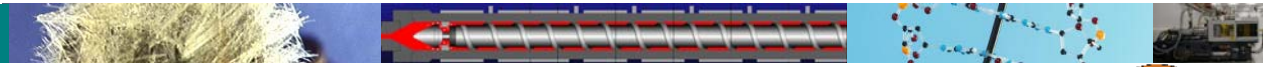

2D Simulation and Validation for Highly-Concentrated, Glass Fiber-Reinforced, Injection Molded Thermoplastic Composites

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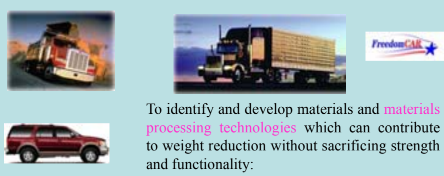
ABSTRACT

Highly concentrated, injection molded fiber-reinforced composite one of the strategies considered by the automotive industry to reduce fuel consumption. The bottleneck of this technology is the uncontrolled anisotropy due to the flow-induced orientation that happen during the forming stage on the parts. The use of simulation software able to compute the fiber orientation can solve this limitation, but commercial software are able only to qualitative describe the orientation. This paper presents the use of a rheological based model for the orientation capable to predict the fiber orientation in center-gated disk and the validation of those predictions with experimental orientation results. A 2-D finite element code that couples the flow field described by Hele-Shaw flow approximation and the equations governing fiber orientation simulate the filling stage of a glass-fiber suspension within commercial concentration. In these simulations, an asymmetric orientation measured at the gate by a modified version of the method of the ellipse is set as initial condition of orientation. The prediction of fiber orientation evaluated in several locations of incomplete center gated parts (10, 40, and 90% of the radial dimension) is compared with experimental results. The experimental results show an asymmetric profile related to the multilayer structure of orientation that that fades from the gate to the end-of-fill region of the molded part more slowly than the predictions do. In addition, the discrepancies observed close to the end-of-fill region can be attributed to the extensional flow in this region, but ignored by use of the approximated flow field used in the simulations. Apparently, coupled simulations including the frontal flow and slow evolution model of orientation are necessary to predict quantitatively the fiber-induced orientation.

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

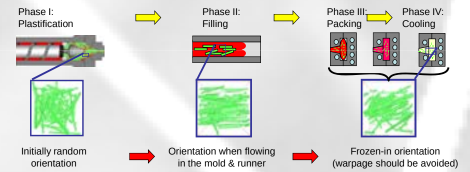
OBJECTIVES

- 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.

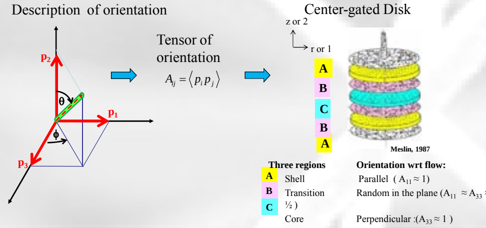
INNOVATION

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

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

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

Evolution of orientation tensor

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

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

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

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

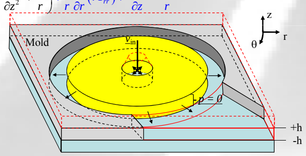
- Hele-Shaw flow approximation of balance equations

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

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

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

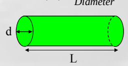
$$\bar{v}_r = \frac{\int_{-h}^{h} v_r(r,z)\,dz}{2h}$$



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	
$v\xi_{str}$	5000 Pa s
η_s	373 Pa s

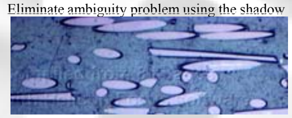
EXPERIMENTAL DETERMINATION OF FIBER ORIENTATION

- Procedure:

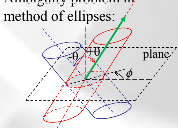
Polishing → Plasma etching → Image acquisition (reflective microscopy using motorized stage) → Semi-automatic image analysis (customized)

- Results

Eliminate ambiguity problem using the shadow

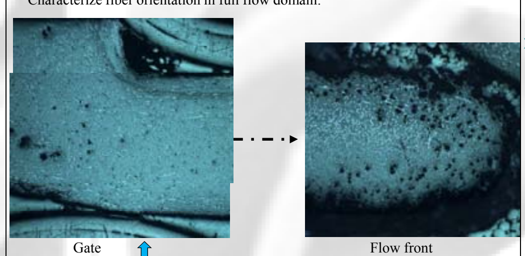


Ambiguity problem in method of ellipses:



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

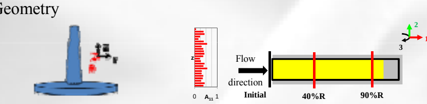
Characterize fiber orientation in full flow domain:



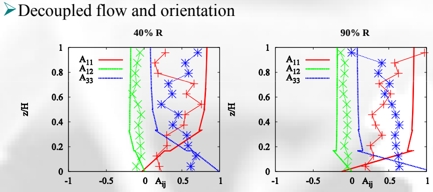
Notice the asymmetry in fiber orientation along the thickness

SIMULATION RESULTS

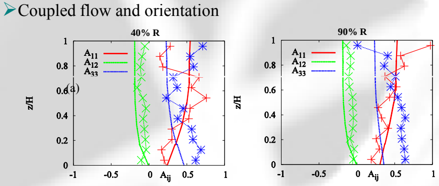
- Geometry



- 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
  - Decoupled flow and orientation



  - Coupled flow and orientation



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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