

Diagnostics of polymer composites by acoustic methods

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Abstract

The most dangerous flaws of polymer composite materials (PCMs) are the low matrix polymerization and the inadequate material composition throughout the whole volume or a considerable part of the product. Besides, such defects as the zones of material excessive porosity or lower density, the irregularity of fiber orientation (reinforcement angle deviation, curvature of fibers in layer planes) and the local inadequacy of material composition can be found in PCMs. These defects are detected by the diagnostic methods based on the correlation between the diagnostic parameters and the properties being sought for. The diagnostic parameters used are the acoustic properties of materials (transmission and damping coefficient of ultrasonic oscillations in the material) which, as well as the physico-mechanical properties (density, porosity, elastic and strength properties) depend on a material. But testing according to only these parameters does not always allow to get the acceptable accuracy of diagnostics and the reliability of the achieved results.

The spectrum analysis of signals having transmitted through the structure under test and carrying information of material structure and properties allows to increase the accuracy of diagnostics. But the application of conventional piezoelectric converters (in case of PCMs diagnostics) to excite high-power broadband ultrasonic impulses is often impossible due to the low efficiency of piezo-excitation of broadband acoustic signals, therefore it is worthwhile to use laser for these tasks. Laser excitation of short pulses with the smooth-time envelope allows to analyze the ultrasonics damping within the broad frequency band (from 0.1 to 20 MHz), which in turn allows to improve the reliability of diagnostics for polymer composite density, porosity, composition, elastic and strength properties.

The use of laser for the excitation of ultrasonics in parts and structures under test opens up new possibilities for the polymer composite diagnostics to determine the material physico-mechanical properties by means of excitation of high-power broadband impulses with the characteristics unattainable by using the conventional piezoelectric converters.

Keywords: polymer composites, diagnostics, acoustic methods, ultrasonics, laser optical-acoustic system.

The provision of structures high reliability, including those structures produced of such PCMs, as carbon- and glass-fiber reinforced plastics, organoplastics, hybrid and other high-modulus PCMs, is one of the major tasks of aircraft construction industry as reliability is the main qualitative characteristic of critical products. According to the terminology standard reliability is determined as a product property to fulfill the given functions preserving its operating characteristics within the specified limits and within a given period of time or a required operating life. Thus, an insufficient reliability of a product means its low quality.

In accordance with the composition, structure and physico-mechanical properties most PCMs can be divided into three main groups: isotropic, transversely isotropic and orthotropic materials. Orthotropic materials are most widely used as they are characterized by the high specific physico-mechanical properties in the given directions. Most PCMs applied in the aviation industry belong to the orthotropic group, namely KMU-4, KMU-7, KMU-11, KMU-15 carbon-fiber reinforced plastics (CFRPs); ST-69N, VPS-25k, VPS-33, STP-97k glass-fiber reinforced plastics (GFRPs); 6NA, 7N, 10T, 11T, 12T, 16V organoplastics and others. The peculiarity of these materials is the anisotropy of physico-mechanical properties, with the anisotropy rate depending on the material structure and being determined by the reinforcing filler lay-up.

The flaws substantially worsen the service characteristics of products and therefore must be detected. Since the reliability of product parts and aggregates depends not only on material properties but also on the existence of hidden flaws, the task of material testing has

become extremely acute. In many cases defectoscopy, i.e. detection of relatively large flaws such as discontinuity, foreign inclusions, etc. is insufficient. Critical parts are to be tested by the diagnostic methods for the estimation of the material composition and physico-mechanical properties without destructing their structure. In order to provide the high reliability of critical structures and parts, the most efficient method of their testing is as follows: the total (100%) testing should be carried out with the methods of defectoscopy and the diagnostic methods are used for the sample testing to confirm the proper characteristics and material state.

Defectoscopy methods are to detect both internal and surface defects such as delamination, cracks, cavities, foreign inclusions, folds, wavy fibers (stria), as well as surface crumpling, scratches, crumbling at hole and slot edges, peeling of surface layers after drilling, chips, etc. Acoustic methods rank first among the methods of nondestructive testing of polymer composite parts and multi-layered adhesive structures. These methods are based on the interaction of elastic oscillations and broadband waves with the parts or structures being tested.

The conventional acoustic methods, the special low-frequency and the non-contact ones [1] are applied for the defectoscopy of polymer composite parts and multi-layered structures. The first group of methods is usually implemented with the help of liquid for providing the acoustic contact between the defectoscope transducer and the product (immersion, jet or contact variants). The special low-frequency acoustic methods are realized by means of dry point contact of the transducer with the object being tested or with the help of an elastic protector connected to the transducer element.

The conventional acoustic methods include the shadow method (through-transition method), echo-method (basic and reverberation variants) and forced vibration method (resonance method). The special low-frequency methods include the impedance and velocimeter methods, the free oscillation method, the oscillation-topographic and heat-oscillation methods, etc. The low specific wave resistance of many PCMs makes it possible to improve their acoustic agreement with liquids (as compared to metals testing). This factor facilitates testing the parts of PCMs by means of the first group methods. Moreover, the speed of elastic wave propagation in polymer composite products is usually slower than that of in metals, and it also facilitates testing the parts of PCMs by the immersion method, i.e. by dipping into the liquid. Here the refraction at the liquid-product interface is reduced, which is a factor favourable for testing. The factors hampering the use of the first group methods are the high coefficient of elastic oscillation damping in PCMs, the sharp diversity of material acoustic properties in the layers of multi-layered structures as well as the roughness and curvature of parts and structures surfaces. The last factor is especially apparent during the contact variant of elastic oscillation input and reception. In order to decrease the oscillation damping in PCMs it is necessary to reduce the operating frequency which leads to lower sensitivity.

Such defects as the low polymerization of the polymer composite matrix, the inadequate material composition throughout the whole volume or a considerable part of the product, zones of material excessive porosity or lower density, the irregularity of fiber orientation (reinforcement angle deviation, curvature of fibers in layer planes) and the local inadequacy of material composition can be found in PCMs. These defects result in lower material strength at shearing, compression and tension in various directions.

Acoustic, thermal, electric and other non-destructive methods are applied for the diagnostics of physico-mechanical properties of PCMs. The primary ones are the ultrasonic methods (by the number of tasks being solved). These methods do not require bulky equipment and can be implemented not only under the laboratory conditions but also under the shop or field conditions.

The methods of technical diagnostics are indirect ones and they are based on the correlation between the diagnostic parameters (acoustic characteristics of PCMs) and the physico-mechanical properties of PCMs by means of comparing the non-destructive and destructive test results. The most informative and easily-measured diagnostic parameters is the speed and damping of ultrasonic oscillations during the transmission of acoustic signals in the object being tested (plates or sheets of PCMs, multi-layered adhesive structures, etc). But testing according to these parameters only does not allow to get the acceptable accuracy of diagnostics and the reliability of the achieved results. Therefore it is necessary to find such diagnostic parameters which can be determined with the high accuracy and reliability directly in the parts or structures of PCMs without their destruction and preferably at the one-side access. It is also necessary to solve the task of getting the complex diagnostic parameters and establishing closer correlation between these parameters and the certain characteristics of PCMs. The

spectrum analysis of signals having transmitted through the structure under test and carrying information of CFRP structure and properties is required to increase the accuracy of diagnostics. But the application of conventional piezoelectric converters for these tasks is often impossible due to the low efficiency of piezo-excitation of broadband acoustic signals.

The use of laser is highly effective for the excitation of high-power broadband ultrasonic impulses for the diagnostics of PCMs [2, 3]. The laser optical-acoustic system (LOAS)* is designated for the diagnostics of CFRPs, GFRPs, organoplastics, hybrid composite and carbon-carbon materials, laminated materials of ORAL and SIAL types and other similar materials directly in structures without their destruction.

The diagnostic methods using LAOS allow to determine the physico-mechanical characteristics of PCMs such as density, porosity, composition (proportion of polymer matrix and fiber filler), matrix polymerization degree, modulus of elasticity, compressive, tensile and shear strength, fatigue damage.

The structures are tested by the laser-acoustic technique of signal transmission or reflection (ultrasonic method). Elastic (ultrasound) oscillations are excited with the help of laser impulses generated by the laser and delivered to the zone of polymer composite structure under test through the fibre-optic cable.

The diagnostics implies the spectrum analysis of signals having transmitted the structure material under test and carrying information of CFRPs structure and properties. The effective excitation of short pulses with the help of the optical-acoustic effect allows to carry out the analysis of ultrasonics damping within the broad frequency range. Fig. 1 shows the action of the laser thermal-optical excitation of acoustic impulses.

The action of LOAS is based on the laser thermal-optical excitation of ultrasonic impulses (the so-called optical-acoustic effect), the reception of signals having transmitted through the material under test and carrying information of the material structure and physico-mechanical properties and the analysis of the signals reflected from the object being tested or scattered by the imperfections of material structure.

LOAS (Fig. 2) consists of the following units:

- pulsed solid-state laser with Q-switching and high pulse frequency for the excitation of broadband ultrasonic signals;
- laser optical-acoustic transducer;
- fibre-optic cable;
- power supply unit including:
 - power supply of the laser;
 - power supply of the optical-acoustic transducer;
- information-measuring complex including:
 - analog-digital converter board or oscilloscope;
 - personal computer;
 - program package for the received data processing.

• Designed at the International Laser Centre of M. V. Lomonosov Moscow State University

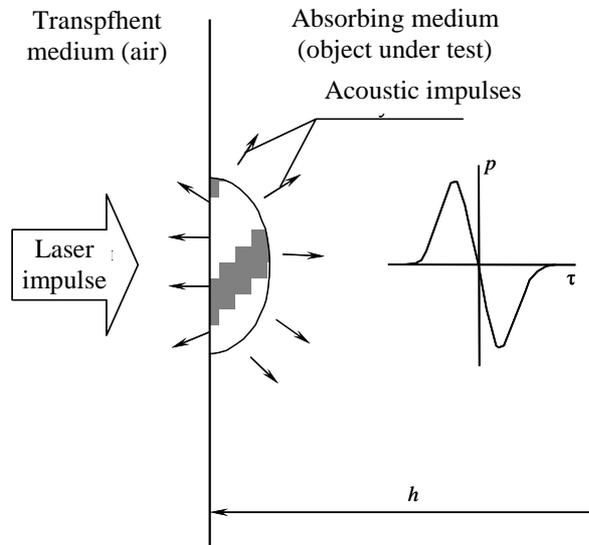


Fig. 1. Action (diagram) of laser thermal-optical excitation of acoustic impulses in the structure being tested; \square area of increased temperatures; p – pressure of acoustic impulses in the direction of normal to surface – in the fig.: in the diagram field; τ – time of impulse effect; h – thickness of object under test

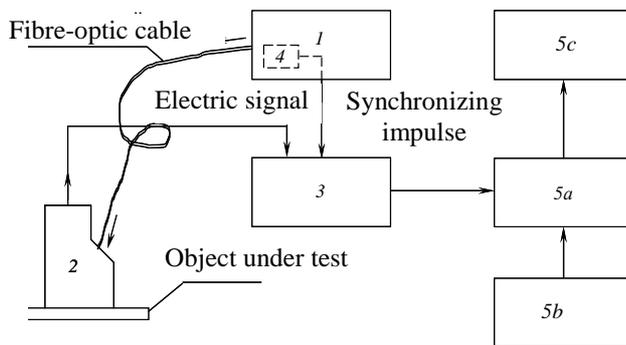


Fig. 2. Structural diagram of LOAS: 1 – pulsed laser; 2 – optical-acoustic; 3 – digital memory oscilloscope; 4 – clock system of oscilloscope triggering; 5 – information-measuring complex: 5a – system unit, 5b – control board, 5c – display

One of the advantages of the laser-acoustic method is that it allows to carry out the diagnostics of thin CFRPs structures (with the thickness of (1.5–3) mm). Moreover, this method makes it possible to estimate the degree of matrix polymerization in CFRPs premolded billets meant for the production of integrated structures such as wing panels, fuselage sections, etc., in which molding of skins and premolded load-bearing structures is to be performed during one operation. The laser-acoustic method also allows to increase the reliability of diagnostics for polymer composite density, composition, elastic and strength properties.

LOAS allows:

– to increase the reliability of critical products for the aero-space engineering, shipbuilding industry, construction industry, etc.;

– to increase the accuracy and reliability of diagnostics by means of effective spectrum analysis of information-carrying signals;

– to detect macro- and micro-defects in thin-walled laminated structures.

Over the last years “VIAM” FSUE has developed a number of normative-technical documents (NTD) giving the methodical instructions for determining the various physico-mechanical properties of PCMs and detecting the flaws directly in critical parts and structures without their destruction [4–8]:

1. Technical recommendation TR 1.2.1701–2000 «Determination of CFRPs density and composition by acoustic methods»;

2. Technical recommendation TR 1.2.1732–2001 «Estimation of CFRPs shear and compressive strength by the non-destructive acoustic methods»;

3. Methodical material MM 1.2.006–2001 «Ultrasonic tomographic control methods for the estimation of physico-mechanical properties and composition of composites»;

4. Technical recommendation TR 1.2.1763–2002 «Estimation of binder polymerization in CFRPs premolded billets by the ultrasonic method with the help of position control system»;

5. Methodical material MM 1.2.022–2002 «Estimation of matrix polymerization degree at various production stages of integrated structures of CFRPs by the laser-acoustic method»;

6. Methodical material MM 1.2.027–2003 «Shear strength estimation of CFRPs integrated structure part joints by the laser-acoustic methods»;

7. Methodical material MM 1.2.036–2004 «Estimation of matrix polymerization degree at various production stages of integrated structures of GFRPs and organoplastics by the non-destructive method»;

All the above-mentioned NTD are available in FSUE «VIAM». By request of enterprises the institute can also develop new diagnostic methods based on the state-of-the-art non-destructive test facilities, i.e. the advanced equipment for the determination of diagnostic parameters, including the laser optical-acoustic system.

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