THE NUMERICAL SIMULATION FLOW MOLDING PROCESSES OF SHORT FIBER COMPOSITES

Agic Ante
Faculty of Chemical Engineering and Technology
10000 Zagreb, Croatia
Fax: ++ 385 (1) 455 07 25

Introduction

The short fiber reinforced polymers, compared with continuous fiber reinforced structures have advantages in mass production geometrically complex parts by typical polymer processing methods. During flow molding processes (injection, compression, transfer molding) fiber orientation change occurs inevitably and the anisotropy caused by fiber orientation affects on microstructure properties, geometric instability and other physical properties of molded parts. In order to optimize properties and processing conditions fiber composite structures, numerical simulation of the flow and orientation fields are required. Along mold flow direction the domain of orientation state can be classified into; an entrance, a fully developed and fountain flow region (Fig 1.). In the thickness direction, it can be recognized three domains of orientation state; surface, transition and core layer. In this work flow and orientation state with front advancements were solved by finite element method.

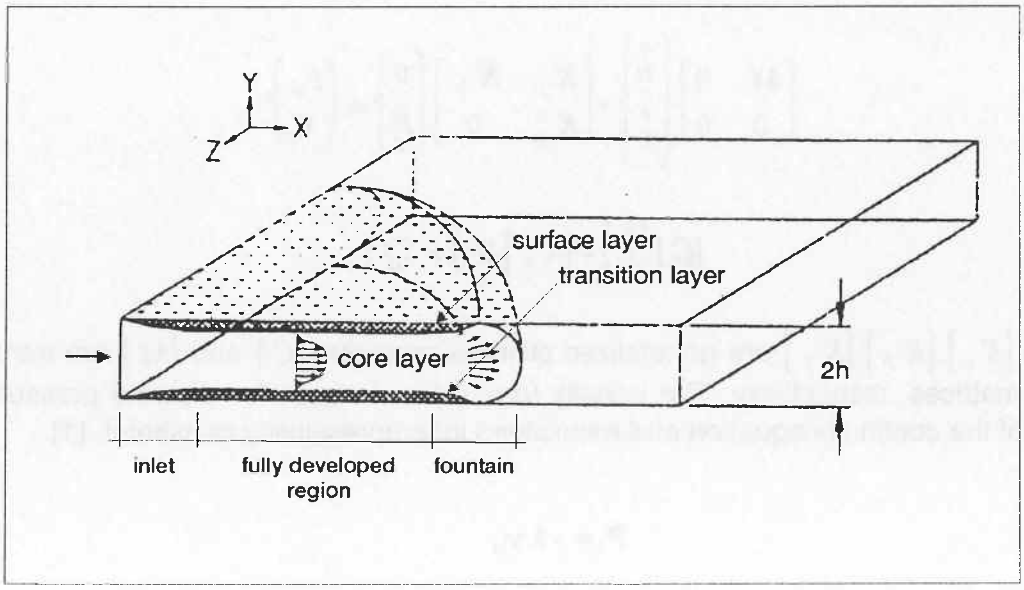

Figure 1. The flow regions for mold filling process

Flow field description

Governing equations of momentum, continuity and energy are simplified as follows:

$$\rho \frac{\partial v}{\partial t} = \nabla \cdot \sigma \qquad (1)$$

$$\nabla \cdot v = 0 \qquad (2)$$

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \cdot \nabla T) + \eta \cdot \overset{\circ}{\gamma}{}^2_m \qquad (3)$$

where **v** is velocity vector, T is temperature, ρ is density, k is thermal conductivity, C_p is heat capacitance at constant pressure, η is viscosity , σ is stress tensor, $\overset{o}{\gamma}_m$ is magnitude of the strain rate tensor $\overset{o}{\gamma}_{ij}$. The coupling come from last term on the right in the equation (3). The finite element approximation for velocity, pressure and temperature can be represented in the form

$$\{v\} = [N_v]\{\underline{v}\} \qquad (4)$$

$$\{p\} = [N_p]\ \{\underline{p}\} \qquad (5)$$

$$\{T\} = [N_T]\ \{\underline{T}\} \qquad (6)$$

where $\{\underline{v}\}$, $\{\underline{p}\}$ and $\{\underline{T}\}$ are nodal point vectors for the velocity, pressure and temperature fields, respectively. By using Galerkin's method, transient state matrix equations of velocity and temperature were derived as below

$$\begin{bmatrix} M & 0 \\ 0 & 0 \end{bmatrix} \begin{Bmatrix} \overset{o}{\underline{\upsilon}} \\ \overset{o}{\underline{p}} \end{Bmatrix} + \begin{bmatrix} K_\upsilon & K_p \\ K_p^t & 0 \end{bmatrix} \begin{Bmatrix} \underline{\upsilon} \\ \underline{p} \end{Bmatrix} = \begin{Bmatrix} F_v \\ 0 \end{Bmatrix} \qquad (7)$$

$$[C]\left\{\overset{o}{T}\right\} + [K_T]\{T\} = \{Q\} \qquad (8)$$

where $[K_v],[K_P],[K_T]$ are generalized stiffness matrices, $[C]$ and $[M]$ are transient and mass matrices, respectively. The penalty formulation is uses for discrete pressure field in place of the continuity equation and maintained incompressibility constraint, [1].

$$P_\lambda = -\ \lambda\ v_{i,i} \qquad (9)$$

$$\lambda = \mu(\gamma_{ij}, T) \cdot \beta \qquad (10)$$

An iterative procedure [2] is used to solve equation (7) with Uzava's scheme, and constant convergence accelerator. To ensure uniform continuity enforcement a viscosity-dependent penalty parameter λ is introduced (where is μ local viscosity, β is large constant machine dependent). The finite element matrix equations were solved by applying fully implicit time stepping scheme and the Newton-Raphson technique for velocity and temperature simultaneously, [3],[5].

Fiber orientation phenomena

The orientation state of the fibers defined by use second order tensors. Such tensor has defined as the dyadic product of the unit vector p averaged over all possible directions (Fig. 2).

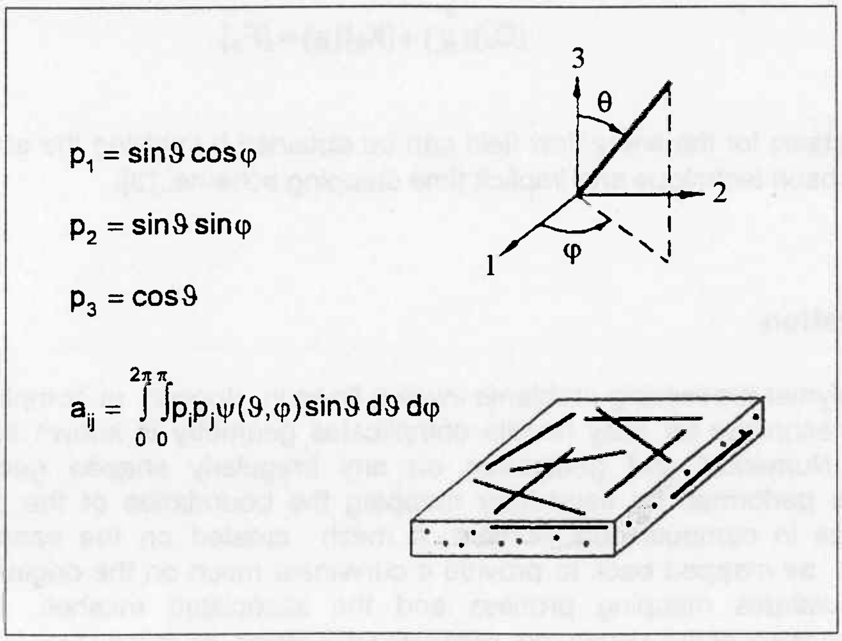

Figure 2. Definition of fiber orientation

The fiber orientation field are described by evolution equations for second order orientation tensor a_{ij},proposed by Advani and Tucker, [3].

$$\upsilon_k \frac{\partial a_{ij}}{\partial x_k} + \frac{\partial a_{ij}}{\partial t} = -\frac{1}{2}\left(\omega_{ik} a_{kj} - a_{ik}\omega_{kj}\right) + \frac{1}{2}\lambda\left(\overset{o}{\gamma}_{ik} a_{kj} + a_{ik}\overset{o}{\gamma}_{kj} - 2\overset{o}{\gamma}_{kl} a_{ijkl}\right) + \frac{1}{2}C_I \overset{o}{\gamma}_m \cdot \left(\delta_{ij} - 3a_{ij}\right) \quad (11)$$

where is C_I and λ are Interaction coefficient fiber/matrix and shape factor respectively, ω_{ij} and $\overset{o}{\gamma}_{ij}$ are the vorticity and strain rate tensors, respectively, δ_{ij} are the Kronecker delta tensor. The fourth order orientation tensor a_{ijkl}, was approximated as a linear combination of linear and quadratic second order tensors, [3].

The spatial orientation field is discretized using nodal values for a_{11} and a_{12} components

$$\{a\}^T = \{a_{11}, a_{12}\} = [N_\vartheta]\begin{Bmatrix} \underline{a}_{11} \\ \underline{a}_{12} \end{Bmatrix} \tag{12}$$

Finite element formulation of the orientation equation are obtained by applying Galerkin's method

$$[C_\vartheta]\{\overset{o}{\underline{a}}\} + [K_\vartheta]\{\underline{a}\} = \{F_\vartheta\} \tag{13}$$

Orientation states for the entire flow field can be obtained by solving the above equation by Newton-Raphson technique and implicit time stepping scheme, [3].

Grid generation

Industrial polymer processing problems involve flows in domain of complicated geometry. A mapping technique for easy handle complicates geometry is known as numerical grid generation. Numerical grid generation on any irregularly shaped geometry (physical domain) has performed by essentially mapping the boundaries of the body to a more regular shape in computational domain. A mesh created on the transformed, simpler domain can be mapped back to provide a curvilinear mesh on the original regular shape. Figure 3 illustrates mapping process and the associated meshes. Automatic mesh generation consists of the elliptic grid generator described as follow, [4]

$$a \cdot x_{\xi\xi} - 2bx_{\xi\eta} + cx_{\eta\eta} + J^2\left(P \cdot x_\xi + Q \cdot x_\eta\right) = 0 \tag{14}$$

$$ay_{\xi\xi} - 2by_{\xi\eta} + cy_{\eta\eta} + J^2\left(P \cdot y_\xi + Q \cdot y_\eta\right) = 0 \tag{15}$$

$$a = x_\eta^2 + y_\eta^2$$

$$b = x_\xi x_\eta + y_\xi y_\eta$$

$$c = x_\xi^2 + y_\xi^2$$

$$J = x_\xi y_\eta - x_\eta y_\xi$$

where J is the transformation Jacobian, and a, b, c are geometric coefficients. The grid control function P and Q have selected in order to achieve proper boundary points and force grid line to intersect boundary in normal fashion.

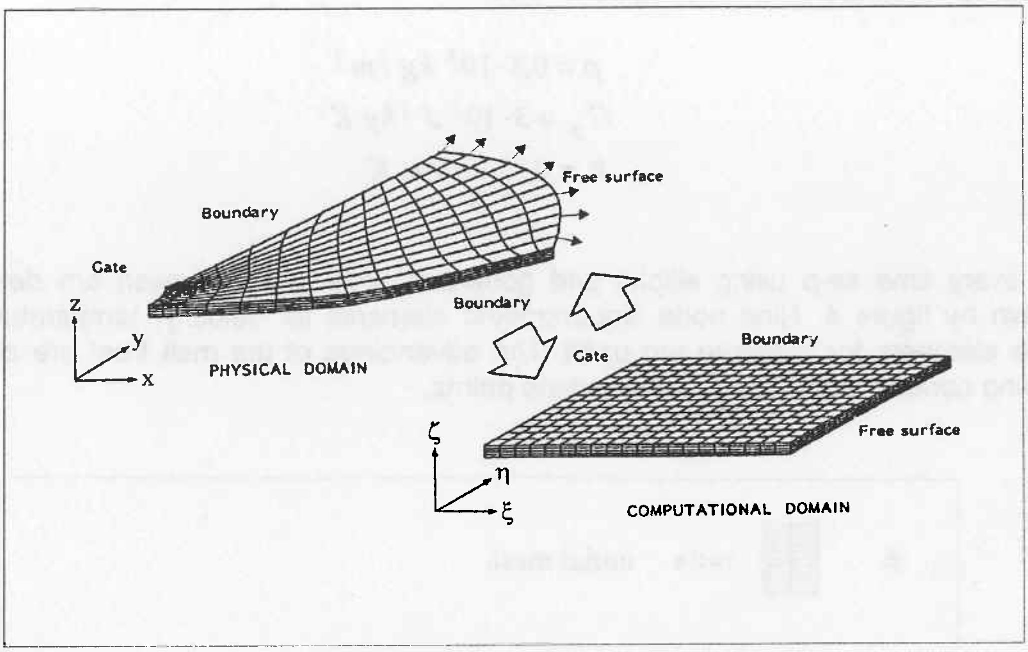

Figure 3. The numerical mapping between physical and computational domain

Central differencing of equations (14) and (15) yields a coupler pair of difference expressions that are then solved to obtain the location of the mesh node's x(i,j) and y(i,j). The procedure requires only the specification of the fluid boundaries, i. e. the inlet gate, the mold side walls touched by the fluid and the free surface. After grid generation, the automatic remeshing and moving contact algorithms are essential for these type problems. The node location in old mesh element are performed by parametric inversion [5]. The bounding box of each element is identified and the coordinates of the node of interest on the new mesh are checked against each bounding box.

Numerical Results and Discussion

For rectangular shaped cavities numerical result was obtained. The polypropylene fiber suspensions are chosen as model example. Temperature of the fiber suspension at the inlet is 500 K with and mold temperature are taken 325 K. Viscosity of the suspension is a power-law function of shear rate and temperature, [1].

$$\eta = \eta_0 \left[1 + \left(\frac{\eta_0 \overset{o}{\gamma}}{1{,}6 \cdot 10^5} \right)^{0{,}32} \right]^{-1} \qquad (16)$$

Error in printing revealed during talk?

$$\eta_0 = 2 \cdot exp(5000/T)$$

The other materials constants are as follows:

$$\rho = 0{,}8 \cdot 10^3 \; kg/m^3$$
$$C_p = 3 \cdot 10^3 \; J/kg\,K$$
$$k = 0{,}15 \; J/s\,m\,K$$

For every time step using elliptic grid generator finite element mesh are determined as shown by figure 4. Nine node isoparametric elements for velocity, temperature and four node elements for pressure are used. The advancings of the melt front are corrected by moving contact algorithm for intermediate points.

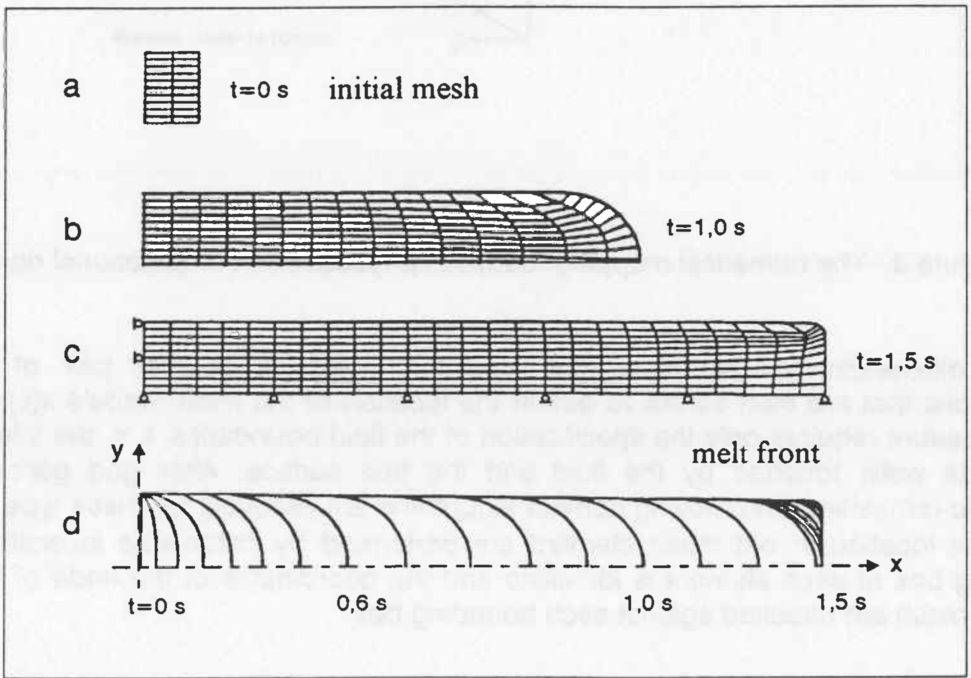

Figure 4. Finite element mesh with melt front movement

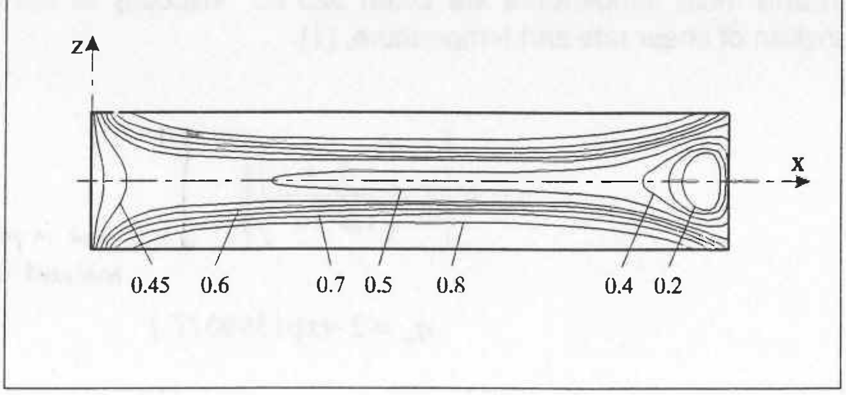

Figure 5. Fiber orientation contour plot (component a_{11})

Figure 5 show contour line plot of tensor component a_{11} of orientation tensor. The situation when each corner of the mold is complete filled. It is easy observed nonhomogeneous and anisotropic orientation behavior. In corner region orientation changes are rapid, and result from this region must be taken with experimental verification.

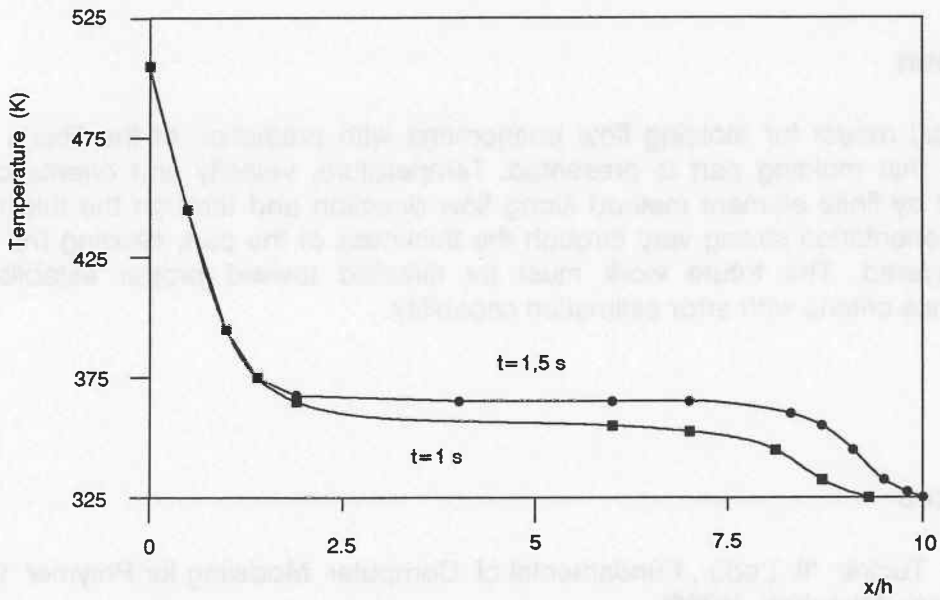

Figure 6. Temperature distribution in midplane Z=0

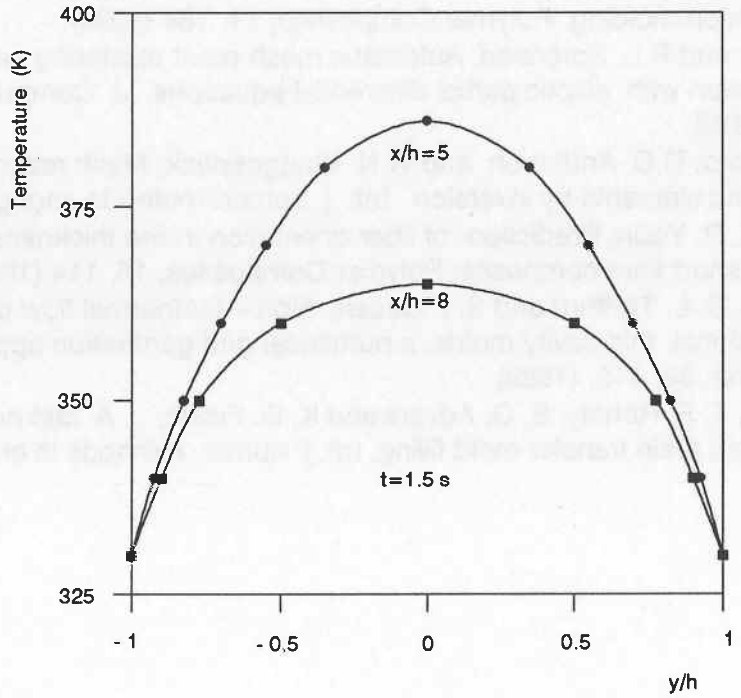

Figure 7. Temperature distribution across the gapwidth

Temperature distributions across midplane of the cavities characterize temperature gradients along mold flow direction (Fig. 6). In the fountain region temperature distribution by rapid shear strain rate changes. Temperature profiles across gapwidth depend on location of the cross-sections along flow direction, as it evident by Figure 7.

Conclusion

A numerical model for molding flow phenomena with prediction of the fiber's orientation states in thin molding part is presented. Temperature, velocity and orientation field are calculated by finite element method along flow direction and through the thickness of the part. The orientation strong vary through the thickness of the part, causing the molding to appear layered. The future work must be directed toward proper establishment the convergence criteria with error estimation capability.

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