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INCREASING THE ACCURACY OF DEFECTOSCOPY BY THE METHOD OF ACTIVE THERMOGRAPHY OF PRODUCTS MADE OF NON-METALLIC HETEROGENEOUS MATERIALS AND USED IN ENGINEERING

Abstract. *Nowadays, non-metallic heterogeneous materials are widely used in mechanical engineering, which is primarily due to their unique properties, such as strength, light weight, corrosion resistance, and high vibration, sound, and heat insulation characteristics. At the same time, non-destructive control methods that would allow to obtain the most complete picture of the defective state of products made of such materials are of great importance. The main task of the work is the development of optimal algorithms for determining each defect of a product made of non-metallic heterogeneous material with the establishment of its exact location, including the depth of occurrence, as well as its geometric parameters. The method of thermal non-destructive testing is considered promising. Studies of the accuracy of determining the parameters of defects in non-metallic heterogeneous materials by the specified method have been carried out.*

Keywords: *non-metallic heterogeneous materials; thermal control method; flaw detection; infrared equipment.*

1. INTRODUCTION

Nowadays, non-metallic heterogeneous materials are widely used in mechanical engineering, aerospace engineering, and other sectors of the economy, which is primarily due to their unique properties, such as strength, light weight, corrosion resistance, and high vibration and sound, thermal insulation characteristics. At the same time, such materials are characterized by specific technological and operational defects. First of all, this applies to delaminations that are visually imperceptible, but can lead to a serious weakening of the structure and, as a result, cause the failure of a product made of non-metallic heterogeneous material [1]. Taking into account the responsibility of the assignment of nodes and aggregates, especially in aircraft structures, non-destructive control methods that would allow obtaining the most complete picture of the defective state of products made of non-metallic heterogeneous materials are of great importance.

The main task of the work is the development of optimal algorithms for determining each defect of a product made of non-metallic heterogeneous material with the establishment of its exact location, including the depth of occurrence, as well as its geometric parameters. To date, the method of thermal non-destructive testing is considered to be one of the most promising for flaw detection of products from the specified class of materials [2]. This type of flaw detection is based on visualization of the thermal field of the surface of the research object using infrared equipment and analysis of anomalies of this field.

2. LITERATURE REVIEW

As a rule, temperature fields arise as a result of thermal stimulation of the material (active thermal control). However, sometimes they are formed as a result of the operation of the product being diagnosed (passive thermal control). The work considers active thermal control, in which thermal energy is excited by heating the surface with a single thermal pulse or their sequence. In this case, the amplitude and time parameters of the thermal field at each point of the surface of the control object carry information about the presence and geometric characteristics of defects [3].

There are several methods of stimulating thermal energy in objects during real research. The most convenient and closest to the conditions of measuring products in mechanical engineering and aviation engineering is the so-called one-sided control mode, in which heating and registration of a thermal image in the form of a thermogram is carried out from the same side of the defectoscopy object [4]. Figure 1 shows a diagram of the location of the research object and the means by which flaw detection is carried out.

With this approach, temperature changes on the surface of the sample under study are analyzed in the defect-free zone $T_{fl} = f(x, y, t)$ and in the projection of the defect $T_f = f(x, y, t)$ after heating the surface with a single thermal pulse of finite length t. Figure 2 [4] schematically shows the change in the temperature of the surface of the tested sample in the defective and defect-free zones during the implementation of one-sided excitation of thermal energy during

It is clear that during heating, the excess temperature of the investigated surface increases and reaches its maximum value at the moment of time t, which, according to Figure 2, corresponds to the end of the thermal pulse. During the cooling of the surface of the object, in the process of propagation of the heat wave through the volume of the material and heat exchange with the environment, the excess temperature decreases to zero. At the same time, there is a difference in excess temperatures and the speed of their change in defect-free and defective zones [2].

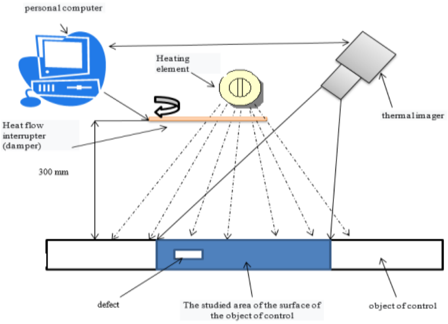

Figure 1 – The scheme of conducting active thermal imaging control

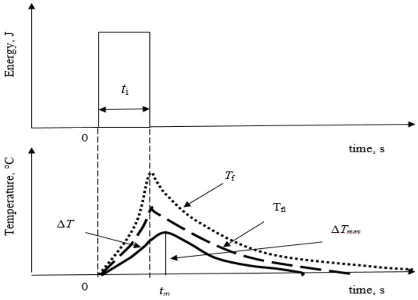

Figure 2 – Changes in the temperature of the surface of the research object over the defective and defect-free zones during unilateral thermal imaging control

This is due to the difference in thermophysical properties in the specified zones and, as a result, different conditions of heat wave propagation. In the zone above the defect, the regular nature of the thermal field changes, and so-called temperature anomalies appear, which are characterized by an absolute temperature contrast, i.e., the temperature difference in the defective and defect-free zones $\Delta T = f(x, y, t)$, which can be defined as follows:

$$\Delta T(x,y,t) = T_f(x,y,t) - T_{fl}(x,y,t), \tag{1}$$

It should be noted that depending on the ratio of thermal conductivities in the defective and defect-free zones, $\Delta T = f(x, y, t)$ can have both a positive and a negative value. With this definition, $\Delta T > 0$ for defects whose thermal conductivity is lower than the thermal conductivity of the main non-metallic heterogeneous material. Accordingly, if the defects are more thermally conductive than the main material, then $\Delta T < 0$. It is even possible to invert the sign of ΔT during cooling [4].

The dependence of the temperature contrast on time has an extremum $\Delta T_{\max}$ at the moment of time t_m, which is the optimal time for observing the defect. Both of these parameters are the main parameters of the amplitude method of thermal control and depend not only on the thermophysical characteristics of the studied non-metallic heterogeneous material, but also on the depth of embedment and the size of the defect itself [5].

In [4] it is shown that for a semi-infinite object that is heated by a Dirac pulse, the optimal time for observing an internal defect in the form of a material discontinuity can be determined as the time it takes for the heat wave to reach the defect, reflect from it, and return back, that is:

$$t_m = \frac{l^2}{a} = \frac{l^2 \cdot c \cdot \rho}{\lambda}, \tag{2}$$

where l – the depth of the defect;
a – coefficient of thermal conductivity;
c – heat capacity;
ρ – density;
λ – thermal conductivity coefficient.

Expression (2) can be used for a very short thermal pulse, i.e. $t_m >> t_i$, which is quite difficult to implement in practice ($t_i \approx 10$ μs). If the pulse length is commensurate with the optimal defect observation time, then the estimation formula [2] can be used:

$$l^2 = a \cdot (t_m - t_i) \tag{3}$$

3. MAIN MATERIAL PRESENTATION

In the work, carbon fiber samples with a thickness of 4 mm were studied, in which defects in the form of layers were specially formed at various depths (air gaps up to 0.2 mm thick and with an area of more than 1.5 cm^2), which are the most common types of defects for the class of materials that is considered The minimum depth of defects is $l \approx 1$ mm. Taking into account the passport data of the coefficient of thermal conductivity for carbon-plastics in the transverse direction of the layers $a \approx 4.5 \cdot 10^7$ m^2/s, the maximum length of thermal pulses, which is necessary for thermal stimulation of the defect in the structure of such a material $t_i \leq 1$ s. This makes it possible not to use expensive xenon flash lamps, which are traditional for generating a heat wave during active thermal control of metals and metal composite materials. In the experiment, for this purpose, an electric heater with a mechanical interrupter of the heat flow in the form of a movable flap (Fig. 1) was used, which allowed the formation of heat pulses with a length of (0.5...20) s. thermal radiation power density $P \approx 10^4$ W/m^2.

It should be noted that the studied surfaces are characterized by relatively low relaxation rates of excess temperature fields. This made it possible to use infrared devices without special requirements for their speed. In the experiment, a thermal imager with a frame rate of ≈ 1 Hz was used.

Among the advantages of infrared technology devices used in thermal control, in addition to non-contact and fast operation, it is also necessary to include high resolution, which ensures the detection of local temporary temperature contrasts on the surface of the investigated objects [6]. Given that the accuracy of flaw detection of products made of non-metallic heterogeneous materials by the amplitude thermal method (measurement of maximum temperature contrasts) is determined by the accuracy of the used thermal imagers, it is necessary to pay attention to instrumental and methodical measurement errors.

A significant drawback of non-contact methods of measuring temperature using infrared devices is the lack of data on the emissivity of the surface of the research object under experimental conditions. The object's ability to emit infrared radiation can vary, as it depends not only on the material itself, but also on the properties of the surface (for example, roughness, the presence of dirt, oil films, etc.) and the direction of observation of this surface [7, 8]. It is the uncertainty in setting the coefficient of emissivity of the surface of the research object that is the main difficulty in temperature calculations based on the results of thermal imaging measurements. And, therefore, this introduces an additional methodical error into the results of determining the depth of defects in non-metallic heterogeneous materials.

Therefore, before conducting studies of thermal processes on the surfaces of samples for the purpose of their defectoscopy, the coefficient of surface emissivity was determined at reference points. The latter necessarily included surface points with a surface condition different from the basic one. For example, with a different roughness, the presence of scratches, coatings, films and the like, which could be perceived as defects according to the thermogram. This operation must be carried out during defect inspection of products that were in use, since the state of the surface at different points can be significantly different from each other.

Determination of the emissivity coefficient was carried out in the following order. In the characteristic zone of the studied surface without temperature anomalies, reference points were chosen, the temperatures of which were measured by a contact thermometer (thermocouple). At these same points, the temperature was measured with a thermal imager with preset shooting parameters (reflected background temperature, ambient temperature and humidity, distance to the research object). In the event that a difference in the results of temperature measurement by the contact and non-contact method was recorded, such 9a value of the emissivity coefficient was selected from the panel of the thermal imager, which reduced this difference to zero. The value of the emissivity coefficient obtained in this way was taken as a characteristic of the surface at the investigated reference point and used in further thermal imaging control.

There is one more factor that significantly affects the result of temperature measurement by infrared devices. In work [7], studies the influence of the observation angle on the coefficient of emissivity perceived by measuring equipment were carried out. It can be seen from Figure 1 that during flaw detection of products by amplitude thermal imaging control with one-sided access to the research surface, it is practically impossible to ensure the normality of the location of the thermal imager in relation to the investigated area.

Therefore, to increase the accuracy of determining the depth of occurrence and parameters of defects of products made of non-metallic heterogeneous materials, the influence of the angle at which the measuring device is located to the surface of the object under investigation should be taken into account.

For metals, the emissivity coefficient is constant in the range of viewing angles 0...40º, for dielectrics (which in most cases include non-metallic heterogeneous materials) - in the range of angles 0...60º. Beyond these ranges, the emissivity coefficient changes significantly when observing tangentially [9].

The calculation of the actual surface temperature, in which the influence of the observation angle on the measurement accuracy is taken into account, was carried out according to the expression [10]:

$$T_{fact} = \frac{T_{rad}}{\sqrt[4]{\dfrac{\varepsilon_{mea}}{K_{ang}}}} \tag{4}$$

where T_{fact} – the actual temperature of the surface of the control object;
T_{rad} – radiant temperature perceived by a thermal imager;
ε_{mea} – the measured value of the emissivity coefficient;
K_{ang} – coefficient of influence of the observation angle.

For dielectrics, the dependence of K_{ang} on the observation angle is most accurately described by the expression [10]:

$$K_{ang} = -0{,}0014 \cdot \varphi^3 + 0{,}022 \cdot \varphi^2 - 0{,}1 \cdot \varphi + 1{,}1 \ , \tag{5}$$

where φ – the angle of observation of the studied area of the surface of the control object.

With the help of the described method, thermal imaging studies of control carbon-plastic samples were carried out; in this study, the peculiarities of temperature distribution in the defective zone were studied. An analysis of the texture of the temperature field in the delamination type defect zone and defect-free zones was carried out. Figure 3 shows the thermogram of the investigated surface and graphs of changes in temperature contrasts at the specified points of the surface over time.

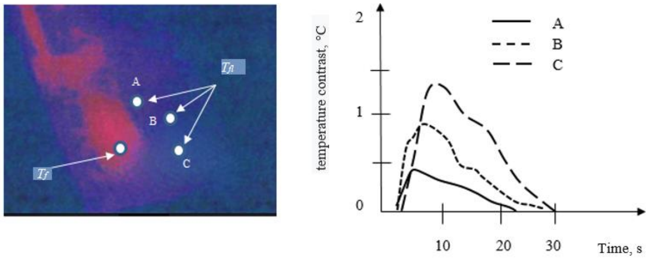

Figure 3 – Thermogram of the studied surface and graphs of changes in temperature contrasts at the specified points of the surface over time

It can be seen from the figure 3 that the change in the contrast amplitudes at the time t_m of optimal observation of the defect depends on the position of the defect-free zone relative to the temperature anomaly (defect area). Accordingly, the calculated value of the depth of the defect is changed. Obviously, given that the conditions of heat removal in zones A, B, and C are the same, it can be concluded that such a difference in the readings is caused by the presence of a methodical error from not taking into account the difference in the coefficients of the emissivity of the surface at the reference points.

4. CONCLUSIONS

As a result of the conducted studies of thermal processes on the surface of control carbon-plastic samples, it was possible to detect the majority of defects (the equipment used did not allow detecting 7% of embedded defects). At the same time, thanks to the use of the proposed method of eliminating the methodical error caused by the difference in the emissivity coefficient at the investigated points of the surface, it was possible to increase the accuracy of determining the depth of the defects.

References: **1.** *Bezimyanniy Yu.G.* Acoustic control of materials with a developed mesostructure *Physico-chemical mechanics of materials* - 2007. – No. 4. – pp. 53–65. **2.** *E.Yu. Gordienko, N.I. Glushchak, Yu.V. Fomenko, G.V. Shustakova, I.I. Dzeshulskaya, Yu.F. Ivanko* Diagnostics of composite materials of aircraft elements by active thermography *Nauka innov*: 2018, 14(2). – pp. 39–50. **3.** *Vavilov*

V.P. Thermal control of aerospace products *In the world of non-destructive testing*. 2003. T20, No. 2. pp. 4–10. **4.** *Vavilov V.P.* Infrared thermography and thermal control. Moscow: Spectrum. 2009. 544 p. **5.** *Maldague X.P.* Theory and Practice of Infrared Technology for Nondestructive Testing. *New-York: John Willey & sons*, 2001. 682 p. **6.** *Oborskyi G.O., Levynskyi O.S., Holofieieva M.O.* Study of the influence of the emissivity of materials on the accuracy of the thermal imaging control method *Technological audit and reserves of production*. – No. 2/3(28), 2016 – pp. 4–7. **7.** *Oborskyi G., Levynskyi O., Holofieieva M.* The effect of surface observation angle on accuracy of non-contact temperature measurement method // *Technological audit and reserves of production*. – №1/2(33), 2017 – pp. 19–23. **8**. *Molnar, V., Sztankovics, I.*: Analysis of Roughness Parameters Determining Tribological Properties in Hard Turned Surfaces, Hungarian Journal of Industry and Chemistry 49(2), pp. 77–84, 2021. **9.** *Gossorg, J.* Infrared thermography. Basics. Technique. Application – M. : Mir, 1988 – 416 p. **10.** *Levynskyi O.S., Holofieieva M.O., Babich Yu.I.* The influence of the observation angle on the accuracy of the thermal imaging method of measurement *Measuring and computing equipment in technological processes*, – No. 2(55), 2016. – pp. 51–54.

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ПІДВИЩЕННЯ ТОЧНОСТІ ДЕФЕКТОСКОПІЇ МЕТОДОМ АКТИВНОЇ ТЕРМОГРАФІЇ ВИРОБІВ З НЕМЕТАЛЕВИХ ГЕТЕРОГЕННИХ МАТЕРІАЛІВ, / ЩО ВИКОРИСТОВУЮТЬСЯ В ТЕХНІЦІ

Анотація. *Нині неметалеві гетерогенні матеріали широко використовуються в машинобудуванні, що пов'язано, перш за все, з їх унікальними властивостями, такими як міцність, мала вага, корозійна стійкість, високі вібро-, звуко- і теплоізоляційні характеристики. При цьому неабиякого значення набувають методи неруйнівного контролю, що дозволяють отримати найбільш повну картину дефектного стану виробів із таких матеріалів. Основною задачею роботи є розробка оптимальних алгоритмів визначення кожного дефекту виробу з неметалевого гетерогенного матеріалу з встановленням точного його розташування, в тому числі, глибини залягання, а також його геометричних параметрів. На сьогоднішній день одним з найбільш перспективних для дефектоскопії виробів із зазначеного класу матеріалів вважається метод теплового неруйнівного контролю. Цей вид дефектоскопії базується на візуалізації теплового поля поверхні об'єкта дослідження за допомогою приладів інфрачервоної техніки та аналізу аномалій цього поля. В роботі досліджувалися вуглепластикові зразки товщиною 4 мм, в яких на різноманітній глибині були спеціально сформовані дефекти у вигляді розшарувань (повітряні зазори товщиною до 0,2 мм та площею більше 1,5 см^2), які є одними з найбільш поширених видів дефектів для класу матеріалів, що розглядається. Вивчені особливості розподілення температури в дефектній зоні. Проведено аналіз текстури температурного поля в зоні дефекту типу розшарування та в бездефектній зоні. Проведено дослідження точності визначення параметрів дефектності неметалевих гетерогенних матеріалів зазначеним методом. В результаті проведених досліджень теплових процесів на поверхні контрольних вуглепластикових зразків вдалося виявити більшість дефектів (використовувана апаратура не дозволила виявити 15 % закладних дефектів). При цьому, завдяки використанню запропонованої методики виключення методичної похибки, що викликана відмінністю коефіцієнту випромінювальної здатності в досліджуваних точках поверхні, вдалося підвищити точність встановленні глибини залягання дефектів.*

Ключові слова: *неметалічні різнорідні матеріали; метод теплового контролю; дефектоскопія; інфрачервоне обладнання.*