

1. Air, dielectric permittivity ε_r=1.

2. Polyethylene of low pressure, ε_r=2,3.

To determine the minimum required density of computational grid for obtaining quality result of the calculation, we conducted a study into convergence of grid by gradual reduction in characteristic size of the element and matching of control parameter at different values of boundary sizes of the element. As a control parameter, we used the value of electric capacitance between the electrodes.

When constructing a finite element model, it is expedient to use elements that are sufficiently small so that they do not influence the control parameter considerably, but not too small, so that they will not significantly prolong the period of calculation. Therefore, when constructing the given finite element model, we used a breakdown of finite element grid into 15574 elements. A thickening of calculation grid was applied to the regions where the electrodes are placed, as well as in the area of placement of intelligent sensor.

The grid was reconstructed at each modeling, linked to the new location of the sensor. Fig. 2 shows a finite element grid of the model.

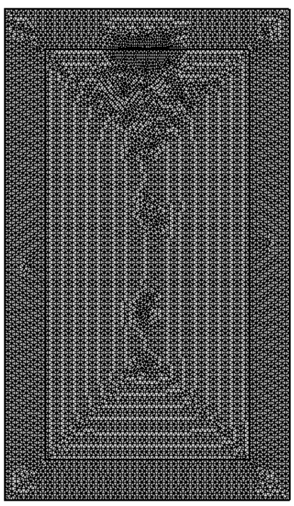


Fig. 2. Finite element grid of the model

The simulation was conducted under the following boundary conditions:

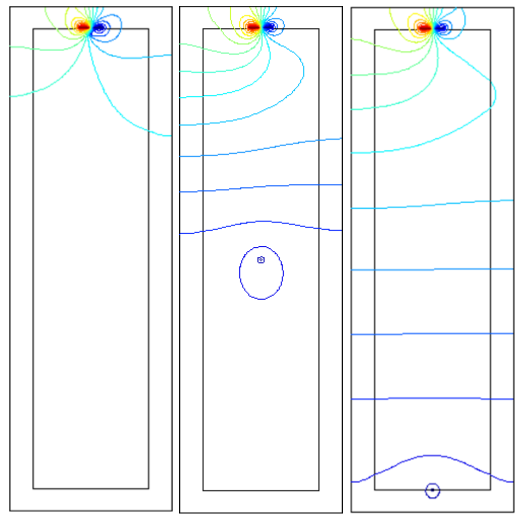
– starting value of electric potential V_0=0 V;
– electric potential in the reference electrode V_d=20 V;
– electric potential in the measuring electrode V_s=0 V;
– electric potential in intelligent sensor V_{sensor}=0 V.

Fig. 3 shows the distribution of electric potential along the surface of the model at different depths of the introduction of intelligent sensor.

Fig. 3 demonstrates that the depth of immersion of the intelligent sensor affects the distribution of electric potential along the surface of the model. Therefore, it is necessary to determine the magnitude of influence of the depth of immersion of sensor on this distribution.

Fig. 4 shows generalized results of the simulation in the form of dependence of relative electric capacitance between the electrodes on the depth of the introduction of intelligent sensor.

As can be seen from Fig. 4, relative electric capacity tends to its assigned value nonlinearly. Therefore, in order to evaluate sensitivity of the electrodes to the intelligent sensor, we built a graph of dependence of the difference in relative electric capacities on the depth of the introduction of sensor, which is depicted in Fig. 5.



a *b* *c*

Fig. 3. Distribution of electric potential along the surface of the model: *a* – depth of the introduction of sensor 1H; *b* – depth of the introduction of sensor 50H; *c* – depth of the introduction of sensor 100H

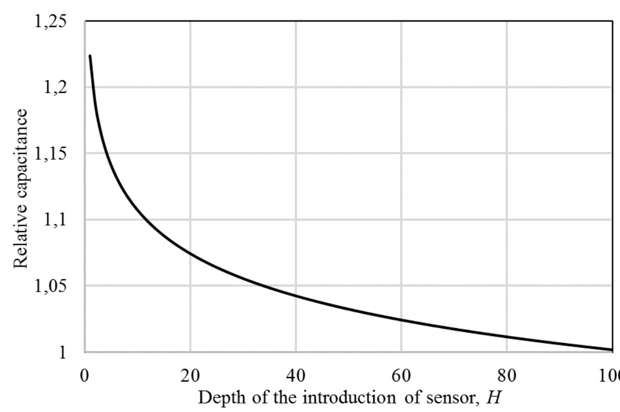


Fig. 4. Generalized results of modeling the depth of the introduction of sensor

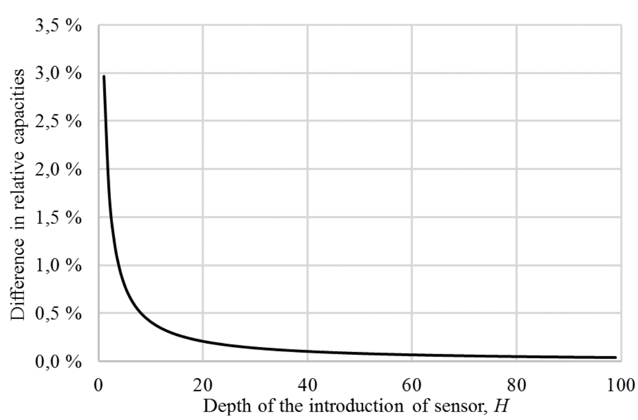


Fig. 5. Dependence of difference in relative electric capacities on the depth of the introduction of sensor

As can be seen from Fig. 5, at the depth of immersion of the sensor exceeding 40N, its identification would be practically impossible.

6. Discussion of results of examining the electrostatic method of control at the introduction of intelligent sensor into PCM

The research conducted demonstrated certain limitations on the creation of intelligent PCM from their geometric dimensions and the depth of the introduction of sensors, taking into account the necessity of receiving signals from them.

It was found that at the depth of the introduction of intelligent sensor into polyethylene of low pressure exceeding 40N, receiving signals from such a sensor is practically impossible. Thus, increasing possible depth of the introduction of sensor can be achieved either by increasing characteristic dimensions of electrodes, which is not always possible, or by changing dielectric permittivity of PCM by the introduction into the polymer matrix of modifiers that alter electrical properties.

The study also confirmed the need to consider a problem of the introduction of intelligent sensors into PCM not only in terms of design structure and technological parameters of processing equipment (extruders, casting machines). When modeling the processes that proceed in equipment, the interaction between sensors and PTP was not revealed, as well as the need for further nondestructive testing of products [27, 28]. It is important to consider the problem with regard to electrical properties of polymeric materials and the capabilities of devices and systems for nondestructive control, through which the signals are received about the depth of the introduction of these sensors.

A shortcoming of present study is a simplified representation of the intelligent sensor in the form of material par. Real detectors possess a certain inner structure and, mostly, consist of several components.

In addition, the study applies to only one type of polymer material. However, the applied methodology might be applied to any PCM with known electrical properties.

Results of research can be used when creating smart materials based on PCM. The proposed technique might be also applied to any dielectric material after adjusting the properties of the material. The obtained results allow conducting a more accurate determination of the depth of the introduction of intelligent sensors into PCM.

The prospects of further research are in determining the impact on accuracy of the depth of the introduction of intelligent sensor into PCM from such parameters as: distance between the reference and measured electrodes, size and shape of the electrodes, distance between the electrode and the product, dielectric properties of PCM.

7. Conclusions

1. We applied a mathematical model and defined parameters of mathematical model for conducting the calculation, namely: the size of element of finite element grid, properties of material and boundary conditions.

2. A series of numerical simulations was performed using different depth of immersion of intelligent sensors into PCM, in the range from 1H to 100H.

3. We received distributions of electric field and the value of relative electrical capacitance for varying depths of the introduction of intelligent sensors into PCM, which allowed us to determine the possibilities of electrostatic control over properties of intelligent PCM.

4. We defined maximum possible depth of the introduction of intelligent sensor into polyethylene of low pressure, at which it is possible to receive signals about the depth of their placement at the given reliability, which is 40H.

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