Microwave technology for modification of large-scale structures made of cured polymer composite materials

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Abstract. An analysis of the results of strengthening modification of cured polymer composite materials in a microwave electromagnetic field has been conducted. It has been demonstrated that the essential factor for achieving the desired effect is a combination of energy flux density and exposure time, ensuring the material is heated to a temperature of 60-80°C. The drawbacks of implementing microwave modification in beam-type chambers with sequentially arranged emitters have been noted. It has been proposed to perform strengthening microwave modification of large-sized products made of polymer composite materials by discretely moving (scanning) a horn emitter across the product surface with a delay at each scanning step. Experimental studies of the temperature field distribution on the irradiated surface have been carried out for various scanning schemes. A rational overlap value of the directional pattern areas with maximum energy flux density at each scanning step has been established at 25%, ensuring uniform heating of the product surface with a spread of no more than ±5°C, which consequently allows for the realization of a uniform distribution of physical and mechanical properties of the modified structure.

1 Introduction

Currently, both the application areas and production volumes of polymer composite materials (PCMs) are expanding in various industries [1]. This is primarily determined by the high specific strength of PCMs compared to metals and alloys, and the ability to form properties specified by operating conditions simultaneously with the product shaping [2-3]. Despite the growing interest in using thermoplastic polymers as binders in PCMs, such as super-structural ones with enhanced physical and mechanical properties that persist at high temperatures for extended periods, thermosetting polymers, particularly epoxy binders, retain predominant use. This is due to their low shrinkage relative to most fillers, sufficient thermal stability, and ability to provide high-quality impregnation [4-5]. All of these factors contribute to the use of such materials in strategically important areas - aviation, rocket and space, shipbuilding - which in turn determines increased requirements for the corresponding parts and structural elements.

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At the same time, PCMs, including those based on epoxy binders, have significant drawbacks. The most important of these include pronounced anisotropy of properties, low impact resistance compared to metals, low thermal conductivity, and increased creep. The shrinkage accompanying the curing process leads to the formation of microdefects in the material volume and the formation of residual stresses due to significantly different thermophysical characteristics of the components, which leads to a decrease in physical and mechanical properties. Another factor causing the formation of internal stresses is the final dimensional mechanical processing [6].

To reduce the disadvantages of PCMs at the preliminary stage of manufacture and during the curing process, various methods of chemical and physical modification of components are used [7,8]. Analysis of known technical solutions for modification and the influence of technological heredity on product properties shows that the modification of cured PCMs based on epoxy binders that have undergone a complete technological cycle becomes important. On the one hand, this eliminates the need to change the established technologies for synthesizing materials from serially produced components, and on the other hand, subsequent operations of the technological cycle will not affect the obtained modification result. The development of research in this direction is relevant for science and practice.

2 Problem statement

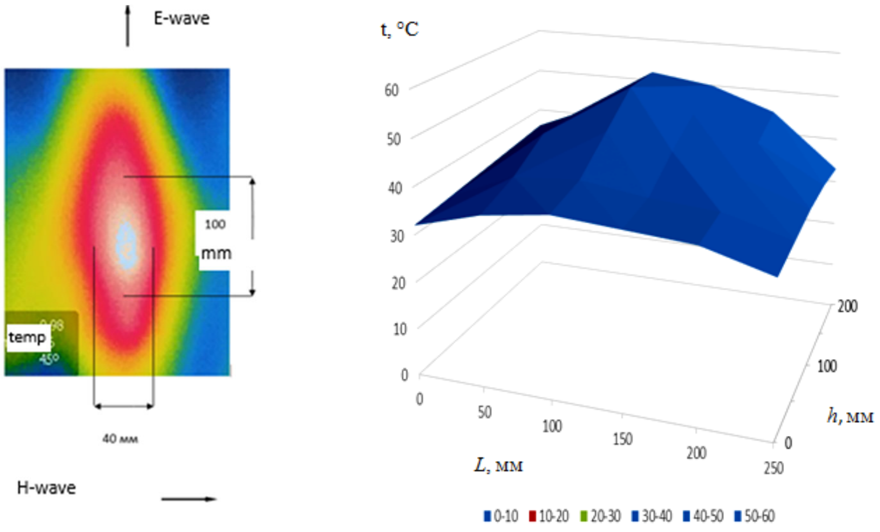
One of the promising directions for physical modification of polymer composite material (PCM) products in Russia and abroad is considered to be treatment in a super-high-frequency (SHF) electromagnetic field [9-11]. However, the conducted research and technical solutions primarily relate to methods of processing components and processes occurring during the curing stage of PCMs. The impact of SHF electromagnetic and other fields on the change in physical and mechanical properties of cured polymer composite materials, consisting of components with drastically different thermal and electrophysical properties, is mainly considered as a destructive natural or technogenic factor. The technological aspects of SHF exposure on cured PCM systems are insufficiently covered in scientific literature, which determines the need for additional research in the field of creating scientific foundations for the technological support of solving this problem.

At Yuri Gagarin State Technical University of Saratov, experimental studies were conducted from 2015 to 2024 on the influence of SHF treatment at a radiation frequency of 2450 MHz on the strength characteristics of cured carbon, glass, and organic plastics under static and dynamic loading. It was established that SHF exposure on fully formed samples of polymer composite material reinforced with carbon fibers, using rational modes, provides an increase in interlaminar shear stress by (16-18) % and elastic modulus by 14-20%. The possibility of obtaining certain effects during SHF exposure on cured PCMs has been confirmed by studies of foreign scientists [12,13].

Analysis of the results of the performed studies shows that one of the significant factors influencing the SHF electromagnetic field on the physical and mechanical properties of PCMs is the heating temperature of the material, which depends on the combined effect of SHF power flux density (absorbed radiation power, for which the integral surface temperature of the sample can be taken as an evaluation criterion) and processing time. It has been established that with various combinations of power flux density and exposure time of the SHF electromagnetic field, causing a similar temperature increase - up to 60...80 °C, a generally similar change in the strength of PCMs, particularly carbon fiber reinforced plastics, is provided in [14].

The authors in [14] have established that the mechanism of the strengthening effect of the SHF electromagnetic field on cured PCMs consists in the temporary transition of the binder into a highly elastic state, promoting the formation of an increased number of "matrix-fiber" contact areas, which ensures an increase in the interlaminar interaction area, an increase in crystallite sizes, and a decrease in porosity. The recorded integral temperatures at which the greatest strengthening effect is observed satisfactorily correspond to the temperature ranges of α-transition (70...170 °C) established by several researchers, accompanied by a decrease in the dynamic shear modulus, and the transition of the epoxy binder from a glassy to a highly elastic state (40...80 °C) [15-17].

However, these results were obtained on laboratory samples with irradiated surface dimensions of 70x30 mm, which is significantly smaller than the aperture surface of the horn radiator at a frequency of 2450 MHz (250x200 mm) and practically allows placing the object of exposure in the area of maximum energy flux density created by the radiation pattern. At the same time, real PCM structures have significantly larger dimensions, multiple times exceeding the area of the horn radiator aperture [2,3].



a *b*

Fig. 1. Thermogram (a) of heating of a carbon fiber plate (250x200 mm) placed at a distance of 200 mm from the plane of the horn emitter opening, and temperature distribution over the surface (b).

Figure 1b presents the temperature distribution on the surface of a carbon fiber composite plate measuring 250x200 mm, placed in a microwave electromagnetic field with an energy flux density of (17-18)x10^4 μW/cm^2. This distribution reveals that the temperature difference between the periphery and the center of the plate ranges from 20°C to 30°C. According to the relationships established in [14] and Figure 1, such temperature variation during microwave modification of cured polymer composite materials (PCM) corresponds to a change in three-point bending fracture stress of more than 14%, which is significant and may lead to dangerous defects and damage in PCM structures during operation. A temperature increase of 10° from the optimal value results in a 12% decrease in bending stress strength, while a 5° decrease leads to a 20% reduction. For interlaminar shear stress, the corresponding decreases are 9% and 12.3%, respectively.

Simultaneously, no significant change in properties is observed when the object's temperature deviates from the specified value within a range of ±5°C. As evident from the thermogram of the heating spot (Figure 2a), an area measuring 40x100 mm from the central axes (±20 mm along the X-axis and ±50 mm along the Y-axis) satisfies this condition.

Typically, microwave processing of large-scale objects is achieved through several sequentially installed microwave emitters, with the number determined by the horn aperture surface and the dimensions of the target object. A characteristic example is the method of thermal treatment of products made from dielectric materials with large volumes and surfaces, which employs a beam-type microwave chamber containing multiple radiating horn systems. The distance between these systems is chosen to ensure that the distribution of total surface power is as close to uniform as possible, given the antenna geometry and its distance from the surface of the object being processed [18].

For microwave processing of large-scale objects with curved surfaces, a beam-type chamber with unlimited volume is considered rational. In this setup, the horn emitter performs a complex controlled scanning motion, equidistant to the processed surface. An alternative scheme involves a reflector antenna with multiple horn emitters working on it, forming a radiation pattern corresponding to the object's contour in cross-section.

The scheme with equidistant emitter movement is characterized by complex kinematics with programmable movements of the horn along three coordinate axes and an additional oscillating motion. However, this scheme is universal, as modern CNC systems can implement any movement algorithm.

The scheme with a special radiation pattern has simple kinematics (rectilinear movement parallel to the longitudinal axis of the object). However, the radiating system is complex in construction. Additionally, forming a radiation pattern of the microwave that changes according to the object's contour may pose difficulties.

The aim of this work is to investigate the microwave effect on extended PCM objects and determine the rational step of discrete displacement of the horn emitter, ensuring minimal temperature differences between adjacent surface areas.

3 Materials and methods

The experiments utilized flat parallel carbon fiber reinforced plastic (CFRP) plates manufactured by LLC "Eurocomplekt" in Kaluga, with dimensions of 500x50x7 mm. Microwave modification was performed using an experimental mobile robotic complex equipped with a "Zhuk-2-02" emitter produced by LLC NPP "AgroEcoTech" in Obninsk, Kaluga region. The emitter provides a maximum incident microwave radiation power of 1000 W at a frequency of 2450 MHz. The experiment employed an energy flux density of (17-18)x10^4 μW/cm^2 and an exposure time of 2 minutes at each point on the object. Under these conditions, according to, maximum enhancement of the physical and mechanical properties of CFRP is achieved [14]. The robotic complex can move along the floor parallel to the target object for up to 5 m on wheels. Screw drives enable vertical movement of 250 mm and horizontal movement towards the object of 150 mm. Control is executed via a laptop using a pre-programmed routine through a cable connection.

The following microwave treatment schemes were implemented:

- Stationary emitter with the horn axis directed at the middle cross-section of the sample (exposure time 6 minutes).
- Discrete (step-by-step) treatment in three steps, with a 2-minute exposure at each step and emitter displacement exceeding the dimensions of the uniform heating area (step size set to 50 mm).
- Discrete (step-by-step) treatment in three steps, with a 2-minute exposure at each step and emitter displacement ensuring contact between uniform heating areas at each step, i.e., 40 mm.
- Discrete (step-by-step) treatment in three steps, with a 2-minute exposure at each step and emitter displacement ensuring a 10 mm (25%) overlap of uniform heating areas.

- Discrete (step-by-step) treatment in three steps, with a 2-minute exposure at each step and emitter displacement ensuring a 20 mm (50%) overlap of uniform heating areas.

During the treatment process, the surface temperature of the samples was monitored by continuous recording of thermograms in the frontal zone using a FLIR E40 (USA) thermal imaging camera. Prior to this, readings at reference points were calibrated using a Testo 830-T1 (Germany) pyrometer.

4 Results and discussion

The thermograms of the samples at the completion of the processing cycle are presented in Fig. 2, while the temperature distribution in the plane of the horn aperture, under the condition of 25% overlap of uniform heating areas, is shown in Fig. 3. The surface temperature of the sample under the investigated processing schemes is provided in Table 1.

Table 1. Temperature (°C) on the sample surface areas under different discrete microwave heating schemes.

Fixed horn	**50mm offset at each step (gap between areas)**	**40mm offset at each step (areas touching)**	**30 mm offset at each step (overlapping areas by 10 mm)**	**20 mm offset at each step (overlapping areas by 20 mm)**
From 45-50 to 136-150	From 35 to 65	From 45 to 85	From 75 to 85	From 120 to 130

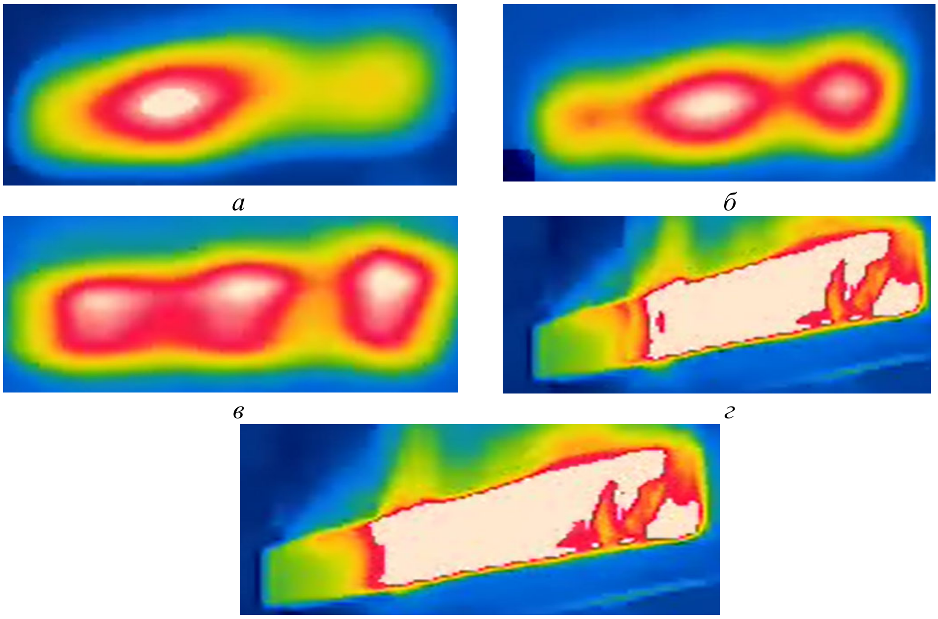


Fig. 2. Thermograms of a sample in the form of a carbon fiber strip; with a fixed horn (a), with a discrete displacement of the horn by 50 mm (b), with a discrete displacement of the horn by 40 mm (c), with a discrete displacement of the horn by 30 mm (d), with a discrete displacement of the horn by 20 mm (d).

It is evident that processing according to schemes 1-3 results in extremely uneven heating of the sample surface (with values ranging from 30 to 100 degrees). Processing according to schemes 4 and 5 leads to relatively uniform surface heating (with a range of 10 degrees). However, with significant overlap of the maximum impact areas, the temperature exceeds the recommended value by more than 1.5 times, which, according to Fig. 1, results in either the absence of the microwave modification effect or a decrease in breaking stresses due to matrix destruction [14]. Thus, for microwave modification of large-scale objects with scanning of the radiating horn, it can be considered rational to overlap the central areas of the radiation pattern at each step by 25% of its corresponding size. In the case of "Zhuk-2-02" type emitters, this corresponds to 10 mm in the horizontal direction and 25 mm in the vertical direction. The temperature distribution in this case over a surface equal to the horn aperture plane will be as shown in Fig. 3.

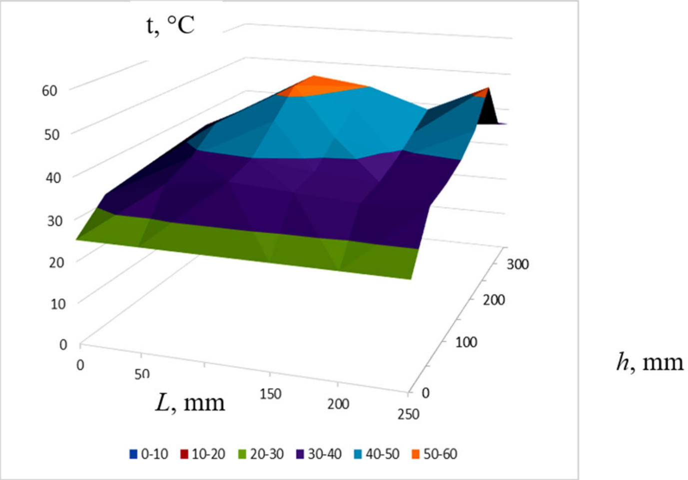


Fig. 3. Temperature distribution over a carbon fiber plate with dimensions equal to the aperture plane of the horn radiator when it is shifted with an overlap of the areas of maximum impact by 25%.

Thus, in the development of technological processes for microwave modification of structures made from polymer composite materials, the displacement of the horn antenna at each new step can be calculated using the following relationship:

$$L = 0{,}5(a - l),$$

where a is the length of the aperture plane of the horn radiator in the scanning direction; l is the width of the main lobe of the radiation pattern with a temperature difference not exceeding (8-10) °C.

Using the first scheme described above to determine the permissible curvature of the surface of the object being processed, which does not require equidistant movement of the horn radiator, experimental studies were conducted. During these studies, the change in the intensity of the microwave electromagnetic field impact was assessed by the temperature of the object of exposure.

To reveal the dependence of the thermal effect of the microwave electromagnetic field on the distance between the horn aperture plane and the surface of the object of exposure, two series of experimental studies were conducted:

The object of exposure, in the form of a carbon fiber panel produced by LLC "Eurocomplect", Kaluga, with dimensions of 250x250x5 mm, was placed at an angle to the vertical plane. The horn radiator was moved vertically for a distance of 180 mm with stops every 45 mm for 30 seconds. The radiator made one reciprocating pass, irradiating the sample. In the initial position of the radiator, the distance from its aperture plane to the opposite point of the panel was 160 mm. As it moved, the distance increased due to the inclination of the panel and reached 210 mm at the top point. Throughout the experiment, thermograms were taken along the trajectory of the horn movement using a thermal imager.

The radiator was moved, shifting it towards the panel by 10 mm at each step of vertical movement, so that the distance from the aperture plane to the panel at the top point after passing 5 steps was 210 - 5*10 = 160 mm. Thus, the initial distance, measured along the axis of the radiator from its aperture plane to the opposite point of the panel, remained unchanged.

The results are presented in Table 2.

Table 2. Change in the average temperature of the panel surface when using different emitter movement patterns.

Parameter	**Scheme 1 Rectilinear movement**	**Scheme 2 Movement with stepwise approach**
Average surface temperature, °C	38.9	37.4
Standard square deviation of temperature	5.04	1.5
Variation coefficient V, %	12.9	5.04
Variation range R, °C	13.3	4.3

A minor (4%) decrease in panel surface temperature is observed when using the second scheme. However, it is important to note the improvement in temperature uniformity, manifested by a reduction in the coefficient of variation by more than twofold. When implementing this processing scheme, it is necessary to consider that the heating temperature of the sample surface will also be determined by the radiation pattern of the *E*-wave emitter, which may vary among different microwave systems.

The modification of large-area structural elements made of fiber-reinforced carbon composite is carried out as follows. The general procedure for setup and operation execution remains constant for all processed objects. Differences pertain to the installation of products depending on their profile and dimensions, as well as programming the emitter movement trajectory in accordance with the schemes (Fig. 4).

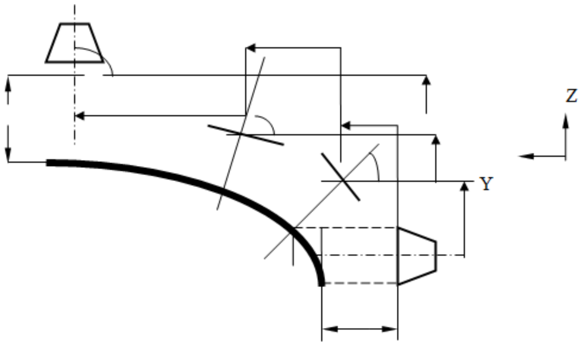


Fig. 4. Trajectory of movement of a horn emitter when processing a large-sized product with a curvilinear profile.

The temperature level is monitored using an electronic recording device: a pyrometer or thermal imager, whose readings are provided to the installation operator or input into the automated control system through an analog-to-digital converter. The antenna is moved to the next position after the surface temperature at the previous position reaches the specified level. Upon completion of the predetermined irradiation time, the emitter is moved to the next position according to a programmed trajectory following one of the schemes (Figure 7). For products with a curvilinear profile, additional coordinated movement in vertical and horizontal planes is performed simultaneously with horizontal displacement (depending on the scheme), including rotation of the emitter to ensure normal incidence of the electromagnetic wave front on the product surface. After traversing the entire length of the product, the emitter transitions to the next position, and the cycle repeats until the entire product surface is covered.

5 Conclusion

It is proposed to perform strengthening microwave modification of large-scale polymer composite material (PCM) products through discrete movement (scanning) of a horn emitter across the product surface, with a delay at each scanning step. The duration of this delay ensures heating of the irradiated area to an average temperature of 80°C, facilitating the transition of the binder to a highly elastic state, which allows for structural changes that contribute to improved physical and mechanical properties of the material.

Based on experimental studies conducted using an experimental microwave robotic complex, it has been demonstrated that the necessary conditions for uniform heating of the entire product surface to the α-transition temperature are created when the areas of the radiation pattern with maximum energy flux density overlap by 25%.

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