Non-destructive inspection of polymer composite products

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Abstract. The paper considers the main types of defects encountered in products made of polymer composite materials for aviation use. The analysis of existing methods of nondestructive testing is carried out, features of their application are considered taking into account design features, geometrical parameters and internal structure of objects of inspection. The advantages and disadvantages of the considered methods of nondestructive testing used in industrial production are shown.

In connection with the rapid growth of the technological development of the aviation industry, extensive introduction of polymer composite materials (PCM) occurs in both lightly loaded and heavy loaded aircraft products. This is due to the fact that some of the metallic units do not meet the technical requirements for specific characteristics, which are presented by prospective aircraft propulsion systems. In addition, the use of composite materials can significantly reduce weight, improve the environmental parameters and economy of the aircraft. The use of PCM in modern technology, especially in aircraft, requires consideration of such factors as anisotropy of rigidity and strength, the non-linear nature of deformation under loading, the probability of destruction along the interface of the layers, and the possible presence of specific internal defects of various types. Among the many defects that arise in PCM, the most frequent ones can be identified, such as: pore defects, interlayer delaminations, peeling of adjacent packets, jammed layers, resin pockets (figure 1), detachment of shells from cellular structure in a multilayer structure (is used in products of sound-absorbing structures) and others [1].

All this diversity can be divided into two large types: operational and production-technological. Operational defects arise under the influence of cyclic loads, the consequences of the human factor, as well as in connection with natural phenomena, such as lightning and others. Industrial and technological, in turn, are divided into chemical, mechanical and geometric. At the same time, one of the main defects that occur at all stages of the product life cycle are bundles and delaminations. They are of decisive importance when deciding on the use of composites in a product. Along with this, the main places for the appearance of delaminations are stress concentration zones, for example, places with an excess of layers of reinforcing material or a sudden change in thickness. The appearance of these defects most often leads to the destruction of the element, at lower loads than their calculated values.

At present, there is a wide range of methods and devices for nondestructive testing (NDT) used for flaw detection of PCM products. This is due to the variety of design features of control objects, their geometric parameters, internal structure, which affects the possibility of using and reliable detection of defects by NDT methods. The main NDT methods used to control the quality of PCM products are:
acoustic, thermal and radiation. These methods, in turn, can be divided into different subgroups, which have their advantages and disadvantages.

Figure 1. Visible defects in the design of PCM flanges: 1 – delamination; 2 – resin pockets; 3 – pores; 4 – folds.

One of the most capacious groups is the acoustic methods of NDT. Considering this group, it is easy to see that of all acoustic methods the low-frequency frequency with frequency not exceeding 1–5 MHz is most often used. Its application is due to strong attenuation and dispersion of high-frequency ultrasonic waves in the matrix, fibers and various inclusions of PCM. The main area of application of the method is the detection of interlayer delamination zones in the layered structure of composite material. At the same time, the main advantage of the method lies in realizing control over practically all materials and structures. The requirement for the curvature of the product is determined solely by the dimensions of the sensor, which ensures the same quality control of concave and convex parts.

Also at the present time the ultrasonic method on the phased array is becoming increasingly popular. It allows you to control complex objects. Unlike traditional ultrasound methods, in which the result is a single A-scan, the phased array method is a set of A-scans. The number of A-scans depends on the number of piezoelements in the converter. Further, the set of A-scans makes it possible to visualize the structure of the material, highlighting the frequency of the amplitude oscillations by converting it into an S-scan (figure 2). At the same time, the minimally detected defect is significantly smaller in comparison with the traditional method. This is due to the smaller size of the piezoelements.

Figure 2. Example of S-scan and A-scan images.

Another widely used ultrasonic method is shadow, based on the weakening of the intensity of elastic vibrations of the ultrasonic frequency from the defective structure in the material. The control process consists in installing ultrasonic oscillation emitting and receiving transducers coaxially from different sides of the monitoring object. Oscillations, passing through the material and falling on the defect, are reflected as a result of which the intensity of the oscillations decreases. This method is well proven for the control of monolithic products. In this case, the advantage of the method is the absence of an uncontrolled zone between the transducers, as well as in the simpler configuration and the minimum necessary requirements for reference samples. However, a significant drawback of the method is the need for two-way access to the object of control.
Along with acoustic methods, the radiation method based on recording and analyzing ionizing radiation after its interaction with the object of control has become widespread [2]. In view of the characteristic features of the structure of the composite material, one of the important conditions for NDT of PCM products is the production of enlarged X-ray images. This is due to the close values of the density of the reinforcing material and binder, resulting in a low contrast of the images, thereby reducing the probability of detecting and recognizing possible defects in traditional radiography. Obtaining magnified X-ray images is possible only with the help of X-ray sources, whose focal spot sizes do not exceed 0.1 mm. Therefore, the main direction in the flaw detection of PCM products has found wide application of the method of microfocus radiography. The method makes it possible to detect heterogeneities in the form of pores, extraneous inclusions, structural inhomogeneities and breakages of reinforcing elements. Unlike traditional methods of X-ray studies, microfocus radiography has a number of important features. The first of these is the possibility of obtaining sharp enlarged X-ray images of various objects. In this case, the size of the focal spot, as well as the distance between the radiation source and the subject, significantly affect the magnitude of the geometric component, that is, the blurring of the resulting image. The second, no less important, feature of microfocus radiography is the possibility of obtaining informative X-ray images of the same objects of investigation with a lower radiation load than classical radiography [3].

However, one of the main drawbacks of the method is the complexity of its application to identify one of the most common technological defect such as delamination, in which the effect of “collapse” is rarely observed. This is due to the fact that in the delamination, the adhesive bonding between the layers of the reinforcing material is destroyed, with no air gap (figure 3). As a consequence, it is necessary to use special loading elements of the inspection object to expose the defect, which leads to complication of the control process.

![Figure 3. Microsection of the sample with destruction in the form of a delamination without load (a) and in a forced-loaded state (b).](image_url)

Along with this, in recent years in radiation flaw detection, there has been a transition to the use of digital X-ray detectors, which makes it possible to convert X-rays transmitted through the object of inspection into optical, outputted to the monitor. The merits of this method include: instantaneous acquisition of an X-ray image, input and storage of control images with further processing of results, the ability to transfer data over external and local networks. This led to the development of the method of computed tomography. This method was widely used in connection with the fact that it makes it possible to detect separately taken carbon fibers and their cliffs in carbon plastics, with a resolution of several μm.

However, like any other method, this method has its drawbacks due to both the high cost of control technology and the complexity of the application for flaw detection of large-sized products. This is due to the fact that in order to restore the volume structure of the monitoring object, it is necessary to
obtain 360 to 720 pictures with a circular rotation of 360°, which is not always possible when controlling large objects.

In addition to all these methods, there is also such a promising method of NDT of PCM products as a thermal method or thermography method [4]. The method is based on measuring, monitoring and analyzing the temperature of the monitored objects. The main condition for the application of thermal control is the presence of heat flows in the controlled object. The process of transferring heat energy, releasing or absorbing heat in an object, causes its temperature to vary with respect to the environment. The temperature distribution over the surface of the object is the main parameter in the thermal method, as it carries information about the features of the heat transfer process, the mode of operation of the object, its internal structure and the presence of hidden internal defects. The heat fluxes in a controlled facility can occur for various reasons. Thermal control, in turn, is divided into two methods, active and passive.

An active method of thermal control is applied when, during operation, the object under inspection is not exposed to sufficient thermal impact, or in the case when the measurement of the temperature of the object during operation is technically impossible, such as with a helicopter blade. This method involves heating the object with special external sources of energy to create heat flows. Unlike the active method, the passive method of thermal control does not need an external source of thermal impact, the thermal field in the object of control arises when it is used or manufactured. With passive control, both the constantly acting natural thermal loading of the monitoring object and the transient thermal processes can be used. The temperature change recorded by the thermal method can reach 0.01 °C, which makes it possible to fix places of energy concentrations in which plastic deformations accompanied by heat release can occur. Based on the obtained data on the location of the energy concentrator, it becomes possible to determine the location and size of the defect. It is obvious that for defectoscopy of PCM products it is expedient to use an active thermal method that allows to detect heterogeneities in the form of delaminations in the layered structure of a composite material, as well as inhomogeneities in the form of shell exfoliations from the cellular structure in a multilayer structure. Thus, there is a wide range of NDT methods and instruments used for flaw detection of PCM products. Such a number of methods is due to a variety of design features, geometric parameters and internal structure of inspected objects, which affects the use of one or another NDT method.

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