Simulation of the Propagation of an Electromagnetic Field in a Laminated Composite Part: Application to Microwave Heating

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Abstract. A coupled thermic and electromagnetic model is proposed in this paper in order to simulate the emerging process of microwave heating for composite materials. Solving the problem in a laminated composite material requires a high degree of discretization in the thickness direction which is made possible by introducing a new simulation approach using the Proper Generalized Decomposition (PGD).

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 heating of the tool and composite in an oven (pressurized/non-pressurized), or conductive heating of mold/platens through heating elements. Conversely to these traditional heating methods that depend on surface heat transfer, microwave (MW) technology relies on volumetric heating. 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. It also enables the processor to direct heating specifically towards the part to be processed, and not the surrounding air or tool, thus maximizing the energy efficiency of the process. 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.

Substantial time and energy benefits have been reported [2, 3]. The shorter cycle is possible as the microwave oven requires minimal ramp-up to set point temperature and the process has less tooling-driven thermal lag. Further, when the oven shuts off, there is no cool-down of the oven itself. As for a domestic microwave oven, it heats only certain non-metallic materials, thus the oven is always cool to the touch. 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 [4]). 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 the composite material (resin matrix, carbon fibers), at micro and meso scales. These models will simulate the way electromagnetic energy is converted to thermal energy within the material volume and the various interfaces. They will also describe how the local heat transfer mechanisms contribute to the overall heat transfer towards the produced part. Previous work proposed such simulations for induction heating applications (frequency lower than 1MHz) [5], when considering microwave frequency (in our case, 2.45 GHz), experimental works have been done [6, 7] and some models have been build [8] but not taking into account the possibility that the composite part could receive microwaves.

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 order 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 [9-12].

DESCRIPTION OF THE PROCESS

As depicted on **FIGURE 1**, the composite part to be heated is placed on the tool. The microwaves are produced by magnetrons in order to create a homogeneous electromagnetic field in the oven cavity which frequency is 2.45 GHz. With such a process configuration, microwaves penetrate in the composite part. Therefore, several phenomena occur with the interaction of the electromagnetic field and the material: the dielectric losses imply heat creation which leads to conduction between the plies of the part and convection between the air of the cavity and the part.

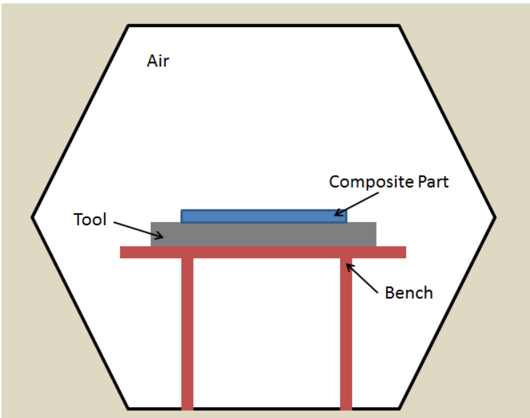

FIGURE 1. Schematic representation of the microwave oven cavity and experimental set-up

ELECTROMAGNETIC AND THERMAL MODEL

All the physical phenomena listed in the previous part can be mathematically expressed with two different approaches which need to be coupled: the electromagnetic part and the thermal part.

Electromagnetic Field Formulation

Three constitutive equations describe the electromagnetic field in the material:

$$\boldsymbol{D} = \varepsilon \boldsymbol{E} \tag{1a}$$
$$\boldsymbol{B} = \mu \boldsymbol{H} \tag{1b}$$
$$\boldsymbol{J} = \sigma \boldsymbol{E} \tag{1c}$$

With $\boldsymbol{D}$ the electric flux density (in C/m^2), $\boldsymbol{E}$ the electric field intensity (in V/m) and ε the permittivity (in F/m)

$\boldsymbol{B}$ the magnetic flux density (in Wb/m^2), $\boldsymbol{H}$ the magnetic field intensity (in A/m) and μ the permeability (in H/m)
$\boldsymbol{J}$ the electric current density (in A/ m^2) and σ the conductivity (in Ω/m)

The electromagnetic properties of the material are characterized by the three constitutive parameters ε, μ and σ. According to these coefficients, a classification of materials is given in **TABLE 1**. With such a classification of materials, the oven cavity, the tool and the part can be modeled and the propagation of an electromagnetic field can be calculated.

TABLE 1. Classification of materials according to their electromagnetic properties

	Vacuum	**Conductor**	**Lossless dielectric**	**Lossy dielectric**
σ	$\sigma = 0$	$\sigma = \infty$	$\sigma = 0$	$\sigma \neq 0$
ε	ε_0	ε_0	$\varepsilon = \varepsilon_0 \varepsilon_r$	$\varepsilon = \varepsilon_0 \varepsilon_r$
μ	μ_0	$\mu = \mu_0 \mu_r$	$\mu = \mu_0 \mu_r$	$\mu = \mu_0 \mu_r$

In addition to these constitutive relations, fundamental laws of electromagnetism (Maxwell's equations) describe the propagation of the electromagnetic field in the material:

$$\nabla \cdot \boldsymbol{D} = \rho_v \tag{2a}$$

$$\nabla \cdot \boldsymbol{B} = 0 \tag{2b}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{2c}$$

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t} \tag{2d}$$

With ρ_v the volume charge density (in coulombs / meter^3), $\nabla \cdot$ the divergence operator and $\nabla \times$ the curl operator

At the interface between two materials, i.e. between the air in the cavity and the part, between the tool and the part and between the plies of the composite, the boundary conditions are (assuming that there are no free charges at the interface):

$$(\mathbf{D}_1 - \boldsymbol{D}_2) \cdot n_{12} = 0 \tag{3a}$$

$$(\mathbf{B}_1 - \boldsymbol{B}_2) \cdot n_{12} = 0 \tag{3b}$$

$$(\mathbf{E}_1 - \boldsymbol{E}_2) \cdot t_{12} = 0 \tag{3c}$$

$$(\mathbf{H}_1 - \boldsymbol{H}_2) \cdot t_{12} = 0 \tag{3d}$$

With n_{12} a unit normal vector directed from medium 1 to medium 2 and t_{12} a unit tangent vector along the separation surface of medium 1 and medium 2.

Heat transfer phenomena

In the composite part, the heat transfer will occurs through conduction:

$$\boldsymbol{\varphi} = -\lambda \boldsymbol{\nabla} T \tag{4}$$

With $\boldsymbol{\varphi}$ the heat flux (in W/m²), λ the thermal conductivity (in W m^{-1} K^{-1}) and T the temperature (in K)

The internal sources mentioned in the introduction which make the interest of the microwave technique can be of two different types. First, there is the power dissipated by the electromagnetism interactions with the material p_{EM} and, according to the material, the heat source due to the exothermic chemical reactions during the heating of the part p_{CR}. Therefore, the heat equation becomes:

$$p_{EM} + p_{CR} = \nabla \cdot \boldsymbol{\varphi} + \rho C_p \frac{\partial T}{\partial t} \tag{5}$$

With ρ the volumetric mass (in kg/m^3) and C_p the specific heat capacity (in J kg^{-1} K^{-1})

The source due to the electromagnetism field can be expressed by:

$$p_{EM}(\varepsilon, \mu, \sigma) = \frac{1}{2} Re\ (\boldsymbol{E} \cdot \boldsymbol{H}^*) \tag{6}$$

As for electromagnetism phenomena, interfacial conditions have to be expressed according to the type of heat transfer that occurs.

- At the interface between the part and the air, convection might contribute to the heat transfers. Therefore, the flux at the surface of the part is:

$$\varphi = h(T_S - T_{ext}) \tag{7}$$

With h the heat transfer coefficient (in W K^{-1} m^{-2}), T_s the temperature of the composite at the interface and T_{ext} the temperature of the air (in K)

- At the contact between the plies and with the tool, the interfacial condition is expressed by:

$$\nabla T_1 . \boldsymbol{n} = \frac{\lambda_2}{\lambda_1} \nabla T_2 . \boldsymbol{n} \tag{8}$$

Finally, a sum-up of all the materials characteristics is expressed with **FIGURE 2.**

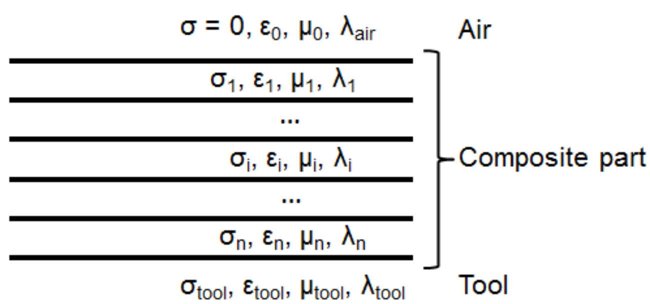

FIGURE 2. Material properties needed to model the microwave process for heating a composite part

RESULTS AND DISCUSSIONS

The one-dimension propagation of an EM wave in the four different materials presented in **TABLE 1** has been solved using the finite differences and the electric field ***E*** is shown in **FIGURE 3**. In the case of a perfect conductor, the EM wave is entirely reflected when it hits the surface which is why the electric field is not transmitted in the material. The propagation of the field in a lossless dielectric is similar to the propagation in the vacuum with a different spatial period which depends on the material properties. In a lossy dielectric, the field is faded as it propagates in the material.

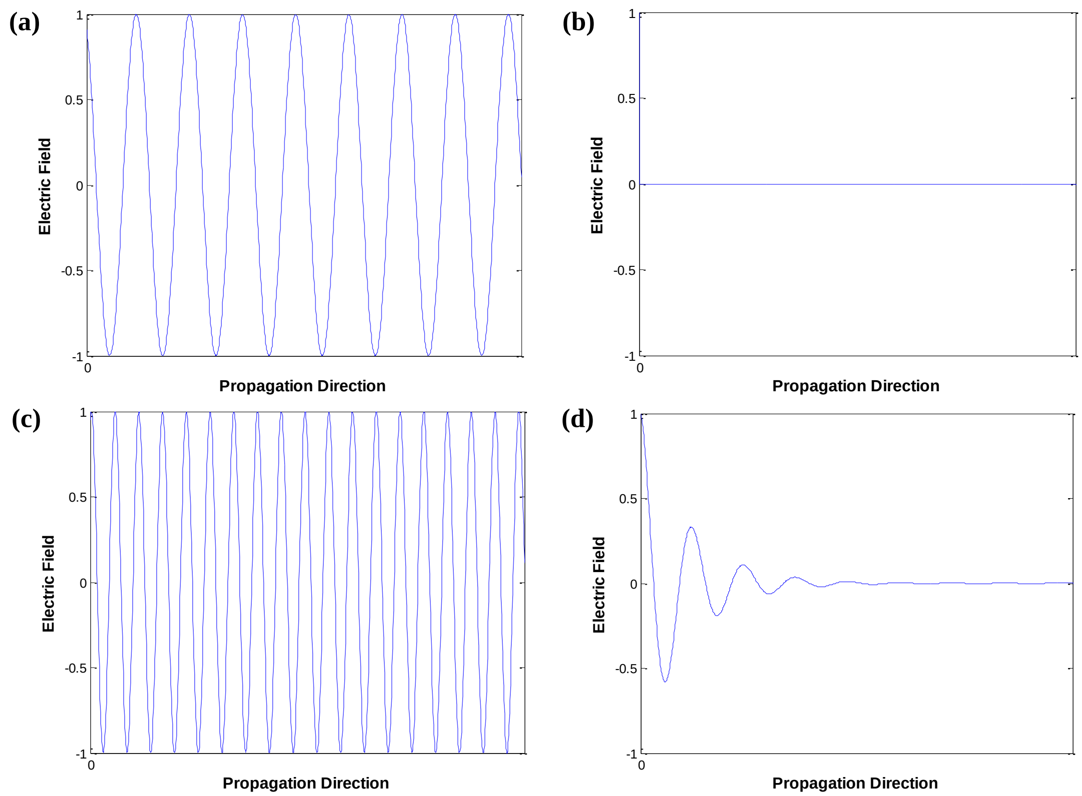

FIGURE 3. Propagation of the electric field in different materials: (a) in the vacuum, (b) in a perfect conductor, (c) in a lossless dielectric (with $\varepsilon_r \mu_r > 1$) and (d) in a lossy dielectric.

The propagation of the electric field in successive layers of different types of materials is presented in **FIGURE 4**. One can note that the electric field is continuous from one layer to another. The fundamental laws impose that the electric field is normal to the propagation direction and because the propagation is in one dimension, the electric field is tangential to the interfaces between the layers which leads to its continuity according to (3c).

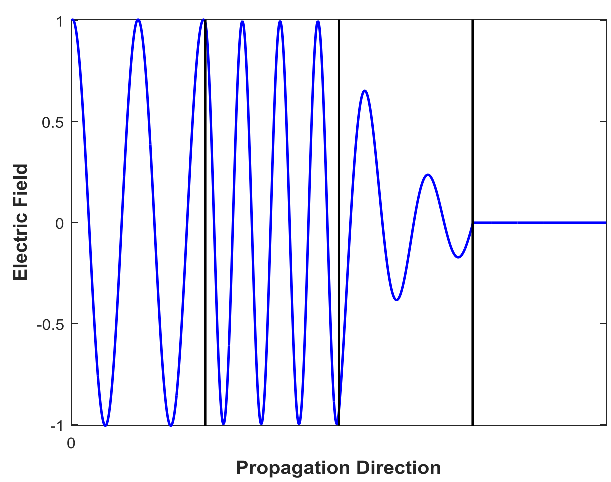

FIGURE 4. Propagation of the transmitted electric field in a medium composed of, from left to right: vacuum, lossless dielectric, lossy dielectric and perfect conductor (materials boundaries are represented by the black vertical lines)

To solve the same problem with a significant amount of plies demands an increasing number of nodes in the propagation direction. In addition, it is necessary to go from 1D to 3D to simulate the process. Therefore, a high discretization is necessary in the thickness dimension and with classical simulation methods, it becomes extremely difficult to solve as the required mesh is highly refined. The use of the PGD method [9-12] is adapted to this case as it transforms the 3D problem into a set of 2D and 1D problems. Each components of the electric field is decomposed according to (9). As a consequence, having a very high number of nodes in the thickness is not a problem anymore as the propagation in this direction is solved as a 1D problem.

$$E_j(x,y,z) \approx \sum_{i=1}^{N} X_j^i(x,y) Z_j^i(z) \quad \text{with} \quad i = 1,2,3 \tag{9}$$

CONCLUSION

A description of the manufacturing process using a microwave oven to heat composite parts has been described and the mathematical formulation of the problem has been defined. The next step of the work is solving the propagation of the electromagnetic field in the laminated composite using the PGD method.

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