A Numerical Study of Online Cure Kinetics Characterization during Liquid Composite Molding

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ABSTRACT

In Liquid Composite Molding (LCM), the resin impregnates the fiber preform and cures to form the composite part. The resin cure is an exothermic process and requires the mold heating profile to be optimized to reduce the cure cycle time and the cure induced thermal stress in the composite part. To optimize and control the cure cycle, it is necessary to obtain the resin cure kinetic parameters, which are usually measured offline by Differential Scanning Calorimetry (DSC) or Fourier transform infrared spectroscopy for neat resin and sometimes can be substantially varied due to the presence of fibers or the resin handling. In this paper, a model-based fitting technique to characterize the cure kinetics during LCM and its accuracy are studied numerically. A non-isothermal cure simulation of a composite part is performed based on a given set of cure kinetic parameters, which are the targets of the fitting process. The Genetic Algorithm is used to determine the cure kinetic parameters by matching the simulated temperature field based on the guessed cure parameters with the temperature history the composite part experienced. An uncertainty in temperature reading, which usually happens in real temperature measurement and control, is introduced to evaluate the accuracy and stability of this characterization technique with respect to various fitting periods during the cure process. Since the mold heating cycle will affect the cure history and the cure kinetics characterization, the influence of the mold wall temperature on the characterization accuracy is also investigated. The results show that by appropriately choosing the mold heating cycle, one will be able to enhance the accuracy and stability of the cure kinetics characterization within a reduced characterization period and hence can reserve more time for the following online cure optimization and control during the cure cycle. A numerical case study indicates great possibility of creating such a self-sufficient cure cycle optimizer by dividing the complete cure cycle into a cure characterization period and a cure optimization period.

KEYWORDS: Cure Kinetics Characterization, Cure Cycle Optimization, LCM, RTM, VARTM, Sensing and Control.

INTRODUCTION

In Liquid Composite Molding process such as RTM and VARTM, the liquid resin infiltrates the fiber preform inside a mold cavity due to the pressure difference between the resin injection gate and the vent. After the resin completely saturates the preform, the resin starts to cure and binds the fibers together to form solid composites.

During the resin infiltration stage, the resin cure process is usually inhibited to maintain the resin viscosity low because the goal is to have the pressure driven resin to impregnate the preform completely before the resin gels. In the resin filling stage, the flow of resin and mold filling pattern can be modeled and controlled effectively based on the well characterized preform permeability, porosity, and resin viscosity [1,2,3,4,5]. Once the resin fills the mold, one will have to control the cure cycle to obtain quality composite parts. The cure cycle optimization has several objectives: (i) to achieve high degree of cure (resin conversion), (ii) to minimize the accumulated residual stress and strain induced by non-uniform temperature and resin conversion the composites experienced during the exothermic cure process, (iii) to control the temperature of the composites from thermal degrading limit, (iv) to minimize the total time required to complete the cure process.

To design a good cure cycle, numerical modeling and optimization techniques have been applied to achieve the above-mentioned objectives by many researchers [6-11]. Due to the relatively small thickness compared with the in-plane dimensions of most of LCM parts, the cure process may be modeled as an 1-dimensional transient heat conduction problem coupled with a heat source term representing the reaction heat released by the polymer molecules cross-linking. The temperature of the mold walls can be controlled to influence the rate of resin cure (cross-linking) and hence achieve satisfactory temperature and cure history of the composites. Evolution strategies [6,7], gradient-based optimization techniques [8,9], and expert systems [10,11], have been used to control the cure cycle of composites. As many of the optimization techniques are coupled with numerical modeling, acquiring reliable and accurate thermal and cure kinetic parameters becomes very important for the cure cycle prediction and optimization. The resin cure parameters can be characterized off-line b [illegible] ning Calorimetry (DSC) and ultrasound [12] or fitted directly from composites thermal history for complete cure cycles [13]. The direct fitting techniques based on composites temperature measurement may be more favorable for LCM processes due to the complexity of such processes and the uncertainty involved in resin handling such as catalyst concentration variation [14]; however, the confidence level of such type of fitting method have not been fully investigated.

In this paper, an evolution strategy (genetic algorithms) fitting technique has been coupled with 1-dimensional cure simulations to study the reliability of the direct fitting method under different temperature measurement noise levels. Furthermore, the feasibility of creating a self-sufficient cure cycle optimizer by dividing the complete cure cycle into a cure characterization period and a cure optimization period will be evaluated.

CURE PROCESS MODELING AND CHARACTERIZATION METHODOLOGY

The heat balance of the composites can be modeled as 1-dimensional heat conduction in the thickness direction as:

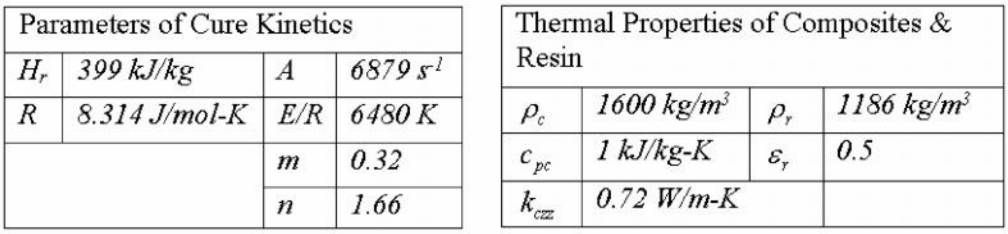
$$\rho_c c_{pc} \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(k_{czz} \frac{\partial T}{\partial z} \right) + \rho_r \varepsilon_r H_r \frac{\partial c}{\partial t} \tag{1}$$

where ρ_c, c_{pc}, k_{czz} are the density, specific heat capacity, and thermal conductivity-in the thickness direction of the composites respectively.

The heat generation rate due to the resin cure is described by the resin density ρ_r, the porosity ε_r, the reaction heat of resin H_r, and the resin cure rate $\partial c/\partial t$. The reaction model of the resin is given by [15]:

$$\frac{\partial c}{\partial t} = A \cdot \exp\left(-\frac{E}{RT}\right) \cdot c^m \cdot (1-c)^n \tag{2}$$

where c is the degree of cure (or conversion) and is ranged between zero and unit, A is the pre-exponential factor, E is the activation energy, R is the universal gas constant. The exponents m, n are ranged between zero and two, and $m+n \cong 2$ [13]. The values used in this numerical case study are listed in Table 1.



Parameters of Cure Kinetics			
H_r	399 kJ/kg	A	6879 s^{-1}
R	8.314 J/mol-K	E/R	6480 K
		m	0.32
		n	1.66

Thermal Properties of Composites & Resin			
ρ_c	1600 kg/m^3	ρ_r	1186 kg/m^3
c_{pc}	1 kJ/kg-K	ε_r	0.5
k_{czz}	0.72 W/m-K		

Table 1. Parameters of cure kinetics [15] and thermal properties [8] used in this numerical study.

The composite part is assumed to be 5 cm thick. Five nodes are used to simulate the heat conduction and cure process through the thickness. By giving a controlled mold wall heating cycle, the initial composites temperature ($T_0=293.17K$), and the initial resin conversion ($c_0=10^{-4}$), the temperature (T) and cure (c) history of the composites can be solved using explicit finite difference scheme from $t = 0$ to $t = t_{total}$. Then, the noise of measurement and control is introduced and hence the temperature measurement becomes $T_{\exp} = T \pm \lambda\Delta T$ with $-1 \le \lambda \le 1$. Based on the temperature measurement, a genetic algorithm optimizer is used to search the values of A, E, m, c_0 by minimizing the objective function from $t = 0$ to $t = t_s$ (which is the time to stop fitting):

$$\Omega_T(0,t_s) = \frac{1}{5t_s}\sum_{node=0}^{4}\int_0^{ts}\left(T_{\exp} - T_{fitting}\right)^2_{node} dt \tag{3}$$

where $T_{fitting}$ is the simulated temperature based on guessed cure parameters A, E, m, c_0.

RESULTS AND DISCUSSION

The baseline temperature and cure histories are shown in Figure 1. Assume the temperature measurement noise level is $\Delta T = 3K$, the fitted temperature and cure results for different values of t_s are shown in Figure 2 and Figure 3. Comparing Figure 2 and Figure 3 one observes that with fitting period $t_s=10000s$, the following temperature and cure predictions agree with the baseline much better than the case with short fitting period $t_s=5000s$. On the other hand, comparison between Figure 2 and Figure 4 shows that with the reduced measurement noise level $\Delta T = 1K$, better fitted results can be obtained for short fitting period $t_s=5000s$.

The results suggest that the confidence level of such direct fitting method increases as the measurement noise ΔT is reduced and the fitting period t_s is prolonged.

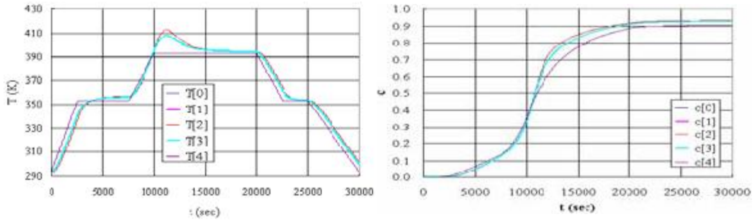


Figure 1. Baseline temperature and cure histories.

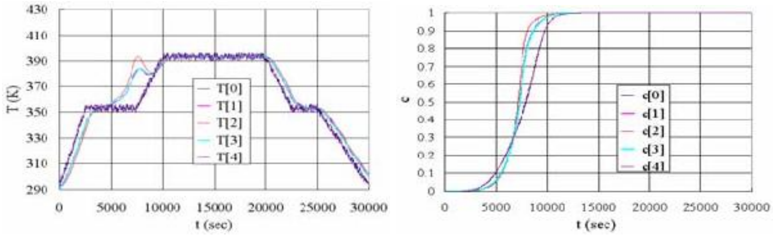


Figure 2. Fitted temperature and cure results for t_s=*5000s* and $\Delta T = 3K$.

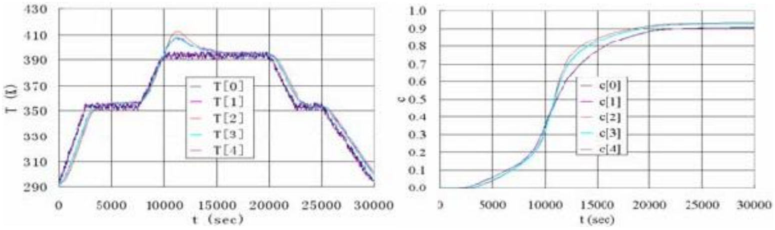


Figure 3. Fitted temperature and cure results for t_s=*10000s* and $\Delta T = 3K$.

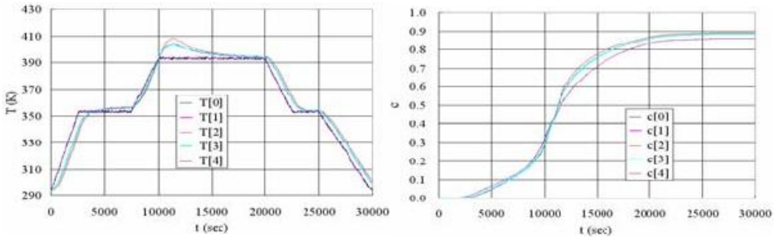


Figure 4. Fitted temperature and cure results for t_s=*5000s* and $\Delta T = 1K$.

To numerically investigate the feasibility of combining this online cure kinetics characterization technique with the online cure cycle optimization, a short fitting time t_s=*5000s* and a higher wall temperature are used during the cure kinetics fitting period. Based on the fitted cure parameters, the remaining cure cycle after t_s is optimized to achieve short cycle time and less thermal gradient and cure gradient in the thickness direction after $c > 0.70$. The noise is introduced through the whole cycle since the noise can be induced from both measurement and control system. The simulations of the integrated cure characterization and optimization are shown in Figure 5. The temperature and cure results of the optimized cure cycle are then calculated again by using the correct cure kinetic parameters listed in Table 1. The results represent the ideal and noise free data the composites should experience during the process and are shown in Figure 6.

Comparing Figure 5 and Figure 6, one can find that the fitting technique provides good temperature and cure predictions which agree well with the ideal data.

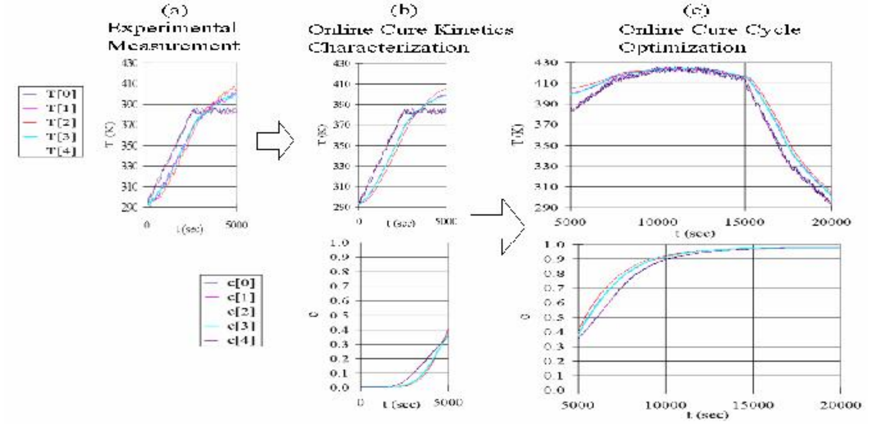


Figure 5. Simulation of integrated cure kinetics characterization and cure cycle optimization (a) Simulated temperature measurement with $\Delta T = 3K$ until t_s=*5000s*. (b) Fitted temperature and cure results. (c) Optimized cure cycle based on the fitted cure kinetic parameters.

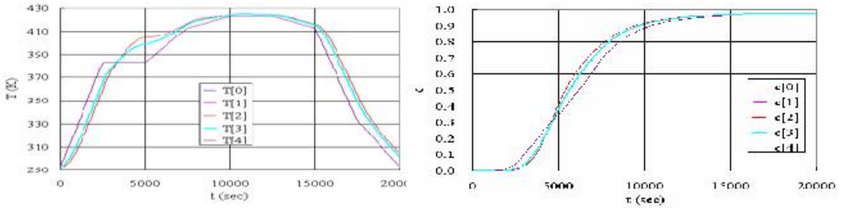


Figure 6. Temperature and cure simulations for the optimized cure cycle using the correct cure kinetic parameters listed in Table 1.

CONCLUSION

To obtain reliable and accurate cure kinetic parameters is very important for LCM cure cycle management. A direct fitting technique consisting of a genetic algorithm optimizer and 1-dimensional cure simulator was developed to assess the confidence level of such a direct fitting approach subjected to different cure fitting periods, temperature measurement noise levels, and mold heating cycle. The results suggest that the confidence level of such a direct fitting method increases as the measurement noise is reduced and the fitting period is prolonged. Hence, it is concluded that the online cure kinetics characterization can be realized based on the direct fitting method if the mold heating cycle and the fitting period are carefully chosen. Furthermore, a simulated case study indicates that it is possible to combine such a cure characterization technique with the online cure cycle optimization to complete a self-sufficient cure characterization-optimization system for LCM processes.

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