Numerical modelling of the microwave assisted pultrusion process

P. Carlone[1], G.S. Palazzo[1]

[1]*University of Salerno – Via Ponte Don Melillo 1, 84084 Fisciano (SA), Italy*
URL: www.unisa.it *e-mail: pcarlone@unisa.it; gspalazzo@unisa.it*

ABSTRACT: This paper deals with the computational modelling of the an innovative variant of the conventional pultrusion process, called the microwave assisted pultrusion processes. The model is based on two weakly coupled sub-model, the electromagnetic sub-model, used to evaluate the electric field distribution and the heat generation rate due to the microwave source and the thermochemical sub-model, used to evaluate the temperature and degree of cure distributions. Performed simulations, obtained solving the formulated theoretical problem using a finite element scheme, evidence the process capabilities, the relevance of an opportune design of the microwave cavity and of the curing die, and the importance of the dielectric properties of the used materials.

Key words: Microwave Assisted Pultrusion, Electromagnetic model, Thermo-chemical model

1 INTRODUCTION

Pultrusion is a continuous manufacturing process used to shape polymeric composite materials into parts with constant cross section. Several numerical and experimental investigations have been performed on different problems related to the pultrusion process, in particular on the analysis of the heat transfer and cure, on the pressure rise in the tapered zone of the die, and on the development of process capabilities. The importance of the analysis of heat transfer and cure in pultrusion is highly recognized to obtain a final product characterized by the desired mechanical properties or to realize a post-die shaping. Two different computational schemes for the solution of thermochemical models of the process have been proposed and validated by the present authors in [1], while an optimization procedure has been developed and tested in [2]. Nowadays the attention is also focused on the development of several variants of the pultrusion process, such as the pull-winding process, the bent-pultrusion process and the microwave assisted pultrusion process.

The microwave assisted pultrusion process [3] is an innovative variant of the pultrusion process, characterized by a high frequency electromagnetic energy source, instead of conventional heating methods, for material curing. Microwave heating [4] is a fast, instantaneous, non contact, and volumetric heating and therefore very interesting for materials processing [5]. Due to the characteristics of microwave heating, the length of the die results minor than the length of the die used in the conventional process, the line speed is relatively higher and the pull load is reduced. The rapid heating of pultrusion precursors allows the manufacture of large section profiles, while the instantaneous feature of this heating method allows the easy creation of a hinge, i.e. an uncured segment of material, simply by switching off the microwave source for a fixed time. Taking into account the complexity of the analysis of microwave processes, generally a computational approach to investigations is preferred [6,7,8,9,10]. This paper deals with the development of a computational finite element model and the analysis of the process by computational simulations.

2 GOVERNING EQUATIONS

2.1 Electromagnetic Sub-Model

The developed computational model of the microwave assisted pultrusion process is based on the solution of two consecutive weakly coupled sub-models. The electromagnetic sub-model is used to evaluate the three dimensional distribution of the nodal electric field by the solution of the Maxwell's equations. The above equations have been solved using a finite element scheme with opportune loads and boundary conditions. The nodal numerical results of the electromagnetic sub-model are post-processed and then used as load input in the thermochemical analysis. Microwave heating is based on the conversion of electromagnetic energy into heat, according to specific loss mechanisms. The specific heat generation rate related to microwaves can be obtained integrating the Poynting vector over the control domain and taking into account the Maxwell equation. The above procedure finally yields:

$$P_{mw} = 2\pi f \varepsilon_0 \varepsilon'' E^2, \tag{1}$$

where f is the microwave frequency, ε_0 is the dielectric constant, ε'' is the loss factor, and E is the electric field.

2.2 Heat Transfer Model

The heat transfer sub-model is based on the energy balance equation, taking into account the exothermic resin cure reaction and convective effect, related to the movement of the processing part. Taking into account that reinforcing fibres are wetted out and impregnated by the resin before entering the die, it is assumed that the resin does not flow, and then the energy balance equation, assuming x axis as the pull direction, for the forming die and the processing material, can be rewritten, respectively, as follows:

$$\rho_d c_{p,d} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_{x,d}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_{y,d}\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_{z,d}\frac{\partial T}{\partial z}\right) + 2\pi f \varepsilon_0 \varepsilon'' E^2, \tag{2}$$

$$\rho_c c_{p,c}\left(\frac{\partial T}{\partial t} + v_x\frac{\partial T}{\partial x}\right) = k_{x,c}\frac{\partial}{\partial x}\left(\frac{\partial T}{\partial x}\right) + k_{y,c}\frac{\partial}{\partial y}\left(\frac{\partial T}{\partial y}\right) + k_{z,c}\frac{\partial}{\partial z}\left(\frac{\partial T}{\partial z}\right) + \rho_r V_r Q + 2\pi f \varepsilon_0 \varepsilon'' E^2,$$

where ρ_d is the die material density, $c_{p,d}$ is the specific heat, $k_{x,d}$, $k_{y,d}$, and $k_{z,d}$ are the thermal conductivities in x, y, and z direction, respectively; V_r is the resin volume fraction, v_x is the pull speed, ρ_c is the composite material density, ρ_r is the resin density, $c_{p,c}$ is the specific heat, $k_{x,c}$, $k_{y,c}$, and $k_{z,c}$ are the thermal conductivities in x, y, and z direction respectively, and R_r is the specific heat generation rate due to resin exothermic cure reaction. Composite material density, specific heat, and conductivities can be evaluated using the rule of mixtures.

2.3 Resin Kinetics Model

During the forming process, polymeric composite materials are subjected to the cure process, characterized by an exothermic reaction which causes an increase of material temperature. Several kinetic models can be found in literature to describe the cure process; generally kinetic models relate the rate of resin reaction R_r to temperature and degree of cure, according to the following equation:

$$R_r(\alpha) = \frac{d\alpha}{dt} = K_0\, exp\left(-\frac{\Delta E}{RT}\right)(1-\alpha)^n, \tag{3}$$

where $\alpha = \alpha(t)$ is the degree of cure (conversion fraction of the reactive specie), t is the reaction time, K_o is a constant, ΔE is the activation energy, T is the absolute temperature, R is the gas universal constant, and n is the order of the reaction (kinetic exponent). Taking into account that the degree of cure is defined as the ratio of the amount of heat evolved during the curing process up to time t (indicating as $H(t)$), to the total heat of reaction (indicating as H_{tr}), yields:

$$\alpha = \frac{H(t)}{H_{tr}}, \tag{4}$$

and, after some manipulation, the heat generation rate can be rewritten as follows:

$$Q = \frac{dH(t)}{dt} = H_{tr} R_r(\alpha). \tag{5}$$

In the pultrusion process, the concentration of the resin species into the forming die is governed by the following hyperbolic equation with nonlinear source:

$$\frac{\partial\alpha}{\partial t} = R_r(\alpha) - v_x\frac{\partial\alpha}{\partial x}. \tag{5}$$

3 RESULTS AND DISCUSSION

This Section deals with the electromagnetic computational simulations of the microwave assisted pultrusion process of a fibreglass-epoxy cylindrical profile. The process scheme is shown in figure 1.
The resin volume fraction of the processing material and the part radius have been assumed, respectively, as 0.361 and 2.5 mm. A cylindrical TM_{010} cavity has been modelled as applicator for the simulated process, assuming that the internal diameter and the length of the device are, respectively, 83 mm and 138 mm, modelling the cavity walls using perfect conductor boundary conditions.

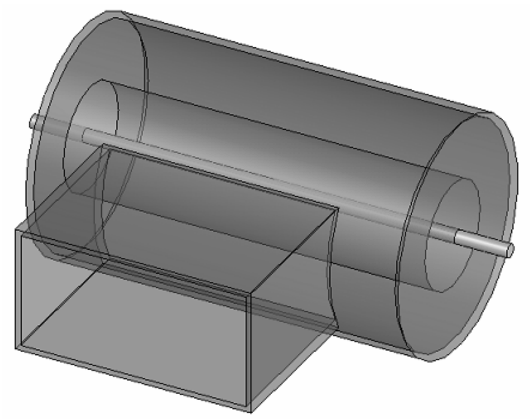

Fig. 1. Process scheme (die external radius 20 mm).

The electromagnetic power, at the conventional industrial frequency of 2.45 GHz, is transferred from the magnetron to the above cavity using a TE_{010} waveguide, whose internal dimensions have been assumed as the standard 86 mm and 43 mm, respectively along the cavity axis and in the orthogonal direction.

Table 1. Electromagnetic computational simulations.

Simulation	Die external radius	Die material
Simulation 1	Empty cavity	
Simulation 2	10 mm	Unfilled PTFE
Simulation 3	10 mm	Filled PTFE
Simulation 4	15 mm	Unfilled PTFE
Simulation 5	15 mm	Filled PTFE
Simulation 6	20 mm	Unfilled PTFE
Simulation 7	20 mm	Filled PTFE
Simulation 8	41.5 mm	Unfilled PTFE
Simulation 9	41.5 mm	Filled PTFE

A hollow cylindrical PTFE forming die has been modelled, assuming the internal radius as 2.5 mm; several simulations, summarized in table 1, have been performed varying the external radius to maximize the electric field inside the processing material. The considered external radius values are 10 mm, 15 mm, 20 mm, and 41.5 mm; in particular, in the last case, a cavity totally filled with the dielectric die has been modelled. The influence of material die properties has been investigated assuming two different sets of properties, used to simulate a filled and an unfilled PTFE.

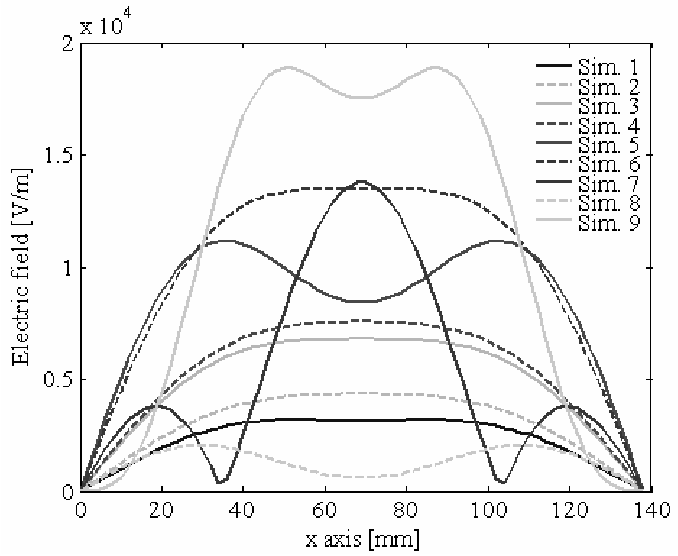

Fig. 2. Electric field at the centreline.

Taking into account that the influence of the pull speed of the processing material on the electric field distribution is negligible, in the electromagnetic sub-model transport phenomena have been neglected; heat and mass transfer phenomena are opportunely modelled in the thermochemical sub-model, assuming pull speed as 10 mm/s. The electric field profiles at the centreline of the processing material for each simulated condition are shown in figure 2.

Table 2. Thermochemical sub-model: computational results.

Simulation	Temperature peak	α_m	α_{std}
Simulation 2	62.5 °C	0.4719	5.819E-3
Simulation 3	65.4 °C	0.4892	6.448E-3
Simulation 4	99.5 °C	0.7065	3.234E-2
Simulation 5	114.1 °C	0.7791	3.067E-2
Simulation 6	136.0 °C	0.8764	2.408E-2
Simulation 7	115.9 °C	0.7655	3.870E-2
Simulation 8	79.7 °C	0.5805	2.287E-2
Simulation 9	150.9 °C	0.9169	1.678E-2

The developed model has been solved using the following initial and boundary conditions:

- the initial degree of cure α of the composite is assumed as null, its initial temperature is equal to the resin bath temperature;
- the temperature and the degree of cure of the processing material in the cross section of the die

entrance is constrained to the above values;

- the composite cross section, at the die exit, is modelled as adiabatic;
- convective boundary conditions are imposed on external die surfaces.

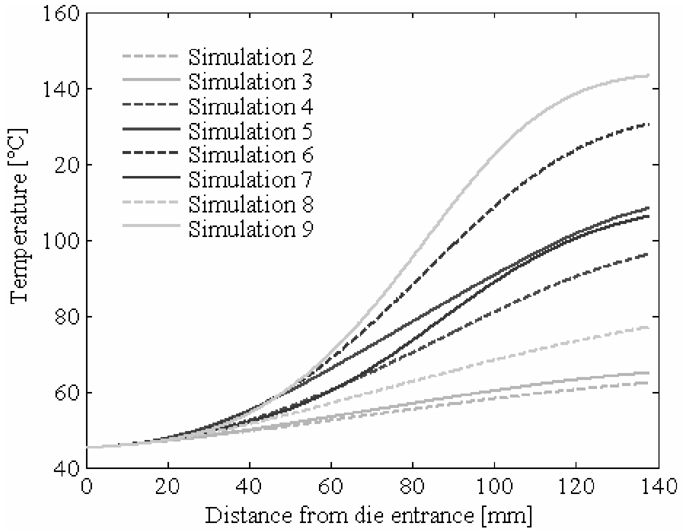

Fig. 3. Temperature profile at the centreline.

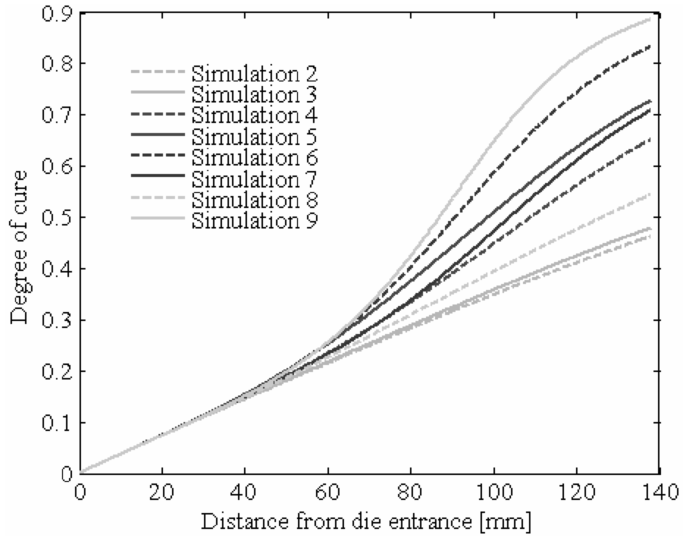

Fig. 4. Degree of cure profile at the centreline.

Some results of the thermo-chemical sub model are summarized in table 2 and shown in figures 3 and 4. As evidenced, satisfactory values of the final degree of cure are achieved only for process conditions described in simulations 6 and 9.

4 CONCLUSIONS

In this paper a computational finite element model of the microwave assisted pultrusion process has been developed. Several geometrical configurations and material properties have been investigated, underlining the relevance of the opportune design of the device and of the choice of proper materials, to obtain an effective manufacturing process. The performed simulations have also evidenced the capabilities of the microwave assisted pultrusion process with respect to the conventional process. The proposed model can be used as an effective tool for process design, analysis, and optimization.

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