Multiscale modeling of the binder polymer composite materials heating using microwave radiation

P V Prosuntsov, S V Reznik, K V Mikhailovskii and E S Belenkov

Department “Rocket and Space Composite Structures” of the Bauman Moscow State Technical University, 5/1, 2-nd Baumanskaya str., 105005, Moscow, Russia

Abstract. The application of microwave heating to cure the binder in the workpiece made of polymer composite materials has a number of advantages over traditional methods, but requires a thorough justification of the process equipment characteristics. The technique of multiscale mathematical modeling of the temperature state of workpieces made of fiberglass, organic plastics and carbon plastics with a fundamentally different physics of heating the reinforcing filler is developed. At the microlevel the technique is used to determine the continual characteristics of the fiber-matrix system. At the macrolevel the technique opens the possibility of predicting the dynamics of the workpiece microwave heating, taking into account the thermophysical, optical and electrophysical characteristics of the materials, the of the chamber shape, the magnetrons location, quantity and individual power, and the spatial position and rotation of the workpiece. The distribution bounds of the electric field strength in microwave heating chambers with different arrangement of magnetrons and the rotation character of the cylindrical work are presented.

1. Introduction
An important stage in the manufacturing of constructions from polymer composite materials (PCM) is the curing of the binder. The quality of the finished constructions from the PCM depends on the uniformity of the workpiece preheating directly. It is difficult to obtain a uniform temperature field in the workpieces made of PCM due to the peculiarities of the arrangement of commercial process equipment - autoclaves, vacuum heat chambers, etc., in which the blanks are heated by convection or thermal emission from the surface, and the thermal inertia of the equipment.

The PCM heating by microwave radiation is of a volumetric nature, which gives undeniable advantages in the formation of homogeneous temperature fields in the workpieces and, besides, it can provide high productivity and energy efficiency [1-8] in the production of multi-element transformable space constructions [9-19]. The practical implementation of these advantages requires a reasonable choice of thermal processing regimes. For this purpose, it is necessary to determine the impact of the physicomechanical, thermophysical, optical, electrophysical characteristics of the PCM, as well as the conditions for heat elimination (convection, emission from the surface, thermal conductivity along the equipment elements) and spatial distribution of microwave radiation on the dynamics of heating (spatial and temporal temperature changes) and workpiece deformation.

2. The levels and results of multiscale modeling
In this paper, the process of curing a polymer binder of a PCM component billet under the action of microwave radiation was considered at two structural levels: a microlevel – a representative PCM element of volume in the form of a parallelepiped with a separate fiber and an epoxy matrix; and
macrolevel – chamber with magnetrons, where the workpiece of a hollow shape cylinder of finite dimensions is irradiated by microwaves.

2.1. Modeling at the microlevel

The tasks of the microlevel were solved using the ANSYS software package (HFSS module). The thermophysical, electrophysical and optical characteristics of the PCM individual components based on the epoxy binder with the glass or carbon fiber binder were used for the parametric modeling. It was considered that the reinforcing fiber had the shape of a cylinder with 10 μm diameter and 27 μm length when calculating the electromagnetic radiation propagation in a representative element of the PCM volume. The surrounding epoxy binder was presented as a parallelepiped with dimensions of 27 × 12 × 12 μm. A plane electromagnetic wave with amplitude of electric field intensity of 4.3 V/m and a frequency of 2.45 GHz was incident on the lateral face of the representative volume element, normal to the fiber axis.

It was found that for glass-reinforced plastic, the distribution of the microwave field strength practically does not change in the whole "fiber-binder" system (figure 1). It was necessary to take into account the occurrence of induced currents in an electrically conductive fiber during the modeling of microwave radiation absorption by carbon plastic. The analysis showed that the depth of the skin-layer would be about 40 μm and complete attenuation of the microwave radiation did not occur in the representative volume element. The results presented in figure 2 show that in this case the electric field strength in the fiber is substantially higher than in the matrix.

Within the framework of the representative volume model, the effective characteristics of coal and glass-reinforced plastic were determined. To find the effective permittivity of the "fiber-matrix" system medium, the Rayleigh method [20] was used. The remaining effective characteristics of the material were chosen from the principle of equality of volumetric heat release in heterogeneous "fiber-matrix" structure and homogenized structure. For the case of PCM with conductive fillers (carbon plastic), the filler gives main contribution to the heat release, and the heat release in the binder is significantly smaller, therefore the averaging process occurs mainly in terms of the heat release in the fiber. For the case of a nonconducting fiber, a mixture method was used in which the volumetric fractions of the filler and binder were taken into account.

Figure 1. The electric field distribution in the fiber (a) and the matrix (b) of fiberglass under the influence of microwave radiation, V/m.
Figure 2. The electric field strength distribution in the fiber (a) and the matrix (b) of carbon fiber-reinforced plastic under the influence of microwave radiation, V/m.

2.2. Modeling at the macrolevel
At the macrolevel, modeling of binder curing was carried out for a PCM billet in the form of a cylindrical tube 1200 mm length, 180 mm external diameter with 5 mm wall thickness, which was placed in a rectangular chamber with 400 mm height, 540 mm width and 1400 mm length with magnetrons with a radiation frequency 2.45 GHz and 2400 watt total power. Two variants of the magnetrons arrangement were considered: two 1200 watt sources on the side faces of the chamber upper surface and four sources on the longitudinal axis of the chamber upper surface (figure 3). The workpiece material was considered homogeneous and isotropic. It was assumed that the thermophysical characteristics of the material did not change during the entire exposure of microwave radiation. Radiation and convective heat exchange of the billet with the environment was taken into account.

The simulation results show that under the influence of intense microwave radiation standing waves are formed in the chamber, which leads to a significant unevenness of the electric field strength (figure 4). It can be seen that the picture of the field strength distribution with the use of four magnetrons becomes shallower, that reduces the temperature fall inside the workpiece. However it is
impossible to achieve an acceptable level of the temperature field uniformity only by introducing additional radiating elements. In addition, the increase of the radiating elements number complicates the installation design and increases the cost of workpiece processing.

In order to increase the uniformity of the workpiece heating, the variants of the microwave heating chamber were considered, in which the workpiece moves in the chamber in various ways. In the first case, it was considered that the heated billet was capable to perform rotational and translational motions with given velocities (figure 5).

![Figure 4](image_url)

**Figure 4.** The electric field strength distribution in the chamber: a) two magnetrons with a power of 1200 W each; b) - four magnetrons of 600 W each.
The analysis of the obtained results (figure 6) leads to the conclusion that the movement of the workpiece inside the chamber can almost halve the temperature gradients in comparison with the version of the fixed workpiece with the same replacement of radiation sources of equal power.

The final stage of the research was the simulation of thermal and electromagnetic processes in a large-sized chamber, allowing rotational motion of the workpiece around its transverse axis (figure 7). It is this option that provides the most uniform temperature distribution and is able to lead to a significant reduction in temperature gradients.
Figure 7. Distribution of the electric field strength when the workpiece rotates about the transverse axis in the microwave heating chamber, V/m: a) - angle of rotation 45 °; b) angle of rotation 90 °; c) - angle of rotation 135 °; d) - rotation angle 180 °.

3. Conclusion
The formation of homogeneous temperature fields in the workpieces made of PCM under microwave radiation is a complex multivariant spatial problem of heat exchange and electrodynamics. The developed technique of mathematical modeling is suitable for a reasonable choice of the quantity, location and power of radiation sources, as well as the location and method of moving the curable PCM workpiece in the microwave heating chamber.

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