Viscous pull force evaluation in the pultrusion process by a finite element thermo-chemical rheological model

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ABSTRACT: This paper deals with the development of computational model to investigate a conventional pultrusion process. The model takes into account several aspects related to heat and mass transfer, crystallization kinetics, and rheological behavior of the considered processing material and allows to evaluate the viscous pull force acting between the internal die walls and the processing material. A finite element scheme has been used to solve the formulated model using suitable boundary conditions.

Key words: Pultrusion, Thermo-chemical Model, Rheological Model, Finite Element Analysis

1 INTRODUCTION

Pultrusion is a continuous manufacturing process used to shape polymeric composite materials into parts with constant cross section. The reinforcement fibres, in the form of continuous strands or mats, are placed on creel racks; fibres are pulled through a guide plate and then impregnated passing by a resin bath. Uncured material crosses a preform plate system to be correctly shaped before entering into the curing die. The die entrance is characterized by a tapered shape to remove the resin excess and make the material inlet easier. A water cooling channel is placed in the first part of the die, to prevent premature material solidification; the heat for material polymerization is provided by heating platens placed on top and bottom surfaces of the die. Outside the die, the cured composite material is pulled by a continuous pulling system and then a travelling cut-off saw cuts the part into desired length. In recent years, several researches have been performed numerically and experimentally on different problems related to the pultrusion process, focusing the attention on the analysis of the heat transfer and cure [1,2], on the pressure rise in the tapered zone of the die [3], and on process optimization [4]. In this paper computational thermo-chemical and rheological model has been developed to investigate a conventional pultrusion process. A finite element scheme has been used to solve the formulated model using suitable boundary conditions. The model evaluates the final three dimensional distributions of temperature into the curing die and the processing material, of degree of cure and viscosity into the workpiece and the viscous pull force acting between the internal die walls and the composite material, which represents the main contribution to the total force. The reduction of the pulling force reduces damages or distortion to the processing material. The theoretical formulation of the thermo-chemical model, the rheological model, and the force model has been provided in Section 2; computational simulations, results and discussion are exposed in Section 3, while Section 4 deals with some concluding remarks and a brief analysis of research perspectives.

2 GOVERNING EQUATIONS

2.1 Heat Transfer Model

The heat transfer model is based on the energy balance applied to the domain defined by the curing die and the processing material. The energy balance equation, for a generic domain, writes as follows:

$$\frac{\partial}{\partial t}\int_V \rho u\, dV = -\int_S \phi_{conv} \cdot n dS - \int_S \phi_{diff} \cdot n dS + \int_V u_{gen} dV, \tag{1}$$

where ρ is material density, φ_{conv} and φ_{diff} are the unitary convective and diffusive fluxes, respectively, u is the specific internal energy, u_{gen} is the rate of internal energy generation, V is the control volume and S its boundary surface.

After some manipulations, the balance equation for the heated die, in Cartesian coordinate system, writes:

$$\rho_d c_{p,d} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_{x,d}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_{y,d}\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_{z,d}\frac{\partial T}{\partial z}\right), \tag{2}$$

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.

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 heat transfer equation for the composite part can be written, assuming x axis as the pull direction, as follows:

$$\rho_c c_{p,c}\left(\frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x}\right) = k_{x,c}\frac{\partial}{\partial x}\left(\frac{\partial T}{\partial x}\right) + k_{y,c}\frac{\partial}{\partial y}\left(\frac{\partial T}{\partial y}\right) + k_{z,c}\frac{\partial}{\partial z}\left(\frac{\partial T}{\partial z}\right) + \rho_r V_r Q, \tag{3}$$

where 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 Q is the specific heat generation rate due to resin exothermic cure reaction.

2.2 *Reaction 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. A description of kinetic models adopted to describe the chemical behavior of resin systems in the pultrusion process can be found in [2]. Generally kinetic models relate the rate of resin reaction R_r (equal to the first derivative of the degree of cure with respect to the time) to temperature and degree of cure. In the present investigation, the resin systems reacts according to the following model [5]:

$$R_r(\alpha) = \frac{\partial \alpha}{\partial t} = K(T)(\alpha)^m (1-\alpha)^n \tag{4}$$

where $\alpha = \alpha(t)$ is the degree of cure (conversion fraction of the reactive specie), t is the reaction time, and K is a temperature dependent parameters, according to the Arrhenius equation:

$$K(T) = A\, exp\left(\frac{-\Delta E}{RT}\right), \tag{5}$$

where A is a constant, ΔE is the activation energy, T is the absolute temperature, and R is the gas universal constant.

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}), and that the resin reaction R_r represents the first derivative of the degree of cure with respect to the time, the heat generation rate can be finally rewritten as follows:

$$Q = \frac{dH(t)}{dt} = H_{tr} R_r(\alpha). \tag{6}$$

The concentration of the resin species into the forming die is governed by the following equation with nonlinear source:

$$\frac{\partial \alpha}{\partial t} = R_r(\alpha) - v_x \frac{\partial \alpha}{\partial x}. \tag{7}$$

2.3 *Rheological Model*

During the pultrusion process the viscosity of the resin is characterized by a slight drop as the temperature initially rises; however, as the reaction progresses, the resin viscosity increases and reaches the larger values near the gelation point, assumed as 0.9 in the present investigation.

The dependence of the resin viscosity on the temperature and the degree of cure has been assumed as follows:

$$\mu = \mu_\infty\, exp\left(\frac{U}{RT} + K\alpha\right), \tag{10}$$

where μ_∞, U and K are constants provided by fitting experimental data [5,6].

2.4 Pull Force Model

The pull load in the pultrusion process has been evaluated according to the four effects model, as follows:

$$f_{total} = f_{col} + f_{vis} + f_{bulk} + f_{fric}, \tag{11}$$

where f_{col} is the collimation force related to the impregnation and preforming processes, f_{vis} is the viscous force generated between the die entrance and the gel point, f_{bulk} is the bulk compaction force, acting normal to the die, and related to the compression of the reinforcement, and f_{fric} is the frictional force into the die. In particular f_{col} can be neglected cause smaller compared to the other terms, f_{bulk} acts in the tapered region of the die and influences also the frictional force f_{vis} which is assumed to disappear in the solid phase, depending on the geometry of the part. Assuming a straight die inlet and taking into account resin shrinkage, the viscous force, due to viscous drag acting between the fibers and the die wall, becomes the most relevant contribution to the total force. The viscous force has been modelled by considering a plane Couette flow with the bottom plate moving at a constant pull speed. This is given by

$$F_{vis} = \frac{v_x}{\lambda} \iint_A \mu(\alpha, T) dA, \tag{11}$$

where λ is the thickness of the resin layer between the solid boundary and the fiber adjacent to the wall. μ denotes the viscosity of the resin and v_x is the fiber pull speed. The length of the die over which the viscous force acts is governed by the gel-point of the resin.

3 COMPUTATIONAL SIMULATIONS: RESULTS AND DISCUSSION

The pultrusion of a work piece with C cross section, already used for validation purpose in [1], has been simulated to investigate the resin viscosity into the curing die and the viscous pull force. Figures 1(a) and 1(b) show, respectively, the geometry of the model and its spatial discretization in the cross section. Only half model has been considered for symmetry reason. A steel die has been considered; die length L, width W, and height H are 915 mm, 72 mm, and 72 mm, respectively. Die is heated by six platens, whose dimensions are 255 mm (length) and 72 mm (width), three platens are placed on the top surface and the remaining on the bottom surface. The temperature of each platen has been assumed as 90°. Consecutive platens are distanced by 30 mm and the empty zone is subjected to convective boundary conditions. Between the die entrance and the first platen, along a distance of 90 mm, a water cooling channel is placed to avoid resin premature gelation. Die cooler temperature is assumed as 50°C. The part enters into the die at the temperature of 30°C. Room temperature is assumed as 30°C and convective coefficient is considered as 10 W/mm^{2}K. Symmetry sections are modelled using adiabatic conditions. Composite section dimensions are shown in figure 1(b). The physical, kinetics, and rheological properties of the considered materials can be found in [5].

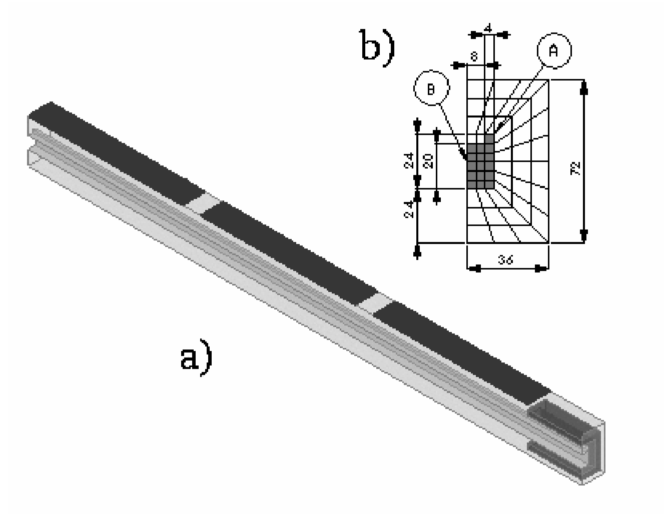

Fig. 1. Case study.

The following initial and boundary conditions have been used to solve the above formulated boundary value problem;

- The initial degree of cure of the composite is assumed as null, its initial temperature is equal to the resin bath temperature, and initial temperature of the die is assumed as the room 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;
- Adiabatic conditions are imposed also in symmetry sections;
- Constant temperatures are imposed to simulate heating platens and the die-cooler;
- Convective boundary conditions are imposed on external die surfaces.

The effect of the pull speed on temperature, degree of cure, resin viscosity, and pulling force has been investigated, assuming pull speed as 1.5, 1.3, and 1.1 mm/s for simulation 1, 2, and 3. Computational results are shown in Figures 2, 3, and 4.

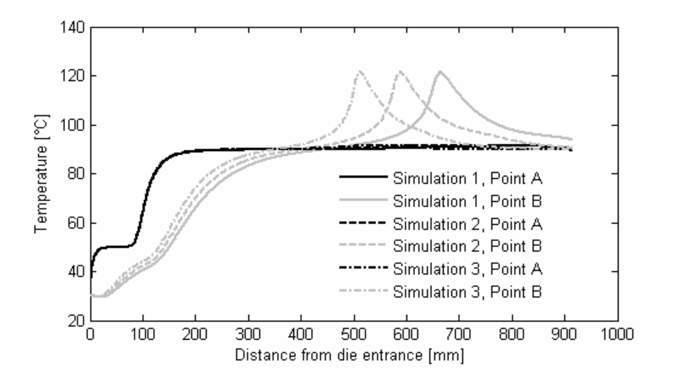

Fig. 2. Temperature profiles.

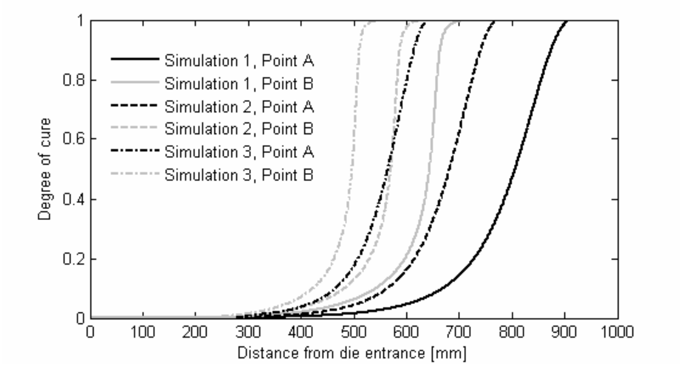

Fig. 3. Degree of cure profiles.

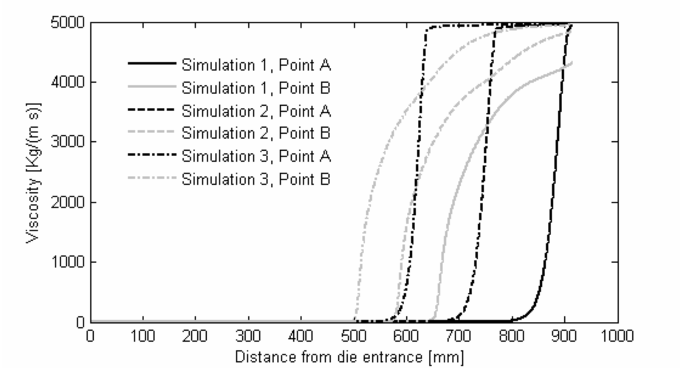

Fig. 4. Viscosity profiles.

Performed simulations evidenced that the pulling force increases with the pull speed, resulting equal to 62.6, 88.9, and 120.4 N, assuming pull speed as 1.1, 1.3, and 1.5, respectively. This trend is strictly related to the specific resin formulation, which is characterized by a very slow reaction at the initial stages of the reaction, working outside the indicated curing temperature range. This trend can be observed in Figures 2 and 3, taking into account that inside the processing part the slow heat conduction results in opportune temperature, allowing a faster cure reaction, evidenced by relatively high temperature peaks, whose position along die axis is determined by the used pull speed. Computational simulations evidenced the relevance of an opportune setting of the heating platens temperatures on the activation of the cure reaction and then on the mechanical characteristics of the final product.

4 CONCLUSIONS

In this paper a finite element model for the analysis of the thermochemical and rheological aspects related to a conventional pultrusion process has been proposed. The model allows to evaluate temperature, degree of cure, viscosity, and pulling force profiles and can be effectively used for process analysis and design.

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