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IFAC-PapersOnLine 48-11 (2015) 204–210

Model-Based Optimal Control of Polymeric Composite Cure in Autoclave System

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Abstract: The fabrication of high loaded aircraft polymeric composite parts requires tools such as heated closed-mold to which a pressure is applied at the correct gelation stage of the resin. The curing process includes the placing of a premixed compound in the mould, a pre-warming to the resin viscosity reaches a minimum, next applying of pressure to remove the gas bubbles and excess resin, and finally consolidation of resin at elevated temperature to its full polymerization. During matched-die molding, at which the mould is heated by the pressurization gas inside an autoclave or by built-in electrical resistance elements, it is particularly important that pressure is applied at the correct gelation stage of the resin within the cured body. To match the independently controlled pressure and mould heating we propose a model-based control approach, which use the mathematical model for epoxy-based thick-walled composite structure cure in the form of coupled kinetic equation of the resin with the heat transfer equation. This model takes into account an exothermal heat, change of the heat capacity and heat transfer coefficient at the phase transition of resin from liquid to gel and further to the solid state, where warmed pressurized gas in autoclave should provide the most uniform temperature field within the cured composite body. We formulate the control law for the inward heat flow as a function, which depends on four parameters determined at the solving of the optimization problem. To optimize this control law we restore the Pareto frontier for the minimized standard deviations of degree of cure and temperature averaged over the cured body. Finally, we compare the abilities to ensure the high quality curing results in the closed moulds heated by autoclave and by the discrete set of heaters positioned along the length of the die.

Keywords: Model-based optimal control, multiobjective optimization, partial differential equations, transient analysis, composite manufacturing process.

1. INTRODUCTION

The high cost of composite manufacturing is partly due to the trial-and-error philosophies adopted in the manufacturing tooling design and process development. It is therefore very desirable to be able to optimize the material quality during manufacturing through the use of process modelling or simulation. Furthermore, process modelling may help to reduce the manufacturing cost and time, and also to predict a desired tooling and process design window within which a reduced number of trials can be conducted. As noted by Baker et al. (2004) and Akovali (2001), the particular importance of modelling the large composite parts manufacturing is due to unobservability of the state of material during cure process. Closed mould or matched-die processes are widely used in the composites aircraft industry for the fabrication and manufacturing of three-dimensional components and products. Compression moulding involves that a pre-weighted amount of premixed compound is placed in a heated three-dimensional mould. The usual procedure is to apply a holding pressure for a dwell period at a single temperature until the onset of gelation and then increase pressure to close the dies. If pressure is applied too early, an excessive amount of the, still highly fluid, resin is expelled from the laminate, which then cures under low pressure once the dies contact on the lands. The result is a voided laminate with a poor surface finish. If, however, the pressure is applied after gelation, it is not possible to close the dies and resin flow can occur to sweep out the voids; and oversize, resin–rich voided laminate results. The moulded products are ejected from the mould when the crosslinking level has reached a sufficiently high level. Post curing is carried out following ejection of the shaped article in a heated oven, in cases where a maximum level of curing is needed.

Two different kinds of applying heating to the molds are most widely used. In autoclave heat is applied by using fans to circulate the pressurization gas over electrically or steam-heated elements. Alternatively, the molds may be internally heated from the discrete set of built-in electrical resistance elements. The main difference between these two technical

10.1016/j.ifacol.2015.09.184

solutions is the following. In autoclaves the inward heat flux, which act on the mold surface is almost uniform, whereas independently controlled built-in electrical heaters such as strip heaters or heated platens can be positioned along the length of the die at strategic locations, determined by the structural features of the cured part. At considering the requirements to the control of the composite cure process, especially for the parts with the varying cross-section and a complex distribution of the material, Baker et al.(2004) and Mallick (2007) noted that despite its prevalence, the autoclave process is most difficult to provide the uniformity of curing state and eliminate the temperature excess at any position inside the prepreg during the cure cycle.

A common approach to the composite cure modeling, simulation and control that was described by Baker et al. (2004) includes the coupled description of the thermal, kinetics phenomena, and resin viscosity change during cure process. Park and Lee (2001), Oh and Lee (2002), Jiazhong et al. (2013), and Liu et al. (2014) have implemented such the approach to the cured composite domains of relatively simple two- and three-dimensional shapes. The first attempts to optimize the cure cycle are relatively recently. Saad et al. (2012) proposed the optimization of the cure cycle in resin transfer molding process to minimize the time of mold filling by a liquid resin. Jahromi et al. (2012) developed the method of cure cycle optimization for thick fiber-reinforced composite parts using dynamic artificial neural networks. Shevtsov with coworkers (2015) presented Pareto-based optimization method of cure cycle for wound composite parts of a complex three-dimensional shape at the closed mould curing process controlled by the set of independently controlled built-in distributed heaters. All these aforementioned models of cure include the kinetic equations for the used resin matrix materials. These equations and their parameters should be identified using Differential Scanning Calorimetry (DSC), Thermal Mechanical Analysis (TMA) data, information about exothermal heat, specific heat capacity and thermal conductivity at all stages of resin phase transformation, and also the numerical identification methods presented by Harsch et al. (2007), Zang et al. (2012), Vafayan et al. (2012), and Wu et al. (2014).

In this paper, we briefly describe the closed-mould composite cure process in autoclave for the spar of the helicopter tail rotor blade. The model-based control strategy used here assumes the formulation of a mathematical model of the controlled cure process that allows an access to both observed and hidden parameters of the process, and building an appropriate control law similar to presented by Shevtsov et al. (2015), but with the different boundary conditions corresponding to heating the mold in autoclave. At the optimization problem statement and implementation, we use the Pareto frontier approach, which is a very efficient at the cases where process quality is characterized by two or more objectives. In this work 4 design variables were used, and two chosen objectives are the conversion and conversion's deviation, averaged over the cured composite body. Finally, we compare the controllability of the closed mould cure process actuated by the set of built-in spatially distributed heater and by the heated pressurization gas in autoclave.

2. CURE PROCESS FOR EPOXY-BASED COMPOSITE SPAR

We consider here the problem of optimizing the cure cycle on the example of composite spar of the helicopter tail rotor blade. The structure of this spar is a tube with varied cross-section and wall thickness along the span. The technology of manufacturing of fiberglass reinforcement with epoxy resin matrix composite spar includes the following stages: winding of a preimpregnated unidirectional glass-fiber tape on a steel mandrel, and then polymerization of a wound prepreg in a mould within approximately 16 hours. After complete cure the mould is slowly cooled and opened, and ready part are released and removed from a mandrel. The quality of a ready part depends on the sequence and magnitude of temperature and pressure actions.

It is important that, unlike crystalline materials, all epoxy based polymers change its state at certain temperature range, and location of this range can be different at the variation of thermal – temporal evolution for the same resin material. Therefore, the terms "gel transition", "glass transition" refer to a range of temperatures rather than to a strictly fixed temperature, as is the case in crystalline solids. Another feature of the thermoset cure reaction is the issuing of the exothermal heat, and the maximum of the exothermic heat can occur at single (one-step reaction) or more (two-stage reaction) temperatures. It is accepted that the amount of evolved heat during the exothermic reaction characterizes the degree of polymerization of thermoset resin. Quantitative assessment of the degree of cure (ie, conversion) is $\alpha \equiv Q(t)/Q_0$ ($\alpha \in [0;1]$), where $Q(t)$, Q_0 – are an actual and the total heat respectively during the polymerization of unit mass. The mathematical description of the cure process is given by the kinetic equations, which relates the degree of cure with its temporal derivative, and includes the parameters inherent for the cured resin material. For the two staged cure reactions (see Fig. 1) that were observed at the dynamic differential scanning calorimetry (DSC) of the studied resin, we used the kinetic equation proposed by Wu et al. (2014)

$$\frac{d\alpha(T,\alpha)}{dt} = \left[k_1 e^{-((\alpha-\alpha_t)/\beta_t)^2} + k_2 \cdot \alpha^m \right] \cdot (1-\alpha)^n , \qquad (1)$$

where exponential terms are

$$k_i = A_i \exp(-E_i/RT) \quad i = 1,2 , \qquad (2)$$

In last two equations, all designations mean the following: k_i - rate constants, A_i - pre-exponential factors, E_i - activation energies, R - universal gas constant, m, n - reaction orders, α_t, β_t - location and width of the first peak, and t - curing time. The first summand in brackets ensures start and fast suppression of the first reaction when the degree of cure is comparable to α_t, and the second one describes the second reaction, which gives a contribution at relatively high conversion. Eight parameters $A_i, E_i, m, n, \alpha_t, \beta_t$ inherent for the cured resin material have been determined using genetic algorithm applied to the experimental DSC data obtained for the different heating rates.