Modeling of absorption of microwave radiation of various frequencies by objects by composite filament

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Abstract. The paper demonstrates that exposing cured phase change materials (PCMs) to a microwave electromagnetic field after treatment significantly enhances their physical and mechanical properties. This method can be applied to three-dimensional printing objects composed of composite filaments. Through a full factorial experiment, it was determined that the radiation power absorbed by the material has the most significant impact on the efficiency of microwave exposure on cured PCMs. This absorbed power is heavily influenced by the dielectric constant and dielectric loss tangent of the components, the surface area of the object, its thickness, and the microwave flux density energy. The influence of these factors on the absorbed power of microwave radiation was simulated for various combinations of dielectric parameters and exposure frequencies.

1 Introduction

The most common 3D printing method, due to the low cost of equipment and the relative ease of implementation, is to construct an object in the form of layers of thermoplastic threads (filaments), which are formed by melting and solidifying (FDM technology). Currently known FDM technologies make it possible to create products ranging in size from a few millimeters to meters of almost any shape and filling density [1, 2].

At the same time, for the industrial implementation of FDM technologies, the problem remains of insufficient strength and rigidity of polymer products, which negatively affects the reliability of structures made from them and makes it urgent to create new polymer materials for use in this technology, as well as improve both the printing process and post-processing of products.

One of the effective methods for solving the first problem is the co-extrusion technology proposed by the Anisoprint company, according to which a bundle of continuous fibers is pre-impregnated with a thermosetting resin and then coated with an outer layer of thermoplastic polymer, which during the printing process ensures the consolidation of individual threads into layers, and the latter into the product. However, this technology is characterized by heterogeneity in the thermophysical and mechanical properties of the thermosetting binder for the tow and its thermoplastic outer layer for forming threads and

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layers into the product, which reduces adhesion between the layers, and can also lead to the occurrence of internal stresses during the cooling process when leaving the printing die heads and on the construction platform as part of a monolayer. This, as well as the possible destruction of the binder in the bundles at a certain operating temperature, are a serious disadvantage of this technology [3-9]. In this regard, it is necessary to use known physical or chemical methods for modifying the polymer binder. Currently, preference is given to physical methods since the use of chemical modification directly during the printing process is practically impossible.

During research by domestic and foreign scientists, it was found that the most effective method in this direction is physical modification by exposing the material to ultrasound, microwave electromagnetic field, ultraviolet radiation, etc. [10, 11]. Methods for changing the properties of dielectric materials when exposed to a microwave electromagnetic field of one of the industrial frequencies (2450 MHz) have been developed and studied [12-15].

However, known methods of physical modification are implemented by influencing PCM components at the stage of their production, or by influencing PCM layers at the stage of impregnation with a binder or curing, which is quite difficult to implement in the working area of additive equipment and causes the likelihood of a negative impact of subsequent post-processing operations on the formed product. complex of properties.

The authors found that microwave exposure at a frequency of 2450 MHz on finally formed samples of carbon fiber-reinforced PCM, when using rational modes, provides an increase in interlayer shear stress by (16-18) %, and an increase in elastic modulus by 14-20%. In this case, heating of the material to (50-70) 0C is noted [16]. The possibility of obtaining certain effects under microwave exposure on cured PCM has also been confirmed by studies of foreign scientists [17-19]. The studies carried out concerned exclusively PCM with a thermosetting binder. The influence of the dielectric properties of PCM components on the efficiency of microwave exposure, which can acquire various combinations during the 3D printing process, has not been studied. The use of lower industrial radiation frequencies, for example, 915 MHz, which have a significantly greater penetration depth, was not considered [15]. Considering the stable trends in the use of composites in additive manufacturing, these issues require separate study.

The purpose of the research was to study the influence of microwave influences of different frequency ranges (2450 and 915 MHz) on the absorption of radiation power by a composite filament used for three-dimensional printing using FDM / coextrusion technology, taking into account different combinations of dielectric properties determined by the ratio of the components and the existing spread of their values, level energy flux density (EFD) and scale factor - the size of the impact object.

2 Materials and methods

Five samples with dimensions of 40x10x2 mm, printed using co-extrusion technology on a 3D printer, were simultaneously processed on an experimental microwave installation created based on the Zhuk-2-02 horn emitter produced by NPP AgroEcoTech LLC (Obninsk, Kaluga region) Anisoprint Composer A4. During the microwave exposure, a continuous recording of the thermogram was carried out using a Flir E-40 thermal imager. Based on thermograms, the dependence of temperature on time and energy flux density was obtained.

3 Results and discussion

The kinetics of PCM heating, as experiments have shown, is determined mainly by two factors: the absorbed power of microwave radiation P and the time of its exposure τ. A fractional factorial experiment was conducted, conducted at two levels of factor significance - energy flux density (EFD), equal to (45-50) x 104 μW/cm^2 and (10-12) x 104 μW/cm^2, as well as time, respectively 60 and 180 s.

Mathematical processing of the results of the implementation of the experimental plan made it possible to obtain an empirical model of the following form:

$$T = 32P^{0,3}\tau^{0,18}, \quad (1)$$

where P – absorbed power of microwave radiation, W; τ - microwave exposure time, s.

The dependence of the microwave heating temperature of a monolayer of carbon fiber-reinforced filaments, obtained by the calculation method according to (1), is presented in graphs in Figure 1.

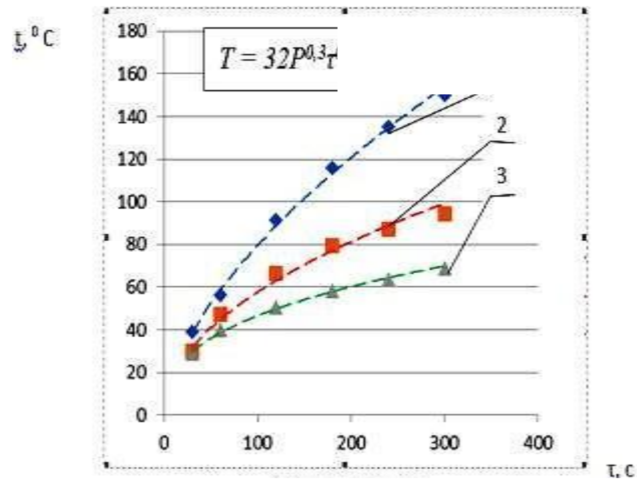

Fig. 1. Dependence of microwave heating temperature of monolayer samples on exposure time and absorbed radiation power: (1) PPE=(45-50)x104, (2) PPE=(17-18)x104, (3) PPE=(10-12)x104 μW/cm2.

It should be noted that the absorbed microwave power is more than 30% a significant factor compared to the exposure time, which is also confirmed by the assessment of these factors using the Student's test.

Based on the implemented experimental plan, the following parameters of the object of influence and the microwave mode were assigned. Sample dimensions L x b x l = 7.0 x 1.0 x l, where L – length, cm; b – width, cm; l – thickness (variable), cm; S = 7 cm^2 – irradiated surface area.

The energy flux density was taken equal to: PPE_1= 0.1 μW/cm^2, PPE_2=0.2 μW/cm^2, PPE_3=0.4 μW/cm^2.

The numerical experiment was carried out in accordance with the following algorithm:

- To perform calculations for l = 0.5 cm if PPE = 0.1 μW/cm^2 and λ = 12.2 cm for a number of combinations tg δ and ε (values are taken by dividing the material taken from the reference data into equal intervals);
- To repeat the calculations according to step 1 when PPE = 0.2 μW/cm^2;
- To repeat the calculations according to step 1 when PPE = 0.4 μW/cm^2;
- To repeat the calculations according to steps 1-3 when λ = 32.66 cm;
- To repeat the calculations according to steps 1-4 for each value l in the interval from 0.5 to 5.0 mm in increments of 0.5 mm.

Based on the calculation results, three-dimensional graphic images of the dependences of the absorbed power of microwave radiation on tan δ and ε were obtained at two values of electromagnetic wavelengths corresponding to higher and lower frequencies: 2450 MHz and

915 MHz, respectively. Dependences for smaller, medium and large values of sample thickness l are presented in Figures 3 and 4.

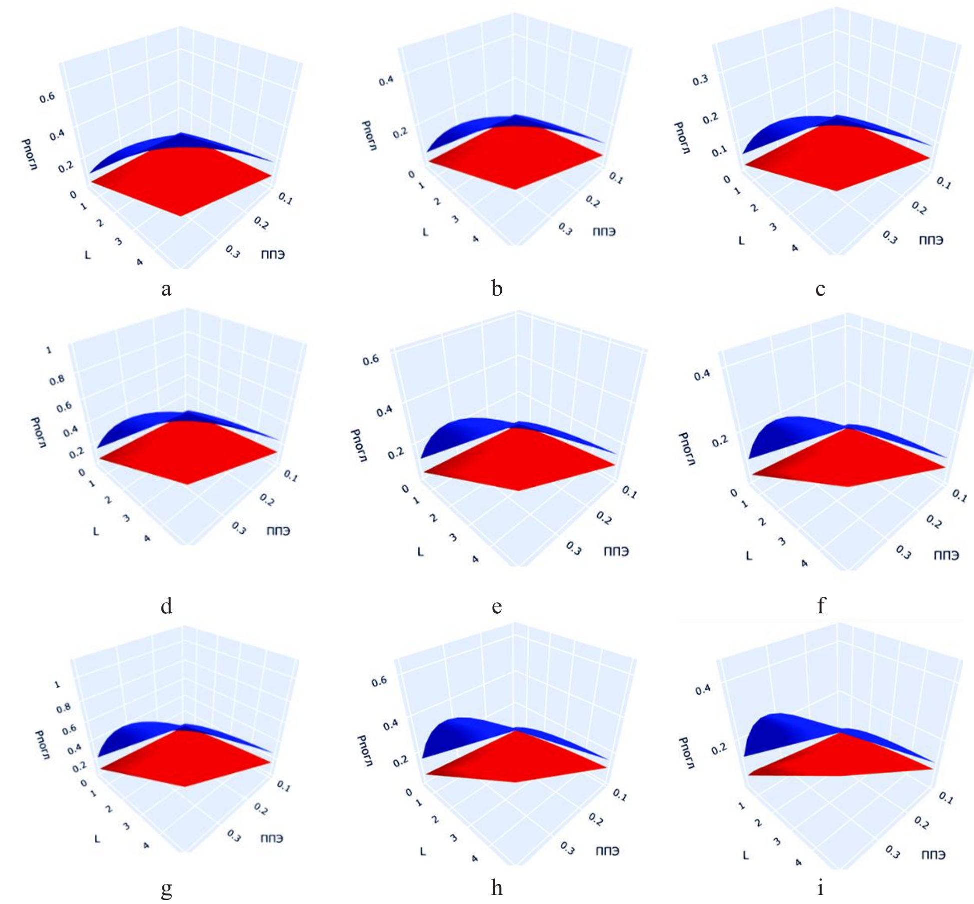

Fig. 3. Dependence of the absorbed power of microwave radiation on the energy flux density (EFD) and sample thickness L at a wavelength of 12.2 cm / frequency 2450 MHz (upper surface) and 32.66 cm / frequency 915 MHz (lower surface): *a* – ε = 3.3; tg δ = 0.17; *b* – ε = 7.15; tg δ = 0.17; *c* – ε = 11.0; tg δ = 0.17; d – ε = 3.3; tg δ = 0.3; e – ε = 7.15; tg δ = 0.3; f – ε = 11.0; tg δ = 0.3; g – ε = 3.3; tg δ = 0.42; h – ε = 7.15; tg δ = 0.42; i – ε = 11.0; tg δ = 0.42.

Analysis of Figure 3 leads to the following conclusions. An increase in the PES, as well as the thickness of the sample, leads to an increase in the absorbed microwave power, and, consequently, in accordance with (9), an increase in the temperature of the material. In this case, both factors affect the absorption of microwave power more intensely at a higher frequency (from the range under consideration). It is noted that power absorption at a frequency of 915 MHz occurs more smoothly and uniformly with increasing sample thickness. At a frequency of 2450 MHz, on the contrary, with small sample thicknesses, a sharp increase in absorption is observed, and then the dependence becomes flatter, which confirms the attenuation of short-wave processes in the volume of the material and is fully consistent with the known dependence of the penetration depth of a microwave electromagnetic wave on its length (frequency).

It is noted that an increase in tan δ expectedly increases the absorbed microwave power, while an increase in the dielectric constant causes it to decrease, which is associated with a lower characteristic impedance of the medium and a larger share of the power therefore passed through the material.

Accordingly, when choosing (developing) a binder for a composite filament reinforced with continuous fiber, it is necessary to consider the ratio of its main dielectric characteristics in order to achieve the greatest effect of subsequent strengthening microwave modification.

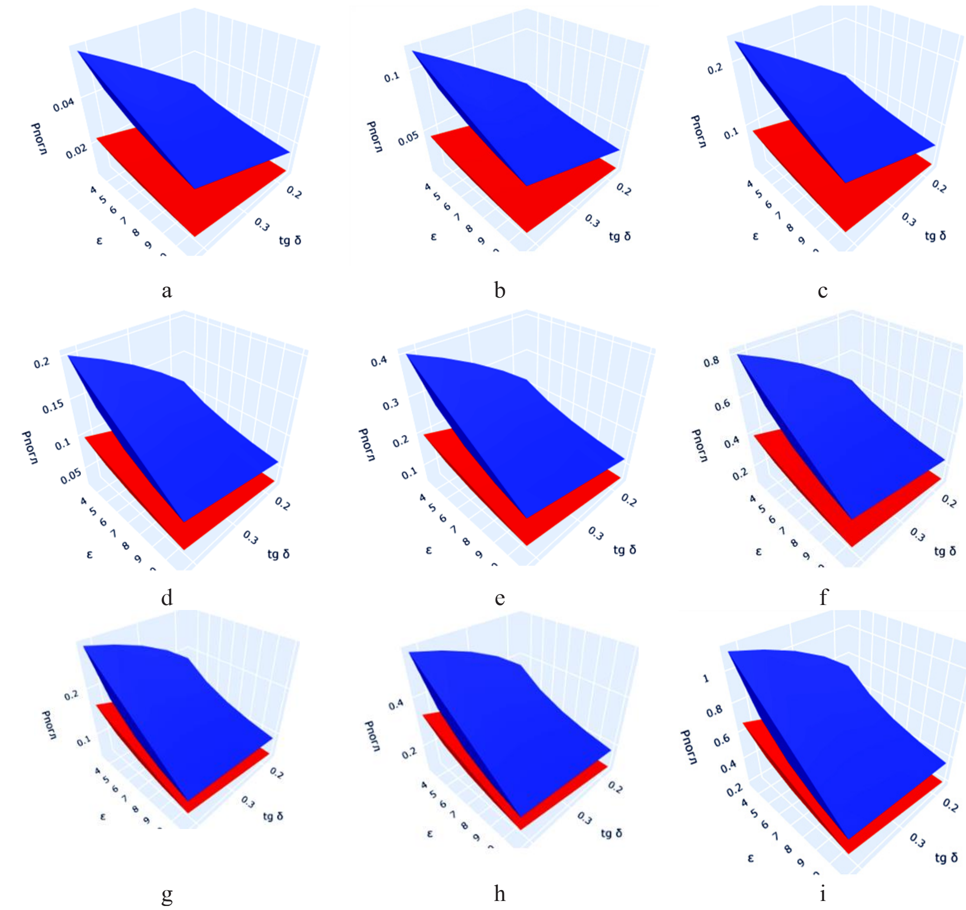

Fig. 4. Dependence of the absorbed power of microwave radiation on the dielectric loss tangent (tan δ) and dielectric constant (ε) at a wavelength of 12.2 cm / frequency 2450 MHz (upper surface) and 32.66 cm / frequency 915 MHz (lower surface): *a* – ППЭ=0.1; *l* = 0.5 mm; *b* – PPE=0.2; *l* = 0.5 mm; *c* – PPE=0.4; *l* = 0.5 mm; d – PPE=0.1; *l* = 2.5 mm; e – PPE=0.2; *l* = 2.5 mm; f – PPE=0.4; *l* = 2.5 mm; *f* – PPE=0.1; *l* = 5.0 mm; g – PPE=0.2; *l* = 5.0 mm; h – PPE=0.4; *l* = 5.0 mm.

When considering the dependence of the absorbed power of microwave radiation on the dielectric loss tangent (tan δ) and the dielectric constant of the material (ε), considering changes in the PPE and thickness of the sample, the following features of the effect of radiation at wavelengths of 12.2 cm and 32.66 cm are noted. On both wavelengths, the influence of tan δ is more significant at lower values of ε. At maximum values of ε and a radiation wavelength of 32.66 cm, the influence of tg δ looks almost insignificant, but at a wavelength of 12.2 cm this influence is more significant. At small values of ε, the dependence of the influence of tan δ on the thickness of the sample at a wavelength of 12.2 cm is significantly manifested. At small thicknesses (0.5-1.5 cm) in the range under consideration), an increase in tan δ leads to a monotonic increase in the absorbed microwave power radiation at different PES levels (Figure 2 a, b, c). At thicknesses of 2 cm or more, the dependence begins to show a decrease in the influence of tg δ and, finally, at maximum thicknesses (5 cm in the considered range) with a multiple increase in this parameter, the increase in absorbed power becomes several times less pronounced (Figure 2 f, g, h).

The foregoing indicates the possible significant uneven heating of samples of large thickness when exposed to short-wave microwave radiation, which can negatively affect the effects of modifying products formed from filaments reinforced with continuous carbon fiber. At the same time, as follows from the graphs, at a radiation wavelength of 32.66 cm, the increase in absorbed power with increasing tan δ remains monotonic over the entire range of PCM sample thicknesses under consideration.

4 Conclusion

An empirical relationship was obtained showing the influence of the power of the microwave electromagnetic field and the exposure time on the temperature of PCM formed from filaments reinforced with continuous carbon fiber. It has been established that microwave power is a significantly more significant parameter than exposure time.

Taking into account the microwave dependences known from thermodynamics, an analytical expression was obtained that relates the microwave radiation power absorbed by a material to its flux density and wavelength, the dielectric characteristics of the material and the size of the object of influence and allows one to predict by calculation the change in the properties of various PCMs using the appropriate operating parameters.

Through a numerical experiment using the obtained expression, graphical dependences were obtained, on the basis of which it was established that the influence of the dielectric properties of the material and the unevenness of power absorption across the thickness of the sample is more characteristic of a radiation wavelength of 12.2 cm (frequency 2450 MHz). Exposure at a wavelength of 32.66 cm provides 2 times greater uniformity of power absorption across the thickness, which can have a beneficial effect on the quality of modification of products. On the other hand, up to a certain sample thickness, the average value of absorbed radiation power with a longer wavelength turns out to be significantly less than with a shorter wavelength. Accordingly, this makes possible a practical recommendation for the use of long waves of microwave radiation with a higher energy density when it is necessary to modify the structure of products as uniformly as possible.

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