IMPROVED CURE SIMULATION IN PULTRUSION PROCESS ABOUT HEATING SYSTEMS: A CASE STUDY

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Abstract
In this work some case studies relationed to the optimization of the die-temperature in the pultrusion of a thermosetting composite are presented. During composite processing, reinforcing fibers are first impregnated with a liquid resin in an injection box or resin bath. Afterwards fibers and resin are preheated in a mold in which the curing process takes place. Nowadays, many industries seek a change of the pultrusion process and adopt different technical approaches in processes to reduce power consumption. The aim of this study is to provide an increase in the number of arrangement possibilities and, hence, enabling the determination of the best heaters configuration capable of minimizing the energy rate and maximizing the degree of cure. Several case studies were conducted where the degree of cure was analyzed for varying heating scenarios on different positions of heaters. Results have shown that it is possible to get a higher cure in less process time if the heaters are placed in an optimum configuration, thus providing a better distribution of the heat along the die length and minimising the service time of the embedded resistances.

1. Introduction

Pultrusion is a continuous composite manufacturing process in which constant cross-sectional parts are produced. While pultrusion machines present different designs, the process is quite similar. In such systems, the reinforcements (fiber) are first pulled through the pre-forming guides that start shaping the fiber reinforcements into the final composite product. These reinforcements are wetted out in an open resin bath or a closed injection box and subsequently enter into a heating die. The heaters initiate the exothermic cure reaction while being pulled through the die. Then, the cured profile is advanced via a pulling system to the cut-off saw where it is finally cut to its final length [1]. A non-uniform degree of cure across the composite cross-section implies a product of undesirable quality. Many variables, such as die temperature, pull speed, and chemical kinetics influences the curing reaction inside the die. Among all, the heater temperature is closely related to the final degree of cure of the product. Hence, the uniformity of cure can be improved significantly by optimizing the die heating environment [2]. The pultrusion process has been investigated both numerically and experimentally in which the main aim is to provide a better comprehension of the process by analyzing the temperature and the degree of cure profiles inside the heating die. During the cure, the phase of the resin is changed from liquid to a rubbery state. Following this transition, the resin is cured and finally the composite part is solidified, where vitrification occurs when the resin glass transition temperature (Tg) becomes higher than the cure temperature. In this study, a general-purpose FE software, ANSYS-CFX has been

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utilized to perform a three-dimensional (3D) conductive heat transfer analysis. Given this, the present paper intends to investigate the influence of heaters position over the degree of cure. In summary, studies with different arrangement were performed enabling the determination of the optimum heaters configuration capable to minimize the energy rate and maximize the degree of cure.

1.1. Heat transfer and development of simulation procedure

Getting a better understanding and enabling to predict a pultrusion process is possible if modeling and simulation are used. Therefore knowledge of the transport phenomena involved is required, which implies the use of mathematical models to predict the physicochemical behavior of the material during processing. For such studies, the mold is usually considered to be the central part of the process, as it is the area where most of the cure reaction and heat transfer takes place. Heat transfer is defined by the thermal energy in transit due to temperature differences. The transfer of energy as heat occurs at the molecular level as a result of a temperature difference [3]. During composite processing, the heat flux provided by the mold must be sufficient to promote the polymerization reaction of the thermosetting matrix (curing). Furthermore, due to the exothermic character of the curing reaction, inside the composite increased temperatures imposed by the cure cycle might occur. This temperature rise can cause degradation of the final product. Thus, the process simulation is entirely necessary for the prediction of pre-heating and die-cooler temperature [4].

The simplest objective function found in the literature for the pultrusion process is shown in (Eq.1) [5]. The uniformity of cure is measured by calculating the root mean square deviation of the composite values degree of cure, in the mold outlet section, relative to a desired curing degree value as written in the following equation:

$$f = \sum_{i=1}^{N} \frac{\left(\alpha^{\max} - \alpha_i\right)}{N-1} \tag{1}$$

Where $\alpha^{\max}$ is the maximum value of the degree of cure to be obtained in the process, α_i is the degree of cure at each grid point and N is the total number of points in the output section of the mold. The authors used the finite difference method to model the pultrusion process and a combination of simplex and genetic algorithm methods to find the optimum cure cycle. Furthermore, in [6] the authors also conducted simulations of the pultrusion process using the method of finite elements. It was revealed that both methods can satisfactorily describe the experimental behavior. However, the finite element method requires a smaller number of discretization points. Joshi and Lan [7] discussed the application of a FE method for pultrusion simulation. According to the authors, the initial temperature conditions namely, the pre-die temperature of composite and the die-cooler temperature are crucial for the cure improvement. In FE analysis, the three-dimensional heat transfer in a continuously moving composite preform is modelled according to (Eq.2):

$$\rho_c C_p \left(\frac{\partial T}{\partial t} + w \frac{\partial T}{\partial z} \right) = \nabla\left(\bar{k}_c \nabla T\right) + \frac{\partial H}{\partial t} \tag{2}$$

where ρ is the density, C_p is the specific heat, k_c is the conductivity, t is the time, ∇ is the differential operator, w is the pull-speed, and z is the pull direction. Subscript *c* denotes composites. The term $\partial H / \partial t$ defines the rate of internal heat generation and is expressed as:

$$\begin{aligned} \frac{\partial H}{\partial t} &= \rho_r v_r H_t \left[\frac{\partial \alpha}{\partial t} + w \frac{\partial \alpha}{\partial z} \right] \\ &= \rho_r v_r H_t \left[B_0 \exp\left(\frac{-\Delta E}{R(T + 273.15)} \right) (1-\alpha)^n + w \frac{\partial \alpha}{\partial z} \right] \end{aligned} \tag{3}$$

where H_t represents the total heat of reaction per unit mass of resin, v the volume fraction, α the degree of cure, B_0 the pre-exponential constant, ΔE the activation energy, R the universal gas constant, n the order of cure reaction, and subscript r the resin. $\partial \alpha / \partial t$ describes the rate of cure reaction of the matrix material using an empirical cure kinetics model. Such Arrhenius type of reaction models are commonly used for describing curing of thermosetting resins [8].

1.2. Material properties and pultrusion parameters

The software used in this work to simulate the pultrusion process is ANSYS CFX™. This software is based on the method EbFVM (Element-based Finite Volume Methods). Such approach is a finite volume method that is similar to the finite element method in defining elements and their form of interpolation functions for the interior of the element. The use of this computational package for studying the pultrusion model is mainly justified by the high ability to simulate problems that include heat transport coupled to chemical reactions in irregular geometries [9]. A chrome steel die was used, whereas the composite section consisted of glass fiber reinforcement and Shell EPON 9420/9470/537 epoxy resin system. The properties of the materials used in the simulation are listed in (Table 1). The cure kinetics parameters in Eq. (2) for the resin are taken from the literature.

For the resin the kinetic parameters corresponds to B_0=1.914x105 (s^{-1}), ΔE= 6.05x104 (J/mol), R=8.3243 (J/mol K), n=2, and H_t=398 (J/g), which means Arrhenius pre-exponential factor, activation energy, universal gas constant, kinetic order, and reaction energy.

Table 1. Material properties used in the simulation

Material	Density ρ (kg/m^3)	Specific heat C_p (J/kg K)	Thermal conductivity J/(m K s)
EPON 9420/9470/537 Epoxy resin	1260	1255	0.169
Glass fibers	2560	670	1.04
Crome (5%) steel	7833	460	40

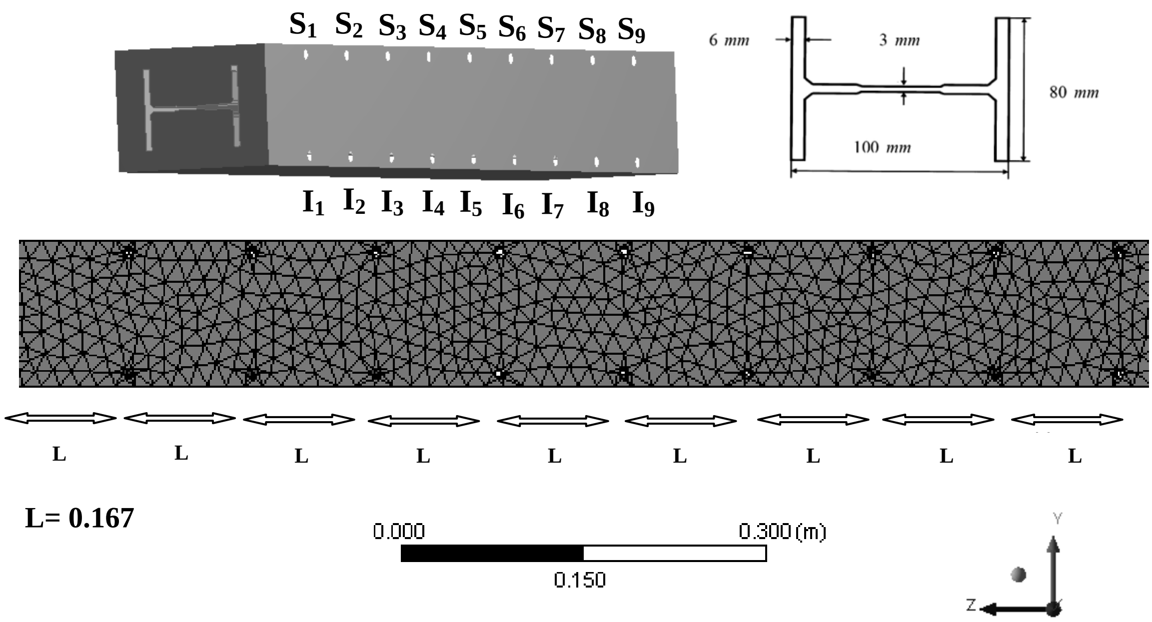

Figure 1. Dimensions of die/composite

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1.3. Details of FE model and pultrusion die

Simulation studies were carried out for the pultrusion of an asymmetric I-section. The details of the die/composite geometry and the FE model are shown in (Fig. 1). A total of eighteen internal heaters with cylindrical cross section of diameter 0.002 m and area of 0.005 m^2, were mounted to heat up the die. The die dimensions were 0.1 m (width) by 0.1 m (height) by 1.020 m (length). A total of 15931 nodes, 66079-elements, solid field were used to create the FE.

2. Results and discussion

The simulation of a pultrusion of a work piece with a "I" cross section has been performed. Some works [3] in this area were studied, where an alternative mold configuration with internal heaters was studied. The aim was to provide an increase of the number of arrangement possibilities and, hence, enabling the determination of the best heaters configuration capable to minimize the energy rate and maximize the degree of cure. Silva et al., [10] showed in his study that significant reduction of energy consumption could be obtained using embedded cylindrical heaters into the mold instead of external planar resistances, like presented by Santos at al.

Based on the above studies, this paper will show some case studies using finite element method with the commitment of modifying the position of the internal mold heaters, leading case studies with different positions. In this study, a general purpose FE software, ANSYS-CFX, has been utilized to perform a three-dimensional (3D) conductive heat transfer analysis. During simulation, the inlet temperature was maintained the same, equal to 300 K and the pulling speed equals to (5 mm/s. The heaters are named as Q_s (superior heaters) and Q_I (inferior heaters) like shown in (Fig. 1).

In case study 1, different heaters configurations, with 401K, were considered as input for the simulation and a pulling speed equals to 5 mm/s was applyed. The purpose of such study was to verify the performance of the cure reaction during the pultrusion process, evaluating the heat distribution along the die. The second case study aimed analysing the effect of different temperature values over the the mean degree of cure. Given this, a minimum degree of cure equals to 0.9 was considered to be reached at the die exit.

As shown in (Table 1), the maximum degree of cure at the die exit was equal to 0.519 (iteration 2). Notice that all heaters were used in this configuration (see Fig. 1). It is clear that the temperature of 401 K is not sufficient to obtain a degree of cure higher of equals to 0.9 for the proposed configuration. Nevertheless, it is possible to observe that different configurations (positions) can be used to reach the desired degree o cure. For example, the mean degree of cure obtained in iterations 6 and 8 are considerably close to iteration 1, but the heater positions are clearly different. On the other hand, other configurations, such as, iterations 5 and 9 present lower mean degree o cure. This result can be explained by the fact that the heat is better distributed when the heaters are distributed equidistantly around the mold (i.e. when superior and inferior heaters are used). However, an optimization study would be necessary to compute the exact positions and temperature values of each heater.

Our results are in general agreement with the results achieved by Santos et al. , and Joshi et al. If cases A and B are compared, it is evident that the degree of cure increases with temperature, as expected. Similar behaviour was observed in all cases. However, only a very small enhancement of degree of cure is observed when the temperature changes 4 K from case E to A. This suggests that the temperature should be carefully adjusted in order to improve the degrre of cure. Although this was not obtained experimentally, we suspect that such sensibility (between temperature and degree of cure) varies with heater positions. Future work should therefore include a more detailed study involving different heater arrangements.

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Table 1. Case study 1

Interation n°	Highest temperature in the composite (K)	Máximum degree of cure at die exit	Connected heaters
1	401.0	0.461	Upper heaters
2	401.0	0.519	All heaters
3	401.0	0.411	$Q1_s$ $Q3_sQ5_sQ7_s$ $Q9_s$
4	401.0	0.489	$Q1_{si}$ $Q3_{si}$ $Q5_{si}$ $Q7_{si}$ $Q9_{si}$
5	401.0	0.392	$Q1_sQ3_sQ4_sQ5_sQ6_sQ9_s$
6	401.0	0.512	$Q1_{si}Q3_{si}Q4_{si}Q5_{si}Q6_{si}Q9_{si}$
7	401.0	0.430	$Q1_sQ2_sQ4_sQ5_sQ6_sQ8_sQ9_s$
8	401.0	0.510	$Q1_{si}$ $2_{si}Q4_{si}Q5_{si}Q6_{si}Q8_{si}Q9_{si}$
9	401.0	0.413	$Q1_sQ2_sQ3_sQ6_sQ7_sQ9_s$
10	401.0	0.485	$Q1_{si}Q2_{si}Q3_{si}Q6_{si}Q7_{si}Q9_{si}$

Table 2. Setting of heaters and Temperature

Setting of heater	Temperature of each heater (K)
A	Q1=373,Q2=378.5,Q3=421.5,Q4=473,Q5=473,Q6=473,Q7=473,Q8=473,Q9=473
B	Q1=371,Q2=376.5,Q3=419.5,Q4=471,Q5=471,Q6=471,Q7=471,Q8=471,Q9=471
C	Q1=369,Q2=374.5,Q3=417.5,Q4=469,Q5=469,Q6=469,Q7=469,Q8=469,Q9=469
D	Q1=367,Q2=372.5,Q3=415.5,Q4=467,Q5=467,Q6=467,Q7=467,Q8=467,Q9=467
E	Q1=365,Q2=365,Q3=413.5,Q4=413.5,Q5=413.5,Q6=465,Q7=465,Q8=465,Q9=465

Table 3. Case study 2

Máximum degree of cure at die exit	Setting of heater
0.908	A
0.903	B
0.904	C
0.900	D
0.893	E

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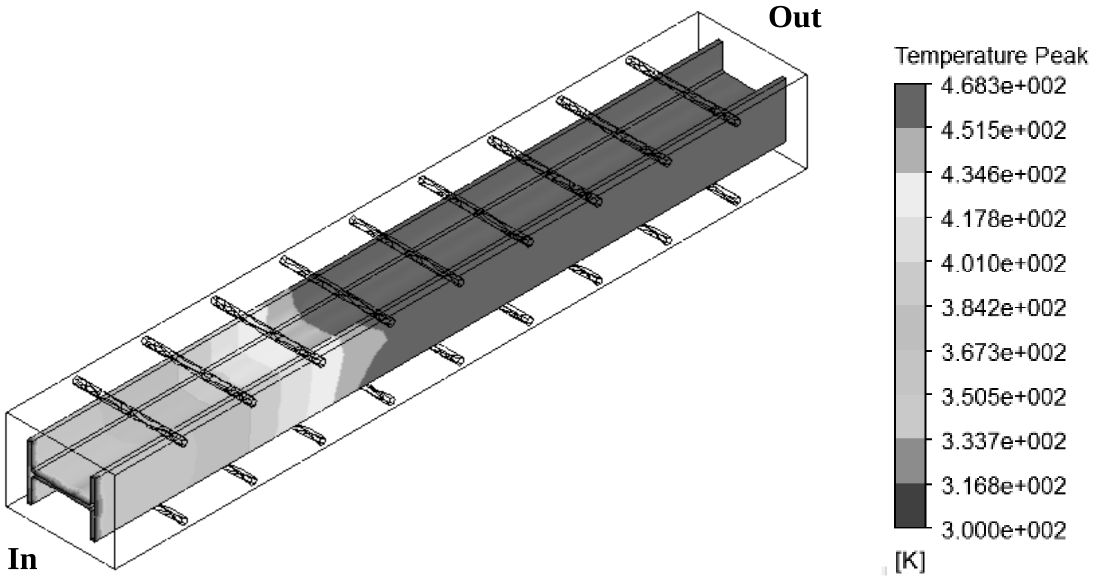

Figure 2. Temperature profiles for Setting of heater C of case study 2 with Pull-speed of 5 $mm.s^{-1}$.

2. Conclusion

Results of this work show that for all interactions the best heaters setting is when the upper and lower heaters are attached simultaneously and due to having a lesser spacing between the heaters. This study shows satisfactory values reaching a degree of cure at die exit equal 0.9 for a pulling speed of 5 mm/s.

Previous work found that the use of embedded cylindrical heatering elements, instead of external planar heaters, leads to a significant reduction of the power consumption on the die heating system. Thus, the relative position of the cylindrical resistances may play an important role on the heating system, providing a better distribution of the heat along the die length. For next steps of the current study, we suggest a deterministic optimization to quantify more precisely spatial position of the heaters.

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References

[1] I. Baran, H.H. Jasper, and A. Remko. Investigation of process induced warpage for pultrusion of a rectangular hollow profile. *Composites: Part B*, 68 (2015) 365-374.
[2] I. Baran, C.C. Tutum, M.W. Nielsen, and J.H. Hattel. Process induced residual stresses and distortions in pultrusion. *Composites: Part B*, 51 (2013) 148-161.
[3] L.S. Santos. Simulação e Otimizaçao do Processo de Pultrusão. MSc Dissertation, *Departament of Chemical. Federal University of Rio de Janeiro, Brazil*; 2009

Excerpt from ISBN 978-3-00-053387-7

[4] T. Hans and R. Hinterhölzl. A numerical approach modeling the braiding process for arbitrary mandrel shapes to calculate preform properties. *Proceedings of the 20th International Conference on Composite Materials ICCM-20, Copenhagen, Denmark,* July 19-24 2015.

[5] J. Li, S.C.J. Joshi, and Y.C. Lam. Curing optimization for pultruded composite sections. *Composites Science and Technology,* 62 (2002) 457-467.

[6] P. Carlone , G.S. Palazzo, and R. Pasquino. Pultrusion manufacturing process development: Cure optimization by hybrid computational methods. *Computers and Mathematics with Applications,* 53 (2007) 1464-1471.

[7] S.C. Joshi, Y.C. Lam, and U.W. Tun. Improved cure optimization in pultrusion with pre-heating and die-cooler temperature. *Composites: Part A*, 34(2003) 1151-1159

[8] W.I. Lee, A.C Loos, and G.S Springer. Heat of reaction, degree of cure, and viscosity of Hercules 3501-6 resin. *Journal of Composite Materials*, 16 (1982) 510-520.

[9] Y.S. Eom , L .Boogh, V. Michaul, P. Sunderland, and J.A. Manson. Time-cure-temperature superposition for the prediction of instantaneous viscoelastic properties during cure. Polymer Engineering & Science, 40(2000)1281-1292.

[10] Silva FJG, Ferreira F, Costa C, Ribeiro MCS, Castro ACM, Castro MRA, Dinis ML, Fiúza A. Optimising the energy consumption on Pultrusion process. Composites: Part B (2014); 57: 12-20

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