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Stochastic multi-objective optimisation of the cure process of thick laminates

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ABSTRACT

A stochastic multi-objective cure optimisation methodology is developed in this work and applied to the case of thick epoxy/carbon fibre laminates. The methodology takes into account the uncertainty in process parameters and boundary conditions and minimises the mean values and standard deviations of cure time and temperature overshoot. Kriging is utilised to construct a surrogate model of the cure substituting Finite Element (FE) simulation for computational efficiency reasons. The surrogate model is coupled with Monte Carlo and integrated into a stochastic multi-objective optimisation framework based on Genetic Algorithms. The results show a significant reduction of about 40% in temperature overshoot and cure time compared to standard cure profiles. This reduction is accompanied by a reduction in variability by about 20% for both objectives. This highlights the opportunity of replacing conventional cure schedules with optimised profiles achieving significant improvement in both process efficiency and robustness.

1. Introduction

The optimisation of the manufacturing of continuous fibre thermosetting matrix composites is critical for minimising cost and the likelihood of occurrence of process failures defects. During the process of cure, the thermosetting resin transforms from an oligomeric liquid to a glassy solid through an exothermic crosslinking reaction. In the case of thick components the heat generated due to the reaction can lead to severe temperature overshoots. These can affect considerably the quality of the manufactured component. The risks associated with temperature overshoots in thick components are dealt with by adopting conservative cure cycles. This in turn results in long processing times and high manufacturing costs.

The selection of optimal cure profiles that can minimise cure time and the occurrence of temperature overshoots or other process-induced defects has been addressed in the literature using single-objective and multi-objective optimisation. Cure time can be reduced by up to 30% for thick parts [1–3] and 50% for ultra-thick parts [4–6], whereas targeting the minimisation of residual stresses in a single-objective profile optimisation context can lead to their reduction by about 30% [7–12]. The optimal solutions obtained in single optimisation setups merging objectives in a weighted sum [13,14] are dependent on the weights which imply a relative prioritisation between the different objectives. Multi-objective optimisation can overcome this limitation by treating the two objectives independently. An approach of this type based on Genetic Algorithms (GAs) has been used to address cure time and temperature overshoot minimisation in thick parts [15]. The results have shown the existence of a trade-off between the two objectives with an L shaped Pareto front incorporating solutions that can achieve improvements of about 50% with respect to both cure time and overshoot compared to standard cure profiles. However, the benefits offered by the exploration of the design space by numerical optimisation can be accompanied by relative instability of some of the solutions with respect to perturbations of nominal process parameters leading to potential risks.

The process of cure involves several sources of variability including environmental/boundary conditions uncertainty and material properties variations [16]. Stochastic simulation has shown that amongst these, tool temperature has the greatest impact on cure time variability [17]. Uncertainty in preform architecture, such as fibre misalignment, can cause variability in residual stresses and also in final distortion of the cured part [18]. Variability in cure kinetics parameters, such as initial degree of cure, activation energy and reaction order, can induce significant variations in temperature overshoot reaching coefficients of variation of approximately 30% [19]. Uncertainty in surface heat transfer and tool temperature can cause significant variability in cure

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time reaching a coefficient of variation of 20% [20]. In the case of optimisation, the level of uncertainty in boundary conditions affects significantly the optimal solution [21]. Consideration of the effects of variability and the potential lack of stability of optimised solutions suggest that the combination of multi-objective optimisation with stochastic simulation is relevant for cure process design aiming to address simultaneously efficiency and robustness.

The present paper describes the development of a methodology for the incorporation of variability in multi-objective optimisation of composites cure. The variability in boundary conditions during curing is characterised and represented using appropriate stochastic objects. An existing multi-objective optimisation methodology of the cure based on GAs [15] is integrated with Monte Carlo to incorporate variability of cure time and temperature overshoot in the set of objectives considered. A surrogate model of the cure is developed using the Kriging method substituting the FE model in the Monte Carlo simulation to reduce the computation effort required for the combination of optimisation and stochastic simulation. The methodology is applied to the cure of a thick flat carbon fibre/epoxy laminate.

2. Methodology

2.1. Cure simulation

A heat transfer cure simulation model was implemented in the Finite Element (FE) solver MSC. Marc to represent the cure of a Hexcel G1157 pseudo unidirectional carbon fibre/Hexcel RTM6 epoxy resin flat panel. The model comprises 26 3-D 8 noded iso-parametric composite brick elements (MSC. Marc element type 175 [22]) representing a 15.6 mm thick laminate. Although the dimensionality of the solution is 3-D, the heat transfer problem is one-dimensional requiring the use of only one element across the in-plane dimensions. Each element represents two layers of fabric with a thickness of 0.3 mm each.

Fig. 1 illustrates a schematic representation of the model. The boundary conditions were implemented using user subroutines FORCDT and UFILM for time dependent prescribed temperature and forced air convection respectively [23]. User subroutines UCURE, USPCHT, and ANKOND were used for cure kinetics, specific heat capacity and thermal conductivity material sub-models [23].

The cure kinetics model for the resin system of this study is a combination of an n^{th} order term and an autocatalytic term [24]:

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

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

$$\frac{1}{k_i} = \frac{1}{k_{i,C}} + \frac{1}{k_d},\ i = 1, 2 \quad (2)$$

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

$$k_{i,C} = A_d e^{(-E_i/RT)},\ i = 1, 2 \quad (3)$$

$$k_d = A_i e^{(-E_d/RT)} e^{(-b/f)} \quad (4)$$

where A_i, A_d are pre-exponential factors, b is a fitting parameter, E_i and E_d the activation energy for the chemical reactions and diffusion respectively, T is the absolute temperature, R the universal gas constant and f the equilibrium free volume, which is expressed as follows:

$$f = w(T-T_g) + g \quad (5)$$

Here w and g are constants and T_g is the instantaneous glass transition temperature following the Di Benedetto equation [25]:

$$T_g = T_{g0} + \frac{(T_{g\infty}-T_{g0})\lambda\alpha}{1-(1-\lambda)\alpha} \quad (6)$$

where $T_{g\infty}$ and T_{g0} are the glass transition temperature of the fully cured and uncured material and λ is a parameter controlling the convexity of the dependence. Model constants are reported in Table 1 [19].

The specific heat capacity of the composite is computed making use of the rule of mixtures as follows:

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

where w_f is the fibre weight fraction, c_{pf} the fibre specific heat capacity and c_{pr} the specific heat capacity of the resin. The specific heat capacity

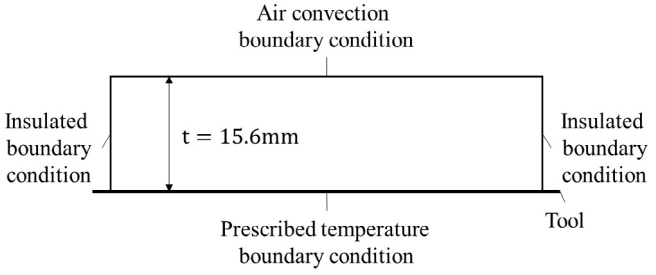

Fig. 1. Schematic representation of the cure model.

Table 1
Parameters values for the cure kinetics [19], glass transition temperature, specific heat capacity [15], thermal conductivity [1] and density material models [27,28].

Parameter		Value
Pre-exponential factor of the nth order term	A_1	19,000 (s^{-1})
Pre-exponential factor of the autocatalytic term	A_2	22,080 (s^{-1})
Pre-exponential factor of diffusion	A_d	6.7610^{18} (s^{-1})
Activation energy of the nth order term	E_1	72,900 ($Jmol^{-1}$)
Activation energy of the autocatalytic term	E_2	57,820 ($Jmol^{-1}$)
Activation energy of diffusion	E_d	138,000 ($Jmol^{-1}$)
Autocatalytic reaction order	m	1.29
Reaction order of the nth order term	n_1	1.97
Reaction order of the autocatalytic term	n_2	1.53
Exponent of diffusion term	b	0.452
Equilibrium free volume model slope	w	0.00048 (1/K)
Equilibrium free volume model intercept	g	0.025
Glass transition temperature of uncured material	T_{g0}	−11 (°C)
Glass transition temperature of fully cured material	$T_{g\infty}$	206 (°C)
Glass transition temperature convexity constant	λ	0.435 ($Jg^{-1}°C^{-2}$)
Fibre specific heat capacity model slope	A_{fc_p}	0.0023 ($Jg^{-1}°C^{-2}$)
Fibre specific heat capacity model intercept	B_{fc_p}	0.765 ($Jg^{-1}°C^{-2}$)
Resin specific heat capacity model slope	A_{rc_p}	0.0025 ($Jg^{-1}°C^{-2}$)
Resin specific heat capacity model intercept	B_{rc_p}	1.8 ($Jg^{-1}°C^{-2}$)
Resin specific heat capacity model step	Δ_{rc_p}	−0.25 ($Jg^{-1}°C^{-2}$)
Resin specific heat capacity model step breadth parameter	C_{rc_p}	1.1 ($°C^{-1}$)
Resin specific heat capacity model step shift parameter	σ	16.5 (°C)
Fibre transverse thermal conductivity	B_{tf}	0.84 ($Wm^{-1}°C^{-2}$)
Resin thermal conductivity model quadratic coupling	a_{Kr}	0.0008 ($Wm^{-1}°C^{-2}$)
Resin thermal conductivity model coupling constant	b_{Kr},	−0.0011 ($Wm^{-1}°C^{-2}$)
Resin thermal conductivity model linear temperature constant	c_{Kr},	−0.0002 ($Wm^{-1}°C^{-2}$)
Resin thermal conductivity model quadratic conversion constant	d_{Kr},	−0.0937 ($Wm^{-1}°C^{-2}$)
Resin thermal conductivity model linear conversion constant	e_{Kr},	0.22 ($Wm^{-1}°C^{-2}$)
Resin thermal conductivity model intercept	f_{Kr}	0.12 ($Wm^{-1}°C^{-2}$)
Resin density	ρ_r	1.11 (gml^{-1})
Fibre density	ρ_f	1.76 (gml^{-1})