Active thermography as a contemporary method for ensuring the quality of composite material products

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Abstract. This paper examines the current trends in the quality control of composites and the perspectives of application of active thermography method to ensure the quality of products made of composite materials. Using NDTtherm™ system of active thermography, the research has been carried out on composite samples and products with inbuilt artificial defects. Based on research results the author highlights the most promising applications of the active thermography method.

1. Introduction

The long-term service of aviation equipment implies high workload and strict requirements for non-destructive testing (NDT) of parts and assembly units in the aerospace industry. In modern aircraft, as of 2015, the volume share of products made of composite materials reaches 50% [3]. Due to well-known features of physical and mechanical properties of composite materials, there is a tendency of constant increase their share by volume in the aircraft industry which makes it relevant to develop, improve and implement new methods to ensure the quality of products made of composite materials. Because of geometric features of composite material products, preference is given to high-efficiency NDT methods that can be used without special preliminary treatment of the inspected object surface and with easy test accessibility.

Active thermography is one of the promising NDT methods that can be used for products made of composite materials (Figure 1).
Unlike passive thermography, the active thermography (AT) method requires heat load monitoring to the inspected object. At the same time the AT method does not require physical contact with the inspected object for the load to the inspection system or for obtaining the response.

At present this method has been successfully used by enterprises manufacturing or operating products and structures made of composite materials. Such large aerospace enterprises like Boeing and Airbus pay special attention to the AT method, include it in their specifications that describe the inspection procedure of the fuselage, cellular panels, etc. [4].

The AT method is included in the international NDT standards (NAS 410, EN 4179, etc.) and in the Russian State standards (GOST R 17359-2015, GOST R 18434-1-2013, etc.). The national standard of the Russian Federation GOST R 56787-2015 [5] concerned with NDT polymer composites recommends the AT method to detect such defects as:

- lamination;
- change of density;
- breaking of connections;
- breaking of connections between fibers;
- breaking of fiber function;
- breaks;
- inclusion;
- moisture;
- porosity;
- change of the thickness;
- emptiness.

In addition, advantages of the AT method are also as follows:

- non-contact application;
- high performance (in certain cases, 5 times faster than ultrasonic or radiographic inspection methods);
- possibility of structure inspection from one side only;
- safety;
- a wide range of inspectable composite materials;
- a wide variety of problems solved by this method.

Like any other method, AT has its limitations:

- it is necessary to ensure uniform heating of entire inspected surface of the part;
- a heavily soiled or glossy surface causes interference and noise and makes it difficult to interpret results;
- going deeper the heat wave attenuates dramatically, so the thickness of the tested layer is usually limited up to 10 mm.

The great opportunities of the AT method are connected to the variety of its technical implementations. There are various approaches to the generation of heat loading (heat stimulation) in the inspected object. According to the physics principle, they can be divided into: optical (flash lamps, halogen lamps, lasers), induction (eddy currents), microwave, electric current, mechanical (ultrasound or vibration), hot or cold gases or liquids. Depending on the problem being solved, different type of the heating profile can be used: apportioned, local, band-pass, “grid”. Modern pieces of equipment that implement the AT method also allows to manage the shape of the heat stimulation pulse: Dirac pulse, rectangular, Gaussian pulse or a sequence of pulses. In addition, the effective NDT technology that uses the AT method is impossible without special software (SW) processing infrared (IR) images of the inspected object [6].
In order to evaluate the perspective of the AT method in practice, the active thermography system NDTherm™ by Opgal is used in this study. It is a high-performance NDT system that implements the AT method. NDTherm™ consists of the following basic elements:

- Uncooled high-sensitive infrared microbolometer camera;
- Halogen lamps with a total power of 3.2 kW;
- Electronic control unit;
- Special image processing Opgal algorithms.

An overview of the system with the identification of main units is shown in Figure 2. The source of heat stimulation in NDTherm™ active thermography system is 4 halogen lamps (pos. 5) which ensure uniform heating of the inspected object surface. By the use of an electronic control unit (pos. 1) it is possible to manage the type of heat stimulation (the shape and duration of the thermal pulse). Heat stimulation is generated by light pulse with duration from 0.1 to 20 seconds. Special SW included in the unit of the image processing and analyzing (pos. 2) allows implementation of special algorithms for processing IR images of the inspected object and the use of tools for analyzing the obtained thermographic defectograms (thermograms).

The results of inspection by NDTherm™ system are presented in the form of time sequences of thermograms after processing by special algorithms. Thus, the output parameters are pixel functions of the dependence of temperature (or its derivative) on time and on coordinates. In general, the algorithms used for processing are determined by the task being solved (type and size of the defects, product material, inspection process conditions, etc.), but NDTherm™ system typically contains a set of the most universal IR image processing algorithms. The purpose of using these algorithms is to increase the ability of flaw detection. In this study, the following algorithms have been used:

- Reconstruction of an image with the use of polynomial fitting;
- First time derivative;
- The second time derivative;
- Fourier transform.

A more detailed description of the practical applicability of the above methods for processing IR images can be found in [7].

2. Experimental studies

In order to evaluate the applicability of the AT method implemented in the NDTherm™ system, experimental research of products and samples made of composite materials has been carried out.

2.1 Flaw detection in composites
Inspected objects with inbuilt artificial defects have been investigated. The results of these studies give positive results for the detection of the following types of defects: lamination in products made of carbon fiber-reinforced plastic (Figure 3), lamination in sandwich panels, lamination in aluminum composites, non-gluing in honeycomb panels (Figure 4), inclusions in glass fiber-reinforced plastic (GFRP), etc.

![Figure 3](image1.png)

**Figure 3.** Detection of laminations in carbon fiber-reinforced plastic (CFRP) sample using AT method: (a) visible image of the sample; (b) thermogram of the sample with detected defects

![Figure 4](image2.png)

**Figure 4.** Thermogram of a honeycomb panels of aerospaces structure with detected artificial defects

Software tools allow building a profile of temperature (brightness of the thermogram) change along the line drawn by the user, as shown in Figure 3b. After selecting the analyzed region of the thermogram, a graph of the brightness distribution along the profile appears. The value on the abscissa axis on this graph correspond the coordinate of a point on the profile (x), and the value on the ordinate axis is a value of brightness in system units (I). This tool allows using a quantitative estimate of defects for categorizing identified heterogeneities.

The detection of defects in complex structures of alternating layers of CFRP and GFRP using the NDTherm™ active thermography system is described in detail in [8].
2.2 Thermal tomography
At ensuring one-side uniform heating of the inspected object surface, it becomes possible to reconstruct the structure of the object or the defect. Thermal tomography (dynamic thermal tomography) uses time sequential of the thermograms showing the dynamics of the thermal response of the inspected object surface (Figure 5) versus classical computed tomography which uses the multi-view images [4].

![Figure 5](image)

Figure 5. Time sequence of thermograms of the reference sample obtained using the NDTherm™ AT system. The images are arranged in an ascending order of thermal response time and accordingly the depth of defects accordingly.

As noted above, the NDTherm™ system provides results in the form of time sequence of thermograms obtained at different times which makes it possible to use thermal tomography in this equipment.

The practical application of thermal tomography is the ability to evaluate the depth of the defect and its length in the depth (Z axis) of the sample. The speed of propagation of heat waves inside one material is constant (under normal conditions) and is determined by the physical properties of the material. Deeper defects appear on thermograms later than less deep ones. Thus, using a reference sample with artificial defects at different depths, like in example in Figure 5, made of the same material as the inspected object it is possible to measure reference values of the response time for specific depths of defects. Further, comparing the maximum amplitude parameter of the thermal response of the detected defect with the similar parameter for the reference defect, it is possible to estimate the depth of the defect, which is detected in the object.

2.3 Material engineering tasks
The properties of composite material are determined by the properties of its components and their configuration. Since the manufacture of composite materials is a technologically complex process, NDT methods for material engineering tasks are of a particular interest. The study of the properties of the composite material components allows improving the technology of its manufacture.

The use of highly-sensitive IR cameras in the equipment that implements the AT method allows registering structural elements with different thermal characteristics. For example, the high contrast of the thermogram shown in Figure 4 allows identifying and analyzing the structure of the product: evaluating the cell size of the honeycomb structure, analyzing their shape, etc. In case of monitoring reinforced composite materials, including CFRP, resolution of thermograms obtained by the
NDTherm™ system helps to identify individual fibers (Figure 6), which makes it possible to detect such defects as breaking of connections and fiber function.

![Figure 6](image)

**Figure 6.** The examples of the structure imaging in samples made of composite materials: (a) layered carbon-carbon composite; (b) CFRP

In [9], technique of pixel function matrices factorization application (functions of the dependence of temperature on time and on coordinates) – “principal component analysis” with the use of equipment for AT is described. Since the main components of these matrices contain information about the thermos-physical characteristics (thermal diffusivity, heat capacity and thermal conductivity) of the material being inspected, this approach provides an opportunity to evaluate the porosity of the CFRP structure.

In this study, the AT method was used for porosity non-contact evaluation in a composite material (Figure 7). The specimens made of CFRP with different porosities and different thicknesses have been studied:

- Specimen №1 – h = 2 mm; porosity = 1.6 %;
- Specimen №2 – h = 2 mm; porosity = 4.4 %;
- Specimen №3 – h = 3 mm; porosity = 4.8 %.

![Figure 7](image)

**Figure 7.** Porosity evaluation task: the AT method for inspection of the CFRP: (a) visible image of the specimens; (b) thermograms of specimens
The use of samples with different thicknesses permits choosing the optimal operation mode of the equipment – the one in which thermal response is more affected by porosity than the difference in thickness. As a result, it was concluded that the porosity of the material affects its thermos-physical characteristics, changing the characteristics of heat propagation inside the sample: on the thermogram in Figure 7, it can be seen that with the same thermal stimulation the IR images of specimens №1 and №2 have a different contrast structural elements of the composite. Thus, the AT method can be used to evaluate the porosity of a composite material by using reference samples.

3. Conclusions
Based on the results of the study, the following promising applications of the AT method can be highlighted:

- Non-destructive inspection of a wide range of composite material products.
- Detection of the most common defects in composite materials – laminations, voids, inclusions, moisture, non-glue, etc.
- Carrying out dynamic thermal tomography of products with the capability to identify the characteristics of the detected defects (linear dimensions and depth).
- Study of the composite materials and components, that they are composed of.
- Evaluation of the thermos-physical characteristics of the material (thermal diffusivity, heat capacity and thermal conductivity, etc.).
- Evaluation of porosity and other physical characteristics of the material affecting its thermal response.

Thus, the use of the AT method allows not only carrying out the flaw detection of products, but also analyzing the structure and thermos-physical properties of the material. Based on the aerospace industrial sector world leaders’ experience at successful application of the AT method in the production and operation of products made of composite materials, this NDT method should be introduced to Russian enterprises. The use of AT method can improve the technology of composite material manufacture by the ensuring of its quality.

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