Composites: Part A 93 (2017) 126–136

Contents lists available at ScienceDirect

Composites: Part A

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

Multi-objective optimisation of the cure of thick components

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ARTICLE INFO

Article history:
Received 22 March 2016
Received in revised form 8 November 2016
Accepted 12 November 2016
Available online 14 November 2016

Keywords:
C. Finite element analysis
C. Numerical analysis
E. Cure

ABSTRACT

This paper addresses the multi-objective optimisation of the cure stage of composites manufacture. The optimisation aims to minimise the cure process duration and maximum temperature overshoot within the curing part by selecting an appropriate thermal profile. The methodology developed combines a finite element solution of the heat transfer problem with a Genetic Algorithm. The optimisation algorithm approximates successfully and consistently the Pareto optimal front of the multi-objective problem in a variety of characteristic geometries of varying thickness. The results highlight the efficiency opportunities available in comparison with standard industrial cure profiles. In the case of ultra-thick components improvements of up to 70% in terms of overshoot and 14 h in terms of process time, compared to conventional cure profiles for ultra-thick components, can be achieved. In the case of thick components reduction up to 50% can be achieved in both temperature overshoot and process duration.

1. Introduction

The continuous expansion in utilisation of thermosetting composites and their adoption as a high performance solution in large complex structures has generated an increased impetus for minimising process costs whilst maximising product quality. The cure stage of composites manufacture involves a number of challenges related to the complex physics governing the cure process and its irreversible character. The trade-off between process cost and the likelihood of process failure due to excessive exothermic phenomena is inherent to the cure of thick thermosetting composites. Fast production necessitates processing at relative high temperature, whilst the autocatalytic character of the curing reaction and the exponential increase in exothermic reaction rate as a function of temperature creates a strong non-linearity manifested as temperature overshoots. Currently, the industry adopts conservative and generic cure profiles which, especially in the cure of thick components, tend to favour very low probabilities of exothermic failure and naturally correspond to longer process duration and higher manufacturing cost.

The selection of cure profiles in order to minimise the cure time and hence process costs has been investigated in the literature in the context of single objective optimisation studies [1–6]. In these investigations considerations related to part quality, such as temperature overshoot or excessive thermal gradient, have been incorporated through the use of constraints. Improvements in cure process duration reach about 30% in the case of thick components [1–3] and 50% in the case of ultra-thick components [4–6]. Similarly, single objective cure profile optimisation studies focusing on the minimisation of residual stresses and shape distortion subject to constraints with respect to cure process duration and/or temperature overshoot have shown potential improvement reaching up to 30% [7–12]. A comprehensive treatment of the problem requires simultaneous consideration of the different objectives related to quality and cost. This has been carried out in the literature by combining objectives in a weighted sum in a single process performance metric [13,14]. However, the selection of weights implies a relative prioritisation between the different objectives leading to cure profiles based on a single objective optimisation setting governed by this selection. Consequently, this approach, as well as pure single objective optimisation treatments incorporating constraints, achieve a limited exploration of the multi-dimensional objective space within the choices made in setting up the problem. The non-linear nature of the phenomena involved in the cure process and the competitive nature of cost and quality generate a complex trade-off that needs to be explored fully to exploit potential efficiency opportunities offered by available processing strategies.

The present paper addresses the cure profile selection problem in a full multi-objective optimisation setting. The two objectives considered - cure duration and temperature overshoot – are minimised simultaneously using a multi-objective Genetic Algorithm (GA) approximating the efficient frontier of the optimisation problem. The methodology developed combines the GA with a finite element (FE) model of the cure process and is applied to the case

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http://dx.doi.org/10.1016/j.compositesa.2016.11.014
1359-835X/

of thick and ultra-thick characteristic composite component geometries.

2. Cure simulation

The coupled thermo-chemical phenomena taking place during the cure have been modelled using the finite element solver Marc® [15]. Three-dimensional isoparametric 8-nodes brick composite elements (Marc® element type 175) for heat transfer analysis were utilised [16]. Time dependent prescribed temperature boundary conditions have been implemented using the FORCDT user subroutine and natural air convection boundary conditions have been applied using the UFILM user subroutine [17]. The sub-models for cure kinetics, specific heat capacity and thermal conductivity were implemented using the UCURE, USPCHT and ANKOND user subroutines [17].The materials utilised were HexForce® G1157 pseudo unidirectional carbon fabric and HexFlow® RTM6 epoxy resin both by Hexcel Composites.

The cure kinetics model proposed by Karkanas and Partridge for the epoxy resin of this study has been used to simulate the cure kinetics [18,19]. The reaction rate depends on temperature and degree of cure as follows:

$$\frac{d\alpha}{dt} = k_1(1-\alpha)^{n_1} + k_2(1-\alpha)^{n_2}\alpha^m \tag{1}$$

where k_1 and k_2 are reaction rate constants, α is the degree of cure and m, n_1 and n_2 are reaction orders. The rate constants are defined as follows:

$$\frac{1}{k_i} = \frac{1}{k_{i,c}} + \frac{1}{k_d} \quad i = 1,2 \tag{2}$$

where $k_{i,c}$ are Arrhenius functions of temperature for the chemical reaction and k_d is a diffusion rate constant, which describes the deceleration of reaction as the instantaneous glass transition of the curing material approaches the cure temperature, expressed as follows:

$$k_d = A_d e^{\left(\frac{-E_d}{RT}\right)} e^{\left(\frac{-b}{f}\right)} \tag{3}$$

$$k_{iC} = A_i e^{\left(\frac{-E_i}{RT}\right)} \quad i = 1,2 \tag{4}$$

Here A_i, A_d are pre-exponential factors, b is a fitting parameter, E_i, E_d are the activation energies for chemical reaction and diffusion respectively, T is the temperature, R is the universal gas constant and f the equilibrium fractional free volume, which for the epoxy system of this study is as follows:

$$f = w(T - T_g) + g \tag{5}$$

Here w and g are constants and T_g is the instantaneous glass transition temperature following the Di Benedetto equation [20]:

$$T_g = T_{go} + \frac{(T_{g\infty} - T_{go})\lambda\alpha}{1-(1-\lambda)\alpha} \tag{6}$$

where $T_{g\infty}$ and T_{go} are the glass transition temperature of the fully cured and uncured material respectively and λ is a fitting parameter. The parameters of the cure kinetics model are reported in Table 1 [18,19].

The specific heat of the composite is calculated using the rule of mixtures:

$$c_p = w_f c_{pf} + (1 - w_f)c_{pr} \tag{7}$$

where w_f is the weight fraction of the fibre. The specific heat capacity of carbon fibres (c_{pf}) has a linear dependence on temperature, whilst the specific heat of resin (c_{pr}) depends on both temperature and degree of cure as follows:

Table 1
Parameter values for the cure kinetics and glass transition temperature material sub-models of the RTM6 epoxy resin system [18,19].

Parameters	Values	Units
$\mathbf{A_1}$	17,580	s^{-1}
$\mathbf{A_2}$	21,525	s^{-1}
$\mathbf{A_d}$	$6.48 \cdot 10^{18}$	s^{-1}
$\mathbf{E_1}$	70,500	$J{\cdot}mol^{-1}$
$\mathbf{E_2}$	59,050	$J{\cdot}mol^{-1}$
$\mathbf{E_d}$	136,800	$J{\cdot}mol^{-1}$
m	1.16	
$\mathbf{n_1}$	1.8	
$\mathbf{n_2}$	1.32	
b	0.467	
$\mathbf{T_{g0}}$	−11	°C
$\mathbf{T_{g\infty}}$	206	°C
$\boldsymbol{\lambda}$	0.435	

$$c_{pf} = A_{f_{cp}} T + B_{f_{cp}} \tag{8}$$

$$c_{pr} = A_{rc_p} T + B_{rc_p} + \frac{\Delta_{rc_p}}{1 + e^{C_{rcp}(T - T_g - \sigma)}} \tag{9}$$

Here $A_{f_{cp}}$, $B_{f_{cp}}$ are the slope and the intercept of the linear dependence of fibre specific heat capacity on temperature, A_{rc_p}, B_{rc_p} are constants expressing the linear dependence of the specific heat capacity of the uncured epoxy on temperature and Δ_{rc_p}, C_{rc_p} and σ are the strength, width and temperature shift of the step reduction in specific heat capacity occurring at resin vitrification. The coefficient values of the specific heat capacity sub-model for both resin and fibre are reported in Table 2 [3].

The longitudinal (K_{11}) and transverse direction (K_{22}, K_{33}) thermal conductivities of the composite can be approximated as follows [3,22]:

$$K_{11} = v_f K_{lf} + (1 - v_f)K_r \tag{10}$$

$$K_{22} = K_{33} = v_f K_r \left(\frac{K_{tf}}{K_r} - 1\right) + K_r\left(\frac{1}{2} - \frac{K_{tf}}{2K_r}\right) + K_r\left(\frac{K_{tf}}{K_r} - 1\right)\sqrt{v_f^2 - v_f + \frac{\left(\frac{K_{tf}}{K_r} + 1\right)^2}{\left(\frac{2K_{tf}}{K_r} - 2\right)^2}} \tag{11}$$

The thermal conductivity of the carbon fibre in the longitudinal direction (K_{lf}) and transverse direction (K_{tf}) can be expressed as follows [21,22]:

$$K_{lf} = A_{lf} T + B_{lf} \tag{12}$$

Table 2
Parameter values for the specific heat and thermal conductivity material sub-models for the materials of the study [3,21,22].

Parameters	Values	Units
$\mathbf{A_{fc_p}}$	0.0023	$J\,g^{-1}\,°C^{-2}$
$\mathbf{B_{fc_p}}$	0.765	$J\,g^{-1}\,°C^{-2}$
$\mathbf{A_{rc_p}}$	0.0025	$J\,g^{-1}\,°C^{-2}$
$\mathbf{B_{rc_p}}$	1.80	$J\,g^{-1}\,°C^{-2}$
$\Delta_{\mathbf{rc_p}}$	−0.25	$J\,g^{-1}\,°C^{-2}$
$\mathbf{C_{rc_p}}$	1.10	$°C^{-1}$
$\boldsymbol{\sigma}$	16.5	°C
$\mathbf{A_{lf}}$	0.0074	$W\,m^{-1}\,°C^{-2}$
$\mathbf{B_{lf}}$	9.7	$W\,m^{-1}\,°C^{-2}$
$\mathbf{B_{tf}}$	0.84	$W\,m^{-1}\,°C^{-2}$
$\mathbf{a_{Kr}}$	0.0008	$W\,m^{-1}.°C^{-2}$
$\mathbf{b_{Kr}}$	−0.0011	$W\,m^{-1}\,°C^{-2}$
$\mathbf{c_{Kr}}$	−0.0002	$W\,m^{-1}\,°C^{-2}$
$\mathbf{d_{Kr}}$	−0.0937	$W\,m^{-1}\,°C^{-1}$
$\mathbf{e_{Kr}}$	0.22	$W\,m^{-1}\,°C^{-1}$
$\mathbf{f_{Kr}}$	0.12	$W\,m^{-1}\,°C^{-1}$