Effect of in-plane and shear viscosity on the flow and fibre orientation of long fibre injection moulded composites.

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Abstract

Many thermoset compounds contain a high volume fraction of long fibres, which (when being injection or compression moulded) prevent fountain flow and induce a plug flow, together with very thin shearing layers along the walls. In addition, experimental short shots exhibit flow fronts whose shapes depart significantly from what can be accounted for by the Hele-Shaw approach.

In view of these two peculiarities, we have developed a model which takes into account both a shear and an in-plane viscosity, and leads to a convenient vorticity-pressure formulation. This model can in particular explain fluid-wall separation downstream of sharp boundary corners, together with the formation of welding lines downstream of salient corners (in multi-facetted parts). Whereas shear viscosity can be shown to exert a dominant effect on the flow with respect to in-plane viscosity, the latter keeps a non-negligible influence on the front kinematics during filling. This is demonstrated by means of comparisons between model predictions and experimental results.

1. Introduction

The growing interest shown by the automotive industry in glass-fibre reinforced polyester composites can easily be explained by the remarkable properties of the injection or compression moulded parts obtained with these materials (which, in particular, exhibit high strength, low weight, corrosion resistance, dimensional stability and short processing time). It is however important to stress the rheological complexity of these compounds, which largely influences the flow and renders mould design difficult. Numerical simulation can therefore be of a great help to significantly improve both productivity and product quality.

A correct modelling of the flow of fibre suspensions requires to take three types of effects into account, namely fibre-wall , fibre-fibre and fibre-matrix interactions. The present work focuses on fibre-wall interaction, since its influence is fundamental in BMC (Bulk Moulding Compound) flows. In this paper, a new model is presented, which accurately represents the driving forces of the flow, taking into account the presence of a thin lubricating skin layer along the walls, together with the strong fibre intermixing in the core region.

2. Mathematical modelling of the plug-flow

2.1 Hypotheses

Our mathematical model of plug-flow is built on the observation that fibre length is much higher than the gap thickness, and that fibre concentration is important, which makes the velocity profile very flat. The flowing material therefore looks like a plug sliding between two plates, while this sliding takes place with friction. Indeed, experiments show that a good surface quality results from the presence of a thin fibre free resin layer adjacent to the mould walls. It is thus reasonable to assume that the fibre filled core layer, which is characterised by its own viscosity (the so-called in-plane viscosity), is surrounded by a thin skin layer in which only shearing is effective.

2.2 Mathematical model

The viscous fluid is supposed to fill a cavity of planar midsurface and constant thickness 2h. The flow is assumed to be creeping, and gravity and inertia are neglected. Letting indices α, β... denote the mid-surface directions, while z stands for the gapwise direction, in-plane momentum equations are written as :

$$\sigma_{\beta\alpha,\beta} + \sigma_{z\alpha,z} = 0 \quad . \tag{1}$$

Integrating eq. (1) from 0 to h, this yields :

$$h\,\sigma_{\beta\alpha,\beta} + \sigma_{z\alpha}\Big|_{z=h} = 0 \quad . \tag{2}$$

According to our two viscosity model, the stress tensor is written as follows :

$$\begin{cases} \sigma_{\alpha\beta} = -p\,\delta_{\alpha\beta} + (v_{\alpha,\beta} + v_{\beta,\alpha}) \quad , \\ \sigma_{z\alpha}\Big|_{z=h} = -\dfrac{\mu_c}{l}\,v_\alpha \quad , \\ \sigma_{zz} = -p \quad , \end{cases} \tag{3}$$

where μ_p is the in-plane viscosity, μ_c is the shear viscosity at the walls and l is the thickness of the lubricating layer. Replacing in eq. (2) the stress tensor σ_{ij} by its expression (3), one therefore obtains the following relation :

$$\frac{\partial p}{\partial x_\alpha} = \mu_p\,\Delta v_\alpha - \frac{\mu_c}{h\,l}\,v_\alpha \quad . \tag{4}$$

Considering on the other hand that the fluid is incompressible, mass conservation is written as:

$$\frac{\partial v_\alpha}{\partial x_\alpha} = 0 \quad . \tag{5}$$

The 2D curl of eq. (4) is thus :

$$\omega - \frac{h\,l\,\mu_p}{\mu_c}\,\Delta\omega = 0 \quad , \tag{6}$$

where ω is defined by the expression

$$\omega = \mu_p\,\varepsilon_{\alpha\beta}\,v_{\beta,\alpha} \quad . \tag{7}$$

Finally, the 2D divergence of eq. (4) brings on the following equation :

$$-\frac{h\,l}{\mu_c}\Delta p = 0 \quad . \tag{8}$$

The strong ω-p formulation of the problem is, therefore :

$$\begin{cases} -\dfrac{h\,l}{\mu_c}\Delta p = 0 \;, \\ \dfrac{\omega}{\mu_p} - \dfrac{h\,l}{\mu_c}\Delta\omega = 0 \;. \end{cases} \tag{9}$$

2.3 Boundary conditions

Flow domain boundaries are the gate, the side-walls and the front(s). Using curvilinear co-ordinates (n,s), and letting χ denote the local curvature of the boundary, the velocity field is :

$$[v_\alpha] = \begin{bmatrix} v_n \\ v_s \end{bmatrix} = -\frac{h\,l}{\mu_c}\begin{bmatrix} p_{,n} + \omega_{,s} \\ p_{,s} - \omega_{,n} \end{bmatrix} \;, \tag{10}$$

while the normal and tangential stress components are :

$$t_n = -p + 2\frac{h\,l\,\mu_p}{\mu_c}\left(p_{,nn} + \chi\, p_{,n} + \omega_{,sn} - \chi\, \omega_{,s}\right) \;, \tag{11}$$

$$t_s = -\omega + 2\frac{h\,l\,\mu_p}{\mu_c}\left(\omega_{,ss} + \chi\, \omega_{,n} + p_{,ns} - \chi\, p_{,s}\right) \;. \tag{12}$$

On the front, the normal and tangential stress components are imposed to be zero. On the side-walls, a sliding condition is assumed, and the normal velocity component vanishes together with the tangential stress component. Along the injection gate, the normal velocity is specified ($v_n = \bar{v}_n$), while the tangential velocity or stress component is set to zero.

3. DISCUSSION

A careful analysis of at the boundary conditions imposed along the side-walls shows that an inconsistency of the model is found in the vicinity of sharp corners. Indeed, the boundary curvature tends to infinity and an intrinsic mathematical incoherency is observed when equations are interpreted in the sense of the theory of distributions. A deeper theoretical and experimental analysis puts to the fore that the fluid is unable to flow along a sharp corner without downstream separation. This can be easily explained as follows : when the fluid flows along the sharp corner, important deformations are experienced due to the quick change of direction of the velocity along the boundary. Because of the presence of fibres, which induce a certain in-plane viscosity, the fluid is unable to sustain such large deformation and jets from the upstream edge, straight in its initial direction. In Fig.1, we indeed observe that the fluid motion is first slightly affected by the corner, since the effect of the in-plane viscosity prevails over the shear viscosity. Subsequently, the pathline deviation of the material points becomes stronger, as a consequence of the increase of the contact surface between the fluid and the walls (which lets the influence of shear viscosity in the skin layer become more important). A certain time is necessary to let the fluid again enter in contact with the side-wall located downstream of the corner. Due to these phenomena, the extremity of the front exhibits a significant curvature near the wall. This causes the front to take a mushroom-like shape, which is typical of in-plane viscosity effects.

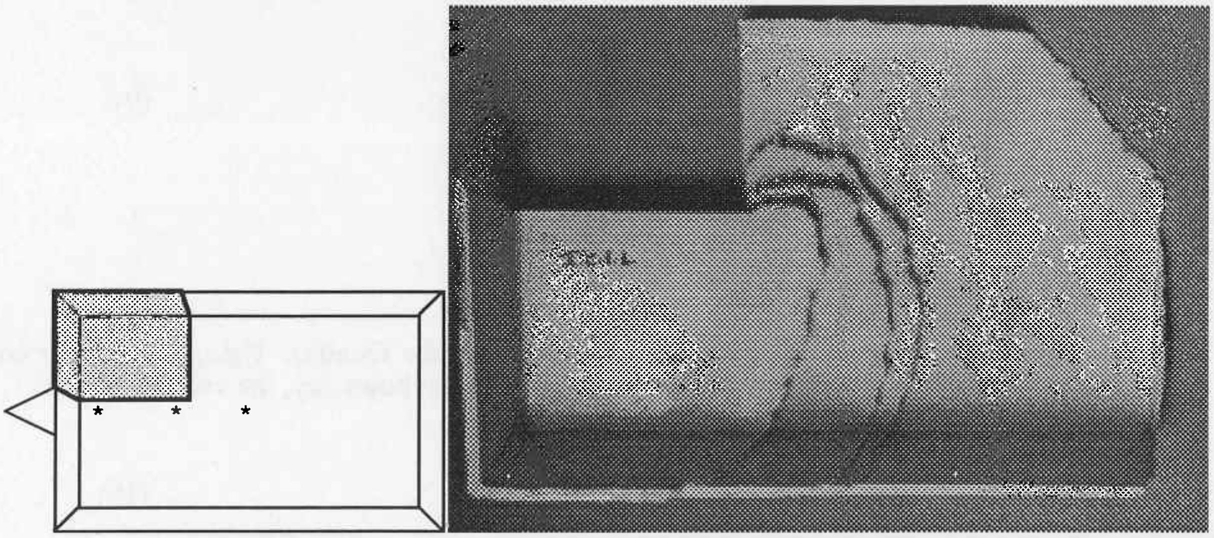

Figure 1 : General scheme of the experimental mould used to analyse the flow along a sharp corner, and detail of a short shot showing the jetting effect and the mushroom-like shape of the fronts, due to the competition between in-plane and shear viscosities. Experiments were performed at the OWENS-CORNING laboratories in Battice, Belgium.

4. CONCLUSION

The injection or compression moulding of long-fibre filled resins involves very complex forces. A new model has been built on, which is convenient to simulate the filling of complex thin parts with a suspension of long fibres. Numerical results will be presented and compared with experiments at the conference.

Acknowledgement

This paper presents research results obtained within the frame of the Belgian Programme on Interuniversity Poles of Attraction, initiated by the Belgian State, Prime Minister's Office for science, Technology and Culture, and within the frame of the COST 512 and FIRST 2439 projects initiated by the Walloon Region of Belgium.

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