MODELLING AND NUMERICAL SIMULATION OF THE STRUCTURAL REACTION INJECTION MOULDING (SRIM) PROCESS

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ABSTRACT

We present a simplified model and a numerical method devoted to simulating the Structural Reaction Injection Moulding (SRIM) process. Examples illustrate the validity of our approach.

INTRODUCTION

The SRIM process (which is used to produce composite moulded parts reinforced with continuous fibres) consists in injecting a thermoset in a mould, in which a fibre mat preform has been placed beforehand [1]. Although SRIM and standard injection moulding differ by the manufacturing equipment used, as well as by their operational parameters (injection pressure, cycle duration, ...), the filling stage can be modelled in similar ways for both processes, provided some differences are taken into account. A first difference is found in the presence of the fibre mat in the cavity. The Hele-Shaw approach is no longer possible for describing the flow in a porous medium, which is governed by the Darcy law. Further differences appear when modelling the thermal exchanges taking place in the injection tool. Besides the fact that the mould is heated in order to speed up the curing reaction, special attention must be paid to the thermal influence of the cold mat and the starting chemical reactions.

When analysing the moulding of thin parts, the main modelling issue is to determine which fields (pressure, temperature, ...) can be treated as being approximately two-dimensional (by neglecting their dependence with respect to the gapwise coordinate), and which fields must be treated as three-dimensional. In what follows, we will present a model which is based on assuming that both the pressure and temperature fields are mainly 2D when processing *thin* SRIM parts. This will be shown by means of dimensional analysis considerations, taking into account the influence of *mechanical dispersion* on heat transfer in the porous medium.

An additional problem to solve when modelling any non-isothermal variant of the injection moulding process, is to find correct temperature boundary conditions to impose

at the moving flow front(s). The simplified approach which is used in the present paper consists in imposingto the resin on the fronts the same temperature as the one observed in the mat preform downstream of the fronts (in their close vicinity) (Carlier and Valembois [2], Tucker [3]).

This will be shown to generate in the flow a cold subregion which has nearly the same temperature as the mat preform, and moves with the fronts while extending progressively its area. This effect has far reaching consequences, since it means that heating the injected resin in order to control the chemical reaction can be useless in some regions when the mat preform is cold.

The numerical scheme which is used here is similar to the method we have developed in a companion paper to simulate the injection moulding of thermoplastics reinforced with long or short discontinuous fibres [4]. In both cases, the algorithm consists in a succession of time steps in which such operations as time integration of the field nodal unknowns, front displacement, remeshing, and extrapolation of the unknowns in the region located between successive flow fronts are performed. Detail is given in [4] and the literature therein.

MATHEMATICAL MODEL AND NUMERICAL METHOD

The flow in the porous mat can be assumed to be governed by the Darcy equation,

$$\mathbf{v} = -\frac{1}{\eta}\,\mathbf{K}\,.\,\nabla p\,, \qquad (1)$$

where $\mathbf{v}$ and p are the average velocity and pressure fields in the liquid phase, η is the viscosity (which can depend both on temperature and curing ratio), and $\mathbf{K}$ is the permeability tensor which is given but can vary throughout the mould. For an incompressible fluid, the continuity equation is written as

$$\nabla\,.\,(\rho_l\ \alpha_l\ \mathbf{v}) = 0, \qquad (2)$$

where ρ_l and α_l are the specific mass and volume fraction of the liquid phase.

Dimensional analysis permits one to simplify the problem. Introducing reduced dimensionless variables, the asymptotical behaviour of the system is easily obtained by letting tend to zero the ratio ε,

$$\varepsilon = \frac{h}{L}, \qquad (3)$$

where L and h stand for a characteristic dimension of the part and its half-thickness, respectively. In most applications, the permeability components in the gapwise direction are not several orders of magnitude lower than their counterparts in the midsurface

where $\mathbf{q}$ is the heat flux vector, T is temperature, c_l is the heat capacity per unit mass of the resin, $\mathbf{k}$ is the heat conduction tensor, and $\mathbf{P}$ is a tensor associated with the geometrical tortuosity of the pores (and which has the physical dimension of a length). Assumptions (ii) and (iii) are valid when the following dimensional hypotheses are satisfied:

$$\frac{L}{h^2}\,\|\mathbf{P}\| >> 1, \quad \frac{1}{L}\,\|\mathbf{P}\| << 1. \tag{8}$$

It is clear that, as $\|\mathbf{P}\|$ may be interpreted as a characteristic length of the pores, conditions (8) are valid in many practical situations involving thin parts.

The simplified energy equation takes the form :

$$h\,(\rho_l\,\bar{\alpha}_l\,c_l + \rho_s\,\bar{\alpha}_s\,c_s)\,\frac{\partial T}{\partial t} + h\,\rho_l\,\bar{\alpha}_l\,c_l\,\bar{\mathbf{v}}.\nabla T = \frac{1}{\eta}\,\bar{\alpha}_l\,\nabla p.\bar{\mathbf{K}}.\nabla p - q + h\,\rho_l\,\bar{\alpha}_l\,\dot{r}\,, \tag{9}$$

where $\bar{\alpha}_l$ and $\bar{\alpha}_s$ are the gap-averaged volume fractions in the liquid and solid phases, c_s is the heat capacity per unit mass of the mat, q is the outgoing heat flux at the wall, and $\dot{r}$ is the rate of heat released by curing per unit mass in the resin (and which is often negligible during the filling stage).

It must be emphasised that the effect of the solid mat is to reduce the velocity of heat advection in the two-phase medium. Indeed, from equation (9), the equivalent velocity of heat transfer is

$$\bar{\mathbf{v}}^* = \frac{\rho_l\,\bar{\alpha}_l\,c_l}{\rho_l\,\bar{\alpha}_l\,c_l + \rho_s\,\bar{\alpha}_s\,c_s}\,\bar{\mathbf{v}}. \tag{10}$$

RESULTS AND DISCUSSION

In a first set of simulations (Fig. 1), we analyse the isothermal filling of a square part. The influence of the permeability of the mat is investigated in three situations. In the first case, this permeability is isotropic ($K_{max}/K_{min} = 1$), and the flow fronts have a circular shape. In the second and third cases, the permeability is selected in such a way that the flow is easier in the *phi* = 0.5 rad or -0.5 rad direction, respectively ($K_{max}/K_{min} = 5$). The shape of the flow fronts becomes elliptic or consists approximately of straight lines. These results can easily be explained.

The second example (Fig. 2) is devoted to analysing the non-isothermal filling of a long rectangular strip, without chemical reaction ($\dot{r} = 0$). The walls are adiabatic ($q = 0$) and viscous heating is neglected. The thermal behaviour of the two-phase medium exhibits a

directions. In this case, pressure variations in the gapwise directions can be neglected. As we will in addition show that viscosity dependence with respect to the gapwise coordinate is itself negligible, the gap averaged equations take the form

$$h\,\bar{\mathbf{v}} = -\frac{1}{\eta}\,\bar{\mathbf{K}}.\nabla p \quad , \tag{4}$$

and

$$\nabla_m . (h\,\bar{\mathbf{v}}) = 0, \tag{5}$$

with

$$\bar{\mathbf{K}} = \int_0^h \alpha_l \mathbf{K}\, dz \,. \tag{6}$$

Here, $\bar{\mathbf{v}}$ and $\bar{\mathbf{K}}$ stand for the average velocity field and permeability tensor, while ∇_m denotes the constrained gradient in the midsurface directions.

The energy equation is in principle governed by the following physical phenomena :

(a) heat advection;
(b) heat diffusion;
(c) mechanical dispersion;
(d) viscous heating;
(e) release of heat by curing;
(f) heat transfer between the liquid and the solid phase;
(g) heat exchanges with the walls of the cavity.

Our simplified model is based on three main hypotheses :

(i) instantaneous thermal equilibrium between the two phases of the flow;
(ii) complete mixing in the gapwise direction;
(iii) negligible mixing in the midsurface directions.

Assumption (i) means that a unique temperature is calculated at any location in the cavity for both resin and mat. As a consequence, the front temperature is easily shown to be equal to the mat downstream temperature. Assumptions (ii) and (iii) are justified by dimensional analysis. Let the law governing heat diffusion and mechanical dispersion in the two-phase medium be written as

$$\mathbf{q} = -\left(\mathbf{k} + \rho_l\, \alpha_l\, c_l\, \|\mathbf{v}\|\, \mathbf{P}\right).\nabla T \,, \tag{7}$$

heat front whose velocity is slower than that of the flow front, as explained in the previous section.

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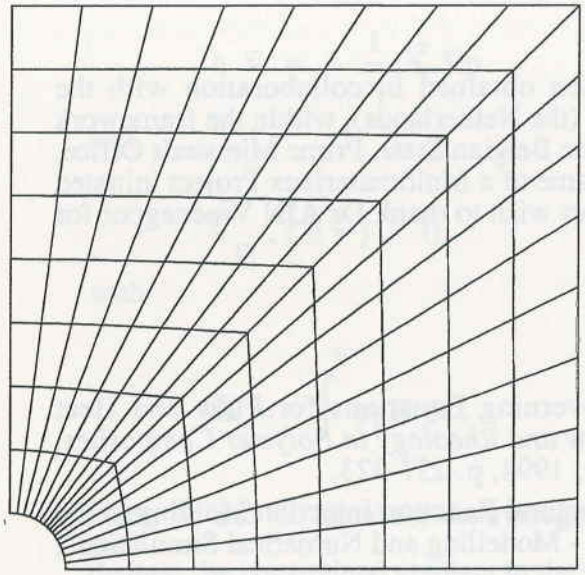
a



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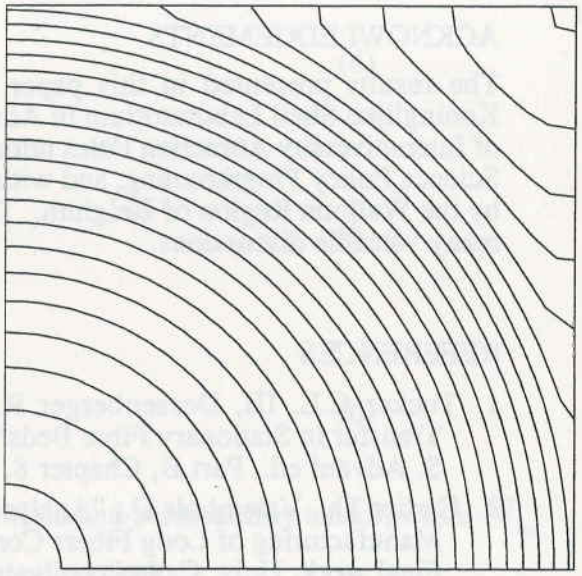

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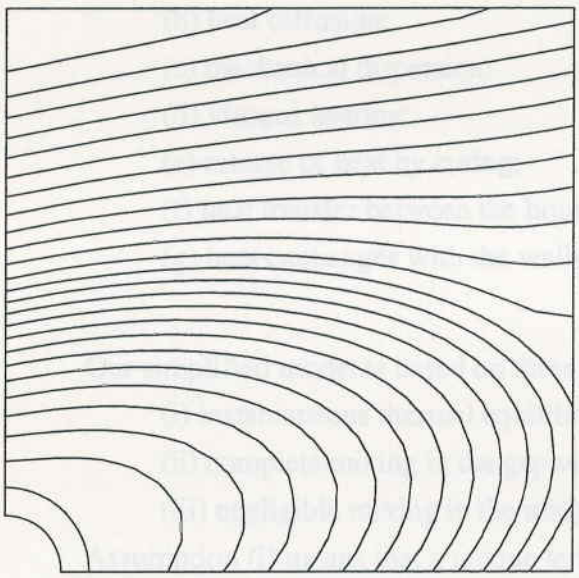

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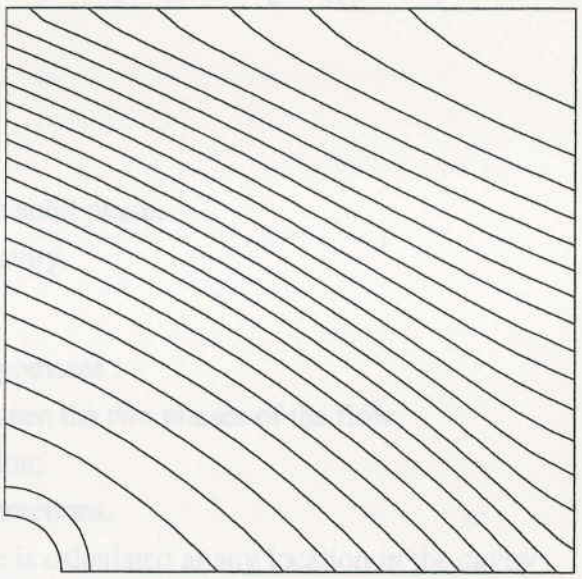
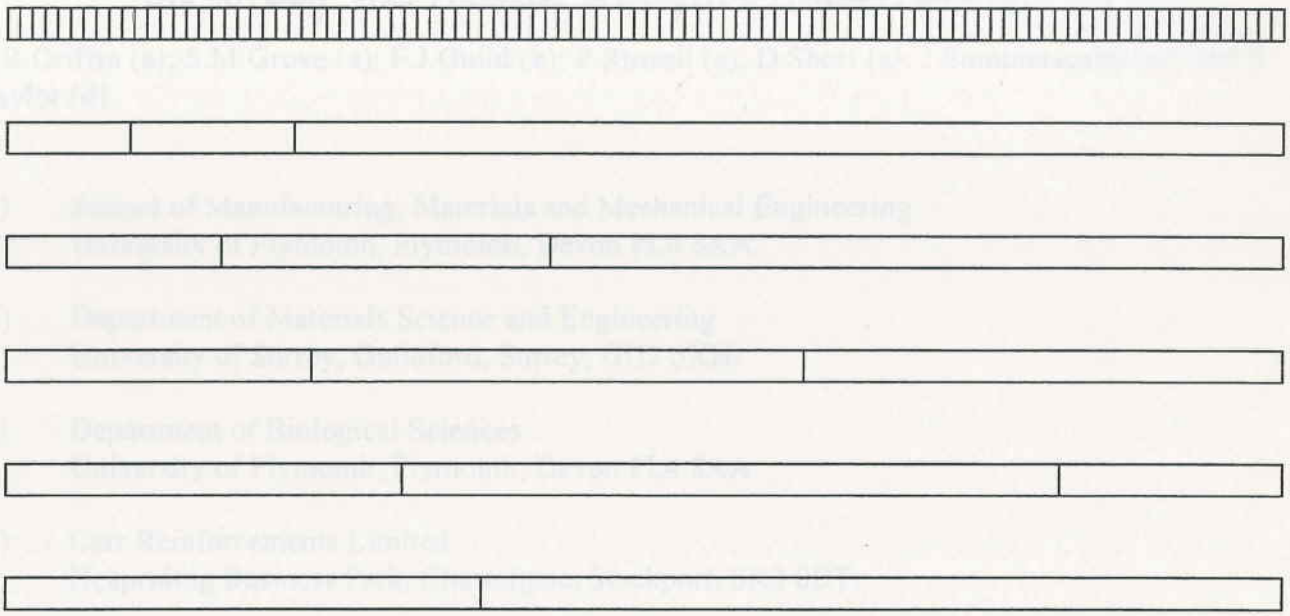


Fig. 1. Isothermal filling of a thin square cavity :
analysis of the influence of the permeability tensor :
fixed mesh (a.) and successive flow fronts :

b. Kmax = 1, Kmin = 1;
c. Kmax = 5, Kmin = 1, phi = 0.5 rd;
d. Kmax = 5, Kmin = 1, phi = - 0.5 rd.



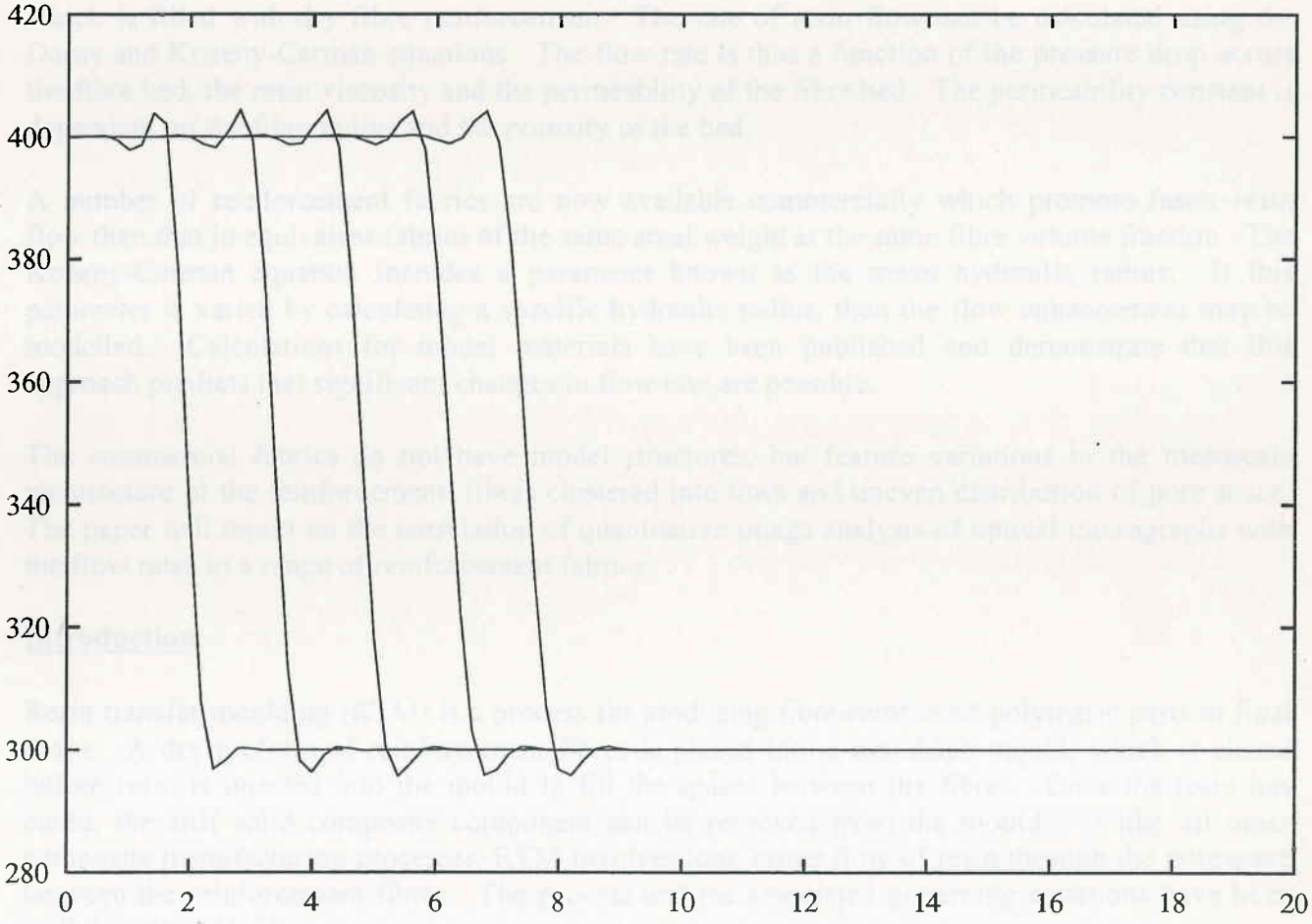


Fig. 2. Non isothermal filling of a rectangular strip : fixed mesh;
successive flow fronts and successive locations of the thermal front;
evolution of the temperature field in the cavity.