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Processing of a Laminated Composite Part by Microwave Heating

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Abstract. Microwave (MW) heating relies on volumetric heat sources due to induction and dielectric phenomena. The main drawback of this technology today is that the complex physics involved in the conversion of electromagnetic energy to thermal energy is not fully understood or even controlled. To overcome this issue, we propose the following work which consist in modelling and simulate the propagation of the electromagnetic field in a laminated composite. The material is composed of carbon fibers and resin matrix. The full simulation from electromagnetics to thermal aspects will provide us with a better understanding of the process and its parameters.

Keywords: Composite processing, microwaves, PGD

INTRODUCTION

Composite parts tend to represent an increasing volume of production in transport industries (aeronautic and automotive). This is due to their combination of high mechanical properties and low mass. Yet, one disadvantage still remains: their long cycle time.

Conventional processing methods for producing polymer composite parts usually involve the application of heat to the material by convection or conductive heating through elements: surface heat transfers rule the process. On the other hand, microwave (MW) technology relies on volumetric heating: thermal energy is transferred through electromagnetic fields to materials that can absorb it at specific frequencies (in the case of MW heating: 2.45 GHz). Volumetric heating enables better process temperature control [1] and less overall energy use, which can results in shorter processing cycles [2]. Furthermore, comparable mechanical properties are shown between parts made with the MW technology and parts made with a traditional curing system (autoclave in the case of [3]). These virtues of the MW technology have attracted interest in developing the method and adopting it for the production of thermoset as well as thermoplastic composite materials.

The main drawback of this technology today is that the complex physics involved in the conversion of electromagnetic energy to thermal energy (heating) is not entirely understood and controlled.

The principal objective of this work is to model the interactions of the MW field with a laminate part, made of a sequence of prepreg composite layers (here, carbon fibers impregnated of a polymeric matrix), at macro and meso scales, that is to say at the scale of the part and also the scale of the ply. These models will simulate the way electromagnetic energy is propagated within the material volume and the various interfaces, then converted to thermal energy. The main challenge concerns the high-resolution description of the electromagnetic and thermal fields in a composite laminate, that involve plies whose characteristic in-plane dimension is orders of magnitude higher than the ones related to the thickness (typical aspect ratio are of tens of thousands). In that situation the use of in-plane-out-of-plane separated representations within the Proper Generalized Decomposition –PGD- framework seems an appealing and valuable route for solving 3D models, very rich in both, the in-plane and the out-of-plane directions, while ensuring a computational complexity of standard 2D models [4- 6].

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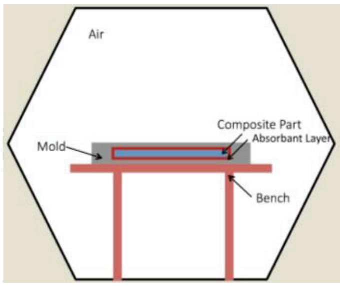
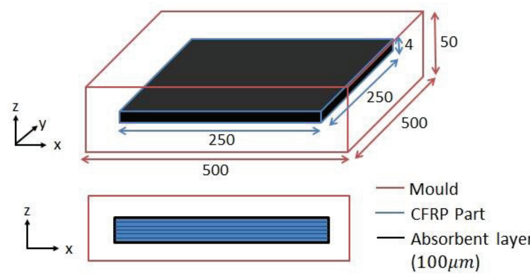
PROCESS DESCRIPTION

One kind of oven cavity used for such a process is a Hephaistos© one (**FIGURE 1a**). A metallic bench is placed in the oven and the composite part (Carbon Fiber Reinforced Polymer material) is displayed on it within a mold made of a material transparent to microwave but coated in its interior surface by an absorbent layer. (**FIGURE 1**).



(a)



(b)

FIGURE 1. Schematic representation of the process (a) and zoom of the mold and composite part with its characteristic dimensions in mm (b)

MODELLING THE MICROWAVE HEATING Electromagnetic Model

A coupled electromagnetic and thermal model is proposed in order to simulate the emerging process o microwave heating for composite material. The physical model for electromagnetism consists of the well-known Maxwell equations, which after some manipulations and assuming a harmonic field, are reduced to:

$$\nabla \times \frac{1}{\mu} \nabla \times \boldsymbol{E} = \boldsymbol{\gamma}^2 \boldsymbol{E} \text{ with } \gamma^2 = i\omega(\sigma + i\omega\varepsilon) \quad \text{in } \Omega \subset \mathbb{R}^3 \tag{1}$$

$$\boldsymbol{n} \times \boldsymbol{E} = \boldsymbol{E^t} \text{ in } \partial\Omega \tag{2}$$

where μ, ε and σ and respectively the permeability, the permittivity and the electrical conductivity, all three of them depending on the considered material and $\omega = 2\pi f$ with f the frequency. $\boldsymbol{n}$ refers to the unit outwards vector defined on the domain boundary and $\boldsymbol{E^t}$ is the prescribed electric field (assumed known) on the domain boundary.

However, it is known [7] that this weak from version of the above strong formulation produces spurious solutions. Even if (1) ensures the verification of the Gauss equation $\nabla \cdot (\varepsilon \boldsymbol{E}) = 0$. its discrete version after approximating the different fields implied in the weak form does not ensure the fulfillment of the Gauss equation. Therefore, a regularization is needed to avoid spurious solutions. The regularized form is then:

$$\nabla \times \frac{1}{\mu} \nabla \times \boldsymbol{E} - \bar{\varepsilon} \nabla \left(\frac{1}{\bar{\varepsilon}\varepsilon\mu} \nabla \cdot (\varepsilon \boldsymbol{E}) \right) = \gamma^2 \boldsymbol{E} \tag{3}$$

whose associated weak form (with Dirichlet BC applying on the whole domain boundary) is:

$$\int_\Omega \frac{1}{\mu} (\nabla \times \boldsymbol{E}) \cdot (\nabla \times \overline{\boldsymbol{E}}^*) d\Omega - \int_\Omega \gamma^2 \boldsymbol{E} \cdot \overline{\boldsymbol{E}}^* \, d\Omega + \int_\Omega \frac{1}{\bar{\varepsilon}\varepsilon\mu} \big(\nabla \cdot (\varepsilon \boldsymbol{E})\big)\big(\nabla \cdot (\varepsilon \overline{\boldsymbol{E}}^*)\big) \, d\Omega - \int_{\partial\Omega} \frac{1}{\bar{\varepsilon}\varepsilon\mu} \big(\nabla \cdot (\varepsilon \boldsymbol{E})\big) \cdot (\mathbf{n} \cdot (\overline{\bar{\varepsilon}\boldsymbol{E}^*})) d\Gamma = 0 \tag{4}$$

In-plane-out-of-plane Separated Representation

As the composite part considered in the process is a plate, its characteristic in-plane dimension is orders of magnitude higher than the ones related to the thickness as shown on **FIGURE 1b**. In that situation, the use of the inplane-out-of-plane separated representation within the Proper Generalized Decomposition (PGD) framework allows writing the electric field in the 3D separated form:

$$\boldsymbol{E}(x,y,z) \approx \sum_{i=1}^{N} \boldsymbol{X_i}(x,y) \circ \boldsymbol{Z_i}(z) \tag{5}$$

where the bullet ∘ denotes the Hadamar product. Thus, the electric field is expressed as a finite sum of functional couples involving a function depending on the in-plane coordinates (x,y) and the other involving the coordinate related to the thickness (z). Thus, the 3D solution is obtained from a number (in the order of N) of 2D problems involving the in-plane coordinates and the same number of 1D problems involving the thickness.

Such a separated representation seems an appealing and valuable route for solving 3D models, very rich in both, the in-plane and the out-of-plane directions, while ensuring a computational complexity of standard 2D models [4]. This separated representation is especially interesting for addressing domains in which at least one of its characteristic dimensions is much smaller than the others, and the solution exhibits significant richness in the thickness direction implying the necessity of using a fine enough representation (mesh) to capture the transmission conditions at the ply interfaces. When using standard mesh-based discretization the use of a fine mesh in the thickness direction within a 3D discretization usually implies extremely fine meshes in the whole domain, involving a prohibitive number of degrees of freedom. The use of separated representations makes independent the in-plane and the thickness approximations and the use of different discretization techniques for solving the associated problems related to the in-plane and the thickness coordinates is possible.

Thermal Model

From the electromagnetic solution, the thermal source term Q can be determined and the thermal model defined and solved. The heat conduction model inside the laminate allows calculating the temperature field at each position and time $T(x,y,z,t)$ by solving the heat equation:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (\boldsymbol{K} \cdot \nabla T) + Q(x,y,z,t) \tag{6}$$

where $\boldsymbol{K}$ represents the thermal conductivity tensor defined at the ply level and which in the case of unidirectional reinforcement or fabrics becomes anisotropic justifying its tensorial character.

Again, the too different in-plane and thickness characteristic lengths, motivates the use of a separated representation of the temperature field, which now writes:

$$T(x,y,z,t) \approx \sum_{i=1}^{M} X_i(x,y) Z_i(z) \Theta_i(t) \tag{7}$$

TEST CASE

The teste case described on the geometry description on **FIGURE 1b** is simulated in the following paragraph. The mesh is composed of 60x60 elements in the plane (x,y) and 3000 elements in the out-of-plane direction. The composite material is composed of a stack of plies described by the sequence $[(0°, 90°)_{10}]_{sym}$. The material properties are given in **TABLE 1.**

TABLE 1 Dielectric Material properties used in the simulation. For anisotropic materials, tensor is reduced to its diagonal [11-component, 22-compoenet, 33-component].

Dielectric property	0°-oriented CFRP ply	90°-oriented CFRP ply	Mold	Absorbent layer
Relative permittivity	[13 1 1]	[1 13 1]	2	1
Relative permeability	[1 1 1]	[1 1 1]	1	1
Electrical conductivity (S/m)	[5000 10 10]	[10 5000 10]	0	10000

The boundary conditions applied are:

$$\boldsymbol{n} \times \boldsymbol{E} = \begin{pmatrix} \cos(2\pi n x) + \cos(2\pi n y) \\ \cos(2\pi n x) \\ \cos(2\pi n y) \end{pmatrix} \text{ with } n=10 \tag{8}$$

The results of the simulation are depicted on **FIGURE 2** and **FIGURE 3**. We can see that the electric field is down to zero when arriving on the absorbent layer. The discontinuity observed comes from the interface conditions which needed to be enforced in the simulation tool. The temperature distribution in the thickness shows that the process allows us to heat the part of about 200°C in 30s. A future concern would be to optimize the process such as the heating would as much homogeneous as possible to ensure part quality.

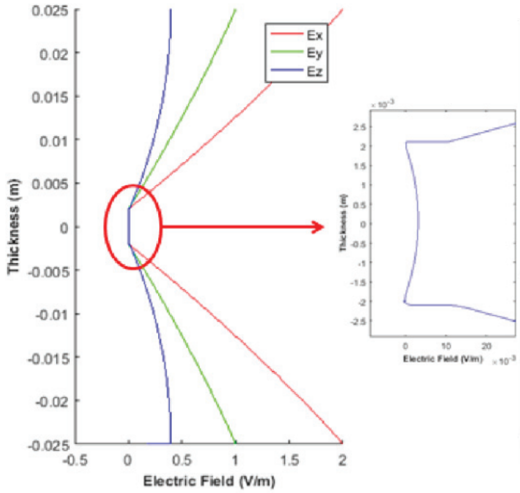


FIGURE 2. Electric field distribution along the line (x_{middle},y_{middle},z) with zoom at the composite interface.

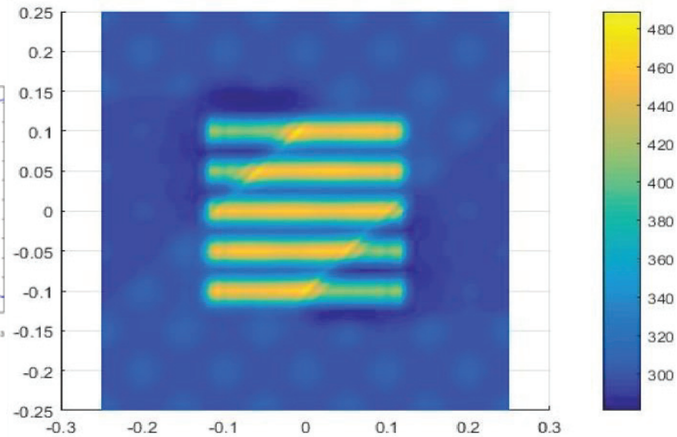


FIGURE 3. Temperature field (in K) in the plane (x,y,z_{middle}) showing the inmpact of the electric field distribution on the heating

CONCLUSION

The modelling of the electromagnetic heating of a CFRP plate has been presented in the paper. First steps of the simulation tool have been detailed and show that the simulation approach chosen (in-plane-out-of-plane representation within the PGD framework) ensures good results and fast computation. The coupling between electromagnetism and thermic physics has also been presented. Further simulation work is to develop the simulation tool to take into account the plies scale in laminates and use the tool in an optimization approach of the process.

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