SIMULATIONS AND EXPERIMENTS ON THE EFFECTS OF MILLIMETER-WAVE HEATING OF ORTHOTROPIC AND ANISOTROPIC CFRP COMPOSITES

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ABSTRACT

This paper presents both theoretical and experimental work on the heating of carbon fiber reinforced plastic (CFRP) by millimeter (mm)-waves. In contrary to the standard methods using autoclaves, samples are cured using a 30 GHz gyrotron furnace. Heating experiments, showing the strong influence of the fiber orientation in the samples on their heating behavior are performed with cured samples in the same gyrotron system they were obtained from. Using a finite differences time domain (FDTD) numerical model the heating processes of CFRP slabs are modeled and discussed with the experiments.

High interest exists in industrial use of carbon fiber reinforced plastic (CFRP) composite materials due to their unique combination of characteristic mechanical features. They exhibit high specific tensile and flexural strengths, and high moduli as well as good vibration stability which make them a suitable material for structural components in transportation systems. The main obstacle for widespread applications are high manufacturing costs, a major cause being high curing temperatures between 100 and 200 °C. Reaching them by conventional processing in electro-thermal or gas furnaces is a time and energy consuming procedure. For materials with a high electrical conductivity, like CFRP, the use of microwaves for processing has been reported to offer benefits [1, 2] such as selective heating of composites, high heating rates, reduction of processing time and lower energy consumption as well as better process control. This work presents theoretical and experimental research in the heating and processing of CFRP by millimeter (mm)-waves in gyrotron furnaces. For mm-waves, very strong coupling occurs due to the dielectric properties of CFRP, which enables heating of workpieces directly and homogeneously.

Fabrication experiments were performed by stacking up to 16 layers of unidirectional preimpregnated CFRP in an orthogonal layup. These samples were placed on aluminum plates or on a

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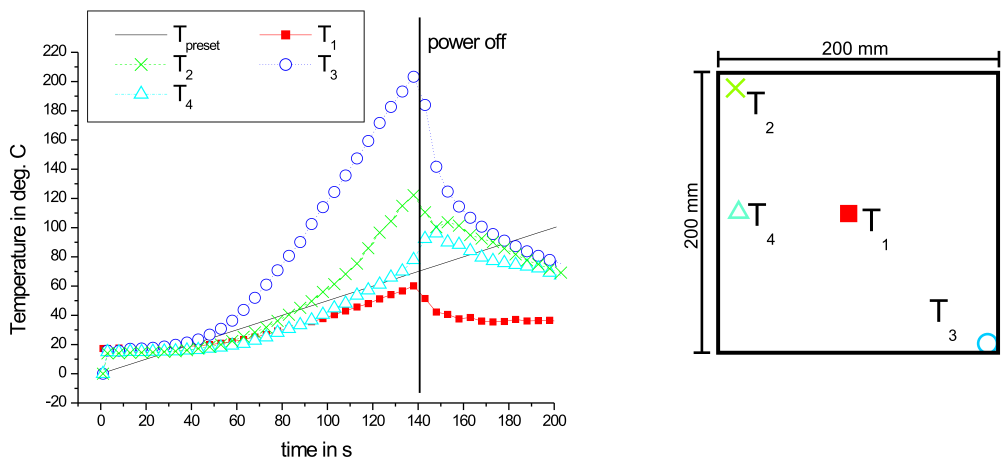
steel framed PTFE plate, covered by a mm-wave transparent polymer foil and sealed against the ambient atmosphere. This setup was established as a modification of the differential pressure resin transfer molding (DP-RTM [3]) to adapt this technique to the requirements of millimeter-wave heating. It was evacuated with a vacuum pump for the time of the heating process and placed in a hexagonal conducting structure used to generate a homogeneous field distribution [4] within the gyrotron applicator. Processes with heating rates of up to 15 K/min, processing times of approx. 30 min and process temperatures of up to 150 °C were implemented. Thermocouples in direct contact with the samples and at several positions on the polymer foil were used to determine the temperature distribution and control the process. Using the steel/PTFE-frame, the resulting cured sample plates with multi-axial carbon weave display a comparative quality to conventionally processed material. These experiments and former results of experimental fabrication [5] also demonstrated the importance of knowing the heating mechanisms of CFRP in mm-wave fields to secure accurate process control by adaption of the temperature measurement.



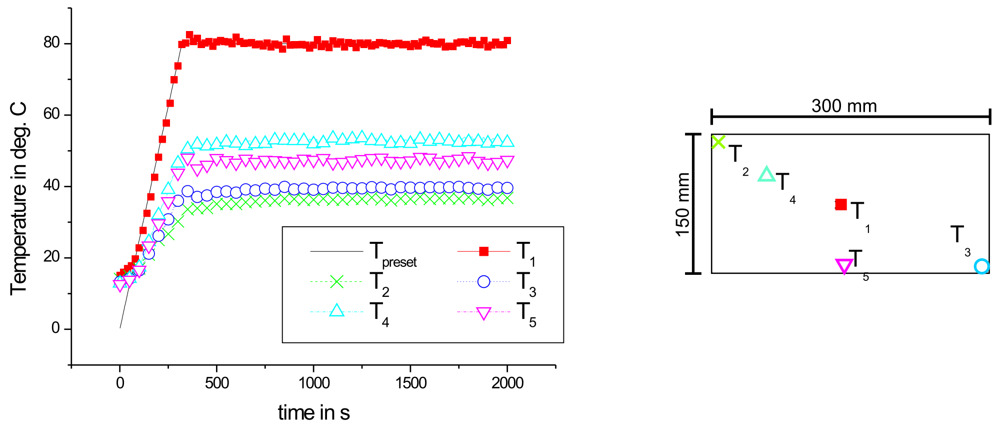
(a) measured temperatures

(b) points of measurement on slab

Figure 1. Measured temperatures in a process of a $200\ \mathrm{mm} \times 200\ \mathrm{mm} \times 5\ \mathrm{mm}$ sample, controlled by the sample temperature in the middle of the top surface with a heating rate of 30 K/min

To allow a better understanding of the production of these cured samples, heating experiments were carried out with cured CFRP samples and stacked CFRP single-layers. Samples with roughly the same geometry as in the curing experiments and multi-layered multi- or unidirectionally oriented fibers were heated up to approx. 100 °C by mm-waves. The temperature distribution was measured with thermocouples and IR imaging. The distributions of these two sample types differed strongly after the same heating process. In the experiments with multi-directional samples a strong (s. fig. 1) temperature gradient between hot edges and a cooler center could be observed. In the case of the unidirectional samples (s. fig. 2), the temperature gradient was overall lower but inverted and higher temperatures could be observed in the center of the samples.

These processes were also simulated with the THESIS 3D [6] simulation tool. The temperature problem of microwave heating can be numerically decoupled from the calculations of the electromagnetic field because of the very small time scale of the resonant field in comparison to the thermal diffusion. THESIS 3D uses a FDTD numerical model for the solution of the nonlinear heat conduction equation in geometries of rectangular parallelepipeds.



(a) measured temperatures

(b) points of measurement on slab

Figure 2. Measured temperatures in a process of a $300 \text{ mm} \times 150 \text{ mm} \times 2 \text{ mm}$ sample, controlled by the sample temperature in the middle of the top surface with a heating rate of 15 K/min

The solution was derived emanating from isotropic heat conductivity and dielectric parameters (the general thermal conductivity $\widehat{\sigma}_T(\vec{x}, T)$ at the temperature $T(\vec{x}, t)$, the heat capacity $c_V(\vec{x}, T)$ and the density $\rho(\vec{x}, T)$ of the material, $\vec{x}$ denotes space, t time):

$$c_V(\vec{x}, T)\rho(\vec{x}, T)\frac{\partial}{\partial t}T(\vec{x}, t) - \nabla\left(\widehat{\sigma}_T(\vec{x}, T)\nabla T(\vec{x}, t)\right) = p_{\text{eff}}(\vec{x}, t), \tag{1}$$

This determines the temperature fields for the material. In case of e.g. electromagnetic heating of a substrate, the effective power density is the sum of the terms

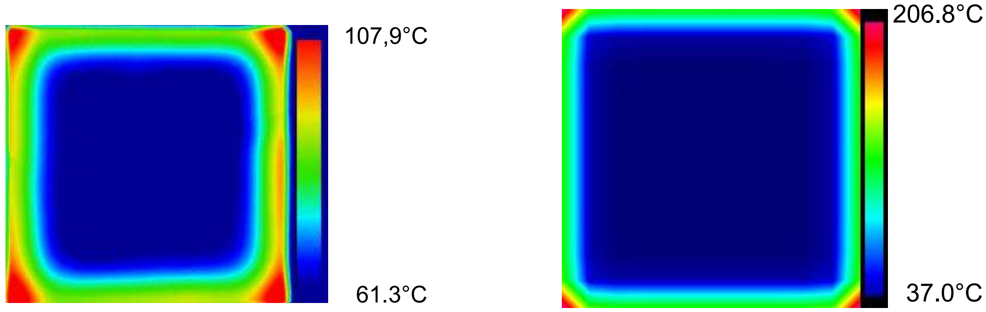
$$p_{\text{eff}}(\vec{x}, t) = p_{\text{conv}}(\vec{x}, t) + p_{\text{cond}}(\vec{x}, t) + p_{\text{rad}}(\vec{x}, t) + p_{\text{elec}}(\vec{x}, t) + p_{\text{chem}}(\vec{x}, t). \tag{2}$$

They describe the convection (at the edges of the material), conduction and radiation heat losses or gains, as well as the electromagnetic power input and the thermal influences of e.g. exothermal chemical curing reactions. For the rather simple geometries in our case, an analytic field solution was used to determine the electromagnetic power density $p_{\text{elec}}(\vec{x}, t)$. In the case of multi-directional (so called orthotropic) material, the results of isotropic calculations were in accordance with the experiments if averaging of the anisotropic dielectric and thermodynamic properties over the layers was assumed (s. fig. 3).

This method cannot be used for the unidirectional samples where the anisotropic properties of the material cannot be neglected. An implementation of the anisotropic heat conduction of the sample considers the tensor nature of the thermal conductivity:

$$\widehat{\sigma}'_T = \begin{pmatrix} \sigma_{T\parallel} & 0 & 0 \\ 0 & \sigma_{T\perp} & 0 \\ 0 & 0 & \sigma_{T\overline{\perp}} \end{pmatrix}. \tag{3}$$

$\sigma_{T\parallel}$ is the value parallel to fiber, $\sigma_{T\perp}$ is the value within fiber layer and perpendicular to fiber, $\sigma_{T\overline{\perp}}$ is the value perpendicular to both (and it is usually the same as $\sigma_{T\perp}$). Applying this modification, the results of the calculations indicated that they do not suffice to completely explain experimental behavior and that the anisotropy of the electrical conductivity and dielectric



(a) IR image of experiment (approx. 20 s without mm-wave power)

(b) simulated temperature profile

Figure 3. Infrared image (a) and simulated temperature profile (b) of an $200\ \mathrm{mm} \times 200\ \mathrm{mm} \times 5\ \mathrm{mm}$ sample

properties of unidirectional CFRP has to be considered as well. Currently, this issue is addressed with an adapted model for the interaction with the electromagnetic field to obtain a simulation code for unidirectional samples. A model limited to the case of material boundaries which are oriented alongside or perpendicular to the fiber direction could be implemented and first calculations have been done which better describe the experimental results. With this simulation tool, in combination with thermodynamic modeling of curing reactions of the resin, we hope to obtain further insights in the material processing and an enhancement of the complete process.

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