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Numerical Simulation of Microwave Heating of High-Energy Radio-Absorbing Composites

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Abstract

This study presents a novel approach to analyzing high-energy radio-absorbing composites (HRCs) by combining computational modeling and experimental measurements of temperature field distribution under microwave irradiation using a waveguide-based setup. Unlike previous studies that mainly focus on nanofillers or bulk dielectric properties, our work investigates the thermal response of a composite with a single macroscopic SiC sphere (d = 20 mm), embedded in epoxy resin (ED-20) and fluoroplastic (PTFE) matrices, both as an individual sphere and in grouped configurations. This setup enables direct observation and modeling of localized heat accumulation and dissipation pathways. Temperature distributions were examined in filler and at a boundary of filler-matrix at various distances from the filler–matrix interface under different power levels and thermal boundary conditions in ED-20 and PTFE. The results demonstrate that the ED-20 matrix with a 20 mm SiC filler offers an optimal balance between microwave energy absorption and thermal stability. However, at power inputs above 400 W and heating rates exceeding 10 °C/s, signs of thermal degradation and matrix damage were observed. These findings provide new insights for the design of thermally robust, structurally optimized HRCs with tunable electromagnetic performance.

Keywords: high-energy radio-absorbing materials; matrix structure; radio-absorbing filler; mathematical modeling; temperature fields; energy dissipation

1. Introduction

At present, for technological processes of acceleration, destruction, deformation there is a need to obtain materials with predictable functional properties that can be controlled by external influence [1–4]. Therefore, a present-day task is to develop new high-energy composites and technology of electrophysical influence on them to initiate functional activity associated with the release of energy. Such materials include a new class of high-energy radio-absorbing composites (HRCs) which combine the properties of radio-absorbing and high-energy materials [5–10].

Usually, radio-absorbing materials consist of an organic or inorganic matrix which contains an absorbing component in the form of powder, fibers, nano- and micro-fillers. Numerous studies have explored microwave-absorbing polymer composites using nanostructured fillers such as carbon nanotubes, graphene, and ferrite nanoparticles, which offer uniform absorption and lightweight structures [11–24]. However, these approaches often lack the ability to control localized heating and temperature gradients within the material bulk. Additionally, most experimental setups rely on thin-film geometries, making it difficult to analyze heat transfer behavior in larger volumes [25–29].

All known radio-absorbing materials can be divided into two large groups: applied materials (radio-absorbing coatings) and structural bulk materials [30]. Modern radio-absorbing materials are an integral part of devices and equipment in radio and electronic engineering, in particular, ultra-high frequency systems [31–35]. They have also found wide application in electromagnetic compatibility, protection from electromagnetic effects on biological objects, protection of radio electronic equipment [25,36–38]. The materials have good radio-absorbing properties only under certain conditions of external influence (temperature, frequency, etc.) [39]. Currently available radio-absorbing materials are capable of interacting with electromagnetic radiation and converting it into heat. The effect of a high-power electromagnetic radiation source on a radio-absorbing material leads to its heating. As a result, significant thermal stresses arise at the binder/filler boundary, which can lead to partial or complete destruction of the material. Destruction of radio-absorbing materials can be caused by the burnout of the binder (matrix) or the absorbing dispersed filler. Thus, the efficiency of absorption of electromagnetic radiation by the radio-absorbing material depends on the electrophysical properties of the matrix and filler. This will allow to obtain the specified functional properties of the radio-absorbing material in a wide range of frequencies and temperatures [25].

On the other hand, the above limitations for the radio-absorbing material can become the main important parameters for a new class of materials, i.e. high-energy radio-absorbing composites. Large thermal stresses in the composite during the dissipation of electromagnetic radiation in the filler can be used for special functional properties of HRCs. The functional properties of HRCs are the control of intense heat release in the composite, which is aimed at the processes of destruction, deformation, damage of the filler and/or matrix. Such composites can be used in mechanical engineering, materials science, mining, etc.

Thus, HRCs can be called high-energy materials, since energy in them is released as a result of chemical transformations under microwave exposure. HRCs can also be classified as radio-absorbing composites, since microwave energy is absorbed by the filler, but they differ from the latter in high temperature and microwave energy dissipation rate. Therefore, the HRC structure must have a polymer matrix into which fillers of various shapes capable of absorbing microwave energy with high functional activity are impregnated.

In this regard, to obtain specified functional properties of HRCs, general requirements for this class of materials are defined [40,41]:

- the matrix structure of the composite with a radio-absorbing filler of various shapes;
- the radio-absorbing filler must have a dielectric loss coefficient ε'' of at least 7.2, which will ensure its heating temperature from 500 °C and higher at a rate of at least 10 °C/s during the dissipation of microwave energy. Such conditions ensure the destruction and mechanical damage of the polymer matrix;
- the choice of the matrix material (binder) depends on the functional purpose of HRCs. For example, for initiating transformations, for high-temperature destruction of the polymer, for destruction (during the conversion of thermal energy into mechanical energy).

In this work, we propose an alternative design of high-energy radio-absorbing composites (HRCs) based on a macroscopic silicon carbide (SiC) filler (d = 20 mm) embedded in epoxy (ED-20) and fluoropolymer matrices. This configuration enables a detailed analysis of temperature distribution fields under microwave exposure and offers controllable energy dissipation behavior, relevant for high-performance thermal and electromagnetic applications. Although numerous studies have reported on the use of high-energy radio-absorbing composites based on polymer matrices filled with silicon carbide (SiC), most of them focus primarily on the macroscopic dielectric or shielding properties. In contrast, this study offers a novel approach by combining both computational and experimental analysis of temperature field distribution under microwave exposure. Specifically, a large single SiC filler (20 mm) embedded in an ED-20 epoxy matrix was investigated, allowing detailed insight into localized thermal behavior. Unlike previous studies, we examined not only the maximum temperature reached within the filler as a function of microwave power, but also the temperature at the matrix–filler interface, the heating rate, and the temperature gradients at specific distances (1, 2, and 4 mm) from the interface in both ED-20 and PTFE matrices. This level of spatial resolution in thermal field analysis under high-energy microwave irradiation has not been previously reported and provides important data for optimizing the thermal and structural design of radio-absorbing composites.

Thus, the aim of the scientific research is to substantiate the structure of high-energy radio-absorbing composites, which ensures the implementation of specified functional properties during the dissipation of microwave energy.

For this purpose, the following tasks were solved:

1. Research and optimization of the HRC structure to ensure specified functional properties.
2. Research on temperature distribution fields in HRCs during microwave heating based on mathematical models of electrodynamic and thermal processes.

Analysis of the temperature distribution field allows the identification of overheating zones and "cold spots", providing valuable insights for optimizing the composite formulation and ensuring uniform thermal performance.

Such analysis is especially critical for high-energy radio-absorbing composites (HRCs), given their active nature and potential safety risks under uncontrolled thermal conditions.

2. Materials and Methods

The problem of optimizing the HRC structure of and ensuring necessary parameters of microwave heating is solved step by step. First, the problem of choosing radio-absorbing fillers and their shape is solved. The best location of the filler in the volume of the polymer matrix is solved using numerical modeling of the energy dissipation pro——cess during microwave heating.

2.1. Justification and Selection of Materials

Epoxy resin and polytetrafluoroethylene (fluoroplastic) were used as the matrix material, which are of scientific and practical interest for creating the VRC structure. These polymers have different dielectric and thermal properties, so their use as a binder in the VRC will provide different heat transfer conditions at the filler/matrix interface. This, in turn, expands the possibilities for creating VRC structures with specified functional properties when studying the effect of microwave exposure modes on energy dissipation. The choice of epoxy compound as a polymer binder is justified by a number of reasons. Thus, epoxy resin is one of the main large-tonnage thermosetting binders for obtaining composites, while it has high electrical insulation and adhesive properties with a decomposition temperature in the temperature range of 350-450 C, as well as high wear resistance and chemical resistance, non-toxicity. Therefore, in this work, ED-20 epoxy resin was used as a polymer matrix, and polyethylenepolyamine was used as a hardener [42–44].

Fluoroplastic polymer grade F-4 has higher dielectric properties in contrast to epoxy resin, the value of tgδ = 0.0002, which allows it to be classified as a radio-transparent material. In addition, fluoroplastic is heat-resistant, begins to melt at 327 °C, but does not pass into a state of viscous flow, is a flame-retardant polymer, and has high resistance to water absorption. Fluoroplastic decomposes at temperatures above 415 °C. From this point of view, fluoroplastic is of scientific interest for its use as a polymer base for VRK. The criteria for selecting a radio-absorbing filler are, first of all, the permittivity ε^ and the tangent of the dielectric loss angle tgδ, as well as the dielectric loss coefficient ε^(δ), the reflection coefficient, the thermal conductivity coefficient, the specific heat capacity and the density of the material [45–49]. In addition, the filler material must be accessible and cheap. Therefore, it is advisable to use fillers such as silicon carbide, basalt, magnesite and chromite. Silicon carbide is a compound of silicon and carbon with the chemical formula SiC. The main characteristics of silicon carbide are hardness, wear resistance, chemical inertness and heat resistance [50].

Basalt is a rock of volcanic origin with the chemical composition: SiO_2 45-52%, Al_2O_3 15-18%, Fe_3O_4 8-15%, CaO 6-12%, MgO 5-7%, etc. The main characteristics of basalt are strength, plasticity

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during heat treatment, environmental friendliness, resistance to changes in humidity and temperature, wear resistance, fire resistance, resistance to aggressive environments [51,52].

Magnesite is a mineral with the chemical formula MgCO3. The main characteristics of magnesite are strength, fire resistance, environmental friendliness, chemical resistance, refractoriness, antifriction properties [53].

Chromite (chrome ore) is a rock with the chemical composition FeO×Cr2O3. The main characteristics of magnesite are strength, chemical resistance, fire resistance, environmental friendliness, low coefficient of thermal expansion, and anti-corrosion properties [54].

Thus, cheap, accessible materials were chosen for the filler with the best radio-absorbing properties: silicon carbide [55,56], basalt [52,57], magnesite [52,57] and chromite [54]. Then, the dielectric properties of composites with the specified fillers were experimentally determined.

2.2. Selection of Parameters of the Microwave Measuring Line

Waveguide methods which are based on direct measurement of the reflected and transmitted waves in the waveguide section with the object under study, have been widely used to measure dielectric parameters [58–61].

The microwave measuring line (Figure 1) is a rectangular waveguide, which is connected to coaxial-waveguide transitions on both sides. When a test microwave signal passes through the closed measuring line with the sample, the complex reflection (S11) and transmission (S21) coefficients are measured [62–64]. To increase the sensitivity of the measurements, it is necessary to place the sample in the region of the maximum electric field. To do this, it is necessary to determine the length of the microwave measuring line, the thickness of the sample and its location.

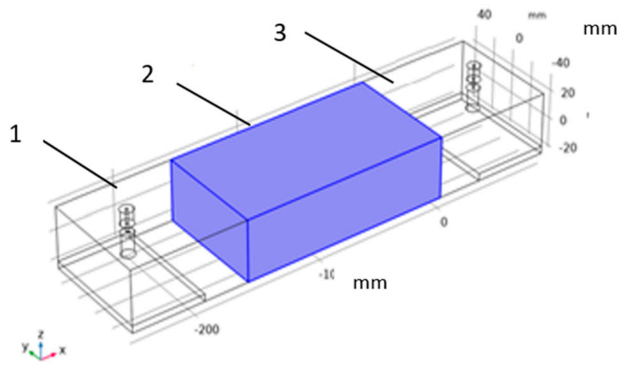

Figure 1. Geometric model of the microwave measuring line: 1 - coaxial-waveguide transition (S21); 2 - measuring line; 3 - coaxial-waveguide transition (S11).

To determine the geometry of the measuring microwave line, the distribution of the electromagnetic field strength was studied using mathematical simulation in the Comsol Multiphysics software environment. Since a coaxial-waveguide transition was used to carry out measurements, its mathematical model was built (Figure 2a) and the parameters of S11 were determined in the frequency range of 2.17-3.3 GHz (Figure 2b) to verify the 3D model.

At the next stage of simulation, the length l of the microwave measuring line was determined. For this purpose, the results of the electric field strength distribution in the microwave measuring line at a frequency of 2450 MHz were obtained (Figure 3).

During the mathematical simulation, a series of numerical calculations of the strength *E* distribution in the microwave measuring line was carried out. As a result, the optimal length *l* was determined, at which the maximum value of the strength *E* in the microwave measuring line is equidistant from the input and output ports of the coaxial-waveguide junctions S_{11} and S_{21}.

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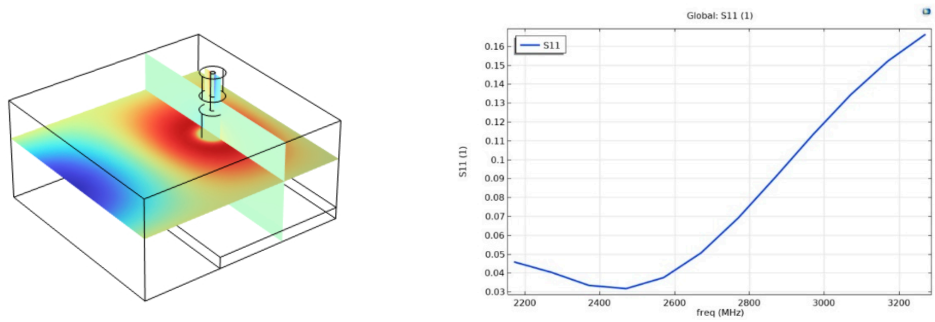

(a) (b)

Figure 2. Results of numerical simulation: a - distribution of electric field strength in the coaxial-waveguide junction; b - graph of the dependence of S11 (dB) on frequency (MHz).

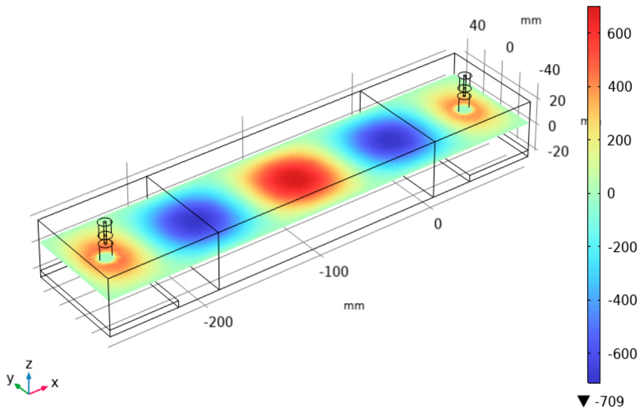

Figure 3. Distribution of electric field strength in the microwave measuring line.

According to the waveguide method a sample is placed in a waveguide section and complex scattering parameters of the two ports are measured using a vector network analyzer. This method requires the sample preparation. To reduce error in conducting experimental measurements of S parameters, the thickness of the object must be less than half the wavelength in the specified frequency range.

This thickness can be determined by the formula:

$$d = \frac{c}{\sqrt{\varepsilon} \cdot 2 f_{max}}$$

where c is the speed of light, fmax is the maximum frequency in the experiment, ε is the expected value of the permittivity.

Based on the results of mathematical simulation, we designed and made a microwave measuring line (Figure 4b) consisting of two arms (2), between which a measuring cell (3) is located, and the entire measuring line is connected to a coaxial-waveguide junction (1). The length of the arms and the measuring cell depends on the thickness of the sample being studied, while the total size of the measuring line should not exceed the calculated value L.

Before starting measuring S parameters, standard calibration of the vector network analyzer (model S5045, Planar LLC, Russia) and accurate measurement of the thickness of the sample under study, located in the measuring cell, were carried out [65,66]. Mathematical processing of the measurement results was carried out by the NRW (Nicolson-Ross-Weir) method for the material of thickness d, installed in the air waveguide line. According to the simulation results, it was found that the convergence of the microwave signals S11 and S21 of the calculated 3D model and the parameters measured using the vector network analyzer showed a convergence of 96%.

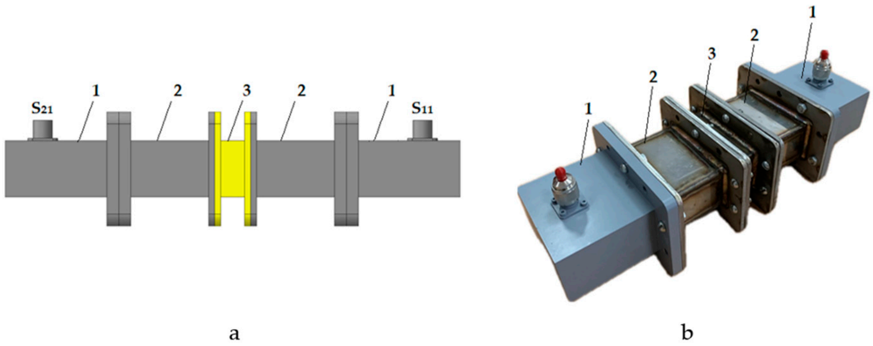

Figure 4. Microwave measuring line: a – 3D model, b – photo.

2.3. Measurements of Dielectric Properties

A well-known problem in the development of microwave installations is the lack of data on the electrophysical properties of objects due to their great diversity in the structure and composition of matrices, fillers and other additives (plasticizers, fire retardants, etc.). In this regard, the issue of measuring the dielectric properties of HRCs is relevant.

Table 1 shows the results of measurements of permittivity ε', and the dielectric loss tangent tanδ of composites with an epoxy matrix and various fillers using a vector network analyzer.

Table 1. Dielectric parameters of composites with an epoxy resin matrix with various absorbent fillers.

Composition of the cured composite (matrix + filler)	Dielectric loss tangent, tanδ	Permittivity, ε'
ED 20	0,029	3,5
ED 20 + silicon carbide	0,801	9,0
ED 20 + chromite	0,095	5,4
ED 20 + basalt	0,086	3,7
ED 20 + magnesite	0,115	6,1

The measurements show that the composites with chromite, basalt and magnesite fillers have close values of dielectric loss and permittivity. The composite with silicon carbide filler has a comparatively high value of tanδ = 0.801 and permittivity ε'= 9.0 and effectively interacts with the microwave electromagnetic field. Thus, it is proposed to use silicon carbide SiC which has better absorption properties and withstands higher heating temperatures without its chemical destruction as a filler in the composite.

2.4. Methods

One of the main objectives of the work is to study the process of microwave energy dissipation when exposing on HRCs. For this purpose, numerical simulation of the composite heating process in the microwave electromagnetic field was performed in the COMSOL Multiphysics® software environment. The microwave energy dissipation process was studied at a radiation power of 300 - 1200 W at a frequency of 2450 MHz in the installation with a traveling wave chamber. Microwave chambers of this type have the simplest design and differ from others in better matching with the generator, i.e. they have a higher efficiency. Microwave energy from a power source with a generator is fed to the working chamber via a transmission line, where the composite is heated (Figure 5). On the other hand, the chamber is connected to a matched load to reduce reflection and create a traveling wave effect.

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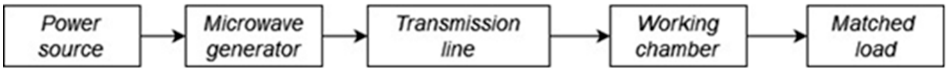

Figure 5. Structural diagram of the microwave installation.

The microwave traveling wave chamber is a section of a waveguide (Figure 6) with geometric dimensions a = 45 mm, b = 90 mm, l = 500 mm, in which the fundamental type of wave TE10 with a wave length λ = 16.7 cm is excited in the waveguide [31]. The location and size of the HRC sample in the microwave chamber are selected so that it is at the maximum strength E of the electric field of the electromagnetic wave. Then, the height of the HRC sample is 40 mm, the width is a, because it is limited by the dimensions of the waveguide, the length is chosen provided $\lambda/2$ (where λ is the wavelength).

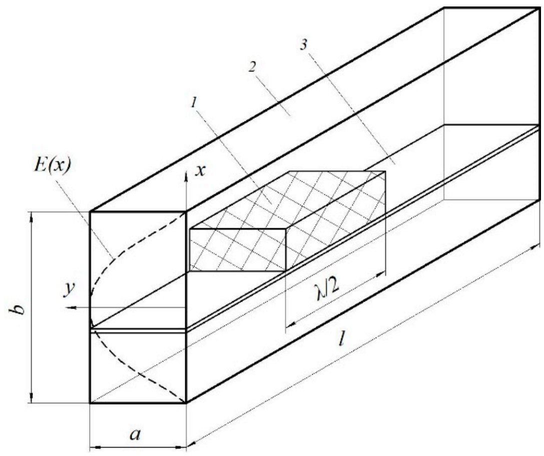

Figure 6. Scheme of the arrangement of the HRC sample (1) in the microwave traveling wave chamber (2) on the substrate (3), where E(x) is the electric field strength diagram.

2.5. Selection of the Shape and Size of the Filler

The structures of a polymer composite with a filler in the form of a single sphere (Figure 7a) and multiple spheres (Figure 7b) have been considered. The shape of the fillers can be different, but is conventionally assumed to be spherical. In this case, a filler of irregular geometry is approximated by spherical particles during simulating. The sizes of the silicon carbide absorber vary from 1 mm to 40 mm. The maximum filler size of 40 mm is limited by the dimensions of the microwave chamber.

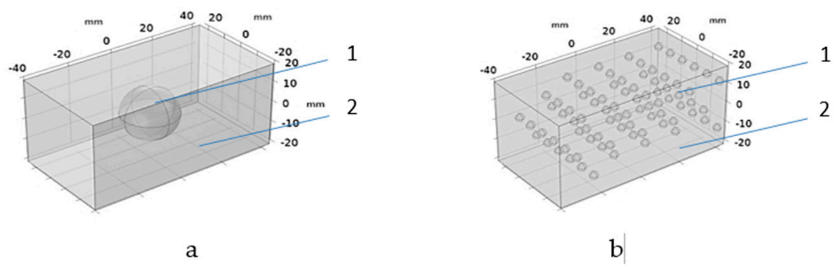

Figure 7. Diagram of the filler arrangement in the HRC matrix in the form of one sphere (a) and multiple spheres (b), where 1 is the filler, 2 is the matrix (binder).

The filler size was selected based on the results of numerical simulation of the microwave energy dissipation process of an absorbing sphere of different diameters (Table 2). The mathematical models describing the microwave heating processes of dielectrics were taken as a basis, namely the equations

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of electrodynamics (Maxwell's equations) and thermal conductivity (Fourier's thermal conductivity equation) with the corresponding initial and boundary conditions. Microwave heating was carried out at a power of P=800 W and time τ=60 s.

Table 2. Dependence of temperature throughout the volume of the filler sphere on its diameter.

Diameter of the filler sphere *d*, mm	Maximum temperature, °C	Average temperature, °C	Temperature gradient in the filler sphere, °C	Heating rate, °C/s
40	445	384	106	7.0
30	629	587	76	10.0
20	542	526	30	8.3
10	329	328	2.7	5.0
5	285	285	0.2	4.3

Thus, microwave heating of the filler in the form of one sphere with a diameter of d = 30 mm and d = 20 mm makes it possible to achieve high temperatures of 629 °C and 542 °C in the volume of the absorber, which are significantly higher than the destruction temperature of the HRC matrix (Figure 8).

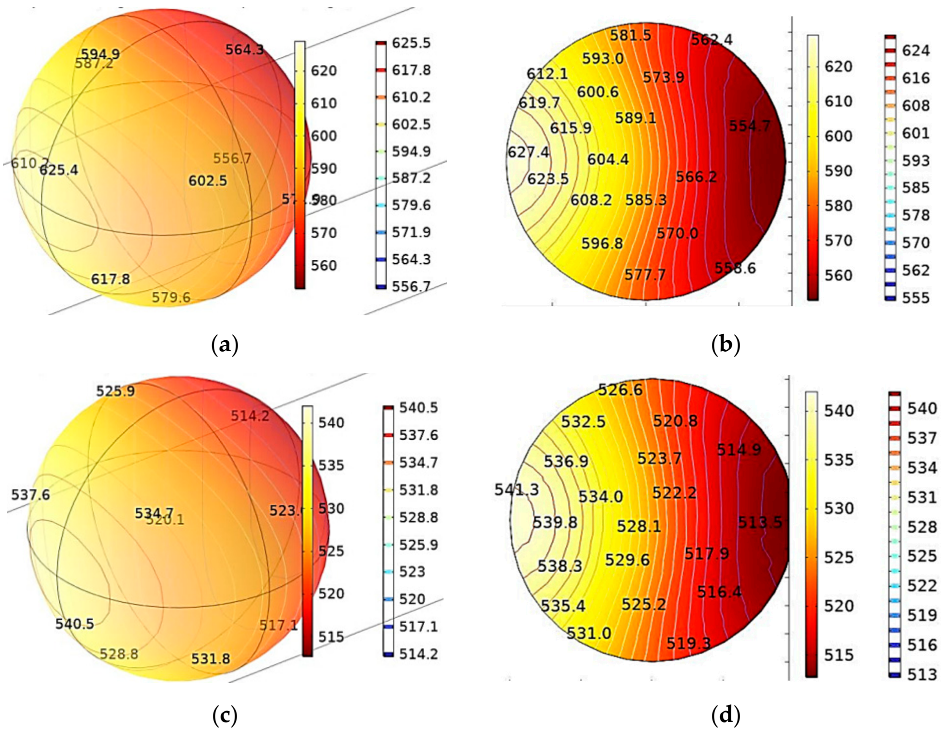

Figure 8. Temperature distribution fields of the filler with a diameter of *d* = 30 mm (a,b) and *d* = 20 mm (c,d) during microwave heating: (a,c) - in volume, (b,d) - in section.

It was found that the filler with a diameter of 20 mm provides a high heating rate of 8.3 °C/s at a maximum temperature difference of 30 °C in the sphere volume with a maximum dielectric loss tanδ = 1.1 (Figure 8). These results correspond to the general requirements for HRCs (see the introduction), therefore, further in the work, a composite with a filler of 20 mm in diameter is considered. If the filler diameter is less than 10 mm, the maximum temperature difference in the volume tends to zero (Table 3). Thus, a filler of less than 5 mm in diameter can be used in the composite to obtain a uniform temperature distribution in the HRC volume.

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Table 3. Influence of microwave radiation power on the temperature characteristics of the HRC with a polytetrafluoroethylene matrix (PTFE).

Microwave radiation power, W	Maximum temperature in the filler, °C	Maximum temperature at the boundary F/M*, °C	Filler heating rate, °C/s
300	304	302	4.6
600	588	584	9.3
900	872	866	14.1
1200	1156	1149	18.8

* F/M - phase boundary between filler and matrix.

3. Results

3.1. Study of the Microwave Energy Dissipation Process During Heating of the HRC with a Filler in the Form of a Sphere with a Diameter of d = 20 mm (Figure 7a)

To study the process of the microwave energy dissipation at different power levels, temperature distribution fields in the composite during its heating were obtained. HRCs with a matrix of polytetrafluoroethylene (PTFE) and epoxy resin (ED-20) were considered.

It was found that at microwave radiation power of 900 W or more, heating of the PTFE matrix (tanδ = 0.0003) above 500 C was observed at a filler heating rate of more than 10 C/s (Table 3). In this case, matrix damage occurred at a distance of l = 1 mm from the phase boundary between the filler and the matrix, since the temperature was 525 ○C (Table 4). Such conditions meet the requirements for HRCs.

Table 4. Influence of microwave power on temperature distribution in the polytetrafluoroethylene (PTFE) matrix at a distance (l) from the phase boundary between the filler and the matrix.

Microwave radiation power, W	Matrix temperature at *l* = 1 mm from the F/M phase boundary*, °C	Matrix temperature at *l* = 2 mm from the F/M phase boundary*, °C	Matrix temperature at *l* = 4 mm from the F/M phase boundary*, °C
300	184	118	42
600	360	205	86
900	525	300	105
1200	698	389	140

* F/M - phase boundary between filler and matrix.

The following results were obtained in studying the microwave energy dissipation process in the HRC with an epoxy resin matrix (ED-20) at different power levels. It was found that the heating of the ED-20 matrix (tanδ = 0.03) above 500 °C and the filler heating rate of more than 10 °C/s were observed at a microwave radiation power of 400 W and more (Table 5). In this case, the matrix destruction occurs at a power of 600 W at a distance of l = 1 mm from the phase boundary between the filler and the matrix, and at a power of 900 W and more at l = 2 mm (Table 6). Accordingly, the matrix temperature at a distance of l = 1 mm and l = 2 mm is above 600 °C. Such conditions meet the requirements for HRCs.

In order to obtain more contrasting temperature distribution fields in the volume of the HRC with matrices of PTFE (Figure 9a) and ED-20 (Figure 9b), a higher microwave power of 1200 W was used. It was found that the HRC with an ED-20 matrix heated up by 589 ○C higher compared to the PTFE matrix. This is explained by the fact that the epoxy resin has higher intrinsic dielectric losses than PTFE. Therefore, as a result of the microwave energy dissipation, the temperature is higher by 507 ○C at the F/M boundary and by 592 ○C in the filler in the HRC with an epoxy matrix compared to the PTFE matrix.

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Table 5. Influence of microwave radiation power on temperature characteristics of the HRK with an epoxy resin matrix (ED-20).

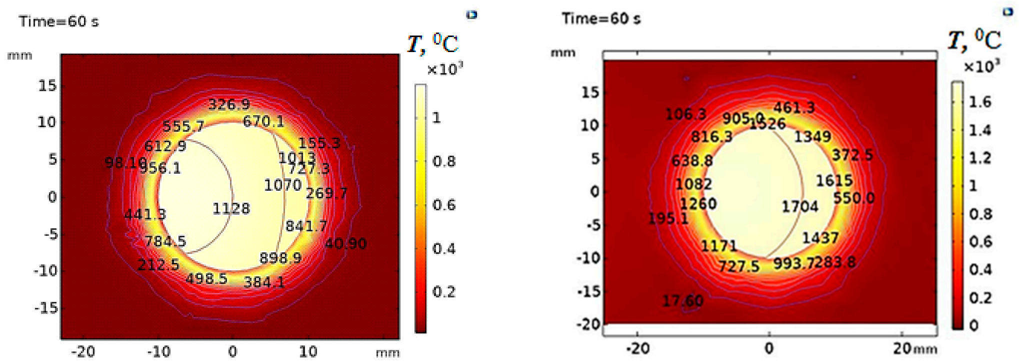
Microwave radiation power, W	Maximum temperature in the filler, °C	Maximum temperature at the boundary F/M*, °C	Filler heating rate, °C/s
300	452	450	7.1
400	648	644	10.8
600	884	879	14.3
900	1316	1309	21,5
1200	1748	1738	28.7

* F/M - phase boundary between filler and matrix.

Table 6. Influence of microwave radiation power on the temperature distribution in the epoxy resin matrix (ED-20) at a distance (l) from the phase boundary between the filler and the matrix.

Microwave radiation power, W	Matrix temperature at *l* = 1 mm from the F/M phase boundary*, °C	Matrix temperature at *l* = 2 mm from the F/M phase boundary*, °C	Matrix temperature at *l* = 4 mm from the F/M phase boundary*, °C
300	300	218	119
400	444	295	144
600	601	403	205
900	897	600	301
1200	1205	786	387

* F/M - phase boundary between filler and matrix.



(a) (b)

Figure 9. Temperature distribution fields at a microwave power of 1200 W in the cross-section of the HRC with a matrix: a – made of polytetrafluoroethylene (PTFE); b – made of ED-20 epoxy resin.

It was found that the damage of the ED-20 matrix as a result of microwave energy dissipation in the HRC was achieved at a lower power of 600 W than for the PTFE matrix. The temperature field dissipation in ED-20 is more than 2 mm from F/M at a high heating rate above 14.3 ОC/s. Thus, HRCs with an ED-20 matrix have higher dissipation rates of the high-energy radio-absorbing composite.

3.2. Study of the Process of Microwave Energy Dissipation During Heating of HRC with a Multiple Sphere Filler (Figure 7b)

Unlike the previous case, the intensity of heating of the HRC with a multiple sphere filler depends not only on the parameters of the microwave exposure, but also on the diameter of the filler and its distribution in the matrix. To study the process of microwave energy dissipation in the HRC with a multiple sphere filler, a geometric model was built (Figure 10), where the absorbing filler is uniformly distributed throughout the volume of the matrix made of ED-20 epoxy resin. In this case, the efficiency of the microwave energy dissipation process is determined not only by the maximum temperature in the volume of the composite, but also by the uniformity of the temperature field in the HRC, which depends on the thermophysical properties of the matrix material.

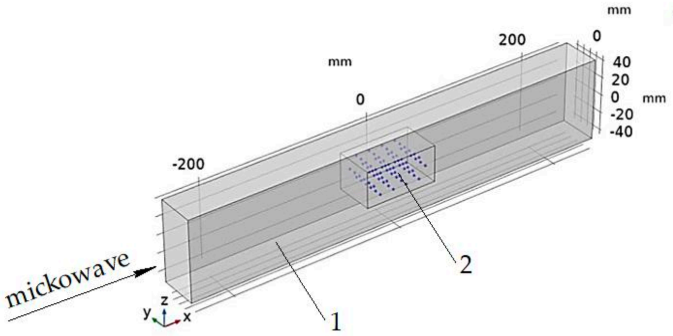
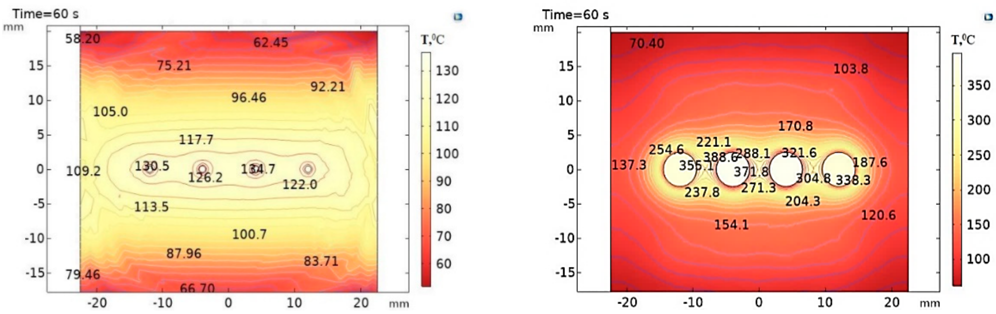


Figure 10. Geometric model of a microwave chamber (1) with a HRC sample (2) with a multiple sphere filler.

The results of the temperature field distribution in the HRC with a multiple sphere filler of different diameters were obtained. Table 7 presents the results for the maximum microwave power of 1200 W. It was found that the HRC sample with a multiple sphere filler with a diameter from 1 mm to 5 mm was heated in the microwave field less intensively than the HRC with a filler with one sphere. Thus, for spheres d = 5 mm, the average temperature in the matrix volume is 185 °C. Even at a microwave power of 1200 W, the temperature in the matrix does not reach 500 °C. Therefore, the use of a multiple sphere filler for HRCs is not advisable, since the matrix is not heated up to 500 °C and higher, therefore, destruction and intense damage of the matrix do not occur. This is explained by the equalization of the temperature field in the HRC volume due to more intensive heat exchange between the matrix and the multiple spheres of the filler (Figure 11).



(a) (b)

Figure 11. Temperature distribution in the volume of HRC with fillers d = 5 mm at a microwave power of 1200 W in sections: a – xz; b – yz.

Table 7. Dependence of the average temperature in HRC on the diameter of the filler spheres at a microwave power of 1200 W.

Filler sphere diameter, mm	Average temperature in the spheres of fillers, °C	Average temperature in the matrix volume, °C	Average temperature difference between filler and matrix, °C
1	148	121	27
2	198	125	73
3	238	136	102
4	372	157	215
5	482	185	297

4. Discussion and Novelty of the Approach in Thermal Engineering of Polymers

In this scientific study, within the framework of polymer engineering, the design of a new class of high-energy radio-absorbing composites (HRC) providing high intensity of microwave energy dissipation during heating is scientifically substantiated for the first time.

High-energy radio-absorbing composites (HRC) can be classified by some features as high-energy composites (HEC), in which energy is released as a result of chemical transformations. In turn, high-energy radio-absorbing composites (HEC) differ from HEC by a low level of thermal energy of microwave radiation absorption or its dissipation.

The article proposes a new approach to the classification of HRC, which combines two separate classifications (HEM and HEC), opening up broad opportunities for research in the field of interaction of microwave electromagnetic radiation with composites of various structures to implement their specified functional properties.

It has been established that high-energy radio-absorbing composites (HEC) are a new type of functional materials possessing the properties of a radio-absorbing and high-energy material, characterized by a high heating rate to temperatures from 500 to 2000 °C and higher, which provides such composites with specific areas of application as an initiating or primary substance for fuel ignition, for initiating the explosive transformation of other substances (for example, rocks), for solving special problems in dual-use devices (conversion of thermal energy into mechanical energy), in the processes of sintering or decomposition of materials capable of effectively absorbing microwave energy, etc.

General requirements for a new class of materials (HEC) have been formulated:

- matrix structure of a composite with a radio-absorbing filler;
- the radio-absorbing filler must have high dielectric properties, ensuring its heating temperature during microwave energy dissipation of at least 500 C, which is associated with the destruction temperature and mechanical destruction of the polymer matrix material;
- the radio-absorbing filler must ensure a high heating rate of at least 10 C /s during microwave energy dissipation;
- the choice of matrix material (binder) depends on the functional purpose of the VRC, for example, for initiating transformations (during ignition of rocket fuel), for high-temperature destruction of the polymer with the release of initiating substances, for destruction during the conversion of thermal energy into mechanical energy.

In this paper, for the first time in the framework of thermal engineering of polymers, the design of a new class of high-energy radio-absorbing composites is substantiated, providing a high intensity of microwave energy dissipation during heating. A new approach to the classification of VRCs is proposed, combining the features of high-energy materials and radio-absorbing composites. This opens up broad prospects for research in the field of interaction of microwave radiation with polymer matrices of various nature. A direct relationship is established between the dielectric properties of the matrix and the mechanisms of thermal destruction. The relationship is that thermal breakdown is a consequence of a decrease in the active resistance of the dielectric under the influence of heating in an electric field. This leads to an increase in the active current and a further increase in the heating of the dielectric up to its thermal destruction.

During the curing of thermosetting matrices, shrinkage occurs due to different coefficients of thermal expansion of the matrix and filler, which leads to the occurrence of residual internal stresses and the formation of voids in the area of the “matrix-filler” contact. Under the influence of a microwave electromagnetic field, the number of areas of contact interaction “matrix-filler” increases, due to which the connectivity of dispersed structures increases and the redistribution of the load in the material improves. When a microwave electromagnetic field acts on thermoplastic matrices, the thermoplastic polymer melts due to dielectric heating and the skin effect in areas adjacent to the carbon fibers. The thermoplastic, which has temporarily passed into a viscous-flowing state due to microcapillary effects enhanced by the wave component of the electromagnetic field, affects the filler, forming numerous microformations in it after hardening. At the same time, also due to the increase in the fluidity of the thermoplastic binder, there is a partial or complete filling of the voids in the monolayer remaining after the binder has hardened.

5. Conclusions

As a result of the simulation of the microwave heating process of the HRC with a silicon carbide filler in the form of one sphere and multiple spheres and matrices made of epoxy resin and fluoroplastic, temperature distribution fields were obtained under conditions of different heat transfer. This made it possible to optimize the HRC structure, which ensures the implementation of specified functional properties during the dissipation of microwave energy.

It has been established that the optimal structure of HRC is a composite with a radio-absorbing filler made of silicon carbide in the form of one sphere d = 20 mm based on an ED-20 matrix. This structure of the HRC provides such a temperature distribution between the matrix and the filler during the dissipation of microwave energy, which allows to implement the specified functional properties of the composite. In this case, destruction and mechanical damage of the matrix occur at a low level of microwave power of 400 W and a filler heating rate of more than 10 °C/s.

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