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Pultrusion manufacturing process development: Cure optimization by hybrid computational methods

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Abstract

This paper develops a hybrid approach, based on genetic algorithms and simplex method, to optimize the accuracy of a manufacturing process by material pultrusion. The numerical model, proposed in a recent paper of the same authors, is solved by a finite difference scheme. The analysis technically shows the efficiency of the optimization algorithm.

Keywords: Pultrusion; Cure optimization; Genetic algorithms; Simplex method; Finite element method; Finite difference method

1. Introduction

Pultrusion manufacturing process is widely used to shape composite materials into parts characterized by constant cross section. During the pultrusion process fibres are impregnated into a resin bath and then the wetted reinforcement is pulled through a heated die to be correctly shaped and cured. Pultrusion is a continuous process, characterized by remarkable automation and, nowadays, it is more and more used to obtain complex parts for aeronautical, spatial and civil applications.

The influence of thermo-chemical aspects on the mechanical properties of the final product has been carefully analysed by Wilcox et al. in [1]. An experimental investigation performed by Carlsson et al. [2] has shown that mechanical, as well as, surface properties of the processed part are affected by several process parameters, such as pre-heater temperature, heating platens temperature, cooling temperature, and pull speed. Manufacturing defects, such as void and microcracks, usually related to non optimal cure profiles into the processing parts, affect linear and nonlinear behaviour of pultruded composites [3]. Several computational models [4–10] have been proposed to analyse temperature and degree of cure profiles in the processing parts, however, very few works have been focused on the optimization of the above profiles.

An optimization procedure based on a Galerkin weighted residual finite element formulation was proposed by Coelho et al. in [11]. The simulated annealing method was used to avoid local minima and then the solution was refined using a successive quadratic programming (SPQ) procedure. An objective function based on economic criteria

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was implemented, using opportune constraints for the minimum value of the degree of cure and the temperature peak into the composite material. A different approach, based on the combination of numerical model and mathematical procedures, was proposed by Li et al. [12] and by Joshi et al. [13]. Several process parameters, such as heating platens temperatures, pull speed, resin bath temperature, and cooling temperature, were considered to optimize material cure, taking into account that the processing material temperature can not exceed the degradation temperature of the considered resin system. The above method has shown to be quite efficient, although the output of the solution was affected by the combination of the process parameters considered at the first step of the optimization procedure.

In this paper a hybrid method, based on the use of genetic algorithms and of the simplex method, for pultrusion process optimization, is proposed. Objective function is evaluated and minimized by an iterative procedure based on the combination of above techniques with a finite difference model [14]. The finite element model, developed in [14], is then used to validate and analyse the obtained solution.

2. Governing equation

The optimization method, briefly outlined in Section 1, is applied, as already mentioned, to a pultrusion manufacturing process. This Section provides a concise description of the analytic model. Specifically, the heat transfer model, for the heated die, writes as follows:

$$\rho_d c_{p,d} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_{x,d}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_{y,d}\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_{z,d}\frac{\partial T}{\partial z}\right). \tag{2.1}$$

where T is the temperature, ρ_d is the die material density, $c_{p,d}$ is the die material specific heat, $k_{x,d}$, $k_{y,d}$, and $k_{z,d}$ are the thermal conductivities into the die, respectively, in x, y, and z direction.

Assuming x as the pull direction, energy conservation equation, for the composite material, writes:

$$\rho_c c_{p,c}\left(\frac{\partial T}{\partial t} + v_x\frac{\partial T}{\partial x}\right) = k_{x,c}\frac{\partial}{\partial x}\left(\frac{\partial T}{\partial x}\right) + k_{y,c}\frac{\partial}{\partial y}\left(\frac{\partial T}{\partial y}\right) + k_{z,c}\frac{\partial}{\partial z}\left(\frac{\partial T}{\partial z}\right) + \rho_r V_r Q. \tag{2.2}$$

being ρ the density, c_p the specific heat, k_x, k_y, and k_z the thermal conductivities (in x, y, and z direction respectively), which are assumed to be constant. Moreover, using the subscripts r, f, and c to indicate the resin, fibre and composite material, respectively; V_r is the resin volume fraction, v_x is the pull speed, and Q is the specific heat generation rate due to resin exothermic cure reaction.

Heat generation rate Q:

$$Q = \frac{\mathrm{d}H(t)}{\mathrm{d}t} = H_{tr} R_r(\alpha), \tag{2.3}$$

where $H(t)$ is the amount of heat evolved during the curing process up to time t, H_{tr} is the total heat of reaction, and R_r is the rate of resin reaction, related to the degree of cure α and the absolute temperature, according to the Arrhenius equation, as follows:

$$R_r(\alpha) = \frac{\mathrm{d}\alpha}{\mathrm{d}t} = K_0 \exp\left(-\frac{\Delta E}{RT}\right)(1-\alpha)^n, \tag{2.4}$$

being K_o the pre-exponential constant, ΔE the activation energy of the resin reaction, R the gas universal constant, and n the order of the reaction (kinetic exponent).

Finally, the concentration of the resin species, into the forming die, is given by the following transport equation:

$$\frac{\partial \alpha}{\partial t} = R_r(\alpha) - v_x\frac{\partial \alpha}{\partial x}. \tag{2.5}$$

3. Optimization techniques

3.1. Genetic algorithms

In engineering sciences there are several problems which need to select a solution among several possible combinations. Such problems are usually defined as NP-HARD problems; an analytical solution cannot be achieved,