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# Influence of microwave electromagnetic field on interlayer strength in cured polymer composite materials

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It has been established that exposure to a microwave electromagnetic field with an energy flux density that is rational for each type of composite (carbon-, glass-, organoplastic) contributes to an increase in the specific work of delamination by 18.6%, 12% and 20%, respectively, which satisfactorily correlates with an increase in strength of these materials under three-point bending and interlaminar shear.

**Keywords:** carbon fiber reinforced plastics, fiberglass plastics, organoplastics, delamination, microwave electromagnetic field.

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The analysis of scientific and technical information indicates the intensive development of the production of polymer composite materials (PCM) reinforced with fabrics based on carbon, glass, aramid fibers and their application in the aerospace and defense industries, wind energy, as well as automotive and shipbuilding, and construction. By 2026 the growth of market of high-quality carbon fiber from 3.9 billion dollars in 2019 up to 8.0 billion dollars is predicted, and the annual increase in the production of fiberglass is currently 8−10% annually, and this trend will increase [1].

PCMs are characterized by a well-marked difference in the values of strength parameters depending on the orientation of the acting loads relative to the product and the reinforcement scheme. The most dangerous from the point of view of damage to PCM products are the interlaminar shear stresses, the value of which for most PCMs is by 1−2 orders of magnitude lower than tensile−compression [2,3]. To improve the physical and mechanical characteristics of PCM the various chemical, physical, mechanical, electrical methods, as well as design solutions are used. Many researchers consider the modification of PCM during curing by exposure to a ultrahigh frequency (UHF) electromagnetic field as one of the promising methods, this is confirmed by the results of studies by domestic and foreign scientists [4–6]. The authors and a number of foreign researchers [7,8] consider it more expedient to use UHF exposure to finally cured PCMs (directly on products), since in this case it becomes possible to exclude the unpredictable effect on the formed properties of the material of subsequent operations of the technological cycle with a significant increase in strength characteristics (14−16%) [7,9]. The purpose of this paper is to study changes in the adhesive interlayer interaction in PCMs, as one of the components of the UHF influence mechanism of electromagnetic field on increase in their physical and mechanical characteristics.

The samples of carbon-, glass- and organoplastics were tested for interlaminar shear of these materials in accordance with GOST 32659-2014, and the microstructure was studied after delamination tests in accordance with GOST R 56815-2015. We used samples of carbon fiber and fiberglass produced by LLC „Evrokomplekt“, Kaluga, and of organoplastic produced by JSC TsVM „Armocom“, Khotkovo, Moscow region with size $25 \times 10 \times 5$ mm. UHF treatment of the samples was carried out on an experimental setup based on a microwave emitter „Zhuk-2-02“ produced by LLC NPP „AgroEcoTekh“, Obninsk, Kaluga region at a frequency of 2450 MHz, energy flux density (EFD) and time equal to $(17-18) \cdot 10^4\,\mu$W/cm$^2$ and 2 min for carbonplastic, for glass- and organoplastics — $(45-50) \cdot 10^4\,\mu$W/cm$^2$ and 5 min. Under these modes, heating temperatures in the range of $(65-70)^\circ$C are typical for carbonplastic, for glass- and organoplastic (35−40) and $(42-45)^\circ$C, respectively, and the maximum efficiency of UHF exposure in relation to the limiting stresses increasing of three-point bending and interlaminar shear is established. UHF influence of the electromagnetic field was evaluated as the ratio of the parameter of the test sample to the corresponding parameter of the reference sample.

The results of test for reference and test samples are presented in Figs. 1 and 3. The analysis of the obtained results allows us to note the following features of interlayer strength in PCM. The UHF impact of the electromagnetic

Average for five samples values of compliance $(C)$ of delamination $(G_{1C})$

| Sample | Carbonplastic | | Glassplastic | | Organoplastic | |
|---|---|---|---|---|---|---|
| | $C$, mm/N | $G_{1C}$, J/m$^2$ | $C$, mm/N | $G_{1C}$, J/m$^2$ | $C$, mm/N | $G_{1C}$, J/m$^2$ |
| Reference | 0.00118 | 1.99 | 0.00094 | 1.426 | 0.005 | 27.0 |
| Test | 0.0008 | 2.36 | 0.0009 | 1.608 | 0.0037 | 32.36 |

field contributes to the limit stresses increasing of the interlaminar shear of carbon-, glass- and organoplastic on average by 16.3; 9.6 and 15.2%, respectively. The stresses change for carbonplastic upon EFD increasing is of an extreme nature. The energy flux density affects the stresses in carbonplastic to a much greater extent than it was noted for other studied materials, which may be associated with that carbonplastic heating is accompanied by a skin-effect on the surface of conductive fibers, which causes an intense temperature increasing in the interfacial and interlayer space of PCM.

The reference samples of all the materials studied are characterized by a relatively rapid load increasing before damage, almost in direct proportion to time, and the loss of the coupling between the layers (delamination, destruction) within 3–7 ms. This may indicate the simultaneous

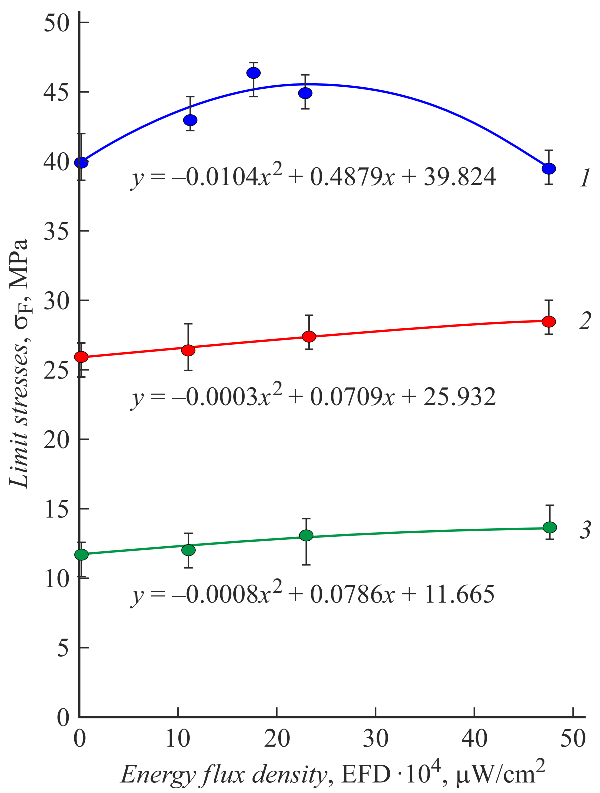


**Figure 1.** Interlaminar shear stresses of carbon- (*1*), glass- (*2*), and organoplastic (*3*) vs. UHF energy flux density of electromagnetic field. Exposure time 2 min. Value of EFD = 0 corresponds to parameters of the reference sample.

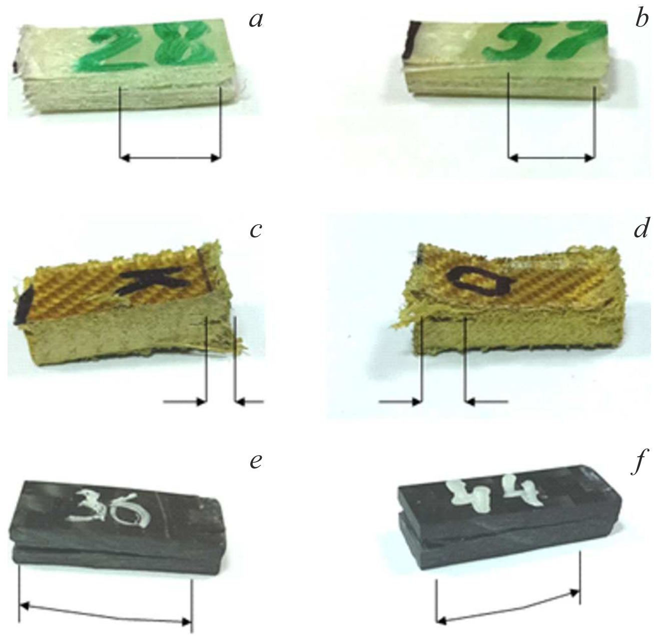


**Figure 2.** Lamination of reference (*a, c, e*) and test sample (*b, d, f*) of glass-, organo- and carbonplastic.

inclusion in the work of the entire matrix in contact with the reinforcing component and the almost simultaneous breaking of interlayer bonds. The load increasing in the test samples occurs more smoothly, the dependence of the process on time has a curvilinear nature with a short section of a relatively rapid increasing and a further gradually decreasing of intensity.

Loss of coupling between the layers, leading to delamination, occurs within 30 ms for carbonplastic and 20–25 ms for organoplastic and glassplastic. In this case, the specific work of delamination does not correlate with the loads that cause it for both reference and test samples. Also note that increase in the delamination work of PCM test samples is accompanied by decrease in their compliance, which is most pronounced (by 32.2%) in carbonplastic. The nature of damages in reference and test PCM samples has the following features. For glass- and organoplastic a rapid closure of the crack is noted after the action termination of the delamination load, the residual deformation of glassplastic in the delamination area is minimal. At the same time, the length of the crack in the reference and test samples differs little, which, along with a slight load

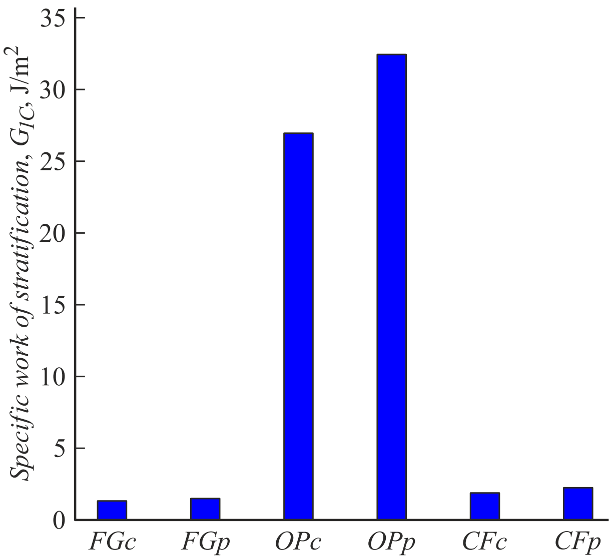


**Figure 3.** Specific work of PCM delamination: FG — glassplastic, OP — organoplastic, CF — carbonplastic. Index „*c*" relates to reference, „*p*" — to test samples.

increasing, leads to a minimal change in the delamination work. In this case, the organoplastic is characterized by a small crack length and multiple delaminations of the sample in the area adjacent to its beginning. The crack in the carbonplastic samples extends almost through the entire length of the sample, the delamination is characterized by a significant residual deformation with a wide crack opening, which may indicate a high level of internal stresses between the layers of the composite. In general, the results obtained, which showed the specific delamination work increasing by 12, 18.6, and 20%, respectively, for glass-, carbon-, and organoplastic (see Table), can be considered to be in good agreement with the above-mentioned increase in the breaking stresses of the interlaminar shear.

We propose the following explanation for the obtained results. A feature of the thermosetting matrix in PCM is the irreversible nature of changes in it upon reheating, which determines the increased temperature resistance of these materials compared to PCM on a thermoplastic matrix. At the same time, it is known [10,11] that when cured epoxy matrix is heated to the temperature of about 50°C, its plasticity increases without destructive changes, and the minimum density is reached at temperature of 80°C. When PCM is exposed to UHF of electromagnetic field, the matrix and the reinforcing component are heated under certain conditions to the specified temperatures. Correspondingly, the probability of conformational rotations of molecule units increases, voids in the structure of the interfacial layer (IFL), as a result of which new areas of contact interaction „matrix–fiber" in the IFL are formed during recuring. As a result, there is increase in the contact area in the IFL and between the layers.

The results obtained may be important for improving the reliability and survivability of structural elements of technical systems made of polymer composite materials, or allow a significant reduction of the structure weight.

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## Conflict of interest

The authors declare that they have no conflict of interest.

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