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A temperature distribution prediction model of carbon fiber reinforced composites during microwave cure

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ABSTRACT

Compared with the conventional thermal curing, the microwave can cure the composites much faster and generate more even temperature distribution. A model was established in this study to investigate the heat transfer and temperature distribution in the composites during the microwave cure. The numerical model considered the electromagnetic heating, the attenuation of microwave propagating in the material, the exothermal reaction of curing, the heat transfer in anisotropic composite laminates, the electromagnetic and thermal influence of the mold and the bagging materials at the boundaries. And the material properties of macroscopic model were calculated from microscopic model by multiscale homogenization method without costly measurements. The model was used to analyze a case study, and the simulation results showed good agreement with the experimental outcomes.

1. Introduction

The carbon fiber reinforced polymer composites have been increasingly utilized in various areas of engineering. The current manufacturing methods cure composite materials mainly by thermal conductance, like autoclave and RTM (Resin Transfer Moulding) processing. However, these methods suffer from the problems of long manufacturing time and low efficiency, and better methods of curing composites are demanded by the industry (Li et al., 2014a).

The microwave curing technology is a relatively new methodology of curing the composites, and it has the advantages of fast curing and low energy consumption (Lee and Springer, 1984). The major advantages of the microwave processing are derived from its volumetric heating ability that allows for more quick and uniform curing of composites (Thostenson and Chou, 1999). Li et al. (2014b) pointed out that the uniformity of temperature distribution in the microwave curing process has significant effects on the quality of the cured parts. Many researches investigated the temperature distribution in the conventional curing processes, like the temperature distribution in the thick laminates (Guo et al., 2005), the simulation and improvement of temperature distribution of composites (Xie et al., 2013) and the process induced stresses (Ruiz and Trochu, 2005) during the autoclave cure. It is crucial to establish appropriate model to analyze the thermal phenomena in the microwave curing process for its physical model is quite different from the mere heat conduction and convection in those conventional curing processes. However, there have been quite few researches done to address this problem. Many researches made theoretical and qualitative deductions that the volumetric heating of the composites in microwave radiation can lead to a more uniform temperature distribution compared to the conventional thermal curing (Clark et al., 2000), thus leading to better interlaminar shear strength (Nightingale and Day, 2002) and other changes in mechanical and physical properties (Papargyris et al., 2008) of composites. Kwak et al. (2015) tested various material properties of the microwave cured composites and the penetration depth to prove that high-quality composites can be manufactured by microwave. Some other researchers established models to quantitatively analyze the heat transfer in the composites by microwave curing. Specifically, the composites were modeled as the impedance network in some studies to examine the interaction between electromagnetic field and composites (Wasselynck et al., 2010) and the heating energy generated by the microwave (Bui et al., 2014). Carlone and Palazzo (2008) established a model to simulate the microwave assisted pultrusion which considered the electromagnetic heating and thermochemical behavior of composites. The analysis of the temperature distribution of the composites (Feher, 2009) and validated their work in their self-developed microwave oven (Feher and Thumm, 2004), and the adhesives in the composites (Frauenhofer et al., 2012) by the models of electromagnetic heating was also conducted. But many of these

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Nomenclature

E	Eelectric density
B	Magnetic density
w	Circular frequency
μ	Permeability
H	Magnetizing field
J_f	Free current density
D	Electric displacement field
ε_0	Permittivity of free space
ε	Dielectric constant
Q_e	Heat of dielectric heating
$\hat{\sigma}_e$	Conductivity matrix
σ	Conductivity
β	Attenuation coefficient
E_0	Transmitted electric density at the interface
Q_r	Exothermal heat of cure reaction
V	Volume fraction
H_r	Exothermic enthalpy per unit mass
α	Cure degree
A	Pre-exponential coefficient
$\triangle E$	Activation energy
R	Universal gas constant
T	Temperature
n	Reaction exponent
ρ	Density
C_p	Heat capacity
k	Thermal conductance
R'	Reflection coefficient
T'	Transmission coefficient
Q_1	Convective cooling energy
h	Heat transfer coefficient
Q_2	Surface-to-ambient radiation
ζ	Surface emissivity
υ	Stefan-Boltzmann constant
q	Heat flux density
Q	Heat energy
S	Surface area
r	Electric resistance
L	Length
U	Electric voltage
I	Electric current

Operators and descriptors

$\triangledown$	Differential operator (Del)
$\triangledown^2$	Laplacian operator
$\frac{\partial}{\partial t}$	Partial differential to time
$\frac{\partial^2}{\partial x^2}\ \frac{\partial^2}{\partial y^2}\ \frac{\partial^2}{\partial z^2}$	Second order partial differential
$\int$	Integration operator
$\triangle$	Increment quantity descriptor
$\vec{?}$	Vector descriptor
$\bar{?}$	Average descriptor

Subscripts

$\perp$	Perpendicular to the fibre direction
$\|$	Parallel to the fibre direction
x,y,z	Orthogonal axes system
1,2	Diagonal points of the microscopic model
α	Ambient air
f	Fiber
m	Resin matrix

established models failed to address some important influencing factors in the curing processes, especially the attenuation of microwave energy penetrating in the multiphase composites, the electromagnetic and thermal influence of bagging materials and the molds and the exothermal curing reaction of composites.

In this paper, a Finite Element Method (FEM) based model was proposed to quantitatively study the temperature distribution during the microwave curing of the composites. The material properties of the macroscopic model were obtained by calculations from the microscopic model by the homogenization method. This method can calculate the effective material properties of the composites from the microscopic model with the easily available material properties of the fiber and the matrix (Kanouté et al., 2009). Then the macroscopic model can be utilized to simulate the thermal behavior of the microwave cured composites, which considered the electromagnetic heating, the attenuation of microwave propagating in the material, the exothermal reaction of curing, the heat transfer in anisotropic composite laminates, the electromagnetic and thermal influence of the mold and the bagging materials. A case study was devised to demonstrate the functions of the established model, and the corresponding experiment was conducted and validated its accuracy.

2. Numerical modeling

The numerical model used for the temperature field distribution of composites during microwave cure is illustrated in Fig. 1. The macroscopic level of the model is in the form of composite laminates, which consists of the sub-models including electromagnetic heating, attenuation of electromagnetic energy, exothermal reaction, heat transfer and boundary conditions. The material properties of macroscopic model are calculated from the microscopic model, which makes the model more expedient to use. Although the macroscopic material properties can be got from experimental tests, Hassani and Hinton (1998) stated that it is obvious that the volume and cost of these measurements are impracticable for all types of composite laminates of different constituents and fiber volume fractions.

The model was established in the FEM simulation tool COMSOL Multiphysics 4.3a software.

2.1. Electromagnetic heating

The electromagnetic field distribution can be described by the Maxwell's equations, which can be written as Eqs. (1)–(4):

$$\Delta \times E = -\frac{\partial B}{\partial t} = -jw\mu H \quad (1)$$

$$\Delta \times H = J_f + \frac{\partial D}{\partial t} = jw\varepsilon_0\varepsilon E \quad (2)$$

$$\Delta \times E = 0 \quad (3)$$

$$\Delta \times H = 0 \quad (4)$$

The electric conductivities of anisotropic composites are defined as matrices. In a single composite laminate layer, the fiber reinforcements on the transverse direction and the thickness direction are uniformly distributed and thus have approximately the same material properties. Therefore, we assume that the electric conductivities in these two directions all equal to $\sigma_\perp$. The electromagnetic power absorbed by the dielectric material per unit volume $Q_e(x, y, z, t)$ is determined as Eq. (5).

$$Q_e(x, y, z, t) = \frac{1}{2}\vec{E}(x, y, z, t)\hat{\sigma}_e\vec{E}(x, y, z, t) = \frac{1}{2}(\sigma_{||}E_{||}^2(x, t) + \sigma_\perp(E_\perp^2(y, t) + E_\perp^2(z, t))) \quad (5)$$