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Analysis of the effect of processing in an ultrahigh frequency electromagnetic field on the interlayer interaction of cured polymer composite materials with various fillers

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The effect of exposure to a microwave electromagnetic field on samples of cured carbon-, glass-, and organoplastics on an epoxy matrix on the strength and change in the nature of interlayer damage during bending deformations has been studied. An increase in the limiting stresses by 14.5, 9.1 and 11%, respectively, a decrease in the size of the delamination region during deformation by 1.5–2 times and its predominant localization in the internal volume of the composite was established. In the control samples, the exits of interlayer cracks to the surface of the material are noted.

Keywords: polymer composite materials, flexural strength, interlaminar shear, damage, microwave electromagnetic field.

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The construction and commissioning of advanced aircraft equipment require proactive development of novel materials with enhanced operational performance and improvement of shaping techniques for structural components, including those made of polymer composite materials (PCMs), which are being produced and used in ever-growing quantities [1,2]. Depending on the function of structural components, one may choose PCMs reinforced with fabrics based on carbon, glass, or aramid fibers (carbon plastics, glass plastics, or organoplastics). Although PCMs have several advantages (primarily in specific strength) over metals and alloys, they are characterized by stark (1–2 orders of magnitude) differences in strength parameters corresponding to different reinforcement arrangements and orientations of applied loads relative to the component [3]. Physical modification within the fabrication cycle is considered to be the most efficient approach to improving the characteristics of PCMs. Microwave processing of the initial components and PCMs in the course of shaping and curing is one promising technique of this kind [4,5]. The authors of this study and several research groups abroad conduct investigations into the effects of a microwave electromagnetic field on fully cured PCMs as parts of a finished product [6,7]. Unpredictable influences of subsequent process operations on the material properties are excluded in this case. However, the mechanism of enhancement of physical and mechanical characteristics of PCMs through the use of the discussed method remains underexplored. The aim of the present study is to examine the variation of ultimate stresses under three-point PCM bending and the corresponding pattern of damage at the interlayer interaction level with energy parameters of a microwave electromagnetic field.

PCM samples were subjected to three-point bending tests in accordance with GOST R 57866–2017. These samples had the shape of beams $75 \times 10 \times 5$ mm in size made of carbon and glass plastics produced by OOO „Evrokomplekt" (Kaluga) and organoplastic produced by AO TsVM „Armokom" (Khotkovo, Moscow Oblast). Microwave processing was performed using an experimental setup, which was constructed based on a „Zhuk-2-02" microwave radiator produced by OOO NPP „AgroEkoTekh" (Obninsk, Kaluga Oblast), at a frequency of 2450 MHz and an energy flux density (EFD) of $(10-12) \cdot 10^4$, $(17-18) \cdot 10^4$, and $(30-34) \cdot 10^4\,\mu$W/cm^2. The processing time was 5 min. Five samples of each material were processed in one run. The current surface temperature of samples was monitored in the course of microwave processing with a FLIR E40 thermal imager. Variations of a parameter were determined based on its values averaged over five reference and test samples for each material.

The results of experiments for reference and test samples are presented in Figs. 1 and 2.

It follows from Fig. 1 that the dependence for carbon plastic is extremal in nature with the stresses being maximized at EFD values of $(10-20) \cdot 10^4\,\mu$W/cm^2. Glass plastic and organoplastic samples are characterized by dependences increasing monotonically with EFD. Microwave processing of PCMs in the studied EFD range contributes to a 14.5, 9.1, and 11% increase in ultimate stresses for carbon plastic, glass plastic, and organoplastic, respectively. The surface temperature under microwave treatment changes from the initial one (20°C) to 110–120, 35–40, and 42–45°C for carbon plastic, glass plastic, and organoplastic samples, respectively. The elevated temperature of carbon plastic samples is attributable to the skin effect in conductive carbon fibers. the temperature was 65–70°C in the region of EFD values where the stresses for carbon plastic were maximized.

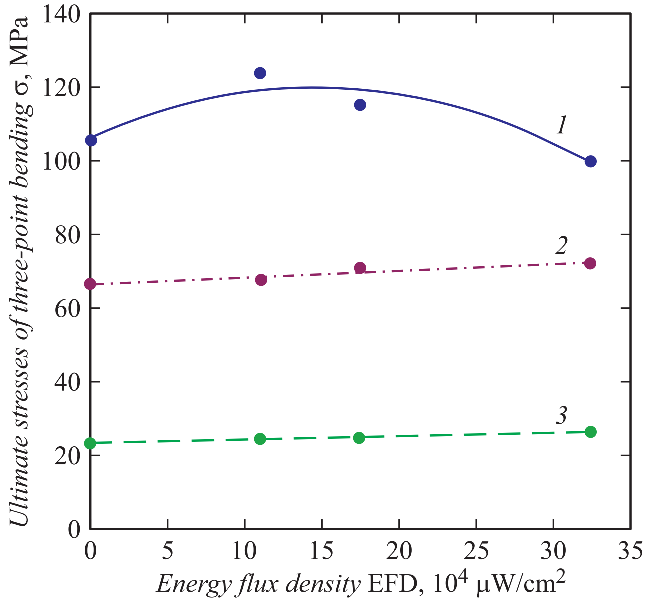

Figure 1. Dependences of ultimate three-point bending stresses for carbon plastic (*1*), glass plastic (*2*), and organoplastic (*3*) samples on the microwave EFD.

It can be seen that carbon and glass plastics feature a considerable residual deformation that is more pronounced in reference samples and is attributable to the physical and mechanical properties of their fillers. Corrugation and wrinkle deformations are seen on the surface of glass plastic samples in the vicinity of the point of load application. This effect is less pronounced for carbon plastic, since the load-carrying capacity of carbon fibers is higher. Residual deformations of organoplastic samples remain insignificant even after loading to a bending deflection of 9–10 mm. The side faces of carbon and glass plastic samples reveal significant deformations of internal layers in the form of wrinkles (more prevalent in glass plastic) and local delamination (more pronounced in carbon plastic). The area of these damaged regions in test samples is 1.5–2 times lower than in the reference ones. In reference carbon plastic samples, this damage is seen even on the surface. In test samples, delamination is localized primarily in internal layers and does not penetrate to the surface. Delamination in the form of cracks is less pronounced in glass plastic, although individual fractures in the area of fiber tension

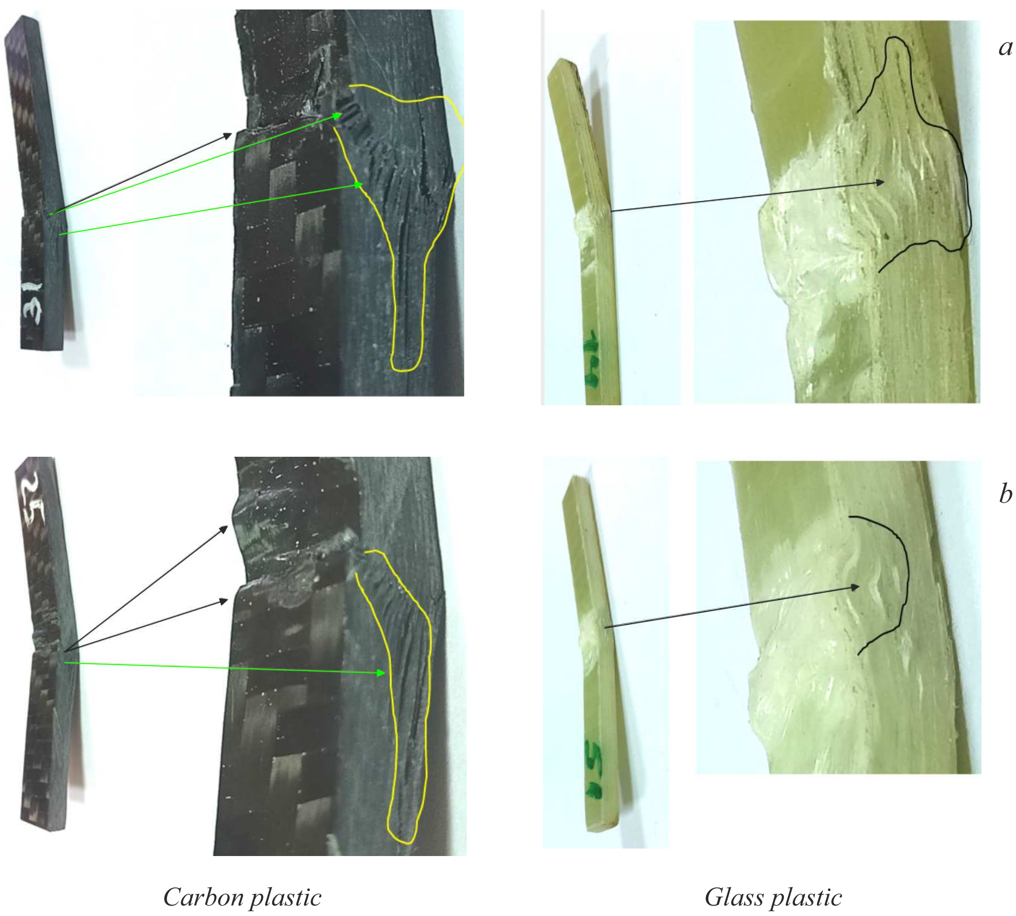

Figure 2. Interlayer damage of reference (*a*) and test (*b*) samples.

emerge in reference samples. Organoplastic is characterized by extended delamination in near-surface layers in the compression area. The indicated damage and defects may be credited to the cohesive fracture mechanism (see [8] for details) brought about by the highly oriented fibrillar supramolecular structure of aramid fibers [8]. Fibrillas feature high strength and rigidity, but that is exactly what induced the macroheterogeneity of fibers. Subjected to bending stress, neighboring fibrillas assume different stress-strain states, thus causing the formation of defects in the form of splitting and delamination of fibers within the most impaired sections. Owing to the enhancement of cohesive interaction forces in test samples, fibrillas have the capacity to better redistribute the load within a fiber, thus reducing damage. Thus, microwave processing allows one to enhance the adhesive and cohesive strength of organoplastics, which is a significant improvement with regard to the specifics of structure and properties of their reinforcing fibers.

We propose the following explanation for the obtained results. It is known [9] that the plasticity of a cured epoxy matrix heated to a temperature on the order of 50°C increases without any destructive changes, and its density is minimized at a temperature of 80°C. As was demonstrated above, the matrix and the reinforcing component are heated to the same (or similar) temperatures under certain conditions of microwave processing of PCMs. This raises the probabilities of conformational rotations of molecular units and filling of voids in the interphase layer. New regions of contact matrix–fiber interactions form during recuring. The area of contact between layers increases as a result, thus enhancing the interlaminar strength and the strength of a PCM sample as a whole.

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Conflict of interest

The authors declare that they have no conflict of interest.

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