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Gordiyenko[1], E.Yu., Glushchuk[1], N.I., Fomenko[1], Yu.V., Shustakova[1], G.V., Dzeshulskaya[2], I.I., and Ivanko[2], Y.F.

[1] Verkin Institute for Low Temperature Physics and Engineering, the NAS of Ukraine,
47, Nauky Ave., Kharkov, 61103, Ukraine
+380 57 340 22 23, fax +380 57 340 33 70, ilt@ilt.kharkov.ua
shustakova@ilt.kharkov.ua (for correspondence)
[2] Kharkiv State Aircraft Manufacturing Company,
134, Sumska St., Kharkiv, 61023, Ukraine
+380 57 700 34 39, info@ksamc.com

NONDESRUCTIVE TESTING OF COMPOSITE MATERIALS OF AIRCRAFT ELEMENTS BY ACTIVE THERMOGRAPHY

Introduction. *Composite materials (CM) are widely used in modern aircraft production. Due to the specificity of CM properties, thermal nondestructive testing (TNDT) is the most promising method for detection of flaws in aircraft construction elements made of CMs. Until now, TNDT has not been implemented in the Ukrainian aircraft industry.*

Problem Statement. *To study the dynamics of excess temperature fields on the surface of CM test samples using the active thermography.*

Purpose. *To develop a technique for optimal detection of defects in CM elements and estimation of defect parameters.*

Materials and Methods. *The fiberglass and carbon fiber test samples with the most dangerous and frequent defects at various depths are to be studied. To detect the defects and to determine their parameters, the method of optimal observation of their image temperature contrast was used after stimulating the samples by thermal pulse of finite duration (0.2—3 s).*

Results. *Experimental dependences of temperature contrast for each defect image as function of observation time have been obtained under various regimes of thermal stimulation and positions of reference (defect-free) area. Requirements for the thermal pulse parameters have been elaborated. Algorithms for optimal processing of thermal images sequence have been designed. A protocol of procedure for the TNDT of aircraft CM elements without metallized layers has been developed.*

Conclusion. *90% defects and depths of their location have been detected using technical means without special requirements to their response time. To detect the remaining 10% defects (in air-filled honeycomb samples and in samples with metallized layers), a thermal stimulation source with a shorter pulse duration and a thermal imager with a higher frame rate are required because of high relaxation rates of the excess temperature fields.*

The study was supported by the NAS of Ukraine in the framework of research project «Development of Infrared Diagnostic Complex and Procedure for Detecting Defects in Composite Materials of Aircraft Elements and Other Equipment».

Keywords: thermal nondestructive testing, composite materials, and aviation.

Due to their unique properties such as durability, strength, light weight, resistance to corrosion and fatigue, etc., the composite materials (CM) [1] are widely used in manufacturing advanced passenger and military aircrafts and helicopters. For instance, the share of composite materials in the total weight of well-known B787 *Dreamliner* aircraft by US *Boeing Commercial Aircraft* (BCA) and A380 airbus by European *Airbus SE* exceeds 50%. The share of composite materials in the weight of advanced small aircrafts reaches 65%. For example, in *Diamond*, *Grob* and other aircrafts only engines are made of metal. The nodes and aggre-

gates of composite materials are used in Russian *Superjet100*, *IL*96, *TU*204, in Russian and Ukrainian helicopters *Ka*52 and *MSB*2 and many others.

However, specific defects related to both manufacture (intrinsic flaws) and operation (customer induced damages) are inherent in the items made of composite materials. They are invisible on the surface of CM elements, but can lead to a crucial weakening of the structure and, consequently, to a catastrophe.

The conventional methods of nondestructive control often do not give a full understanding of defects of CM parts because of their specific structure, composition, and thermal physical properties [2]. As of today, the nondestructive thermal control (TC) method is considered by leading air- and spacecraft manufacturers among the most promising ones in flaw detection of CM parts [2—5], and both *BCA* and *Airbus SE* currently are using the TC as standard method for flaw detection of some fiberglass and carbon plastic structures.

The TC method is based on visualization and analysis of temperature field dynamics on the surface of controlled object using special technical means and algorithms. Usually, the inspected surface is preheated by a single thermal pulse or their sequence (the active TC) [6]. In this case, information about intrinsic damages and their parameters is contained in amplitude and time characteristics of thermal field in each point of the surface. The most effective is heat stimulation of the object by a very strong (energy density of dozens kJ/m^2) and short (several milliseconds) pulse.

Therefore, the corresponding devices from leading manufacturer *Thermal Wave Imaging Inc.* (TWI) [7] include high-frequency frame thermographers, halogen- or pulse xenon-based heaters, as well as computer system for data collection and processing.

It should be noted that all foreign technologies for TC in aviation are know-hows of their developers and created for specific composite materials. Although the thermal control is considered the most promising method for nondestructive control used in aerospace industry for CM flaw detection it has not been applied in Ukraine. Therefore, the researches concerning the development and implementation of methods for thermal diagnosis of CM structural elements in the national aircraft-building are very important.

This paper contains results of experimental study of thermal processes on the surface of composite material samples. The study aims at developing a method (protocol) for optimal detection of intrinsic flaws and determination of their parameters. It is a stage of creation of domestic technology for thermal control (devices and methods) within the framework of R&D innovative project of the NAS of Ukraine «The Creation of IR Diagnostic Complex and Methods for Detection of Flaws in Composite Materials of Aircraft Elements and Equipment».

The research has been made in cooperation with Kharkiv State Aircraft Manufacturing Company (KSAMC).

MATERIALS AND METHODS OF THE RESEARCH

The studied reference samples were given by KSAMC Nondestructive Control Laboratory. They were flat plates either continuous solid or honeycombed, made of fiberglass or carbon plastic and their combinations in accordance with real parts of aircraft structures. Each sample had several steps with different thickness (from 1 to 25 mm), the intrinsic flaws typical for given material and most frequently occurring in manufacture and operation of aircrafts were made intentionally at various depths. The most defects are delamination (air gaps of 0.1—0.2 mm between the layers with an area over 1 cm^2), the most dangerous and widespread defect of composite materials used in aviation [5].

The active TC method was used to detect flaws and to determine their parameters. The so-called one-sided control, when heating and image recording were made on the same side of the object, was chosen as most appropriate mode to the real test conditions in aviation [5]. Fig. 1 shows the arrangement of means and objects of control used in the experiment.

The so-called amplitude approach was implemented. It is based on the analysis of temperature dynamics on the sample surface in the defect free area $T_{df}(x, y, t)$ and in the defect projection $T_d(x, y, t)$ after heating the object by a single thermal pulse of finite duration t_{pulse}. Fig. 2 [5] shows typical time dependences of surface temperature above the defect and the defect free areas.

While heating, the excess temperature on the front side of the object grows and reaches its peak at time t_{pulse} corresponding to the end of thermal pulse. At the stage of surface cool-down, heat wave propagates deep into the sample and heat exchange with environment takes place, the excess temperature drops down to zero. The difference in thermal physical properties of material in the defect and the defect free areas leads to different conditions for heat wave propagation. As a result, the excess temperatures on the surface above these areas and their time dependences differ as well. In the area above the defect, a regular thermal field changes, with a local temperature signal appearing $\Delta T(x, y, t) = T_d(x, y, t) - T_{df}(x, y, t)$. It is called absolute temperature contrast and measured in temperature units. Time dependence of temperature contrast has a maximum ΔT_{max} reached at a certain time τ_{max} that is optimal defect observation time (Fig. 2). Both parameters, ΔT_{max} and τ_{max}, depend on flaw location depth and geometric size, thermal physical properties of the material and are basic informative parameters of the amplitude TC method.

It should be noted that as the duration of thermal pulse increases the excess temperature above the defect and the defect free areas can differ significantly as early as at the stage of heating (Fig. 2). In the case of long heat stimulation, the maximum local temperature signal can appear while heating, and optimal conditions for flaw detection will not be reached at the stage of cool-down. Therefore, while designing the heat source, in addition to its energy properties, it is necessary to take into account the required pulse duration.

For the ideal semi-infinite object heated by

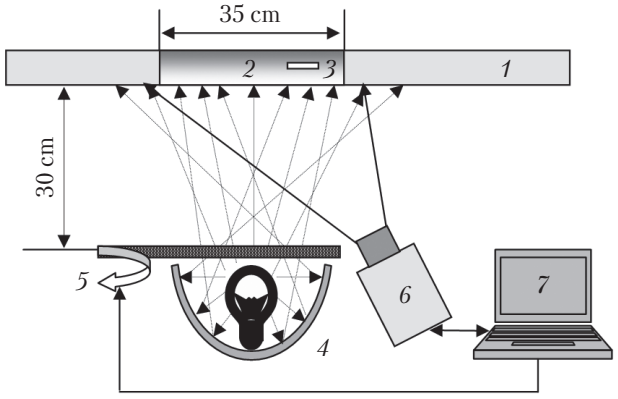

Fig. 1. Arrangement of control means and objects: *1* — reference sample, *2* — studied area of surface, 35 × 35 cm², *3* — intrinsic flaw, *4* — IR source with a reflector, *5* — heat flux interceptor (shutter), *6* — thermograph, *7* — PC

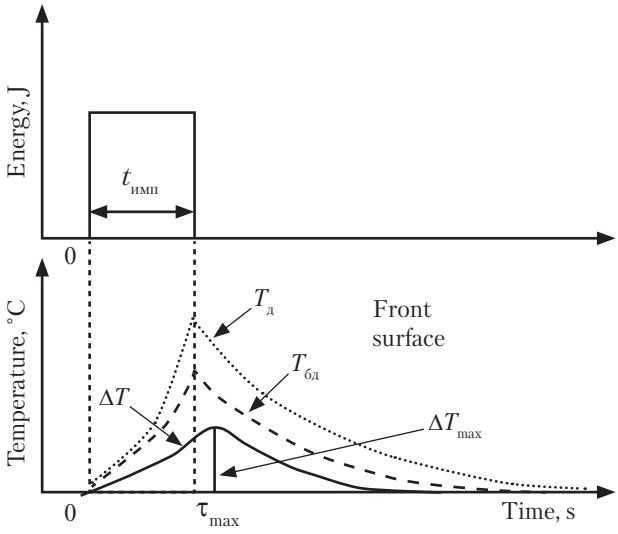

Fig. 2. Change in temperature of sample surface above the defect and the defect free areas

Dirac pulse, the optimal time for detection of intrinsic flaw (material discontinuity) can be determined as time for which the heat wave reaches the flaw, reflects from it and comes back [5]:

$$\tau_{max} = l^2/a, \qquad (1)$$

where l is defect location depth, $a = \lambda/C\rho$, (m²/s) is material thermal diffusivity, λ is thermal conductivity, C is heat capacity, and ρ is density.

Formula (1) can be used for estimating the air defect location depth if it does not exceed the

half-thickness of the object, at a very short thermal pulse $\tau_{max} >> t_{pulse}$, where $t_{pulse} \approx 5—10$ μs.

If the pulse duration is comparable to, but still less than the optimal observation time $\tau_{max} > t_{pulse}$ (see Fig. 2), the formula below can be used:

$$l^2 = a\,(\tau_{max} - t_{имп}). \qquad (2)$$

The minimum depth of defect location in the studied samples is $l_{min} \approx 0.7$ mm; maximum thermal diffusivity and thermal conductivity of carbon plastic and fiber glass samples across the layers are $a \approx 4.7 \times 10^{-7}$ m^2/s and $a \approx 1.4 \times 10^{-7}$ m^2/s, respectively. Then, maximum durations of thermal pulses required for stimulation of samples in order to detect flaws located at minimum depth can be estimated as $t_{pulse} \leq 1$ s and $t_{pulse} \leq 3.5$ s for carbon plastic and fiber glass samples, respectively.

The estimate has enabled not to use expensive xenon pulsed flash lamps that are conventionally used in TC for heat stimulation of metals or composite materials with metallic layers. Electric heater shaped as a flat helix with reflector and mechanic shutter of heat flux was used as thermal stimulus. The IR radiation density of the heater was $P \approx 10^4$ W/m^2. The shutter enabled to form single pulses of heat flux with a duration of 0.25—20 s and, correspondingly, with an energy density $Q \approx 2.5 \times 10^3—2 \times 10^5$ J/m^2. Also, matrix of four IKZ-500 E40 IR reflector lamps with the same shutter was used.

Rather low rates of relaxation of excess thermal fields on the studied surfaces made it possible to use thermal imagery devices without any special requirements for their speed of response. The two thermal imagers, the one based on uncooled matrix of detectors with a format 384 × 288 elements and a frame frequency of 20 Hz [8] and the other with mechanical scanning based on single-element cooled detector and a frame frequency of ≈ 1 Hz [9].

Both devices were designed by the authors of this research, which enabled to maximally adapt their hardware and software components for the fulfillment of assignment.

RESULTS OF STUDYING THE THERMAL PROCESSES ON THE SURFACE OF REFERENCE SAMPLES

The main task of this stage was to develop optimal algorithms for detecting each defect and

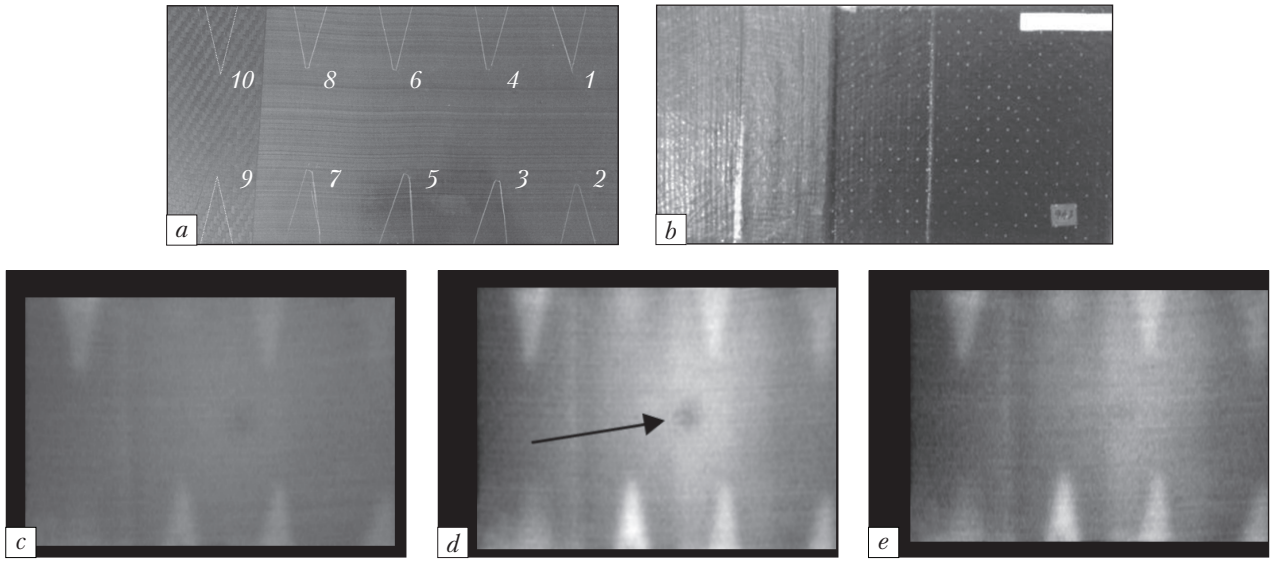

Fig. 3. Detection of flaws in monolithic four-step carbon plastic sample: *a* — appearance of the sample with marked positions of ten flaws; *b* — sample backside coated with organic plastic; *c* — thermogram of sample fragment in 4 s after the end of thermal pulse; *d* — summary thermogram of 50 consecutive thermograms; *e* — summary thermogram with suppressed thermal pulse distortions and false reflections

determining its precise localization, shape, size, and depth of location.

An IR-imaging study of dynamics of excess thermal fields on the surfaces of all reference samples at different power and duration of thermal pulses has been carried out. Before the start of thermal pulse, a thermogram was recorded to be used for further processing thermographic film to count external flaws, reflections, etc. Synchronously with the start of pulse, a sequence of 30—100 thermograms of surfaces were automatically recorded each 1.5 s. The thermograms were processed using methods for image processing and analyzed by mathematical methods given in [5].

The detection of flaws and determination of their parameters are shown below, by example of the two samples:

- monolithic four-step carbon plastic sample coated with organic plastic material and having ten reference flaws at different depth;
- monolithic four-step fiberglass sample having six reference flaws.

Fig. 3 features the appearance of carbon plastic sample with marked location of flaws and the backside coated with organic plastic (*a, b*), a sample thermogram made in 4 s after the end of 2 s thermal pulse (*c*), and summary thermogram of 50 frames (*d*). One can see that summing up of all sequence of thermograms not only increases the signal/noise ratio reducing the uncorrelated noises $\sqrt{N}$ times, where N is number of thermograms [5], but also features thermal imprints of all flaws located at different depth on the summary thermogram. The deduction of the first thermogram recorded at the end of pulse from the summary thermogram (Fig. 3, *e*) enables to decrease irregularities of thermal field caused by spatial distortion of thermal pulse and false reflections. For example, on the thermogram (Fig. 3, *e*), there is neither hypothermic stain that is reflection of cryostat cold window on the sample surface (shown by black arrow), which is observed on the preceding thermograms, nor radial distortion of thermal field.

To determine the depth of location of each defect, the time dependences of surface temperatures in the projection of the defect and the reference (defect free) area have been analyzed. To reduce the measurement error, changes in average temperatures of the sections above the defect and the defect free parts having the same area were considered.

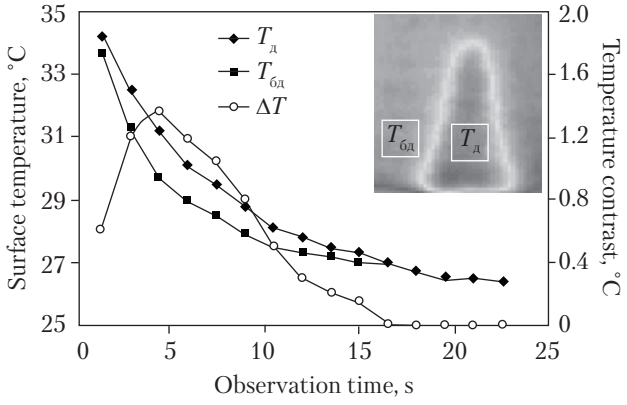

Fig. 4. Dynamics of average temperature of carbon plastic sample surface areas above the defect and the defect free regions and corresponding time dependence of flaw thermal contrast. The inset shows thermal image of the flaw with marked areas where average temperature above the defect and the defect free regions are measured

Fig. 4 shows time dependences of temperature on the surface of 3.8 mm thick step in the projection of flaw no. 5 (located at a depth of 1.25 mm) and temperature above the defect free area of the same step. The pulse duration is 1s. The areas of 6 × 6 pixels where average temperature is measured are shown T_d and T_{df}, are given in the flaw thermogram (inset). As the time dependence of temperature contrast ΔT shows, the flaw maximally manifests itself at τ_{max} = 4.5 s that agrees well with an estimate based on the formula (2): $(\tau_{max})_{est}$ = = 4.7 s, at a thermal diffusivity of the sample $a = 4.2 \times 10^{-7}$ m^2/s.

Fig. 5, *a* features measured time dependences of temperature contrasts for flaws No. 2, 3, 4, 7, and 8 (see Fig. 3, *a*) located at a depth 1.1, 1.5, 2, 2.3, and 4.3 mm, respectively, in the two steps having a thickness of approximately the same thickness (5.5 and 6 mm). The thermal pulse duration is 1.5 s.

Fig. 5, *b* shows an experimental dependence of optimal observation time on the location depth

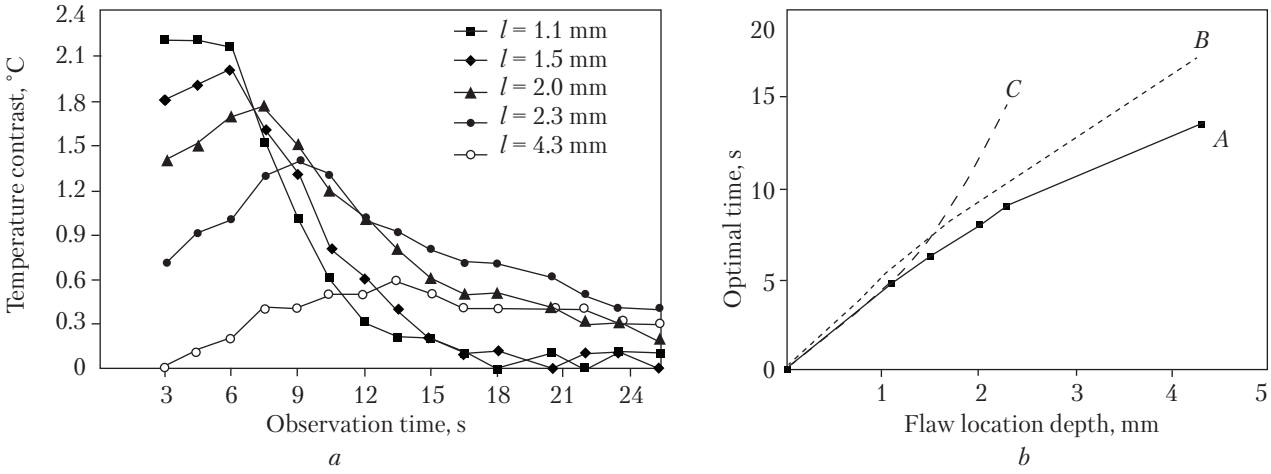

Fig. 5. Dependence of informative parameters on flaw location depth: *a* — dynamics of temperature contrast for flaws located at different depth in the carbon plastic sample; *b* — dependence of optimal observation time on flaw location depth: *A* — experiment data, *B* — estimate based on the individual inversion function [5], *C* — estimate based on the formula (2)

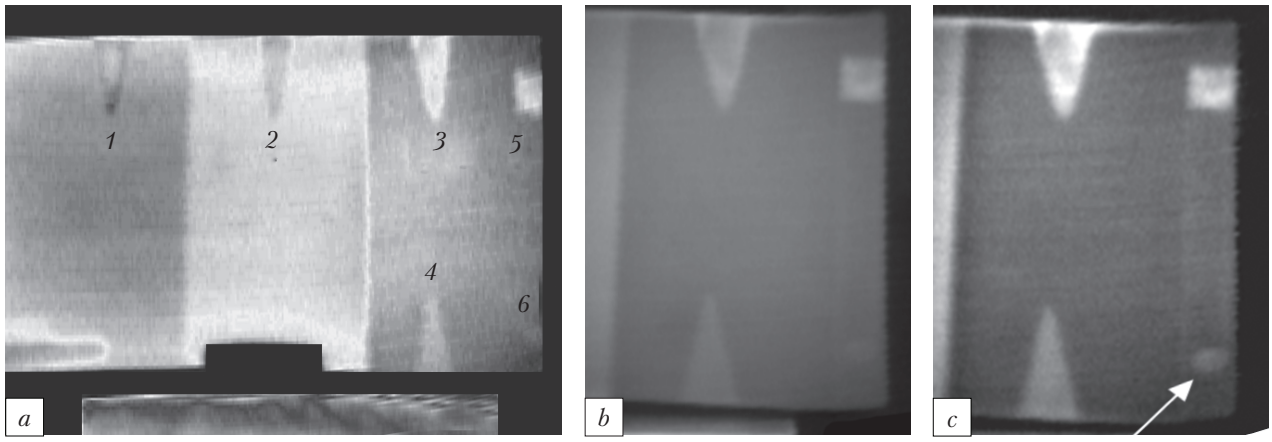

Fig. 6. Thermograms of monolithic four-step fiber glass sample with six flaws: *a* — summary thermogram of the whole sample; *b* — thermogram of sample fragment made at the optimal time of flaw No. 3 manifestation; *c* — summary sample thermogram after deduction of the first thermogram (the white arrow indicates a thermal imprint of the cave)

(*A*), a dependence obtained using the individual inversion function: $l\,[\text{mm}] = -0.005 + 0.177\,\tau_{max} + 0.00424\,(\tau_{max})^2$ proposed in [5] for determining the parameters of delamination in a similar 5 mm thick carbon plastic sample (*B*), and a dependence based on the estimate formula (2) (*C*). It is clear that the dependences *A* and *B* have a similar character. The experimental data (*A*) are described by the polynomial: $l\,[\text{mm}] = 0.0286 + 0.1585\,\tau_{max} + 0.0115\,(\tau_{max})^2$. A difference in dependences *A* and *B* is explained by different thermal physical properties of the samples. At the same time, the estimate dependence *C* radically differs from the experimental curve *A* starting with a depth of 1.5 mm and more.

Fig. 6, *a* bears a thermogram of the four-step monolithic fiberglass sample (with six reference flaws) stimulated by a 2 s thermal pulse. The thermogram was obtained by summing up all film frames (the flaws are numbered with digits). Fig. 6, *b* features a thermogram of sample fragment at the time of maximum contrast for the flaw No. 3

located at a depth of 0.8 mm in a 2.5 mm thick step. The location depth of flaw No. 3 as estimated by the formula (2) based on experimental optimal observation time for this flaw $\tau_{max} = 4.5$ s is $l_{est.} = 0.7$ mm that does not contradict the location depth of this flaw as given in the specification. Fig. 6, *c* shows a fragment of resulting thermogram obtained by summing up all thermograms with the first thermogram of the sequence deducted.

On the thermogram (Fig. 6, *c*) the arrow indicates a thermal imprint of reference flaw No.6 (a cave in material on the reverse side of article having a diameter $D = 10$ mm and located as deep as 1 mm from the studied surface of 2.8 mm thick step. A time dependence of temperature contrast measured for this flaw (Fig. 7, curve *B*) gives an optimal observation time $\tau_{max} \approx 12$ s. To determine the characteristics of the flaws of this kind Shepard and his coauthors [10] proposed a heat trap model in which τ_{max} is interpreted as time required for filling a cylinder having the base and the height equal to the flaw area and location depth, respectively, with incident thermal radiation. The location depth as estimated using this model is $l_{est.} = a \times \tau_{max} / \varpi D\sqrt{2} = 0.035$ mm that is significantly less than that in the specification $l = 1$ mm. An estimate based on the formula (2) gives a better agreement: $l_{est.} = [a\,(\tau_{max} - t_{pulse})]^{1/2} = 1.14$ mm.

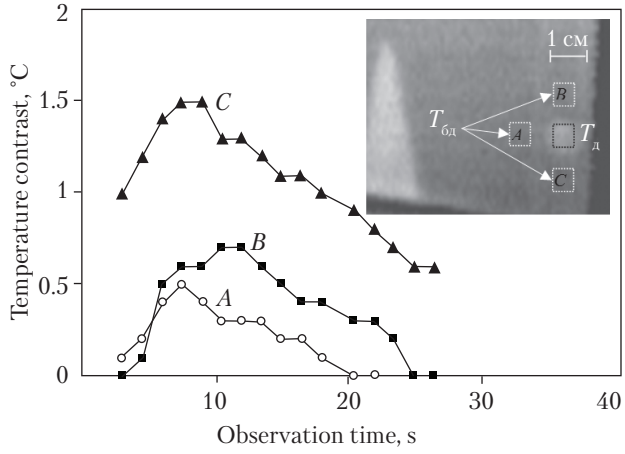

Fig. 7. Time dependence of temperature contrast of the cave located at the edge of monolithic fiber glass sample. The inset shows a thermogram of sample fragment with indicated areas for controlling dynamics of their average temperature. The measurement accuracy is determined by IR imager sensitivity: $\delta = \pm 0.1$ °C

It should be noted that the measured values τ_{max} and, correspondingly, the location depth calculated on their basis depend on the position of

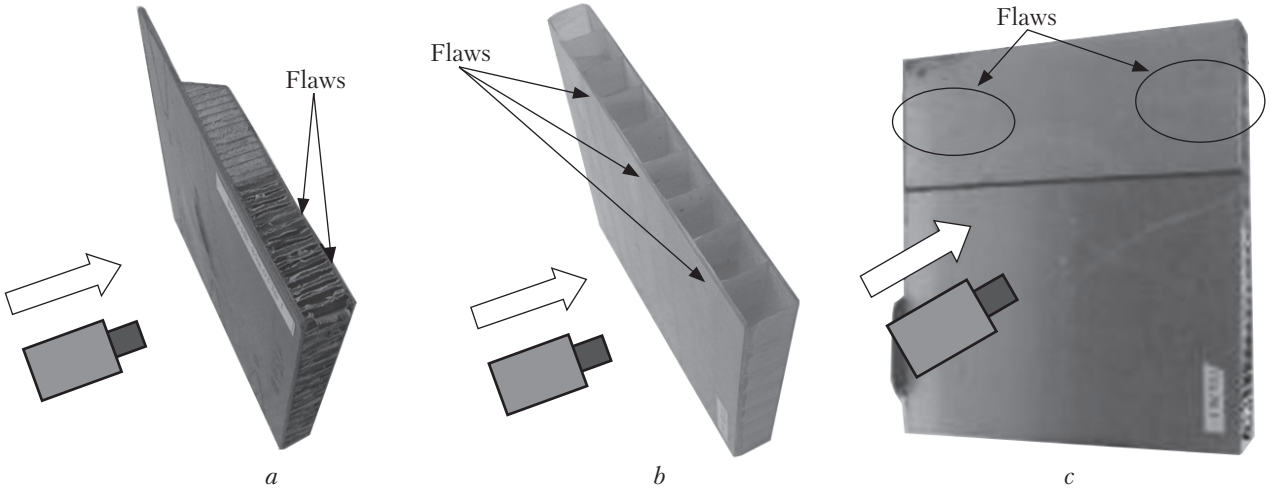

Fig. 8. Reference samples with undetected flaws: *a* — a honeycomb structure partially filled with foam rubber, with seven flaws in the front and back walls of 2 mm-thick monolithic organic plastic material; *b* — a honeycomb air-filled structure of three-layer fiberglass; *c* — a honeycomb structure partially filled with foam rubber, with metallized walls. The undetected flaws are indicated by arrows. Directions of thermal stimulation and survey are shown schematically as well

reference (defect free) area with respect to the defect area and on the distance to edges. Fig. 7 shows time dependences of thermal contrast of the cave. The dependences are obtained for three different positions of the reference area chosen at equal distances from the flaw. The positions of reference areas *A, B,* and *C* are shown in the inset of Fig. 7. It appears that the position of reference area influences both contrast amplitude and time of contrast maximum, with τ_{max} varying by several seconds. Correspondingly, obtained values of flaw location depth will differ as well. Obviously, this is explained by non-uniform longitudinal heat diffusion as a result of different conditions for heat removal for the sample of finite size. The effect of position of the reference area was taken into consideration in the study and TC protocol.

As a result of experimental research of thermal processes, the majority of flaws have been detected on the surface of 20 reference fiber glass and carbon plastic samples. Seven flaws in three sample have not been detected (Fig. 8). They are as follows:

- 2 flaws located in the 2 mm thick back wall made of organic plastic in 17 mm thick honeycomb sample with empty cells (Fig. 8, *a*). According to the authors, the flaws cannot be detected by the single side TC method because of specific configuration of the sample;
- 3 flaws located in the 1 mm thick fiber glass front wall in the 18 mm thick honeycomb sample with empty cells (Fig. 8, *b*). The flaws have not been detected because of their location near the back wall surface. In this case, heat fluxes reflected from the flaw and the back wall of defect free area create small temperature contrasts on the sample surface, which are indistinguishable by IR imaging method.
- 2 flaws in the front metallized wall of honeycomb fiber glass sample with cells filled with foam rubber (Fig. 8, *c*). At the used pulse durations, the flaws are not detected because of a high relaxation rate of excess thermal fields on the metallic layer.

Similar measurements were made for all reference samples with given location depth of the flaws. It should be noted that the location depths calculated by estimate formulas based on experimentally obtained optimal observation time often do not coincide with those given in the sample specification. Therefore, for the real manufacturing conditions the authors recommend to use in the TC procedure the reference dependences $l = f(\tau_{max})$ obtained by approximation of reference measurements for specific structural elements having different thermal physical properties, size, heat removal conditions.

Since the equipment did not enable to detect 10 % of the flaws, now the works are focused on designing specialized diagnostic complex consisting of a heater in the form of nine xenon flash lamps, an original high-speed thermograph, and an original software for control and automatic data processing.

CONCLUSIONS

As a result of the research, requirements for the parameters of thermal pulse (power, duration, spatial homogeneity, etc.) have been established and algorithms for optimal processing of obtained thermograms to detect the flaws of delamination type with a thickness of 0.1—0.2 mm and to determine the depth of their location have been developed. Based on the obtained results a TC procedure protocol as additional nondestructive control method for the structural elements made of composite material without metallized layers has been developed and implemented at KSAMC. The proposed procedure includes:

- Use of IR heater with heat flux shutter and thermal imaging device without any special requirements for speed of operation;
- Stimulation of object by maximally uniform thermal pulse (due to the configuration of radiator and reflector) of finite duration ($t_{pulse} \leq 1$ s) and with a power sufficient for sustainable observation of thermal contrasts of the flaws, but not causing thermal destruction of the studied objects (the maximum temperature on the surface must not exceed 100 °C);
- Automatic record of the sequence of, at least, 50 thermograms of the surface area studied;

- Use of the first thermogram for taking into account the non-uniformity of incident radiation;
- Use of summing up and averaging of all thermogram sequence in order to increase the signal/noise ratio and to simultaneously detect the flaws located at different depth on the summary thermogram;
- Precise localization, determination of shape and size of all flaws detected;
- Analysis of time dependence of temperature contrast for each flow in order to obtain the value of its optimal observation time;
- Determination of flaw location depth based on the optimal observation time, using specially prepared reference dependences or corresponding polynomials.

The developed method has enabled to detect 90% of all dangerous and widespread flaws in the reference samples simulating real carbon plastic and fiberglass structural elements of aircrafts. This confirmed a high efficiency of the thermal contrast method for TC of solid composite elements without metallized layers even using rather cheap technical means without any special requirements for speed of response. However, to detect some flaws in the honeycomb samples and all flaws in the samples with metallized layers it is necessary to use a source of thermal stimulation with a shorter pulse duration (for example, xenon flash lamp matrixes) and IR imaging devices with a frame frequency of, at least, 50 Hz because of high relaxation rate of excess temperature fields.

The research was supported by the NAS of Ukraine in the framework of research project «Development of Infrared Diagnostic Complex and Procedure for Detecting Flaws in Composite Materials of Aircraft Elements and Other Equipment».

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Е.Ю. Гордієнко [1], М.І. Глущук [1], Ю.В. Фоменко [1],
Г.В. Шустакова [1], І.І. Дзешульска [2], Ю.Ф. Іванько [2]
[1] Фізико-технічний інститут низьких температур ім. Б.І. Вєркіна НАН України,
проспект Науки, 47, Харків, 61103, Україна,
тел. +380 57 340 22 23, факс +380 57 340 33 70, ilt@ilt.kharkov.ua,
shustakova@ilt.kharkov.ua
[2] Харьківське державне авіаційне виробниче підприємство,
вул. Сумська, 134, Харків, 61023, Україна,
+380 57 700 34 39, info@ksamc.com

ДІАГНОСТИКА КОМПОЗИТНИХ МАТЕРІАЛІВ ЕЛЕМЕНТІВ ЛІТАКІВ МЕТОДОМ АКТИВНОЇ ТЕРМОГРАФІЇ

Вступ. Композитні матеріали (КМ) широко використовуються у виробництві сучасних літальних апаратів. Через специфіку їх властивостей одним з найбільш перспективних методів дефектоскопії виробів з КМ є тепловий метод контролю (ТК), який у вітчизняному авіабудуванні до сьогодні не застосовується.

Проблематика. Експериментальне дослідження динаміки надлишкових температурних полів на поверхні контрольних зразків з КМ методом активної термографії.

Мета. Розробка методики оптимального виявлення дефектів у виробах з КМ та визначення їх параметрів.

Матеріали й методи. Об'єкт досліджень — скло- й вуглепластикові контрольні зразки з закладеними на різній глибині найбільш небезпечними та розповсюдженими дефектами. Для виявлення й визначення параметрів дефектів використано метод оптимального спостереження їх температурного контрасту при стимуляції зразків імпульсом кінцевої тривалості 0,2—3 с.

Результати. Отримано експериментальні залежності температурного контрасту кожного дефекту від часу спостереження при різних режимах теплової стимуляції та положенні опорної (бездефектної) області. Визначено вимоги до параметрів теплового імпульсу. Складено алгоритми оптимальної обробки отриманих термограм. Розроблено протокол процедури ТК елементів літальних апаратів з композиційних матеріалів без металізованих шарів.

Висновки. Використання технічних засобів без особливих вимог до їх швидкодії дозволило виявити 90 % дефектів і визначити глибину їх залягання. Для виявлення 10 % дефектів в стільникових зразках з повітряним заповненням та в зразках з металізованими шарами необхідним є використання джерела теплової стимуляції з коротшою тривалістю імпульсу та тепловізора з високою частотою кадрів через високі швидкості релаксації надлишкових температурних полів.

Дослідження проведено в рамках інноваційного проекту «Створення інфрачервоного діагностичного комплексу і методики виявлення дефектів в композитних матеріалах елементів літаків і їх обладнання».

Ключові слова: тепловий неруйнівний контроль, композиційні матеріали, авіація.

Э.Ю. Гордиенко [1], Н.И. Глущук [1], Ю.В. Фоменко [1],
Г.В. Шустакова [1], И.И. Дзешульская [2], Ю.Ф. Иванько [2]
[1] Физико-технический институт низких температур им. Б.И. Веркина НАН Украины,
проспект Науки, 47, Харьков, 61103, Украина,
+380 57 340 22 23, факс +380 57 340 33 70, ilt@ilt.kharkov.ua
[2] Харьковское государственное авиационное производственное предприятие,
ул. Сумская, 134, Харьков, 61023, Украина, +380 57 700 34 39, info@ksamc.com

ДИАГНОСТИКА КОМПОЗИТНЫХ МАТЕРИАЛОВ ЭЛЕМЕНТОВ САМОЛЕТОВ МЕТОДОМ АКТИВНОЙ ТЕРМОГРАФИИ

Введение. Композитные материалы (КМ) широко используются в производстве современных летательных аппаратов. Из-за специфики их свойств одним из наиболее перспективных методов дефектоскопии изделий из КМ является тепловой метод контроля (ТК), который в отечественном авиастроении до сегодняшнего момента не используется.

Проблематика. Экспериментальное исследование динамики избыточных температурных полей на поверхности контрольных образцов из КМ методом активной термографии.

Цель. Разработка методики оптимального обнаружения дефектов в изделиях из КМ и определения их параметров.

Материалы и методы. Объект исследований — стекло- и углепластиковые контрольные образцы с заложенными на разной глубине наиболее опасными и часто встречающимися дефектами. Для обнаружения и определения параметров дефектов использовался метод оптимального наблюдения их температурного контраста при стимуляции образцов импульсом конечной длительности 0,2—3 с.

Результаты. Получены экспериментальные зависимости температурного контраста каждого дефекта от времени наблюдения при различных режимах тепловой стимуляции и положении опорной (бездефектной) области. Определены требования к параметрам теплового импульса. Составлены алгоритмы оптимальной обработки полученных термограмм. Разработан протокол процедуры ТК элементов летательных аппаратов из композиционных материалов без металлизированных слоев.

Выводы. Использование технических средств без особых требований к их быстродействию позволило выявить 90 % дефектов и определить глубину их залегания. Для обнаружения 10 % дефектов в сотовых образцах с воздушным заполнением и в образцах с металлизированными слоями требуется использование источника тепловой стимуляции с более короткой длительностью импульса и тепловизора с высокой частотой кадров из-за высоких скоростей релаксации избыточных температурных полей.

Исследования проведены в рамках инновационного проекта «Создание инфракрасного диагностического комплекса и методики выявления дефектов в композитных материалах элементов самолетов и их оборудования».

Ключевые слова: тепловой неразрушающий контроль, композиционные материалы, авиация.