MICROWAVE HEATING OF A THIN LAMINATE COMPOSITE PART

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ABSTRACT. Microwave (MW) technology relies on volumetric heating. Thermal energy is transferred through electromagnetic fields to materials that can absorb it at specific frequencies. 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 and simulate the interactions of the MW field with a composite laminated part, consisting of a stack of layers of different orientations, each layer made of resin matrix and carbon fibers. This simulation will give us a better understanding of how the electromagnetic field is propagated within the material volume and the various interfaces, and then converted to thermal energy.

INTRODUCTION

Composites parts tend to represent an increasing volume of production in transport industry (aeronautic and automotive). This is due to their combination of high mechanical properties and low mass. Although one aspect is still a disadvantage, this concerns 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, which depend on surface heat transfer. Microwave (MW) technology relies on volumetric heating, that means thermal energy is transferred through electromagnetic fields to materials that can absorb it at specific frequencies. 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 (in that case 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].

PROCESS DESCRIPTION

The oven cavity has an hexagonal shape, as a Hephaïstos© one. A metallic bench is positioned in it. The composite part to be heat is placed on the bench, on a tool made of a material transparent to MW.

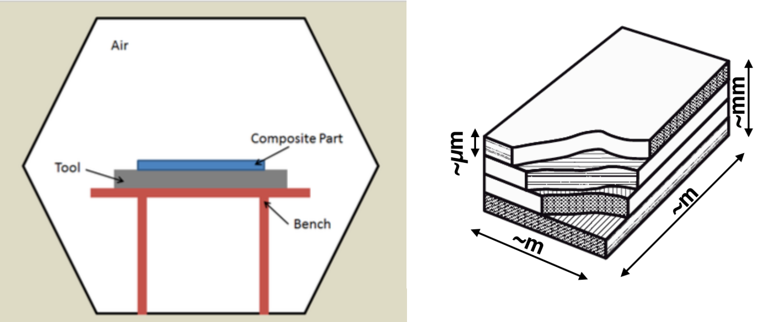

Figure 1: Schematic representation of the process (left) and zoom of the composite part with its characteristic dimensions (right).

ELECTROMAGNETIC MODEL

A coupled thermal and electromagnetic model is proposed in order to simulate an emerging process for composite materials heating. The physical model consists of the Maxwell equations, that after some manipulations and assuming an harmonic electric field, reduced to:

$$\nabla^2 \mathbf{E} = \gamma^2 \mathbf{E}$$

with $\gamma^2 = i\omega\mu(\sigma + i\omega\epsilon)$

where mu, sigma and epsilon are respectively the permeability, conductivity and permitivity, all them depending on the considered material.

Composite laminates 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) (see Fig 1b). In that situation the use of in-plane-out-of-plane separated representations within the Proper Generalized Decomposition –PGD- framework, allows writing the electric field in the 3D separated form

$$\mathbf{E}(x,y,z) \approx \sum_{i=1}^{N} \mathbf{X}_i(x,y) \bullet \mathbf{Z}_i(z)$$

where the bullet denotes the Hadamard's 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 specially interesting for addressing degenerated 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 (e.g. finite elements for the first and finite differences for the last).

The use of space-separated representations in electromagnetic applications has, in our knowledge, never been investigated, and here we prove that we can reach levels of resolution related to hundreds of degrees of freedom along the thickness direction (that has a characteristic size of few millimeters) without having any impact on the in-plane representation, and then in the computational efficiency.

The solution procedure proceeds by calculating at each enrichment iteration a new functional couple. Because the calculating of two unknown functions define a nonlinear problem, a second iteration loop must be considered. In the last, by assuming the function depending in the z-coordinate known (randomly chosen when starting the nonlinear loop) the function depending in the in-plane coordinates is calculated by solving the associated 2D problem. Then, from it, the function depending on the z-coordinate is updated and so on. As soon as the iteration converges, the next functional couple is searched. The enrichment stops as soon as the residual associated to the solution becomes small enough, that we assumed occurs after adding N functional couples. All the details can be found in [7].

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

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

where **K** represents the conductivity tensor perfectly defined at the ply level and that 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, that now writes

$$T(x,y,z,t) = \sum_{j=1}^{M} X_j(x,y) \cdot Z_j(z) \cdot \Theta_j(t)$$

and allows calculating a fully 3D transient solutions while keeping the computational complexity characteristic of 2D solutions (the ones involved in the calculations of function depending on the in-plane coordinates (x,y)). In the case of the parabolic heat equation, the separated representation at the heart of the PGD method allows the time integration in a non-incremental way, that is, the whole temperature history is computed simultaneously. This ability allows impressive CPU time savings, of many orders of magnitude. Obviously, such decomposition requires a prior in-plane-out-of-plane decomposition of the thermal properties, but in the case of composite laminates such a decomposition is very easily accomplished and in the general case it can be performed by invoking a singular value decomposition.

RESULTS

To prove the ability of the proposed technique we consider a laminate with dimensions 1m length, 1m width and only 11 mm thickness. The laminate is composed of 11 plies, the first consisting of a conductor, and the remaining 10 plies alternating lossy and lossless dielectrics. The computational domain is assumed having a 1mm extra-ply consisting of air. The different material properties are summarized in Table 1.

	σ	ε_r	μ_r
Air	0	1	1
Lossy dielectric	0.5	100	1
Lossless dielectric	0	1	1
Conductor	∞	5	1

Table 1: Material properties of the different laminate plies.

The considered mesh consisted of 2401 Q4 finite elements in the plane and 120 linear elements in the thickness (10 per ply and 10 in the air layer). The PGD solution procedure consists in solving a number of 2D problems (on the 2401 Q4 elements mesh) and the same number of 1D problems involving 121 degrees of freedom. The solution obtained corresponds to the one obtained by using of the order of 300.000 Q8 3D finite elements. Moreover, such a 3D solution would imply very distorted elements, with an aspect ratio of 2000, that could induced difficulties when using the finite element method.

In the solution we considered simple boundary conditions leading to a unidirectional solution in order to compare the solution with the one obtained by solving the associated 1D model. These boundary conditions are

$$\mathbf{E}^T(x, y, z = 0) = (0, 0, 0)$$
$$\mathbf{E}^T(x, y, z = 12mm) = (0, 0, 1)$$

Figure 2 depicts the reconstructed solution through the thickness. Fig. 3 shows the associated displacement field. Finally Fig. 4 depicts the through-thickness temperature at three different times, when considering the real transmitted power (real values of the applied electrical field).

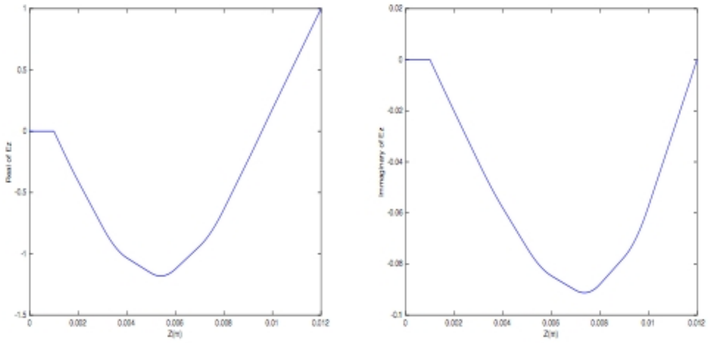

Figure 2: Electrical field through the thickness: real part (left) and imaginary part (right)

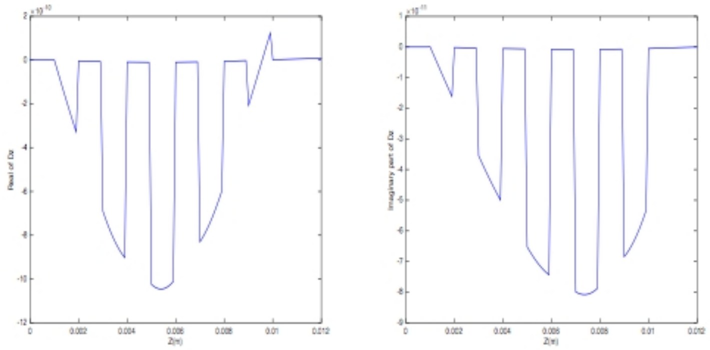

Figure 3: Displacement field through the thickness: real part (left) and imaginary part (right).

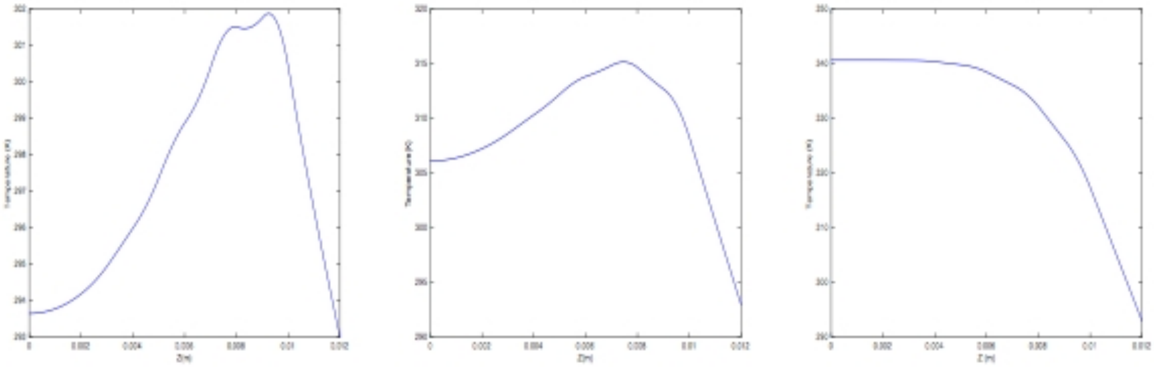

Figure 4: Temperature: (left) t=0.1s, (center) t=0.5s and (right) steady-state.

CONCLUSIONS

In this work we proved that electromagnetic models governing microwave heating can be successfully and accurately solved in composites laminates composed of very thin plies. A very fine 3D resolution is obtained by using an in-plane-out-of-plane separated representation that allows considering very fine approximations in the thickness direction without compromising the computational efficiency that remains the ones characteristic of 2D simulations. Moreover, when addressing time-dependent problems its non-incremental nature allows for further computational savings, sometimes of many orders of magnitude.

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