Impact load influence on hardened polymer composite materials with metal elements built in the structure after microwave electromagnetic field treatment

I V Zlobina and N V Bekrenev
Yuri Gagarin State Technical University of Saratov, 77, Politekhnicheskaya str., Saratov, 410054, Russia
E-mail: irinka_7_@mail.ru

Abstract. During the operation of air and land transport systems, as well as of small-sized vessels, the possibility of influence on their load-bearing structures and dynamic loads shell, including those initiated by a solid body impact, is high. Currently, a significant part of the structural elements of these products is made of fiber-reinforced polymer composite materials (PCM). Impact force is transmitted to the load bearing structures through the PCM product and can lead to the destruction of the connection and damage to the structures themselves. The structure of the PCM includes metal constructions in the form of grids and cellular elements, which creates additional stress concentrators and can affect the perception of shock loads. The studies of the perception of shock load by samples from hardened carbon plastics with a lightning-resistant copper mesh inbuilt in the surface layer and three-layer structures with intermediate cellular elements after their processing in a microwave electromagnetic field were carried out. The obtained results indicate the redesign of the matrix after exposure to a microwave electromagnetic field, and can be used in the development of technologies for final processing of the products made of PCM to increase their resistance to impact force.

1. Introduction
The analysis of scientific and technical literature, conference proceedings and exhibitions proves the widespread use of polymer composite materials based on carbon, glass and aramid fibers, as well as fabrics in the power engineering, aviation, automotive, shipbuilding industry, rocket production and space technology. According to Marketsand Markets research company, the global market for carbon plastics will rise to $35.74 billion by 2020 [1]. The market for the production of composites is constantly expanding and covers not only the aerospace industry and wind energy, but also the construction and manufacture of small vessels, the automotive industry, and robotics [2-6].

For modern polymer composites products, a complex structure is highly indicative, including both metal elements of mesh lightning protection coatings (LPC) distributed in the surface volume and supporting cellular structures located between the outer composite shells, which causes certain difficulties in calculating, designing and manufacturing such products [7]. The three-layer structures of the carrier (“working”) shell consist of the outer layers of the polymer composite material and the so-called cellular filler connecting them, usually made of a lightweight aluminum alloy. They are aimed at the perception and transmission of distributed loads influencing on the structural elements of the aircraft. Bearing layers perceive stretching-compression, a shift in the plane of the layers and transverse bending, and protect the cellular core from external influence, providing rigidity of the structure [7-9].
The presence of LPC inbuilt metal structures and cellular fillers introduces additional factors that affect the difference in the perception of the operational loads of PCM structures from the calculated ones. This should be taken into account when developing technologies for processing and strengthening the modification of products from hardened PCM with LPC built-in elements. The foregoing demonstrates the need for research and development of methods for improving the performance characteristics of PCM structural elements of various technical systems, taking into account the presence of metallic elements of various designs in their composition.

2. Problem statement
The development of aviation and rocket complexes are highly mobile and used in hypersonic speeds conditions in the atmosphere and near space, which demands high mechanical and thermal strength of their structural elements with complex shapes, strongly affecting the distribution of dangerous mechanical and thermal stresses, as well as the perception of impact (dynamic) loads, including impact loads by high-speed solids. Under the influence of dynamic (impact) loads, some negative features of fibrous composite materials appear, in particular, anisotropy in reference to the load direction relative to the reinforcement scheme, reduced fracture viscosity. It requires technological and construction strengthening measures.

To improve the physic and mechanical characteristics of PCM, various chemical, physical, mechanical, electrical methods, as well as constructive solutions are used. One of the potentially productive methods is the final modification of the structure of hardened PCM in the process of short-term exposure to the microwave electromagnetic field, as evidenced by our results [10, 11]. Short-term (up to 2 minutes) processing of cured PCM in a microwave electromagnetic field helps to improve the damping properties when perceiving an impact load of (7-24.4) %, depending on the reinforcement scheme and the matrix material. Processing PCM with built-in metal elements in the microwave electromagnetic field helps to increase the static strength by 16%, the strength under low-cycle loading almost in 2 times. However, the influence of processing PCM with metal elements by impact loads in the microwave electromagnetic field on the perception of PCM needs additional studies.

The purpose of this research was to study the effect of the impact on the hardened PCM modified in the microwave electromagnetic field with the metallic elements of impact loads distributed in the volume.

3. Research methods
The 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 with LabView software (Mayorov IP, Orel) were used to carry out the studies. In the experiments, three-layered samples in the form of balsks with a cross section of 15.5 x 15.0 mm and a length of 117 mm were used. The thickness of the outer plates of carbon fiber type VKU - 1.5 mm, the thickness of the cellular elements made of aluminum alloy - 0.3 mm. The samples with LPC in the form of a copper grid produced by the Textilmash plant comprised themselves as plates 1.8 mm thick with dimensions of 70x70 mm. The main material is carbon fiber of the VKU type, the outer protective layer of LPC grid is fiberglass. The impact load was ensured by a ball Ø 22.5 mm weighing 47.44 g made of hardened steel SH-15 (HRC 50 ... 55) falling with a height of 330 mm. Orientation of impact load was provided with a tubular guideway.

The authors used 5 control samples of each material that were exposed to a microwave electromagnetic field for 1 minute with a frequency of 2450 MHz at a distance of 200 mm which corresponded to the energy flux density (EPD) of 17x104 μW/cm². Under these modes, according to our previous research [10-13], the maximum increase in PCM strength is ensured under the action of static loads. To simulate the processing technology of large-sized aircraft shell, “Zhuk-2-02” installation (OOO NPP “AgroEkoTech”, Obinsk, Kaluga region) with a horn radiator was used for processing.

The scheme of testing is shown in figure 1.
Figure 1. Scheme of measuring complex setup for testing 1 - sample; 2 - hitting ball; 3 - sample sticking; 4 - analogous-to-digital converter; 5 - computer system unit; 6 - monitor; 7 - strain gauge force sensor; 8 - supporting frame

Impact pulse is fixed rigidly in the frame of the sample. It is transmitted to the supports and the frame of the loading device. The impact pulse is transmitted to a strain gauge through the frame. In the process of research, the kinetics of increase in shock load was recorded and the current picture of its growth and decline after the end of the impact was recorded.

4. Results and discussion
The screen shots of the monitor screen of an experimental strain gauge are shown in Figures 2 and 3. The results of processing the experimental data are in the table.

Figure 2. Kinetics of the impact force of a steel ball falling from a height of 330 mm on VKU-type carbon fiber with a cellular core: control sample (a), processed sample (b). The time is measured in ms along the horizontal axis
Figure 3. Impact load kinetics of a steel ball falling from a height of 330 mm on VKU-type CFRP plastic with LPC based on the “Textilmash” copper grid: control sample (a), processed sample (b). The time is measured in ms along the horizontal axis.

Table 1. Average recorded impact loads (N) of a ball falling on a sample/

| Sample type          | Three-layer construction with cellular filler | VKU-type plastic with LPC grid |
|----------------------|-----------------------------------------------|--------------------------------|
| Control $P_c$        | 71,23                                         | 48,1                           |
| Processed $P_P$      | 56,4                                          | 41,4                           |
| Impact load change $\Delta = P_c / P_P$ | 1,26                                          | 1,16                           |

It can be seen that PCM processing in a microwave electromagnetic field at the modes adopted in the experiment leads to a decrease in the impact load transmitted by the sample by an average of 26% for samples with cellular elements and 16% for samples with LPC.

At the same time, a certain decrease in the period of attenuation of sample vibrations caused by a falling ball was established. In addition, a twofold increase in the impact load peaks for cellular structures was recorded, which may be associated with additional ball rebounds from the surface due to its increased elasticity.

The study of the samples impact surface appearance revealed the upraise of significant longitudinal stratifications of control samples with cellular elements, extending almost the entire thickness of the outer layer (Figure 4 a). At the same time, the presence of cracks and exfoliations in the processed samples was not detected (Figure 4 b).

Figure 4. Impact load surface of samples with cellular filler: control (a), processed (b)

The length of the longitudinal cracks and delaminations in the control sample was more than 50 mm, almost from the point of impact to the end surface. Moreover, the outer layer is characterized by stratification in both the vertical and horizontal planes, which is manifested in the small width of the exfoliated fiber complexes (1 mm and less). The underlying layers of the PCM exfoliated only in the vertical plane in the form of plates. In general, the obtained results correspond to the previously obtained data on the impact strength of PCM without metal elements. The difference lies in the slight discrepancy between the periods of attenuation of post-impact vibrations, which may be connected with the inclusion...
of metal structures that have not changed their properties after microwave exposure into the work on the perception of the load. The impact load damping mechanism for hardened PCM samples with metal elements can be suggested as follows. As it was established earlier [12, 13], the effect of a microwave electromagnetic field leads to a decrease in the size of agglomerates and pores, an increase in the number of agglomerates and an increase in the fractal dimension of their surface, which increases the number of points of contact interaction between the matrix and fibers. This contributes to increasing the solidity of PCM, uniform redistribution of the load in its volume and improving conditions for the dissipation of impact load energy, which is not hampered by significant voids and heterogeneous agglomerates. Intense production of Joule heat in the area of the metallic elements of the LPC grids and cellular structures leads to intensification of diffusion processes in the contact area with the volume of PCM, some softening of the matrix and its closer contact with these structures, which increases the coherence of the whole structure and its strength and rigidity. At the same time, relatively soft metal structures that have a complex spatial shape, receiving impact energy from the outer layer of PCM, redistribute it and quench during plastic deformations, which reduces the fraction of the impact load transmitted to the underlying layers of the composite material.

5. Conclusion
It was established that after short-term processing in a microwave electromagnetic field, a stable decrease in the impact load transmitted by hardened polymer composite materials to related structures for three-layer cellular elements and materials with a LPC in the form of a copper grid, to 26 % and 16 % respectively. At the same time, a practical absence of cracks and exfoliations typical for control samples is seen.

The obtained results indicate the increase in the mechanical strength of PCM with metal elements and the redesign of the matrix after exposure to a microwave electromagnetic field, and can be used in the development of technologies for final processing of the products made of PCM to increase their resistance to impact loads.

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