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NUMERICAL SIMULATION OF THE PULTRUSION PROCESS WITH TEMPERATURE- DEPENDENT THERMAL PROPERTIES

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Abstract. *Pultrusion is a manufacturing method for fiber-reinforced composite with constant cross-section. In this process, a fiber creel is impregnated in a resin bath and passes through a heated die with a constant pulling force where the elevated die temperature induces the curing resin process. The pultrusion process is an advection-reaction-diffusion problem modeled by two partial differential equations: an energy and a degree of cure transport equations. These equations are coupled by a reactive source-term from the resin curing exothermic reaction. In this work the pultrusion process of a thermosetting composite with circular cross-section is numerically simulated to obtain the temperature and the degree of cure distributions inside the pultruded material, considering variable thermal properties (thermal conductivity and volumetric heat capacity as a function of the temperature). A two-dimensional parabolic model using the finite element method was employed. Results showed that the degree of cure development is delayed for the variables properties simulation, requiring a larger die length to reach a suitable design value of the degree of cure in comparison with the constant properties case.*
Keywords: *pultrusion, temperature-dependence, thermosetting composite, finite element method*

1. INTRODUCTION

Pultrusion process has gained significance as a composite manufacturing method over the past few years. It is a high productivity continuous process for composite materials with constant cross-section. Pultrusion of thermosetting matrices consists of two phases, namely impregnation and curing, as schematized in Fig. (1). At first, a fiber creel passes through a resin bath. The fiber impregnated with liquid resin is pulled with a constant speed through a heated die where the elevated temperature induces the curing resin process.

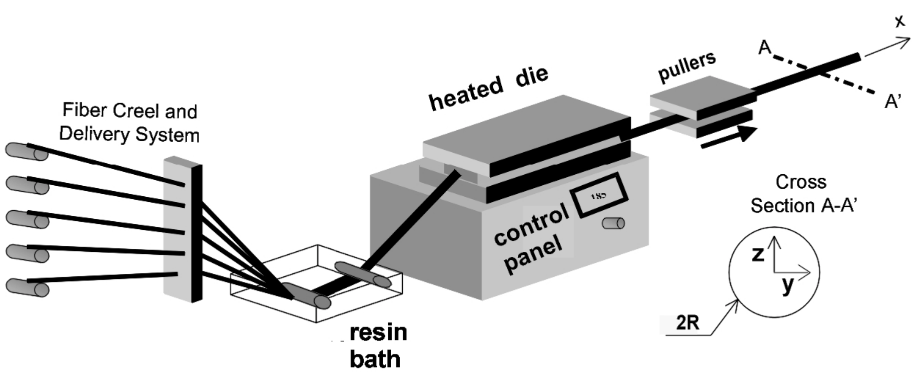

Figure 1. Schematic representation of the pultrusion process

Several works have been studied the pultrusion process: Roux et al. (1998) present experimental and numerical model results for the pultrusion of fiberglass/epoxy composites. In the numerical solution, the die temperature and degree of cure were obtained employing the finite volume method. The experimental measurements of the axial die temperature were conducted at one-second intervals as thermocouples traveled through the pultruded material. These authors performed the measurement of the axial degree of cure by the analysis of the dielectric composite material properties.

After the pultrusion machine pullers were pulling solid manufactured product, the sensors were inserted between the resin-wet fibers and allowed to pass through the heated die extension.
Ghorthala et al. (1994) and Suratno et al (1998) also simulated numerically the pultrusion process considering that the resin thermal conductivity and specific heat were constant thermal properties during the manufacturing procedure.

Yi et al (1997) studied the effect of temperature-dependent thermal properties during the curing cycle of thermosetting resins, but the combined effect of the heat transport due to resin-flow is neglected.

At this context, the objective of the present work is to study numerically the effect of variable properties (thermal conductivity and volumetric heat capacity as a function of the temperature) during the pultrusion process of thermosetting composite materials. Results obtained for the temperature-varying thermal properties are compared with the constant properties case. The influence of the pultruded bar cross-section radius on the thermal properties variation is also analyzed.

2. MATHEMATICAL FORMULATION

The present pultrusion process mathematical modeling is divided in two parts: the heat transfer problem and the resin-curing model. The pultrusion is considered a steady-state, two-dimensional process and the composite material properties are isotropic. The heat transfer process that occurs within the pultruded bar is expressed as:

$$\left[u C_p(T) \frac{\partial T}{\partial x} \right] - \vec{\nabla} \cdot \left[k(T)\, \vec{\nabla} T \right] - \frac{\partial}{\partial x}\left[k(T) \frac{\partial T}{\partial x} \right] = \dot{q} = \rho_r \Delta H \frac{D\alpha}{Dt} \tag{1}$$

where:

u = pulling speed;
$C_p(T)$ = volumetric heat capacity (density·specific heat);
T = temperature [^{0}C];
α = degree of cure;
y, z = coordinate axis at the bar cross-section;
x = axial coordinate;
$\vec{\nabla}\cdot$ = divergence operator at the bar cross-section;
$\vec{\nabla}$ = gradient operator at the bar cross-section;
$\dot{q}$ = volumetric heat rate due to the resin-cure reaction;
$k(T)$ = thermal conductivity;
ΔH = total heat of reaction per unit mass of resin and
ρ_r = resin density.

The boundary conditions are: $T = T_e$ (ambient temperature) at $x = 0$ (die entry) and $T = T_{set}$ (control set point temperature) at $y^2 + z^2 = R^2$.

For the variable properties simulation, the thermal conductivity and volumetric heat capacity of the resin are dependent of the temperature, as follow:

$$k(T) = k_0 + AT \qquad \text{and} \qquad C_p(T) = C_{p_0} + BT \tag{2}$$

where k_0 = 0.662; $A = 9.53 \cdot 10^{-4}$; $C_{p0} = 1.23 \cdot 10^6$; $B = 1.21 \cdot 10^4$ according to the data provided by Scott and Beck (1992). The degree of cure (α) is defined as the ratio between the energy liberated by the reaction until an instant of time (t) and the total energy liberated in whole cure reaction. The degree of cure variation with the time is calculated according to the expression:

$$\frac{D\alpha}{Dt} = \left[C_1 \exp\left(\frac{E_1}{RT^*} \right) + C_2 \exp\left(\frac{E_2}{RT^*} \right) \alpha^m \right] (1 - \alpha)^{2-m} \tag{3}$$

with: m = order of the reaction = 0.98 – 0.0023·T; C_1, C_2 = pre-exponential constants; E_1, E_2 = activation energy; R = universal gas constant; T^* = absolute temperature [K].

3. SOLUTION METHODOLOGY

The heat transfer process and the resin cure kinetics equations in this parabolic approximation are solved by a commercial code named PDEase2D employing the Galerkin finite element method.

The computational domain, cross-section of the pultruded bar showed in Fig. (2), is discretized using an adaptive triangular elements unstructured mesh and the axial direction (pulling axis) is evaluated by a time-like marching technique. Iterative algorithms are used to solve the algebraic equation system.

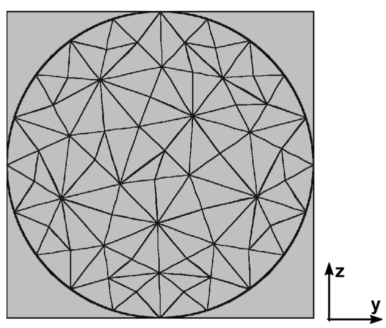

Figure 2. Computational domain

Finite element modeling has been the preferred method for converting the spatial components of complex sets of continuous partial differential equations (with well defined boundary values) to a set of discrete nodal equations for numerical solving. In this method the spatial area of interest is gridded into small patches called finite elements over which the variables are represented by simple polynomials. If a sufficiently fine grid is used and a sufficiently high order polynomial is used, a solution can be found to within any preset error limit. At the present work the Galerkin Finite Element Method of weighted residuals with quadratic basis to convert continuous partial differential equations into discrete nodal equations is used. This method insures highly accurate results and rapid convergence.

One difficult decision to make, when accuracy is required, in implementing the finite element method, is how to divide the area of interest into patches. Small patches require excessive computer time and memory. PDEase2D code solves this problem for the user by starting with a coarse grid of triangular patches (the most universal patch geometry that can be selected) and then using an iterative process to refine the grid to suit the problem. As each iteration is completed, the program determines the error in each patch and subdivides only those patches where the error exceeds a default or user specified error limit. After subdividing, recalculation is fast because of the good starting estimate provided by the previous iteration. In this way the code uses fine gridding only in those areas where sharp curvatures and tight geometries exist, providing near optimum speed and memory utilization.

4. RESULTS

The results obtained for the temperature and degree of cure using the present parabolic approach was previously compared with the data provided by the literature. These results (with constant thermal properties) are presented in Pantaleão et al. (2000) and showed that both temperature and degree of cure distributions were in good agreement with the work of Suratno et al. (1998). The influence of the resin temperature-dependent thermal properties (thermal conductivity and volumetric heat capacity) is analyzed in the present study applying Eq. (2).

The composite material properties are calculated by the mass fraction method presented in Roux et. al (1998). The fiber volume fraction used is 0.5. The resin and fiber properties values for the constant properties simulation are listed in Tab. (1). Figs. (3) and (4) show the temperature and degree of cure profiles at the pultruded bar centerline for the variable and constant thermal properties with the control set point temperature and the pulling speed given by: T_{set} = 180 [^{o}C] and u = 2.0 m/min = 0.0333 [m/s], respectively.

Table 1: Resin and fiber properties values

	k [W/(m·K)]	Cp [J/(Kg·K)	ρ [Kg/ m^3]
Resin	0.6858	$1.35 \cdot 10^6$	1200
fiber	0.76	$8.35 \cdot 10^5$	2540

At the beginning of the pultrusion process, the temperature and degree of cure profiles for constant and variable properties are almost coincident, but due to exothermic reaction evolution, the temperature and degree of cure increase suddenly implying in high thermal properties variations. After this region, the constant and variable properties distributions show larger differences, the temperature maximum value is attenuated and shifted far away from the die entrance, occurring a delay in the degree of cure development.

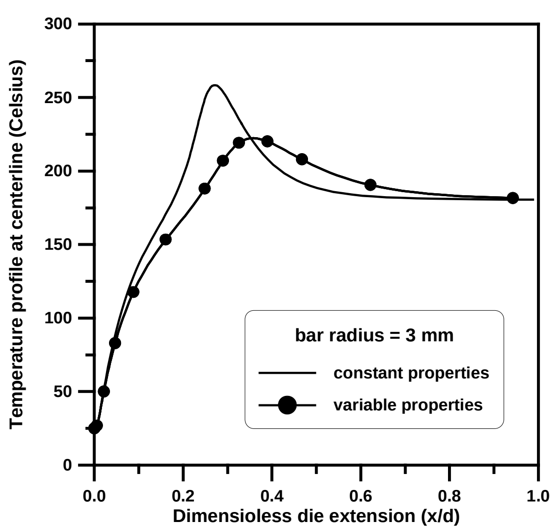

Figure 3. Comparison between the temperature profile for constant and variable properties

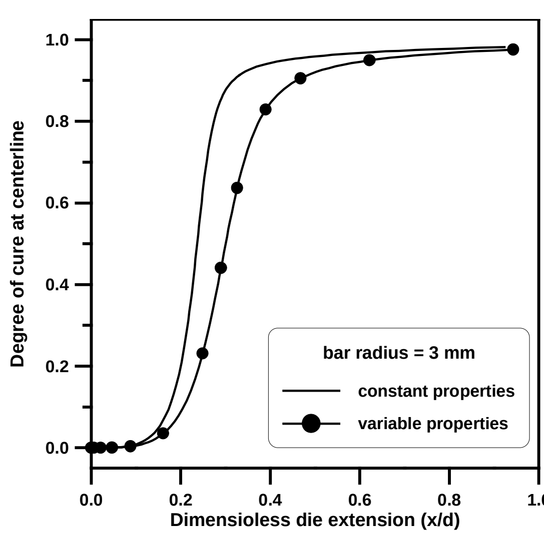

Figure 4. Comparison between the degree of cure for constant and variable properties

Figs. (5) and (6) show the influence of the pultruded cross-section radius (R) on the temperature and degree of cure centerline profiles considering variable properties. Three values were used: R = 3, 6 and 12 mm. As the radius increases, the temperature profile at the pultruded bar centerline maximum value also increases and is displaced to the right. The degree of cure illustrated in Fig. (6) exhibits a large delay for higher pultruded bar radius.

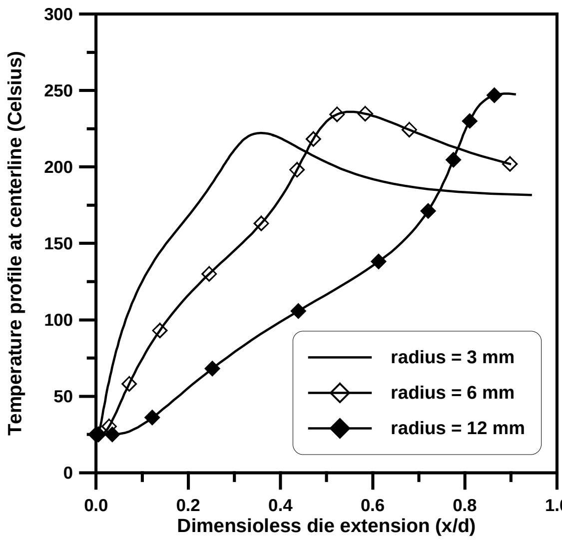

Figure 5. The influence of the pultruded bar cross-section radius in the centerline temperature profile

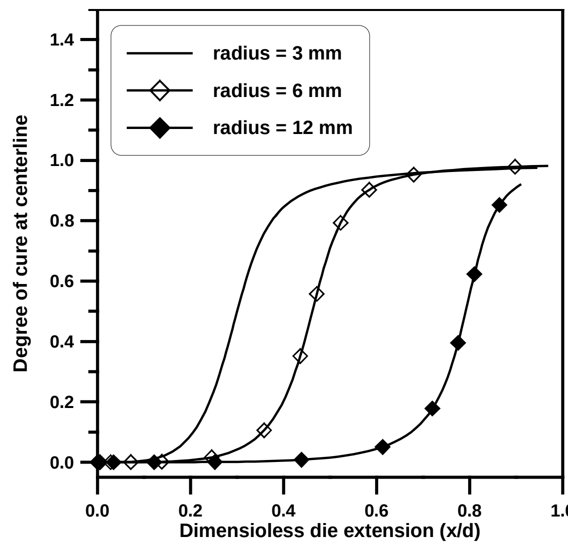

Figure 6. The influence of the pultruded bar cross-section radius in the degree of cure

5. CONCLUSIONS

At the present work the pultrusion process is numerically simulated considering the temperature dependence of the thermal properties. Results showed that the degree of cure development is delayed in the variables properties simulation, requiring a larger die length to reach a suitable design value of the degree of cure in comparison with the constant properties case. Besides, as the pultruded cross-section radius increases the volumetric heat capacity and the thermal conductivity maximum values also elevate and the profile is displaced towards the die exit extension.

6. Acknowledges

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