Composites: Part B 68 (2015) 365–374

Contents lists available at ScienceDirect

Composites: Part B

journal homepage: www.elsevier.com/locate/compositesb

Investigation of process induced warpage for pultrusion of a rectangular hollow profile

Ismet Baran [a,*], Jesper H. Hattel [b], Remko Akkerman [a]

[a] *University of Twente, Faculty of Engineering Technology, NL-7500AE Enschede, The Netherlands*
[b] *Technical University of Denmark, Mechanical Engineering Department, 2800 Kgs. Lyngby, Denmark*

ARTICLE INFO

Article history:
Received 2 May 2014
Received in revised form 15 July 2014
Accepted 21 July 2014
Available online 16 September 2014

Keywords:
B. Cure behavior
B. Thermomechanical
C. Computational modelling
E. Pultrusion

ABSTRACT

A novel thermo-chemical–mechanical analysis of the pultrusion process is presented. A process simulation is performed for an industrially pultruded rectangular hollow profile containing both unidirectional (UD) roving and continuous filament mat (CFM) layers. The reinforcements are impregnated with a commercial polyester resin mixture (Atlac 382). The reactivity of the resin is obtained from gel tests performed by the pultruder. The cure kinetics parameters are estimated from a fitting procedure against the measured temperature. The cure hardening instantaneous linear elastic (CHILE) model is adopted for the evolution of the resin elastic modulus using the temperature-dependent elastic response provided by the resin supplier. The numerical model predictions for the warpage trend at the end of the process are found to agree well with the warpage observed in the real pultruded products. In addition, the calculated warpage magnitude is found to be in the measured range of warpage magnitude for the manufactured part.

1. Introduction

Pultrusion is a continuous and a cost effective composite manufacturing process in which constant cross sectional profiles are produced. While pultrusion machines vary in design, the process is essentially same. All reinforcements are first fed through the pre-forming guiders which start shaping the fiber reinforcements into the finished product. These reinforcements are wetted out in a resin bath and subsequently enter the heating die. The heaters initiate the exothermic chemical reaction during which the resin is being cured. The cured profile is advanced via a pulling system to the cut-off saw where it is cut to its final length. A schematic view of the pultrusion process is given in Fig. 1.

In general, industrially pultruded parts contain both unidirectional (UD) roving and continuous filament mat (CFM) layers impregnated by a thermosetting resin. The UD roving provides longitudinal tensile strength in the length of the profile. On the other hand, the CFM provides transverse strength across the width of the profile. A UD layer is transversely isotropic (TI), whereas the CFM layer can be considered as quasi isotropic (QI) since it consists of long swirled fibers randomly oriented in the plane of the mat. Therefore, the CFM layer has equal material properties in the in-plane directions [1] and the out-of-plane properties are different than the in-plane properties [2].

Among the matrix materials used in the pultrusion industry, polyester and epoxy resins are some of the most common materials. These two types of resin system behave differently in terms of curing dynamics. Both systems have inherent characteristics such as chemical shrinkage, viscosity and polymerization reactivity which are crucial for the pultrusion process. The polyester resin has higher chemical polymerization reactivity than the epoxy resins which provides a faster curing during processing. Therefore, higher pulling speeds can be used for the pultrusion of a polyester based composites [3]. Moreover, the gelation occurs at lower conversion rates or degree of cure values for the polyester as compared to the epoxy and the volumetric shrinkage varies between 6% and 12% for the polyester resins. This value can be further decreased to 2% by mixing the unsaturated polyester with “low profile” or “shrink-reducing” additives [3].

The process induced mechanical variations are generated by various mechanisms inherently existing in composite manufacturing processes such as chemical shrinkage of the thermosetting resin and mismatch in the coefficient of thermal expansion (CTE) of the fiber reinforcement and the resin [4–6]. In addition, the UD roving and the CFM layers have also different curing behavior owing to different fiber volume fractions used for these layers which results in unwanted residual deformations during the

---

* Corresponding author.
E-mail address: I.Baran@utwente.nl (I. Baran).

http://dx.doi.org/10.1016/j.compositesb.2014.07.032
1359-8368/

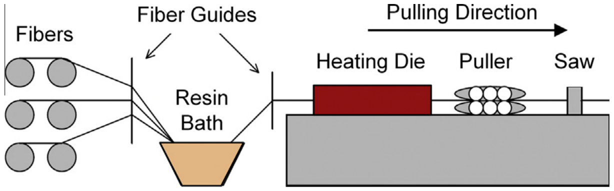

Fig. 1. Schematic view of a pultrusion process.

process. Therefore, the evolution of the process induced distortions must be well understood in order to have a better control of the mechanical behavior of the pultruded profiles. Since running a production line by trial and error is an expensive and time consuming task, the development of a numerical simulation tool to predict the process induced deformations in terms of warpage and spring-in is highly required.

Several thermo-chemical analyses of the pultrusion have been carried in literature [7–18] in which the temperature and the degree of cure distributions inside the heating die were predicted. All these contributions have only been dealing with thermal modelling of pultruded UD profiles from which the temperature and the degree of cure distributions inside the part were calculated. In addition to these thermo-chemical studies in the literature, state-of-the-art process models based on a thermo-chemical–mechanical analysis of the pultrusion for UD profiles have recently been proposed by the authors [19–21]. The development of the process induced stresses and distortions were specifically addressed in [19] in which a three dimensional (3D) transient thermo-chemical model was sequentially coupled with a 2D quasi-static plane strain mechanical model. The proposed model in [19] was further improved by using the generalized plane strain elements as well as 3D elements in [21]. The usage of (generalized) plane strain elements was found to be computationally fast for the calculation of the process induced deformations in the transverse directions.

Modelling the pultrusion process containing both UD and CFM layers has not been considered in the literature up to now. A numerical simulation tool embracing the thermo-chemical and mechanical aspects of the pultrusion for an industrial rectangular hollow profile is hence being developed in the present work. Two different micromechanics approaches are used to calculate the instantaneous mechanical properties of the UD and the CFM layers. The Atlac 382 commercial polyester resin [22] is used to impregnate the reinforcements. The resin reactivity is obtained from gel test experiments performed by a commercial pultruder and a cure kinetics model is developed based on the test data. The cure kinetics model is consequently used in the 3D thermo-chemical pultrusion simulation to calculate the temperature and the degree of cure distributions in the part. The cure hardening instantaneous linear elastic (CHILE) model [23] is adopted for the evolution of the resin elastic modulus which is temperature- and degree of cure-dependent. The coefficients used in the CHILE model are fit to the temperature-dependent elastic response provided by the resin supplier [22]. The evolution of the distortions as well as the residual warpage formation is predicted using a 2D quasi-static mechanical model developed in the general purpose finite element software ABAQUS [24]. The warpage pattern is also measured in the real pultruded products and the predicted warpage magnitude is compared with the measured data.

2. Numerical implementation

2.1. Energy and cure kinetics equations

In the present work, a 3D thermo-chemical model is used to calculate the temperature and degree of cure for the pultruded part. Since pultrusion is a continuous equilibrium-based process, the part entering the heating die keeps tracking the temperature and degree of cure profiles at steady state. Therefore, the steady state approach [18], which is convenient for the pultrusion process, is utilized for the energy and cure kinetics equations. The die is also included in this thermo-chemical model. The steady state energy equations are solved simultaneously in Cartesian coordinates for the UD layer (Eq. (1)), the CFM layer (Eq. (2)) and the die (Eq. (3)). Here, x_1 is the pulling or longitudinal direction; x_2 and x_3 are considered as the transverse directions for the UD roving layer and in-plane directions for the CFM layer.

$$(\rho Cp)_{UD}\left(u\frac{\partial T}{\partial x_1}\right) = k_{x_1,UD}\frac{\partial^2 T}{\partial x_1^2} + k_{x_2,UD}\frac{\partial^2 T}{\partial x_2^2} + k_{x_3,UD}\frac{\partial^2 T}{\partial x_3^2} + q_{UD} \quad (1)$$

$$(\rho Cp)_{CFM}\left(u\frac{\partial T}{\partial x_1}\right) = k_{x_1,CFM}\frac{\partial^2 T}{\partial x_1^2} + k_{x_2,CFM}\frac{\partial^2 T}{\partial x_2^2} + k_{x_3,CFM}\frac{\partial^2 T}{\partial x_3^2} + q_{CFM} \quad (2)$$

$$0 = k_{x_1,d}\frac{\partial^2 T}{\partial x_1^2} + k_{x_2,d}\frac{\partial^2 T}{\partial x_2^2} + k_{x_3,d}\frac{\partial^2 T}{\partial x_3^2} \quad (3)$$

where T is the temperature, u is the pulling speed, ρ is the density, Cp is the specific heat and k_{x_1}, k_{x_2} and k_{x_3} are the thermal conductivities along x_1-, x_2- and x_3-directions, respectively. The subscripts UD, CFM and d correspond to the UD layer, the CFM layer and the die, respectively. Lumped material properties are used and assumed to be constant. The source term q in Eqs. (1) and (2) are related to the internal heat generation due to the exothermic reaction of the polyester resin and expressed as [11]:

$$q_{UD} = (1 - V_f)_{UD}\rho_r H_{tr} R_r(\alpha, T) \quad (4)$$

$$q_{CFM} = (1 - V_f)_{CFM}\rho_r H_{tr} R_r(\alpha, T) \quad (5)$$

where H_{tr} is the total heat of reaction for the polyester during the exothermic reaction, ρ_r is the resin density, V_f is the fiber volume fraction, α is the degree of cure, and $R_r(\alpha, T)$ is the reaction of cure which can also be defined as the rate of α, i.e. $d\alpha/dt$. In literature, several kinetic models have been proposed and analyzed to describe the resin curing reactivity [25,26]. In the present work, a well known semi-empirical autocatalytic model [23] which is an Arrhenius type of equation is utilized. The corresponding expression is given as:

$$R_r(\alpha, T) = \frac{d\alpha}{dt} = A_0 \exp\left(\frac{-E_a}{RT}\right)\alpha^m(1-\alpha)^n \quad (6)$$

where A_0 is the pre-exponential constant, E_a is the activation energy, R is the universal gas constant and m and n are the orders of reaction (kinetic exponents).

The material derivative of the degree of cure field (Eq. (6)) is translated into a partial derivative form in a Eulerian frame of reference in the pulling direction and expressed as [19]:

$$R_r(\alpha, T) = \frac{d\alpha}{dt} = \frac{\partial\alpha}{\partial t} + \frac{\partial\alpha}{\partial x_1}\frac{dx_1}{dt} = \frac{\partial\alpha}{\partial t} + u\frac{\partial\alpha}{\partial x_1} \quad (7)$$

and from Eq. (7), the relation of the resin kinetics equation for the steady state approach (i.e. $\partial\alpha/\partial t = 0$) can be expressed as:

$$0 = R_r(\alpha, T) - u\frac{\partial\alpha}{\partial x_1} \quad (8)$$

which is used in the 3D steady state thermo-chemical model.

The equations above are solved using the commercial finite element code in ABAQUS. The evaluation of the degree of cure and the reaction rate has been obtained by means of in-house developed routines implemented in ABAQUS.