HIGH RESOLUTION NDT&E OF CARBON FIBER REINFORCED COMPOSITES

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Abstract. Non-destructive inspection of carbon-fiber-reinforced (CFR) composites applied in aerospace industry attracts a wide attention. In the paper, high frequency focused ultrasound has been applied to studying the bulk mechanical structure and property of CFR material. The technique allows reconstructing the material 3D microstructure by means of layer-by-layer imaging. The operation frequency 50-100 MHz provides inspection of porous, cracks and delaminating, wrinkles and matrix pockets with resolution of 50 mkm. Behavior of the defects under the mechanical loading has been investigated. First results are presented in the paper.

Introduction

Pulsed acoustic microscopy is an unique method for the study of modern materials and high – resolution technical diagnostics [1-5]. For a long time in ultrasonic nondestructive testing operating frequency range of 5-10 MHz was used. This frequency range provides the sufficient penetration depth of the probe beam and spatial resolution of several millimeters. Micron resolution acoustic imaging systems such as acoustic microscopes and C-scanners have been created and used mainly for research purposes. The situation in the industrial NDT began to change with decreasing of acceptable defect size.

Recently, the interest in pulsed acoustic microscopy is based on the successful application of this method to the integrity evaluation and defect detection in microelectronic components. Pulse acoustic microscopy has been successfully used to detect mechanical defects in crystal stacking, assembling and chip packaging [6-8]. It has been shown that the pulsed acoustic microscopy possesses a high potential for the aircraft technology too [9]. Manufacturing of the modern missiles, aircrafts, helicopters, unmanned aerial vehicles are not possible without carbon fiber reinforced composites (CFRC). In comparison with aluminum components, composite parts have a much lower weight and greater strength, flexibility, pressure resistance and corrosion resistance. Currently the problem of nondestructive testing of CFRC and evaluation of defect influence on mechanical properties of the material is not solved, though the service life of aircraft depends on the quality of the composite. The paper shows that pulsed acoustic microscopy can be successfully applied to this problem.

2. Methods and specimens

Pulse acoustic microscopy is based on the use of high frequency focused ultrasound (50-200 MHz) [10,11]. Short probing pulses penetrate into the sample and reflected from the elements of its bulk structure within the area of a focal spot (15-100 μm). Reflected signals are received with acoustic lens from point to point across the scanning area. Data on the amplitude of the received signals are stored and displayed as a grayscale color to form the acoustic image. Impulse acoustic microscopes allow obtaining cross-sectional images (B-scans) or images of planes at different depth (C-scans). Three-dimensional image is formed layer by layer. Pulse acoustic microscope developed by the Emanuel Institute of Biochemical Physics (IBCP RAS, Russia) was applied in the experiments. Frequency 50 and 100 MHz was in use depend on research objective. Acoustic lenses have the long focus and a small aperture angle (16^{o}).

The CFR composite samples were prepared by the prepreg technology and consist of 16 layers. The fibers were T700GC (HEXEL) and the polymer matrix was epoxy of M21 grade. Bulk content of the binder was 35%. Thickness of the samples was 4.32 mm. Carbon fiber plies package had the alternate 0/90 and -45/+45 orientation.

The samples were used for a tensile test. The tensile machine of Switzerland production (Walter&Bai) had the maximum 100 kN load. The samples were uniaxial loaded with deformation step ε of 0.05% up to complete failure or loss of bearing capacity.

3. Results and discussions

Acoustic images in Fig.1 show the microstructure of the specimen with ply orientation 0/90. Images show the surface and first two layers of the composite material. Contrast of the acoustic images is formed due to the difference in acoustical impedance of the carbon fibers and the epoxy matrix, also due to the presence of air cavities and various structural imperfections, such as pockets or non-uniform binder distribution, detaching the layers and individual filaments, porosity, etc. Contrast of the underlying layers depends on the presence of shadow from the upper extended defects. For the specimen #1 orientation of the fibers in the first (Fig. 1a) and second (Fig. 1b) laminate layer was imaged. Porosity is difficult to evaluate. Delaminations and cracks can be observed.

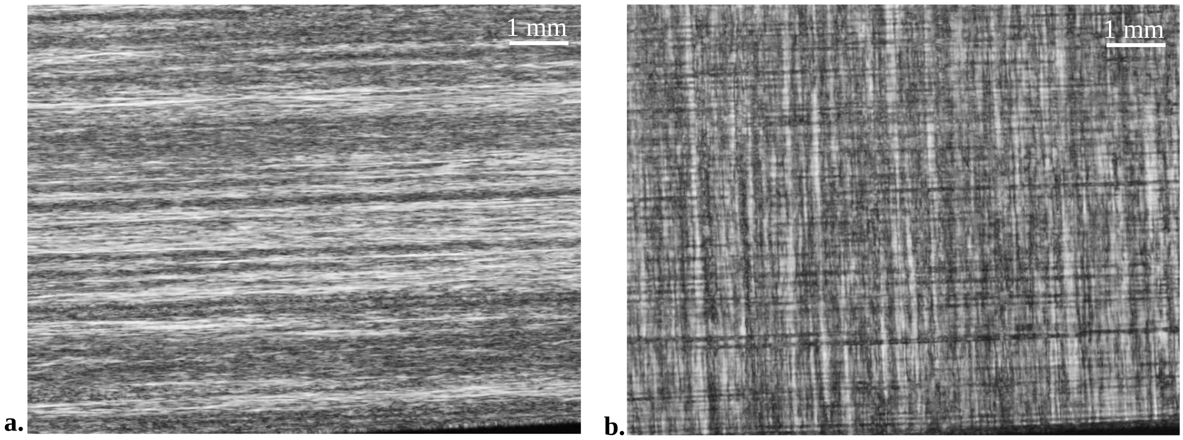

Fig.1 Acoustic imaging the CFRC composite specimen with 0/90 fibers orientation in plies.
a. – the first composite layer; b. – at the depth of the second composite layer.
Operation frequency – 100 MHz; scanning area – 10x7 mm; coupling – distilled water.

Microstructure of the CFRC laminate sample (#2) with ply orientation -45/+45 has been studied. Orientation of the carbon fibers inside the individual layers of the laminate was identified and no any specific defects were founded.

Acoustic images of the first two composite layers with 0/90 orientation after the tensile testing are shown in Fig.2. In the area of minimum load, the microstructure of the sample is changed slightly. In the area of stress concentration air cavity of elongated shape are located, first of all, inside the layers (Fig.2a). These exfoliations with size of 0.5-5 mm are elongated along the reinforcing filaments. It can be assumed obviously that there has been a loss of contact between the reinforcing filaments and the matrix; straightening and relaxation of the fibers cause matrix damage under the mechanical loading. The area of maximal stress is presented in Fig.2b; destruction of the sample occurs and its edge is visible in the image. Inside the composite layers the exfoliations of fibers from matrix have been observed as the bright spots of submillimeter size. Acoustic image of the specimen bulk shows the presence of extensive interlayer delamination, which causes the specimen breaking.

To study the internal microstructure of the CFRC laminate with -45/+45 fiber orientation in the plies after the tensile loading with twice exceeding magnitude fixed for the 0/90 sample in the moment of destruction acoustic visualization was done. The destruction of the sample did not happen, because loading the reinforcing filaments was tangent. A number of "fiber-matrix" exfoliations were observed in the bulk of the CFRC composite specimen.

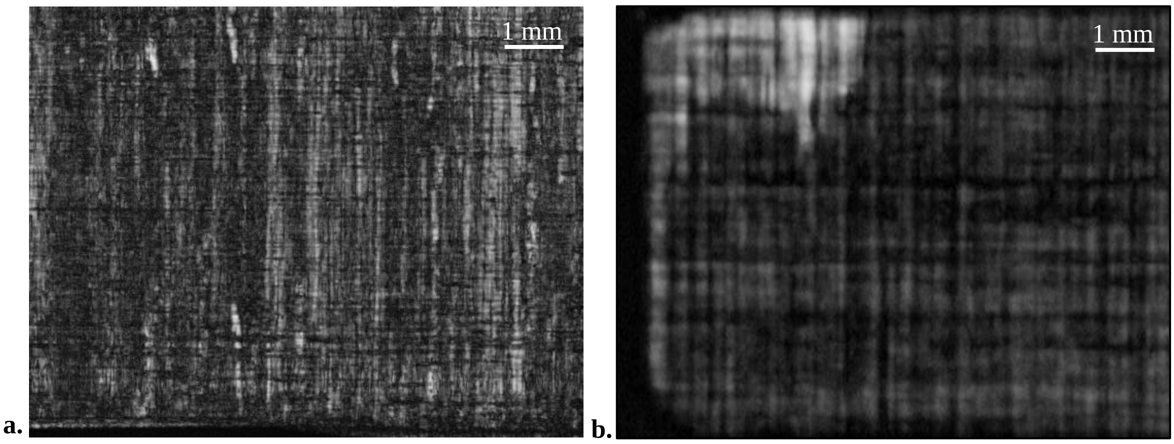

Fig.2 Acoustic imaging the CFRC composite specimen with 0/90 fibers orientation in plies after destruction under the mechanical loading. a. – at the depth of the second composite layer (100 MHz); bright spots correspond to the "fiber-matrix" exfoliations; b. – at the depth of the seventh composite layer (50 MHz); bright area is the interlayer delamination. Scanning area – 10x7 mm; coupling – distillated water.

Conclusion

Impulse acoustic microscopy is an effective technique for the microstructural diagnostics of carbon fiber reinforced material. Using pulse acoustic microscopy method the bulk microstructure of CFRC laminate specimens with (0/90) and (-45/+45) fibers orientation in plies and visible microstructural changes caused by the tensile loading have been investigated. Fiber orientation was different relative to tensile forces. It has been shown method of acoustic microscopy is sensitive to detect sub-millimeter exfoliations between the reinforcing carbon filaments and epoxy matrix, which are precursors of the CFRC material destruction. For the specimen (#1) with the layers package of (0/90) the areas of matrix delamination from reinforcing threads have been identified, zones of interlayer delamination have been revealed near the destruction edge. The total breaking with tensile load is not happening for the specimen (#2) with fibers orientation (45/-45) in the layers; the structural failures are characterized by the binder deformation.

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