Features of the research of the structure and assessment of the quality of composite materials by means of non-destructive testing techniques

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Abstract. In the present paper, features and problems of non-destructive testing (NDT) of composite materials with big inside quantity of pores have been discussed. Solutions for issues of NDT of this materials have been proposed.

The issue of non-destructive testing (NDT) and porosity level evaluation [1] in structures made of materials with a high fraction of pores (more than 2%) is relevant for the modern manufacturing of products made of polymer composite materials (PCM). There is also a general trend towards sophistication of the geometry of PCM parts and assemblies for aerospace and aviation industries. Due to the peculiarities of the PCM physical properties, this sophistication of the geometry of structures may result in areas with an increased fraction of pores, the presence of which hinders defect detection processes prescribed by the engineering documentation for the product. This paper analyses how the porosity of PCM products influences the results of NDT carried out by various techniques.

There are methods for indirect estimation of PCM porosity value, such as helium pycnometry, burning off technique, microscopy of sections, etc. However, these methods are applicable only for small samples and inapplicable for finished parts. They do not solve the problem of objective evaluation of porosity in products.

Figure 1 shows the results of microscopy of thin sections made at the face ends of areas with a) - areal porosity (distributed in one or several adjacent layers of the test object) and b) - volumetric porosity (distributed over the entire volume or the major volume of the test object). In this case, the porosity value (size and number of pores) can be determined only in a specific section, whereas in the finished product, the porosity value can be determined only on its face end and only if the specified area of pore accumulation is adjacent to the side of the part. At the same time, the number and size of pores, their uneven distribution in a section located even at a small distance from the side of the part may differ significantly from the results obtained on the reference section.

The most common techniques of non-destructive testing of monolithic PCM structures are ultrasonic techniques: pulse-echo (reflection) technique and shadow (transmission) technique. Usually, these techniques are quite informative, provided that the ultrasonic attenuation factor enables sounding the test object, i.e. receiving transmitted signals (when NDT is conducted by the shadow technique) or reflected signals (when NDT is conducted by the pulse-echo technique). The ultrasonic attenuation factor is known to have two components caused by scattering and absorption [3]. The scattering phenomenon, in its turn, significantly increases the ultrasonic signal attenuation when there is porosity. As compared to metals, PCMs have significantly higher ultrasound attenuation factors, that impose some difficulties on the process of their non-destructive testing, and the presence of additional areas with an increased fraction of pores in finished PCM products makes it even more difficult to detect defects the dimensions of which are strictly regulated by the engineering documentation for the product.
testing by the pulse-echo technique, the major problem is the presence of areas with a high fraction of pores — partial or complete attenuation of ultrasonic signals at a certain range of thicknesses in the test object can reduce the amplitude of signals from a defect of an unacceptable size, which is below or within this range of thicknesses, so that the defect may not be detected during the scanning control.

Figure 1. Results of microscopy of sections made at the face ends of areas: a) with areal porosity, b) with volumetric porosity.

Figure 2 [4] shows screens of a standard ultrasonic flaw detector, which are obtained during non-destructive testing of a CFRP product by the ultrasonic pulse-echo technique in a defect-free area and in a porous area where the bottom echo-signal amplitude drops by more than 6 dB (the signal amplitude decreases by more than a factor of 2).

Figure 2. A-scans obtained during NDT by the ultrasonic pulse-echo technique a) in the pore-free area, and b) in the porous area.

Figure 3 shows A- and B-scans of samples without porosity and with pronounced volumetric and areal porosity, which are obtained during NDT by the ultrasonic pulse-echo technique using the UDL-2M flaw detector with laser ultrasound excitation.
Figure 3. A- and B-scans of the samples: a) without porosity, b) with volumetric porosity, c) with areal porosity.

Based on the B-scan, it can be concluded that the large accumulation of pores located in one layer or closely spaced layers of a polymer composite material may be mistakenly identified as delamination.
when NDT is conducted with a single-element ultrasonic transducer. Volumetric porosity, in its turn, can lead to the escape of defects as described above. Sometimes, at frequencies above 2 MHz, the complete attenuation of ultrasonic signals is observed in such areas. Thus, it is possible to test such materials by the ultrasonic pulse-echo technique only at low frequencies, which entails a decrease in the testing sensitivity and a significant increase in the dead spot of the transducer (increased size of uncontrolled near-surface areas).

The study of PCM structure by X-ray tomography gives the most complete picture of the volume fraction of pores, their size and occurrence depth, but it has significant drawbacks: a high cost of testing and limited dimensions of the test object. Figure 4 shows a tomography scan of a highly-porous sample, which is obtained using an X-ray tomography scanner with a linear detector and a microfocus X-ray tube.

![Figure 4. Tomography scan of the highly-porous PCM sample.](image)

The tomography scan shows that the porosity of the polymer composite material is actually a large number of delaminations of an extremely small area size occurred in different layers of the material. The average length of such delaminations (pore clusters) is about 1.5-2 mm, and the span is ~0.05 mm. That is, in terms of the requirements of the engineering documentation for the absolute majority of aviation and aerospace industry products, these are not considered as defects.

The presence of porosity also affects the NDT process employing the ultrasonic shadow technique. The amplitude attenuation of the transmitted signal due to ultrasonic scattering at pores in these areas can make it difficult to determine the type of a small-sized defect (with an area less than the transducer area). A drop in the amplitude of the transmitted signal by a certain value in the presence of volumetric porosity can be equivalent to the presence of delamination of an area size comparable with the transducer contact surface area. Figure 5 shows a C-scan of a sample with 6 artificial imitations of defects (red pixels) as well as areas with an increased fraction of pores (dark grey dots).

![Figure 5. C-scan of the sample with artificial imitations of defects and an increased fraction of pores.](image)
With computer-aided testing, it is possible to minimize the negative influence of porosity by selecting the optimal equipment settings. With manual testing of such areas, it is necessary to ensure a tight fit of transducers to the test object (TO) and also to use substantial signal amplification. Ensuring the tight fit of transducers to the test object on regular (flat) surface areas causes no problems, whereas, in contrast, ensuring the tight fit on curved radial surface areas (bending areas) of the test object presents a major challenge.

For non-destructive testing of the above-described areas, the authors have developed [2] special transducers (figure 6) to conduct NDT by the shadow technique. The main feature of the transducers is that they are equipped with profiled face caps made of silicone that provides a high rate of ultrasonic propagation.

During testing, the transducers are rotated by 90° relative to each other, so the transmitting transducer has the maximum contact area with the inner surface of a radial area, and the receiving transducer has a small contact area with the outer surface, which ensures high accuracy in determining the boundaries of defects. Application of these transducers for non-destructive testing of regular areas is not practical due to the lower testing performance as compared to testing using transducers with flat face caps.

**Figure 6.** Assembly view of the transducers for ultrasonic inspection of curved surface areas.

So, the quality evaluation of highly-porous polymer composite materials requires a comprehensive approach employing state-of-the-art NDT aids. The methods for detection and assessment of the influence of porosity on the NDT results, which are analyzed in the article, only make it possible to properly set equipment used for non-destructive testing of PCM products. It is necessary to use a wider range of techniques and aids of non-destructive and destructive testing, as well as computational methods, to quantify the fraction of pores and their influence on the condition of the structure as well as to predict the residual life of the product.

From a physical point of view, the porosity of polymer composite materials differs dramatically from the porosity of metallic materials. An increased pore fraction is usually not a rejection criterion for PCM structures, however, it may cause operational defects in the future. For a more detailed study and understanding of how porosity areas influence the reliability of PCM parts, it is necessary to carry out cyclic structural strength tests of samples in addition to non-destructive examinations.

**References**

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