IMPROVEMENTS IN THE SIMULATION OF ORIENTATION IN INJECTION MOLDING OF SHORT FIBER THERMOPLASTIC COMPOSITES

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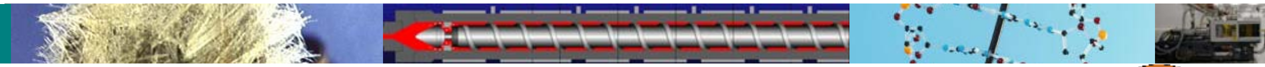


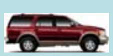
ABSTRACT

The mechanical properties of injection molded short-fiber reinforced thermoplastic composite parts are highly dependent on the orientation distribution of the fibers. A simulation tool capable of predicting fiber orientation accurately as a function of mold design and processing conditions is required as the predicted fiber orientation capabilities in commercial software show large discrepancies when compared with experimentally measured orientation. In this work a two dimensional coupled Hele-Shaw approximation for predicting the flow-induced orientation of glass fibers in injection molded composite parts is presented. In addition to coupling the stresses to fiber orientation for a highly concentrated short glass fiber PBT suspension, the model considers the slowdown of the evolution of orientation due to fiber interaction. Material parameters in the model are determined from basic rheometry rather than using data from injection molding experiments. The equation of motion coupled with stress equations are discretized using the discontinuous Galerkin Finite Element Method. Flow simulations are performed using a measured orientation profile at the gate instead of random orientation assumed in previous studies. Finally, the evolution of fiber orientation in the cavity is determined experimentally using a modified version of the method of ellipses and results are compared against the predicted values of orientation. The fiber orientation predicted in the entry region and the core layer structure at the end of fill region are now in closer agreement with the experimental values, but there are still some discrepancies.

BACKGROUND

High Strength Weight Reduction Materials

Office of FreedomCAR and Vehicle Technologies



To identify and develop materials and materials processing technologies which can contribute to weight reduction without sacrificing strength and functionality:

- Increase the fuel efficiency
- Reduce emissions of class 1-8 trucks

GOAL

To combine numerical simulation and experimental programs to improve the prediction of microstructure in short glass reinforced thermoplastics

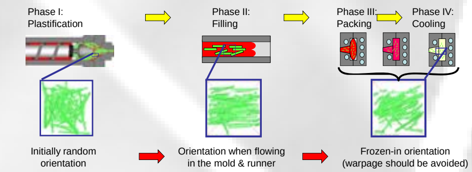
OBJECTIVES

- To simulate the mold filling process for thermoplastic melts reinforced with short fibers using constitutive relations (i.e. stress tensors coupled with a generation expression) which allow coupling between the flow and particle orientation.
- A key aspect of this work will be an experimental evaluation of the predicted fiber or particle orientation distribution throughout an injection molded part.

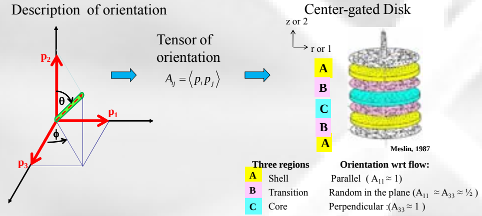
INNOVATION

Use of constitutive relations, which contain the micro-structural aspects of the reinforced melts.

ORIENTATION DURING INJECTION MOLDING



MULTILAYER STRUCTURE



CHALLENGES

- **Model fiber orientation correctly:**
  - **Should the standard model (Folgar-Tucker) be improved to predict the correct evolution of fiber orientation?**
  - **Do interparticle interaction delays orientation in a concentrated solution?**
  - **Can model parameters be determined by by rheometrical experiments?**
- **Measure particle orientation**
  - **Resolve ambiguity in method of ellipses (standard)**
  - **Characterize the orientation along the whole flow domain**
    - **Region close to the wall**
    - **Front**
    - **Asymmetry cavitywise**
    - **Structure of orientation in radial direction**
- **Develop numerical simulation tool to predict fiber orientation using parameters obtained from rheometry**
  - **Do results strongly depend on inlet orientation at the gate?**
  - **Stable and accurate numerical technique for moving front**

MODELLING OF COMPOSITES

- Balance equations for injection molding

$$\underline{\nabla} \bullet \underline{v} = 0 \quad \text{(Mass)} \qquad -\underline{\nabla} p + \underline{\nabla} \bullet \underline{\underline{T}} = \underline{0} \quad \text{(Momentum)} \qquad \underline{\underline{T}} = \underline{\underline{T}}^{fiber} + \underline{\underline{T}}^{matrix} \quad \text{(Stress)}$$

- Short glass fibers
  - Constitutive equation: Folgar-Tucker Model with delay (α)

Evolution of orientation tensor

$$\frac{D\underline{\underline{A}}}{Dt} = \alpha\left[\underline{\nabla}\underline{v}\cdot\underline{\underline{A}} - \underline{\underline{A}}\cdot(\underline{\nabla}\underline{v})^T - 2\underline{\underline{d}}:\underline{\underline{\underline{\underline{A}}}} + 2C_I\left|\underline{\underline{d}}\right|\left(\underline{\underline{I}} - 3\underline{\underline{A}}\right)\right]$$

$$\underline{\underline{d}} = \frac{1}{2}\left(\underline{\nabla}\underline{v} + (\underline{\nabla}\underline{v})^T\right)$$

Stress due oriented particles $\underline{\underline{T}}^{fibers} = \nu\xi_{str}\underline{\underline{d}}:\underline{\underline{\underline{\underline{A}}}}$

- Polymer matrix
  - Newtonian matrix $\underline{\underline{T}}^{matrix} = 2\eta_s\underline{\underline{d}}$

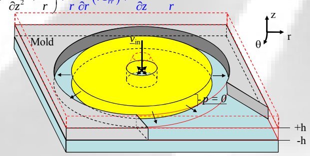
- Hele-Shaw flow approximation of balance equations

$$0 = \frac{\partial p}{\partial r} + 2\eta\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_r}{\partial r}\right) + \frac{\partial^2 v_r}{\partial z^2} + \frac{v_r}{r}\right) + \frac{1}{r}\frac{\partial}{\partial r}(rT_{rr}) + \frac{\partial T_{zr}}{\partial z} - \frac{T_{\theta\theta}}{r}$$

$$v_z = 0; \quad p = p(r)$$

$$0 = \frac{1}{r}\frac{\partial(r\overline{v}_r)}{\partial r}$$

$$\overline{v}_r = \frac{\int_{-h}^{h} v_r(r,z)\,dz}{2h}$$



COMPOSITE MATERIAL

- Material properties
  - Matrix: PBT (Newtonian)
  - Filler: 30wt% short glass fiber
    - Aspect ratio: 30

$\text{Aspect Ratio}(a_r) = \frac{Length}{Diameter}$

- Model parameters obtained from rheometry

Orientation parameters	
C_I	0.02
α	0.40

Stress parameters	
$\nu\xi_{str}$	5000 Pa s
η_s	373 Pa s

EXPERIMENTAL DETERMINATION OF FIBER ORIENTATION

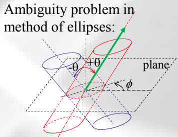
- Procedure:

Polishing → Plasma etching → Image acquisition (reflective microscopy using motorized stage) → Semi-automatic image analysis (customized)

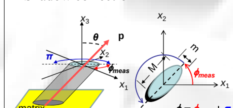
- Results

Eliminate ambiguity problem using the shadow

Ambiguity problem in method of ellipses:



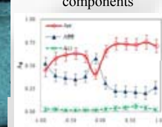
Shadow correction



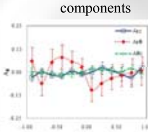
Obtain fiber orientation close to the wall (no reliable results in literature)

Characterize fiber orientation in full flow domain:

Diagonal components



Off-diagonal components

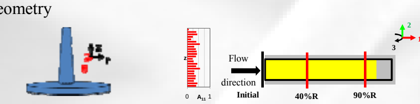


Gate

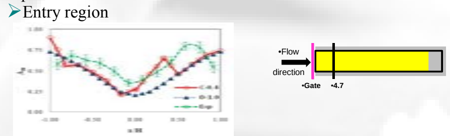
Notice the asymmetry in fiber orientation along the thickness

SIMULATION RESULTS

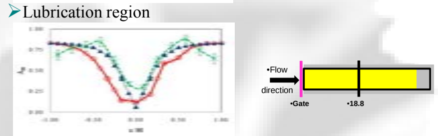
- Geometry



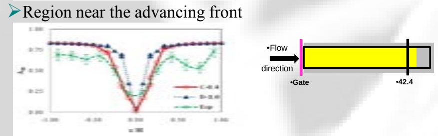
- Center-gated disk (R=3 cm, 2H = 1.38 mm) with experimentally measured initial orientation and a 12x30 mesh
- Numerical technique
  - Solve at every time step (coupled approach)
    - Balance Equation or Hele-Shaw flow approximation
      - Galerkin FEM
    - Constitutive equations
      - Discontinuous Galerkin FEM
    - Find the new mesh coordinates
- Experimental vs numerical fiber orientation
  - Entry region



  - Lubrication region



  - Region near the advancing front



FINDINGS

- Model parameters determined by rheometry can be used to simulate fiber orientation
- Modified procedure let us to improve the fiber orientation measurement using reflective microscopy.
- Experimental measurements show asymmetric profile of orientation that evolves from the gate to the flow front .
- The delay model and coupled flow and orientation improve prediction of fiber orientation.

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