Thermophysical processes models in composite workpieces processed by microwave radiation

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Abstract. The solution that improves energy effectiveness and polymer composite materials parts quality by means of microwave heating with polymer matrix curing is proposed. Thermal state analysis of workpiece for various layout configurations of microwave heating equipment was conducted. It was found that the most uniform heating is obtained inside the rectangular chamber while workpiece is rotating around the transverse axis.

1. Introduction
Polymer composite materials (PCM) are widely used to achieve high mass efficiency of the aerospace structures. Curing of polymer matrix by means of autoclave and vacuum furnaces is an important stage of manufacturing of such structures. The quality of finished PCM products directly depends on thermal field uniformity in a workpiece during heating and annealing. Recently significant benefits of microwave radiation for PCM curing have been educed. These benefits include reduction of production time, saving energy costs and products quality enhancement [1–8] for components of transformable spacecraft [9-19]. To choose optimal heat treatment regime, the effects of PCM characteristics and heat removal conditions on thermal field of a workpiece need to be defined. Also the dependence of power and space distribution of microwave radiation with heating dynamic and temperature pattern uniformity is required.

2. Modeling Processes for Representative Volume Element
The curing process of the polymer matrix should be considered at two structural levels: macrolevel – operating area of the equipment with magnetrons and microlevel – representative volume element (RVE) of PCM. As RVE the model of fiber surrounded by matrix was used for unidirectional carbon-glass-aramid reinforced plastics. It was stated that a plane electromagnetic wave falls on one of the parallelepipped side face and passes through the RVE without reflection and dissipation. Energy absorption of electromagnetic radiation in dielectric materials is accompanied with heat generation. The intensity of heat generation depends on the power and frequency of radiation. At the same time, electric currents are induced in conductive materials. Electromagnetic wave propagation in RSV of PCM is described by Maxwell equations. On fiber-matrix interface (note, that fiber is made of dielectric material) the following boundary conditions were formulated:

\[ H_{r1} = H_{r2} \]

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\[ E_{r1} = E_{r2}; \]
\[ D_{r1} = \frac{\varepsilon_1}{\varepsilon_2} D_{r2}; \]
\[ B_{r1} = \frac{\mu_1}{\mu_2} B_{r2}, \]

where \( \varepsilon_1 \) and \( \varepsilon_2 \) – dielectric constants of fiber and matrix; \( \mu_1 \) and \( \mu_2 \) – magnetic constants of fiber and matrix; \( \mathbf{H}_{r1} \) and \( \mathbf{H}_{r2} \) – tangent vectors of magnetic field strength of fiber and matrix, A/m; \( \mathbf{E}_{r1} \) and \( \mathbf{E}_{r2} \) – tangent vectors of electric field strength of fiber and matrix, V/m; \( \mathbf{D}_{r1} \) and \( \mathbf{D}_{r2} \) – tangent vectors of electric induction of fiber and matrix, C/m\(^2\); \( \mathbf{B}_{r1} \) and \( \mathbf{B}_{r2} \) – tangent vectors of magnetic induction of fiber and matrix, T.

Electric field strength is close to zero for electroconductive carbon fiber. Hence, in this case, the boundary conditions on fiber-matrix interface are described as the following:

\[ E_{r1} = 0; \]
\[ j_s = [\mathbf{H}_{r1}, n_0], \]

where \( n_0 \) – normal to conductive and dielectric medium; \( j_s \) – current density in conductor, A/m\(^2\).

The modeling was carried out in software package Ansys HFSS [20].

The analysis of the obtained results shows that in case of dielectric fiber the field distribution slightly changes in the fiber-matrix system (Figure 1). Modeling of electromagnetic processes in RVE of PCM with a conductive carbon fiber demonstrates that heat generation in the matrix is much less than in the fiber (Figure 2). Such significant difference can be explained by the occurrence of inducted currents in the carbon fiber. The conclusion is the following: in contrast to electromagnetic processes that take place in the PCM with dielectric fibers the major heat generation in PCM with conducting fibers occurs exactly in the fibers.

**Figure 1.** The electric field distribution for glass fiber (a) and epoxy matrix for RVE of glass fiber reinforced plastic (b), V/m.
3. Homogenization Procedure of PCM Characteristics

Homogenization procedure was conducted to represent the PCM as a homogeneous structure material during thermal and electromagnetic processes modeling in microwave heating equipment. To find effective dielectric constant of fiber-matrix system the first order Rayleigh scatter was used [21]:

\[
\Delta_{12} = \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + \varepsilon_2},
\]

where \( V \) – volume fraction of reinforcement in PCM. Mixture rule and condition of heat generation equality in heterogeneous and homogeneous material model were used to obtain other characteristics.

4. Modelling of Heating of PCM Workpiece

Hollow cylinder made of glass fiber reinforced plastic was used as a model for thermal and electromagnetic processes analysis in microwave radiation equipment. It was assumed that cylinder workpiece was placed in a chamber with one or more radiation sources and had the following sizes: outer radius – 90 mm, inner radius – 85 mm, length – 1200 mm. The workpiece material was considered as homogeneous and isotropic. Also heat energy on side faces of workpiece was dissipated by convective and radiation heat transfer with environment. Moreover, thermal and electromagnetic characteristics were assumed constant as well as ambient temperature during whole microwave radiation exposure period.

Heat transfer mathematical model for cylinder workpiece was formulated as following:

\[
c\rho \frac{\partial T(r,z,\phi,\tau)}{\partial \tau} = \frac{\partial}{\partial z} \left( \lambda \frac{\partial T(r,z,\phi,\tau)}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \lambda \frac{\partial T(r,z,\phi,\tau)}{\partial r} \right) + \frac{1}{r^2} \frac{\partial}{\partial \phi} \left( \lambda \frac{\partial T(r,z,\phi,\tau)}{\partial \phi} \right) + q_{mw},
\]

where \( c \) – specific heat, J/(kg·K); \( \rho \) – density, kg/m³; \( \lambda \) – thermal conductivity, W/(m·K); \( T \) – temperature, K; \( q_{mw} \) – microwave absorbed energy, Bt/m³; \( \tau \) – time, s; \( r, z, \phi \) – point location in a model volume in a cylindrical coordinate system.

Initial and boundary conditions were defined as follows:
\[ T(r, z, \phi, 0) = T_f; \]

\[ -\lambda \frac{\partial T}{\partial r} (R_1, z, \phi, \tau) = -\alpha_f \cdot (T \cdot (R_1, z, \phi, \tau) - T_f) - \varepsilon_w \cdot \sigma_0 \cdot (T^4(R_1, z, \phi, \tau) - T_f^4); \]

\[ -\lambda \frac{\partial T}{\partial r} (R_2, z, \phi, \tau) = -\alpha_f \cdot (T \cdot (R_2, z, \phi, \tau) - T_f) - \varepsilon_w \cdot \sigma_0 \cdot (T^4(R_2, z, \phi, \tau) - T_f^4), \]

where \( \varepsilon_w \) – material emissivity factor; \( \sigma_0 \) – Stefan-Boltzmann constant, W/(m\(^2\) K\(^4\)); \( T_f \) – ambient temperature, K; \( \alpha_f \) – heat transfer coefficient, W/(m\(^2\) K).

The modeling results obtained for a chamber equipped with a single 2.4 kW magnetron operating at a frequency 2.45 GHz indicate that electric field intensity distribution was extremely non-uniform (Figure 3). Consequently, the workpiece heating process is non-uniform as well. The difference in the electric field intensity in the order of 10\(^4\) V/m for workpiece local regions can cause local temperature gradients up to dozens degrees.

Figure 3. Electric field distribution in the operating area with single magnetron, V/m.

The chamber design with four microwave radiation power sources of 0.6 kW each was considered for reduction of non-uniform electric field intensity distribution. In this case, as follows from Figure 4, electric field intensity distribution becomes more uniform. Thus, temperature gradients inside the chamber decreases. Nevertheless, installation of additional radiation sources leads to complication of the equipment design and treatment cost increase. Therefore, other microwave radiation equipment versions were considered by varying operating area dimensions, magnetrons placement location and using different alternates of workpiece movement during processing. The preferred variant was the chamber with design that enables the workpiece rotation around the transverse axis during the microwave radiation process. Based on the obtained results it should be noted that more uniform electric field intensity distribution (Figure 5) and workpiece temperatures were acquired (Figure 6). Consequently, the workpiece rotation around the transverse axis can lead to a significant increase of temperature uniformity distribution and, accordingly, to increase the quality of the PCM product.
Figure 4. Electric field distribution in the operating area with four magnetrons, V/m.

Figure 5. Distribution of the electric field strength when the workpiece rotates around the transverse axis in the microwave heating chamber, V/m: (a) angle of rotation 45 °C; (b) angle of rotation 90 °C; (c) angle of rotation 135 °C; (d) -rotation angle 180 °C.
**Figure 6.** Temperature state of workpiece rotating around the transverse axis in microwave radiation installation, °C: (a) temperature field at the moment 30 s; (b) time dependence of the maximum workpiece temperature.

5. **Conclusions**

Physical and mathematical models of the electromagnetic radiation transfer and the heating of RSV of PCM were developed. These models take into account electromagnetic field distribution in each separate component during microwave radiation exposure and allow to make the analysis of thermal state of PCM RSV. The homogenization methods for RSV of PCM characteristics were proposed for material effective properties analysis and subsequent application on macrolevel model. Physical and mathematical models for electromagnetic radiation transfer and heating of a cylinder workpiece made of glass fiber reinforced plastic were developed. These models consider the non-uniform distribution of the electromagnetic field in the processed workpiece of PCM part during microwave radiation exposure. Modeling of the workpiece temperature state for various design-layout schemes of the microwave heating installation was carried out. Analysis of the results showed that the most uniform heating is achieved in a chamber equipped with moving elements, ensuring the rotation of the workpiece around its transverse axis.

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