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

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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 application is high manufacturing costs related to curing temperatures between 100 and 200°C. To reach 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] 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 good 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 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 [2]) 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 [3] 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 have a comparative quality to conventionally processed material. These experiments and former results of experimental fabrication [4] 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.

To allow a better understanding of the production of these cured samples, heating experiments were made 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 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 temperature gradient between hot edges and a cooler center could be observed. In the case of the unidirectional samples, 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 [5] simulation tool. It allows the numerical solution of the nonlinear heat conduction equation using a finite differences time domain (FDTD) numerical model under the influence of the electromagnetic heating field which is modeled based on an analytical field solution. 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.

This method cannot be used for the unidirectional samples where the anisotropic properties of the material can not be neglected. An implementation of the anisotropic heat conduction of the sample indicated that it is not possible to explain the experimental behavior with this alone and that the anisotropy of the electrical conductivity and dielectric properties of unidirectional CFRP has to be considered. Currently this issue is addressed with an adapted model for the interaction with the electromagnetic field to obtain a simulation code for unidirectional samples. 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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