The effect of processing in a SHF electromagnetic field on the parameters of vibro-wave processes generated by the impact of a solid body in cured polymer composite materials under the influence of climate factors

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Abstract. The studies have been conducted on the influence of environmental factors on vibration-wave processes initiated by the impact of a steel ball in control, cured carbon fiber and fiberglass processed in the SHF electromagnetic field. It is shown that the presence of control and experimental polymer composite materials (PCM) in full-scale conditions under the influence of environmental factors for 3 months leads to a significant decrease in the maximum and average values of vibration accelerations and a reduction in the vibration damping time. At the same time, the prototypes are characterized by a smaller decrease in the maximum values of vibration acceleration and stability of average values. In comparison with the initial control samples, the values of these parameters for carbon fiber and fiberglass are reduced by (43-59) % and (40-46) %, respectively.

The use of PCM in the manufacturing of various products is constantly expanding. The structural elements of various technical systems use PCM reinforced with fabrics based on carbon, glass and aramid fibers, or PCM reinforced with individual fibers (fibrous) – carbon-glass-and organoplastics. In structures designed to handle significant loads, carbon fiber is most often used. Fiberglass is used in cases where, along with the load-bearing properties, the structural element must meet the requirements of radio transparency, or it meets increased requirements for deformation resistance. The largest volume of consumption of carbon fiber in the world falls on the petrochemical industry, energy, and aerospace equipment manufacture [1-2]. The use of PCM in automobile and shipbuilding is constantly expanding.

The performance requirements for the PCM is of a paramount importance. PCM and, in particular, carbon fiber and fiberglass used in the production of aviation equipment are subject to requirements for heat resistance, water and weather resistance, tensile strength along the fibers, compressive strength along the fibers, transversal (across the fibers) strength, interlayer shear, impact strength, and manufacturability [3-5].

When operating aircraft, as well as automotive equipment, it is highly likely that dynamic loads are caused by impacts of solid objects with high accelerations: hail, birds, stones, etc. Under the action of dynamic (shock) loads, some negative features of composite materials reinforced with fibers and fabrics are manifested, in particular, anisotropy in relation to the direction of the load relative to the reinforcement scheme; reduced fracture toughness in comparison with metals and alloys. Under the influence of dynamic loads in a sufficiently rigid and elastic structure of a fibrous polymer composite
material, low- and high-frequency damping vibrations may occur, leading to alternating normal and tangential stresses [6-8]. Due to the presence of sufficiently long multidirectional fibers in the composite structure resonance phenomena are likely to occur. They can cause local rupture of bonds in the interface layer of "matrix-filler" that will lead to the formation and growth of cracks, local stratification, strength and bearing capacity weakening of the structure. Vibrations can be transmitted to metal structures and connections mating with the PCM, causing disruption of connections and reducing the reliability of the entire system. The complexity of the material structure and the variety of the product design, as well as the unpredictability of the direction and point of application of dynamic loads, which is typical for mobile technical systems, does not give sufficient accuracy at the design stage to model the behavior of the structure in a specific situation and develop measures to improve its reliability.

At the same time, developers of composite materials and designers are facing the task of ensuring the preservation of the characteristics of materials during long-term operation of products in various climatic conditions. This is due to the fact that the perception of external loads by structural elements is strongly influenced by the aging processes of materials under the influence of the time factor and the environment (changing temperature, humidity, solar radiation, chemical effects). In particular, the experience of operating aviation equipment shows that the most significant impact on the performance of its elements is not mechanical wear and power factors, but the aging process and the impact of moisture accumulated in the porous structure due to capillary effects. In relation to PCM, external factors cause the development of physical and chemical processes in materials, especially in contact interaction zone “matrix-fiber” and with fixing metal elements, which causes changes in operational and, in particular, strength indicators [9-11].

Our studies indicate a positive effect of processing of cured PCM in the SHF electromagnetic field [12, 13]. However, these results were obtained directly after the impact of the SHF electromagnetic field. The tests were carried out after the samples were in the laboratory. At the same time, as shown above, the influence of external factors must be taken into account, both when designing products from PCM, and when developing technologies for their manufacture.

![Setup diagram of the measuring system](image)

**Figure 1.** Setup diagram of the measuring system: 1-sample; 2-striking ball; 3-sample capture; 4-ADC; 5-laptop complex VK-01; 6-support frame; 7-vibration acceleration sensor VS-112.

We investigated the process of emergence and damping of wave processes in cured carbon fiber and fiberglass, initiated by the impact of a steel ball falling from a height of 660 mm Ø 22.5 mm weighing
47.44 g of hard steel SHX-15 (HRC 50...55). The orientation of the impact was provided by a tubular collapsible guide.

An experimental laboratory site based on the computer vibroacoustic complex VK-01 with ZetLab software (Electronic technologies and metrological systems LLC, Zelenograd) and a computer strain gauge unit with LabView software (SP "Mayorov", Orel) were used for the research. The plane-parallel samples of carbon and fiberglass produced by LLC “Eurocomplekt (Kaluga) with dimensions of 250x35x5 mm. were used. 5 control samples of each material were exposed to a 2450 MHz SHF electromagnetic field with an energy flux density (PPE) equal to (17-18) x104 µw/cm2 for 2 minutes. These parameters provide the highest degree of PCM hardening during static tests [13].

The test scheme is shown in figure 1.

The shock pulse is transmitted to the supports and frame of the loading device by a sample fixed rigidly in the frame. Through the frame, the shock pulse is transmitted to the strain gauge. During the research of wave processes in the PCM, the current pattern of emergence and vibration damping fixed by VS-112 sensor was recorded. Statistical analysis of the data obtained in the ZetLab software environment allowed us to determine the vibration characteristics of the samples: the amplitude of vibration acceleration, and the vibration damping time. Signal recording conditions: time interval 0.5 s, frequency 2.5 kHz, sensitivity 0.135, unit of vibration acceleration - m/s2.

The studies were carried out for control and experimental samples grouped into two batches: one was tested directly after SHF microwave processing. Samples of the second batch before testing were under the influence of environmental factors in the city of Saratov in the period from 02.11.2019 to 02.02.2020. the Average temperature during this period was -1.70 C, air humidity 82%, atmospheric pressure-750 mm Hg. The number of cloud days in the specified period was 80%, precipitation in the form of snow, sleet and rain was recorded during 40% of the period. The maximum air temperature was +40 C, the minimum -90 C.

Figures 2-9 show graphs of the kinetics of the wave process in carbon fiber, diagrams 10-12 show the average values for several measurements of the maximum and average vibration accelerations and the values of the damping time of the samples’ vibrations determined on the basis of graphs. Due to the elastic bounces of the ball, measurements were made using the first of the graphs of each wave process.

Figure 2. Wave process in the controlled original carbon fiber sample.
Figure 3. Wave process in the original test carbon fiber sample.

Figure 4. Wave process in a control sample of carbon fiber after 3 months under the influence of environmental factors.

Figure 5. Wave process in a carbon fiber prototype after 3 months under the influence of environmental factors.
Figure 6. Wave process in the original control sample of fiberglass.

Figure 7. Wave process in the original control sample of fiberglass.

Figure 8. Wave process in a control sample of fiberglass after 3 months under the influence of environmental factors.
**Figure 9.** Wave process in a prototype of fiberglass after 3 months under the influence of environmental factors.

**Figure 10.** Average values of maximum and average vibration acceleration in control samples and prototypes of carbon fiber. 1-original, 2-after the impact of the external environment.

**Figure 11.** Average values of maximum and average vibration acceleration in control samples and prototypes of fiberglass. 1-original, 2-after the impact of the external environment.
Analyzing the results obtained, we can note the following. Control and experimental samples of carbon and fiberglass are characterized by a decrease in the values of both maximum and average vibration acceleration after being exposed to the external environment for 3 months. For control samples of carbon fiber and fiberglass, the decrease in the maximum vibration acceleration values was 62% and 87%, respectively. For control samples, the decrease was 60% and 32%, i.e. the changes occurred to a lesser degree. The change in the values of average vibration accelerations is clearly observed in carbon fiber samples-by 59% and 43%, i.e. the tendency to decrease the parameter changes remains. For fiberglass, the dependence is not significant, it can be stated that the influence of external factors does not affect the average vibration acceleration of both control and test samples of fiberglass. In comparison with control samples, the test samples of carbon and fiberglass have a clear tendency to reduce the average values of vibration acceleration: for carbon fiber-by (43-59) %, for fiberglass-by (40-46) %.

The damping time of post-shock vibrations of control samples of carbon fiber, which were under the influence of external factors, is reduced by 22%, fiberglass-by 6%. This parameter does not change under the influence of the external environment in prototypes, or the change is insignificant. At the same time, the fluctuations of prototypes, both original and under the external impact, fade faster, respectively, by 28% for carbon fiber, 29% and 12% for fiberglass.

The decrease in the values of vibration accelerations and the vibration damping time is presumably connected with the penetration of moisture from the environment into the porous structure of the matrix due to capillary effects. The water in the pores acts as an additional damper for shock loads and the resulting oscillatory (wave) processes. A greater reduction in vibration acceleration of fiberglass samples is due to the greater porosity of the matrix and increased hydrophilicity of glass fibers compared with carbon fibers. The obtained effects of reducing the influence of environmental factors on prototypes and reducing the parameters of wave processes in them in comparison with the control ones can be related to and can be explained on the basis of the facts established by us of changing the microstructure of cured PCM under the action of a SHF microwave electromagnetic field [13]. When the size of the matrix agglomerates decreases and their number increases, the surface of the mechanical contact interaction of a much less elastic and rigid matrix with reinforcing fibers increases. This is also facilitated by the growth of the fractal dimension of agglomerates detected at the nanoscale size. As a result, the shock-initiated wave process propagates in elastic carbon or glass fibers that have a significant contact area with a viscous matrix that takes on a significant share of energy, which leads to a rapid damping of the process. In control samples, the contact surface is smaller and the fibers have fewer mechanical bonds that limit vibrations, which allows them to vibrate for a longer time. The differences between the results obtained during tests of glass fiber-based PCM and carbon fibers are mainly determined by the greater elasticity of the fibers and the lower degree of matrix heating, due to the lack of skin effects. Along with reduction of the agglomerates sizes under the action of SHF magnetic field.
their convergence takes place. It causes a decrease in pore size and overall porosity. This fact increases the hydraulic resistance at the mouth of the pore and complicates capillary effects, reduces the volume of liquid entering the matrix. As a result, changes in the studied characteristics of PCM, which were under the influence of environmental factors, are manifested to a lesser extent.

The results obtained confirm the hypothesis of structuring the cured matrix in the SHF electromagnetic field, which increases the contact interaction with the fibers, provides a significant increase in the strength characteristics of the material and contributes to the dispersion of external energy and accelerated damping of forced vibrations in the PCM volume, which reduces the probability of stress concentration and structural failure. Reducing the influence of environmental factors on the vibration-wave parameters of PCM processed in the SHF microwave electromagnetic field allows to predict the performance characteristics of products more accurately, and ensure their stability under the impact of environmental factors.

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