

A proposal to improve a 3D printing technology of composite materials products

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Abstract. The objects formed by 3D printing, in particular from nonmetallic materials, have an essential disadvantage not eliminated at the present time - a significant anisotropy of the structure and, as a consequence, of physical and mechanical characteristics. The research of 3DP technology in combination with the influence of microwave electromagnetic field of various power on the formed three-dimensional product has been carried out. It was established that a microwave electromagnetic field with an average specific power of 2450 MHz causes an increase in the homogeneity of the of powder materials` structure, expressed in a decrease of the pore size by 24% and a decrease in their dispersion by almost 30%. As a consequence of the increase in the homogeneity of the structure, the flexural strength of Zp130- powder plates impregnated with cyanoacrylate has increased to 1.77 times. Thus, the use of the microwave electromagnetic field as a final stage in the formation of products made from composite materials is promising and requires additional studies to justify the serial production technology.

1. Introduction

1.1. Status of the question

Development and introduction of perspective transport systems, in particular aerial vehicles, require creation of new high-strength and light materials and improvement of technologies for forming structural elements from them. 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, rocketry and space technology. However, composite materials are characterized by a pronounced anisotropy of physicomechanical characteristics, determined by the type and orientation of the reinforcing components.

One of the new ways to reduce this shortcoming is to manage the structure of the material by introducing reinforcing components according to a certain law. This operation can be carried out not only by introducing new components, but also by modifying them by electrophysical influences, which is much easier to implement because the process is easily controlled by regulating technological regimes without interfering with the synthesis of the material. However, the use of traditional technologies for practical implementation of this solution is difficult, which causes the need for

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additional research in the field of creating the scientific basis for technological support for the production of composite products.

1.2. Relevance of research

One of the most topical technological trends currently includes additive technologies, in which layer-by-layer build-up of material in accordance with a given computer solid model practically replaces the traditional processes of cutting, pressing and stamping [1-4]. The main advantage of these technologies is the direct reproduction based on a solid model of a product of any complexity without the use of a complex instrument and expensive equipment. At present, significant progress has been achieved in the use of additive technologies not only in rapid prototyping, but also in the manufacture of structural elements of existing technical systems. At the same time, the technologies for manufacturing products made of polymer materials 3DP, FDM and SLA are quite cheap (the cost of equipment is about \$ 1000), but they are imperfect, since products have low strength and durability. Particularly important is the instability of the characteristics from the part to the part and from the installation to the installation. However, scientific research in this area is aimed at developing source materials, methods of components compounding, software that provides maximum accuracy and productivity. One of the alternative ways to improve the technologies of additive production of products from nonmetallic and composite materials may be a directed modification of the structure of existing materials by electrophysical influences. Based on the mentioned above, the solution of the issues of increasing the strength of products made of nonmetallic materials, created based on additive technologies, is an important urgent task.

1.3. Statement of the problem

In the works of Russian and foreign scientists [5, 6], positive effects of the influence of the microwave electromagnetic field on the technological processes of synthesis and modification of nonmetallic materials are reflected, including the positive effect of nonthermal microwave influence on the properties of polymeric materials. We have established when applied to layered carbon plastics with a quasi-isotropic structure, the ultimate bending stress increases by an average of 25%, the interlayer shear stress by 14-15% (confirmed by tests in production conditions), the time to destruction at the ultimate load increases by 1,6 - 2 times [7-10]. The purpose of these studies was the experimental determination of the possibility of improving additive technologies, for example, by 3DP introduction of the structure modification operation in the microwave electromagnetic field.

2. Research methods and equipment

In the experiments we used a 3D printer of the ZPrinter 450 model and a microwave unit with a magnetron OM75S (31) with a frequency of 2450 MHz. We used three microwave power modes: low PI, medium PII and high PIII. The treatment was carried out for 10 and 60 seconds. 3 samples were treated simultaneously. In accordance with 3DP technology there were formed the plate samples of 80 mm long, 8 mm wide and 1.5 mm thick from dielectric powder Zp130. The final impregnation based on Z-BondTM 90 cyanoacrylate was applied to increase strength. The following samples were obtained: I - sample without additional impregnation; II - sample without additional impregnation with microwave processing after formation; III - sample with additional impregnation; IV - sample with microwave treatment after formation and subsequent additional impregnation; V - sample with microwave treatment after additional impregnation; VI - sample with microwave treatment before and after additional impregnation. Accordingly, schemes for introducing microwave modification into the 3D printing process were investigated. The surface of the samples prior to the tests and the surface of the fracture zone were examined using Digital Microscope 2.0 MP 1000X and a computer image analyzer of microstructures AGPM-6M with certified Metallograph software with magnification of x17 and x400, respectively. In addition, the firmness of the obtained samples was studied by the strength of their fracture determined by the digital dynamometer FMI-S10C1 from ALLURIS GmbH & Co. KG with measurement limits of 0-100 N. The authors used a special unit equipped with load strain gauges connected via an analog-digital converter with a computer in which the results were

processed in a special Labview software environment. During the testing, we installed the samples like a two-support beam on the tensometric device of the installation and loaded in the middle section with a bending moment with the help of a lever rotated by an electromechanical drive at a constant speed.

3. Results and discussion

As a result of the research, the following main data was obtained.

3.1. The influence of microwave modification on the structure of materials

The study of the structure of the samples at their fracture (Figure 1) showed that the use of microwave treatment after additional impregnation of the formed samples (Schemes V and VI) causes the formation of microcracks in the binder, which is obviously the reason for lowering the ultimate bending stresses. The formation of microcracks can be associated with various thermal and electrophysical characteristics of the powdered material and binder resulting in different interactions with the microwave electromagnetic field and possible changes in the dimensions and deformations of the individual components of the formed composite material. The microstructure of samples with microwave treatment immediately after formation is shown in Figure 1.

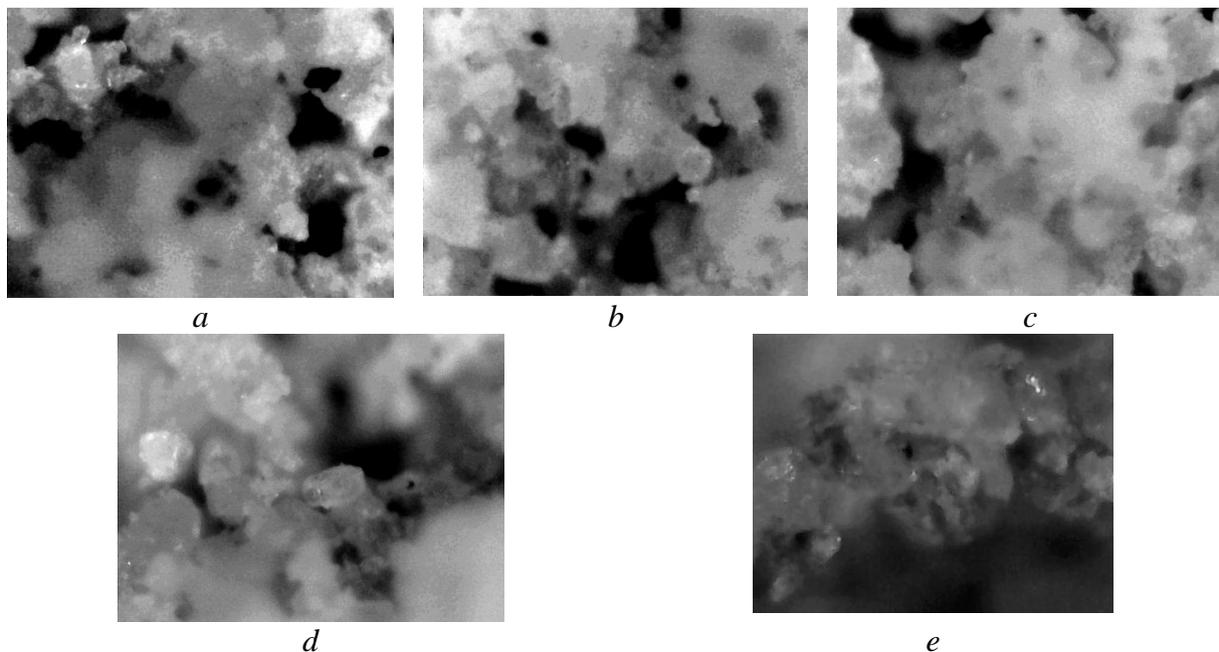


Figure 1. Microstructure of samples (x400): control (a); processed at a power PI for 60 s (b) and 10 s (c); treated at a power PII for 60 s (d) and 10 s (e)

The formation of microcracks can be associated with various thermal and electrophysical characteristics of the powdered material and binder resulting in different interactions with the microwave electromagnetic field and possible changes in the dimensions and deformations of the individual components of the formed composite material. In the sample before the final impregnation with microwave treatment immediately after formation (Scheme II) the gap between the particles (macropores) is reduced by 9.2 - 24%, and in the sample with final impregnation without microwave (Scheme III), practically did not change. When treated with impregnation after microwave treatment (Scheme IV), the homogeneity of the structure further increases - the dispersion of pore sizes is reduced by 25-32%. It can be seen that the large microwave power and the longer exposure time in the investigated range (Figure 1c) contribute to the formation of more dense agglomerates of particles with smaller spaces between them. Increasing the homogeneity of the structure and reducing the size

of the pores after microwave treatment obviously contributes to an increase in the number of bonds between the particles and an increase in the limiting bending stresses.

Thus, based on the study of the microstructure of the samples studied, the following rational technological route can be proposed with the introduction of the microwave modification operation into the 3D printing process: the formation of a product from a powder on a 3D printer, processing in a microwave electromagnetic field, the final stabilizing impregnation. To identify technological regimes, it is necessary to study the strength characteristics of the formed samples. Impregnation of such a modified structure obviously occurs more evenly, the binder penetrates throughout the volume at approximately the same particle-binder concentration, which further increases the probability of uniform adherence of the particles and the formation of a uniformly strong (isotropic) composition.

3.2. The influence of microwave modification on the physical and mechanical properties of samples

Based on the processing of experimental data for samples with microwave treatment after formation without impregnation, the dependence shown in Figure 2 was obtained.

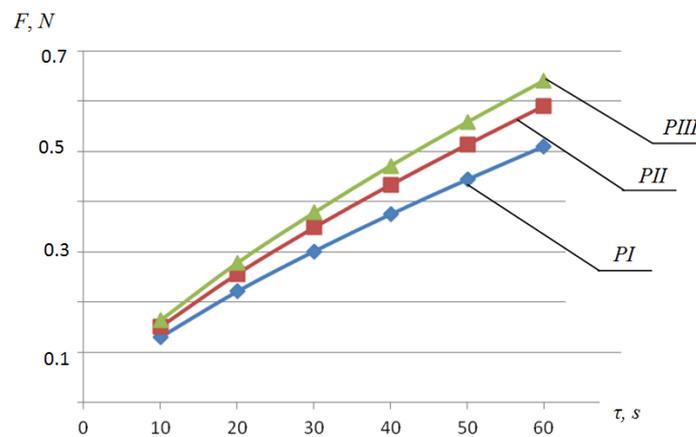


Figure 2. Influence of microwave power P_{density} and time of action τ on the fracture force of samples F.

Based on the known cross-sectional area of the specimens and the determined breaking force, the maximum bending stress acting at the moment of sample destruction was calculated. The greatest effect on increasing bending stresses is achieved at the maximum power density from the investigated range and the maximum time. Where in time has a much greater effect than microwave power. The fact of placing the sample in the microwave electromagnetic field leads to the maximum effect. Here it is important to rearrange the binder and filler at the molecular level and the appearance of new bonds between the components. Figure 3 shows the histogram of the maximum bending stresses $\sigma_{F_{\text{max}}}$ arising upon external loading destruction in samples manufactured according to schemes I-VI, in accordance with the procedure described above.

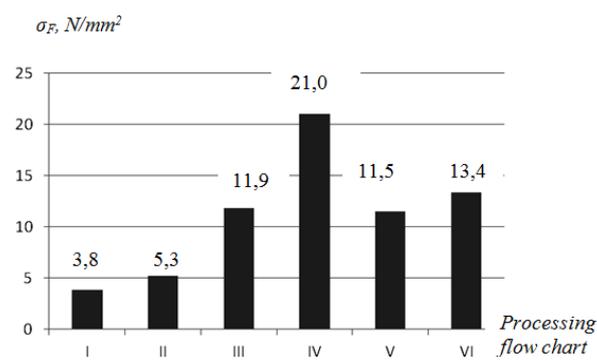


Figure 3. Influence of the place of microwave treatment in the technological cycle on the bending stresses σ_F in the samples in comparison with the treatment without microwave exposure.

The histogram shows that the place of microwave treatment in the technological cycle significantly affects the strength of the formed sample, which is characterized by limiting bending stresses. After microwave treatment immediately after forming in a 3D printer, the flexural strength increases by an average of 1.37 times (II). Processing of generated samples in a microwave frequency field of 2,450 MHz with a high specific power (PIII) followed by impregnation (Scheme IV) provides an increase in flexural strength by 1.77 times compared with existing 3DP (Scheme III) technologies. The use of microwave treatment after impregnation has practically no effect on the flexural strength (Scheme V) or decreases it somewhat, which is in full agreement with the above-mentioned results of the change in the microstructure. Two-stage microwave treatment (before and after additional impregnation) gives an increase in the flexural strength of about 13% (Scheme VI), which can be considered almost insignificant in practice.

Figure 4 shows the graphs obtained on a computer installation in the process of loading samples and characterizing its kinetics before the time of their destruction.

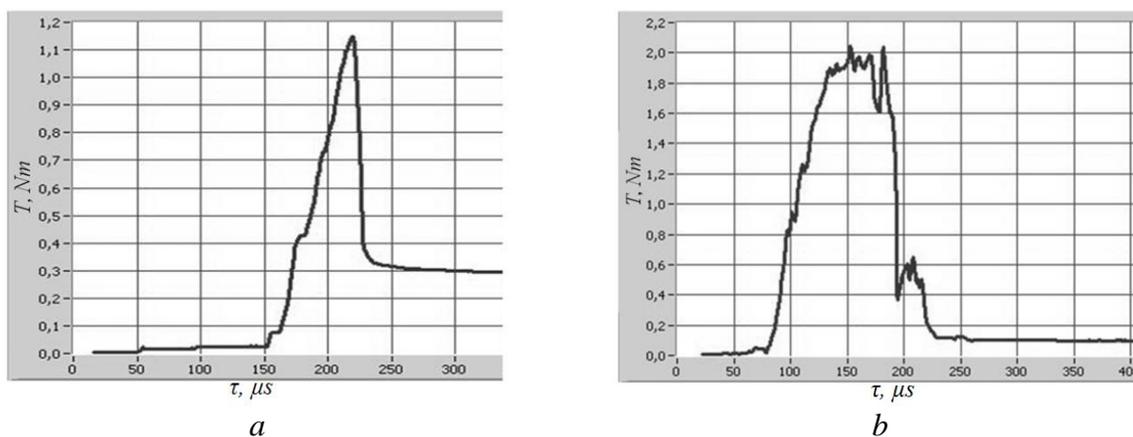


Figure 4. Change in the value of the load from the beginning of loading to the moment of destruction of the samples taken after the final impregnation: a - a control sample, b - processed in a microwave electromagnetic field.

During the analysis of the graphs, an increase in the value of the limiting value of the bending moment for the treated sample was established in comparison with the control value from 1.15 Nm to 2 Nm, i.e. by 74 %, which is explained by the changes in the structure of the processed samples described above. It can be seen that in the loading graph of the processed sample, there is a section in the time interval from 150 to 180 μs , at which the recorded load does not increase, i.e. apparently the sample is elastically deformed, absorbing energy due to the increased number of bonds between the agglomerates in the microstructure and not being destroyed. In the control sample, after reaching the maximum load, its recession corresponding to the destruction takes place simultaneously. In this case, one we speak about the absence of deformations and pure brittle fracture. This result is also important for the load-bearing structures of various technical systems, since it increases the time for making decisions for the operator.

4. Conclusion

Based on the foregoing, it can be concluded that the processing of samples generated by 3D printing methods in the microwave electromagnetic field significantly increases their strength parameters. In this case, the effectiveness of the impact is different for different loading schemes (shear or bending)

and depends on the supplied microwave power and time. The mechanism of material hardening apparently consists in increasing the number of cross-links of the structural components at the macro and micro levels. To clarify this assumption, it is necessary to conduct research involving electronic and atomic force microscopy.

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References

- [1] Kablov E N 2015 Innovative developments of "VIAM" for the implementation of "Strategic directions for the development of materials and technologies for their processing until 2030" *Aviation materials and technologies (Electronic Materials No. 1)* (Moscow) pp 3–33
- [2] Kablov E N 2012 Materials and chemical technologies for aviation equipment *Herald of the Russian Academy of Sciences* (vol 82 No. 6) (Moscow: "Publishing house "Science") pp 520–530
- [3] Bourell D L, Beaman J J, Leu M C, and Rosen D W 2009 *A Brief History of Additive Manufacturing and the 2009 Roadmap for Additive Manufacturing: Looking Back and Looking Ahead* U. S. Turkey Workshop on Rapid Technologies (*Istanbul, Turkey*)
- [4] Ehrenberg R 2013 *The 3-D Printing Revolution: Dreams Made Real One Layer at a Time*, *Science News* (Washington : Science Service Publication) 183 (5) pp 20–25
- [5] Arkhangel'skiy Y S 2011 *Reference book on microwave electrothermy: a reference book* (Saratov Scientific Book) p 560
- [6] Estel L, Lebaudy Ph, Ledoux A, Bonnet C and Delmotte M 2004 Microwave assisted blow molding of polyethylene-terephthalate (PET) bottles *Proceedings of the Fourth World Congress on Microwave and Radio Frequency Applications* No. 11 (Austin, Texas) p 33
- [7] Zlobina I V and Bekrenev N V 2016 *The Influence of Microwave Electromagnetic Field on Mechanical Properties of Composite Materials* Science Intensive Technologies (Moscow: Radio engineering vol 17 No. 2) pp 25–30
- [8] Zlobina I V and Bekrenev N V 2016 The influence of electromagnetic field microwave on physical and mechanical characteristics of CFRP (carbon fiber reinforced polymer) structural Solid State Phenomena Materials Engineering and Technologies for Production and Processing II (*Trans Tech Publications Ltd* vol 870) pp 101–106
- [9] Zlobina I V, Bekrenev N V and Muldasheva G K 2016 *Increasing of the endurance of polymeric construction materials with the multilevel hierarchical structure in the microwave electromagnetic field* AIP Publishing (Melville, New York: AIP Publishing LLC) pp 020236-1–020236-4
- [10] Zlobina I V and Bekrenev N V 2017 Investigation of the microstructure of structural layered carbon plastics, modified by electrophysical effects *Vestnik of P A Solovyov Rybinsk State Aviation Technical University No. 1 (40)* (Rybinsk: Publishing house of P A Solovyov Rybinsk State Aviation Technical University) pp 236–242