Strengthening microwave modification of structural elements of composite materials reinforced with synthetic fibers

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Abstract. The strength characteristics of composite carbon and fiberglass plastics have been studied, after their modification by microwave radiation of various power input. It has been established that the microwave effect on the finally shaped object under various conditions of the parameters increases the ultimate bending stresses of the carbon fiber reinforced plastic by 47–53 %, the GRP by 60 %. At the same time, significant changes in the microstructure are noted, which are manifested in the increase in its homogeneity and density as the contact points of the matrix agglomerates and reinforcing fibers increase.

1. Introduction
Analysis of scientific and technical literature, conference materials and exhibitions testifies to the intensive development of production of composite materials based on carbon fibers and glass fabrics and their wide application in the aviation, automotive, shipbuilding, wind power, rocketry and space technology. According to the research company Grand View Research, the world market of carbon plastic will reach $ 23.55 billion by 2022. According to another research company, MarketsandMarkets, the global market for carbon–fiber reinforced plastics will rise to $ 35.74 billion by 2020 [1, 2]. The aerospace industry accounted for more than 30 % of the consumption of these materials in 2014. The foregoing testifies to the existence and preservation in the near and distant future of the needs of high-tech industries in the use of high-quality composite materials.

However, due to a number of reasons, composite materials and products made of them have a pronounced anisotropy of properties [3]. This causes the need for additional reinforcement in some hazardous areas, leading to weight gain. This is undesirable for aerospace products, especially for highly maneuverable and high-speed objects.

There are different ways of forming a given set of material properties. One of them is the modification of its structure. An effective method of action is the use of microwave radiation (microwave electromagnetic field). This method is applicable to non-metallic composite materials.

We performed experimental studies [4] of the effect of the microwave radiation on the strength of the pultruded carbon and carbon plastics with a quasi–isotropic structure. It is established that the following changes in strength characteristics are noted for the specimens exposed to optimal regimes. The strength of the bending stresses increases by 11–16 %, the shear stresses by 13–21 %, while the interlayer shift tests increase the stress values by 14–15 % compared to the control samples. It should be noted that the temperature of the sample did not exceed 39–40 °С after the treatment was completed.
The foregoing indicates a promising continuation of the work on the investigation of the mechanisms of strengthening under the influence microwave radiation of finally formed products made of composite materials.

2. Formulation of the problem
The analysis of the materials of domestic and foreign scientific publications [5–7] shows that the greatest attention in the development of research in the field of ultrahigh–frequency processing of materials is devoted to the search for fundamentally new solutions for the application of microwave technologies with the aim of replacing existing heat treatment technologies. Recently Russian and foreign scientists V.A. Kolomeitsev, G.A. Morozov, O.G. Morozov, Y.S. Arkhangel'sky, E.V. Kolesnikov, V.A. Tsarev, G. Piushner, J.R.Cannon, W.C. Chew, A. Razek, T.L. White and others made a significant contribution to the development of the theory of microwave heating of dielectric materials. The thermal effects of microwave radiation are manifested mainly in the stages of material formation, in the synthesis of reinforcing fibers, in the curing of the matrix. This does not solve the problem of the appearance of structural heterogeneity in the process of product formation, curing and finishing machining. It, in turn, leads to an increase in residual stresses and a decrease in strength characteristics. However, the thermal effects of microwave radiation are manifested mainly in the stages of material formation, in the synthesis of reinforcing fibers, when the matrix is cured. At the same time, the problem of the appearance, in the process of product formation, curing and finish machining of structural heterogeneities, leading to an increase in residual stresses and a decrease in strength characteristics, is not solved. Most studies of these electrotechnological processes concerned effects on the process of synthesis of components or curing of the composition [5]. There is almost no information about the mechanism of the effect of microwave radiation on the cured structure of the finally formed product. At the same time, the application of this influence on composite materials during their formation is not always expedient because of the need to introduce changes into the smooth and complex technological process of synthesizing the components, laying out the composite layers, curing and finishing.

The aim of our studies is the experimental determination of possible reinforcing microwave modifying of finally formed and cured structure of constructional composite materials such as glass and carbon plastics.

3. Research methods and equipment
We have studied samples from layered glass, carbon plastics in the form of plates with dimensions of 80×15×2 mm. In the experiments we used a microwave installation “Zhuk-2-02” manufactured by LLC "AgroEcoTech", Obninsk, Kaluga region with a radiating horn antenna. The installation generates an electromagnetic field of 2450 MHz with an output power of 1200 W. Three microwave power modes were used: small $P_I$, medium $P_{II}$ and high $P_{III}$. Specific technological regimes are not described due to the procedure for patenting this method of modification.

The processing time was set to 1, 2, 3 minutes at different power levels. Tests of the samples before and after treatment were carried out on a machine equipped with strain gage force sensors and a worm loading mechanism. Processing of the results of measuring the build-up of the load applied to the sample was carried out using a special program (LabVIEW, Orel) and allowed to obtain load graphs (torque on the drive) in dynamics from the moment of application to destruction. Based on the known dependences of the material mechanics, bending stresses were calculated. The surface of the deformation zone was studied using a digital microscope Digital Microscope 2.0 MP 1000X (GAOSUO, China) with an increase in x500 with displaying on the laptop screen.

4. Results and discussion
Based on the results of processing the data of the experimental setup, graphical dependencies were obtained (Figure 1).
At low microwave radiation power, bending stresses increase by an average of 41 \% and are practically independent of the exposure time. While testing the samples after low-power microwave radiation treatment, the flexural stresses increase by an average of 41 \% and practically doesn’t depend on the exposure time. While examining samples processed at medium power, the dependence of the hardening effect on time is also insignificant. The hardening effect is unstable and ranges from 29 \% to 53 \%. Analysis of the test results of samples treated with the use of a high-power electromagnetic field shows an explicit dependence of the hardening of the material on the time of exposure. When it increases from 1.5 to 3 min, bending stresses increase by 46 \%. However, at low values of time, a decrease in strength is observed, which requires an explanation.

The nature of the dependencies for fiberglass differs from the ones shown in Figure 1a: at short exposure time with an increase in the input power of radiation, a stable increase in the strength of the sample is observed, determined from the limiting bending stresses. Finally, at the maximum time of the investigated range of exposure, the maximum hardening effect is achieved at low power, but with its increase the effect decreases sharply. At maximum power, the strength of the sample remains practically comparable with the control one. In this case, obviously, another mechanism of the electromagnetic field’s influence is manifested. With the passage of time, at a small power level, the processes of formation of additional cross links – in the matrix, between the matrix and reinforcing fibers, as well as between the fibers themselves, which form conglomerates (braided bundles). As a result the material acquires maximum strength. The effect of hardening on bending stresses in this case is more than 60 \% and exceeds that achieved one for CFRP.

A study of the microstructure of the deformation zone of the samples (Figures 2 and 3) showed the following.
Figure 2. Microstructure of a control sample made of CFRP (a) and processed with medium (b) and large (c) microwave power x500

Figure 3. Microstructure of a control sample made of fiberglass (a) and processed with medium (b) and large (c) microwave power x500

In the zone of destruction of the control sample made from CFRP (Figure 2a), breaks of the crumbled matrix are seen, which led to a weakening of bonds between the reinforcing fibers. Though they mostly retained uniformity, they did not preserve the shape of the sample due to separate functioning. The structure of a sample processed at low power is characterized by greater monolithicity. One can note the presence of minor cracks, fibers, interconnected structures of the matrix, which have a more developed contact surface. Studying the sample processed at medium power for 3 minutes (Figure 2b), cracks in the matrix are visible, they divide the structure into blocks, although the blocks consist of fiber conglomerates. The microstructure of samples treated at high electromagnetic field power (Figure 2c) has the appearance of “alloyed” blocks and microblocks having a very developed surface. As a result large number of matrix agglomerates with a highly developed surface appear. In consequence of the described effect, flexibility, elasticity of the fiber-matrix system and its strength increase.

In the fracture zone of a control glass made of fiberglass (Figure 3a), breaks in the fibers and particles of the crumbled matrix are seen. The structure of the sample processed at a low power is monolithic, the fibers are linked together by “star” structures of the matrix, which have a developed contact surface. When processing at medium power for 3 minutes (Figure 3b), individual fibers are seen. They are separated from each other, although with the remaining “star” formations on the surface. After exposure for 3 minutes at high power, the sample looks completely destructured.

5. Conclusion

The obtained results can be explained as follows. The investigated carbon fiber plastic has a relatively loose (untight) packing of carbon fibers and a smaller content of reinforcing components. Accordingly, the effect of microwave radiation, which is mainly manifested at the level of the formation of additional cross-linking of the matrix molecules, leads to a greater effect on a material with a smaller content of the carbon reinforcing component. As the radiation power supplied to the GRP increases, dehydration and embrittlement of the matrix and reinforcing fibers are noted. At maximum power, this effect is manifested to a greater extent, therefore an increase in the exposure time causes heating of the material, which adversely affects the adhesion of the components and also the cohesive interaction of the structural components of the matrix. Accordingly, the resistance to the action of loads decreases and reaches a minimum with prolonged processing at the maximum of the investigated power range.

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