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Fiber orientation in the frontal region of a center-gated disk: Experiments and simulation

S.M. Mazahir [a], G.M. Vélez-García [b], P. Wapperom [c,*], D. Baird [a]

[a] Department of Chemical Engineering, Virginia Tech, Blacksburg, VA 24061, USA
[b] Macromolecules and Interfaces Institute, Virginia Tech, Blacksburg, VA 24061, USA
[c] Department of Mathematics, Virginia Tech, Blacksburg, VA 24061, USA

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ABSTRACT

Fiber orientation in the frontal region of a center-gated disk was measured for the first time and compared with orientation predictions using standard Folgar–Tucker and the reduced strain closure (RSC) model in coupled flow simulations. Fiber orientation was experimentally measured along three different heights representative of shell, transition and core layers, in order to understand the evolution of orientation along the radial direction in the frontal region. Orientation predictions of the Folgar–Tucker model and its two modified versions, the delayed Folgar–Tucker model and the RSC model were assessed against the measured experimental data. Orientation predictions with all three models showed a drop in orientation near the front, which was in qualitative agreement with the experimental data. Modified versions of the Folgar–Tucker model showed a relatively larger drop in orientation in the shell layer with predictions being relatively closer to experimental values. However, no significant slowdown was observed with the modified versions in the transition and core layers. With coupling of flow and orientation, the frontal flow region was slightly larger and orientation predictions showed only slight improvement. A significant improvement in the frontal region was obtained when a lower value of the interaction coefficient was used.

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1. Introduction

Short glass fiber thermoplastic composites made by injection molding are finding increased usage as high-strength light-weight materials in various applications. The mechanical, electrical, and thermal properties of these materials are significantly affected by the orientation distribution of reinforcing fibers which develops during the molding operation. Properties of the final solidified part vary throughout the part due to local variations in the orientation of fibers. This is because of the presence of a complex flow field inside the mold which induces orientation of fibers, a phenomenon known as flow-induced orientation. Therefore, in order to precisely control fiber orientation in a molded composite part, it becomes necessary to develop theoretical models and numerical schemes that can accurately predict fiber orientation under complex flow fields.

Fountain flow [1], is a characteristic flow feature associated with the advancing front in injection molding operations that plays a prominent role in the orientation of fibers in injection molded geometries [2,3]. Previous experimental studies on fiber orientation in injection molded geometries such as a center-gated disk have shown that the orientation along the flow direction is not the highest at the mold walls but at locations away from the mold walls [4–6]. From these studies, the drop in orientation near the mold walls may be attributed to fountain flow effects, thermal effects or a combination of the two. However, these studies only report experimentally measured fiber orientation data up to a significant distance behind the front and exclude the frontal region of flow. Mazahir et al. [4] have reported fiber orientation measurements along the direction of flow at three different heights representative of the shell, transition and core layers. However, the measured region covers the flow length of the disk only up to 7 r/H behind the front. Other publications have reported fiber orientation data measured along the thickness of the disk at sparse radial locations [5,6]. Bay and Tucker [5] conducted the first experimental study on fiber orientation in a center-gated disk and reported z/H profiles only up to a distance 7.5 r/H behind the front. Vélez-García et al. [6] reported z/H profiles of orientation only up to

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* Corresponding author. Tel.: +1 540 231 7252; fax: +1 540 231 5960.

E-mail addresses: syedm@vt.edu (S.M. Mazahir), gvelez@vt.edu (G.M. Vélez-García), pwappero@math.vt.edu (P. Wapperom), dbaird@vt.edu (D. Baird).

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a distance 7 *r*/*H* behind the front. In order to gain insights into the effects of the fountain flow on the orientation of fibers in the frontal region of an injection molded geometry such as a center-gated disk, it is crucial to characterize the fiber orientation in the frontal region of the disk.

The Folgar–Tucker (F–T) model [7] has been the most popular model for fiber orientation predictions in injection molded geometries, with varying degrees of success [8–16]. Folgar and Tucker [7] introduced an isotropic rotary diffusion term in the Jeffery's model [17] to account for interaction between neighboring fibers in a fiber suspension. However, in fiber suspensions of commercial interest, rheological studies have shown that the evolution of fiber orientation in startup of shear is much slower than what the F–T model predicts [18,19]. It has been suggested that reduction in the rate of rotation of fibers is caused by interactions between fibers, at high fiber concentrations [20,21]. To slow down orientation kinetics in concentrated fiber suspensions, two modifications to the Folgar–Tucker model have been proposed [19,21,22]. One of the proposed modifications is the addition of a delay parameter known as the slip parameter [18,19] or the strain reduction factor (SRF) [22], which renders the orientation model non-objective. The other modification is the reduced strain closure (RSC) model which achieves the slowdown in orientation evolution while retaining the objectivity of the original model [21]. The modified versions of the Folgar–Tucker model result in improved orientation predictions by slowing down the evolution of orientation in shear flows such as start-up of shear and shear-flow reversal [18,19,21].

In early simulation studies on fountain flow effects in injection molded geometries, a two-step approach was followed. First the orientation was predicted in the lubrication region using the Hele-Shaw flow approximation and then a separate simulation was performed for the fountain flow region [10,23]. Such schemes with separate fountain flow simulations made inherent assumptions about the distance behind the front where the fountain flow starts and the velocity profile at the start of the fountain flow region. Chung and Kwon [2], and Park and Kwon [3] used the pseudo-concentration method of Haagh and Van De Vosse [24] to include the effects of fountain flow on fiber orientation in a center-gated disk. Chung and Kwon [2] used the F–T model [7] for orientation predictions in a center-gated disk made with nylon 6/6 and 43 wt% (fiber volume fraction $\phi = 0.23$) short glass fibers. However, the parameter C_I that represents inter-fiber interactions in the F–T model was selected as $C_I = 0.001$, which is considerably lower than the typical range for short glass fibers (0.006–0.01), recently proposed by Phelps and Tucker [25]. Indeed, values of C_I determined from rheological fitting [4,6,21] for the 30 wt% fiber suspension considered in this paper are an order of magnitude higher than the value used by Chung and Kwon [2]. Park and Kwon [3] used the RSC model for orientation predictions in a center-gated disk and a phenomenological model for C_I that includes nonlinear viscoelasticity of the polymer and kinematic interactions between fibers and the polymer. Moreover, in these two studies, orientation predictions have been compared with the experimental data in the thickness direction only up to a distance 7.5 *r*/*H* behind the front [2,3]. Therefore, with these experimental comparisons and parameter selection, it is difficult to quantify the improvements gained in orientation predictions in the frontal region of a center-gated disk.

This paper has two primary objectives. The first objective is to report the measured fiber orientation data in the frontal region of a thin center-gated disk along the radial direction at three different heights representative of the shell, transition, and core layers. The second objective is to assess predictions of the F–T model and its two modified versions in the frontal region of a center-gated disk in fountain flow simulation.

2. Problem description

A center-gated disk was injection molded using a 30 wt% (volume fraction $\phi = 0.1766$) short glass fiber polybutylene-terephthalate (PBT) suspension (Valox 420). The viscosity of the PBT matrix was measured on a Rheometrics Mechanical Spectrometer (RMS-800) from steady shear and dynamic oscillatory measurements conducted at 533 K. The viscosity of the matrix showed a Newtonian behavior between shear rates $0.1\ \mathrm{s}^{-1}$ and $100\ \mathrm{s}^{-1}$ with $\eta_s = 350$ Pa s [20]. The number average fiber diameter $d = 12.9$ μm and fiber length $l = 364$ μm were determined from a burn-off process for about 1000 fibers. The measured number average fiber diameter and length correspond to $l/d = 28.2$. Weight average fiber length was calculated to be $l_w = 439$ μm [19].

A short-shot disk was made with average measurements, inner radius $R_{in} = 2.97$ mm, outer radius $R_{out} = 51.8$ mm and thickness $2H = 1.38$ mm as shown in Fig. 1(a). In order to exclude the effects of packing, the radial distance filled inside the mold was about 90% of the total radial length of the mold. The resin was first dried overnight in a vacuum oven at a pressure less than 1.35 kPa and the dried resin was fed to the screw under nitrogen atmosphere at 433 K. The suspension was injected into the mold maintained at 363 K using an injection pressure of approximately 20 MPa, with filling time approximately 1 s. This corresponds to a volumetric flow rate $q \approx 11.8\ \mathrm{cm}^3/\mathrm{s}$. The disk was allowed to cool and solidify for about 1 min inside the mold to minimize warpage.

3. Experimental evaluation of the frontal region

3.1. Shape and texture of the advancing front

The shape and the texture of the advancing fronts of 30 wt% short glass fiber/PBT suspension and pure PBT polymer were analyzed under an optical microscope. The center-gated disk of pure PBT was injection-molded under the same conditions of temperature and pressure as the disk made of the fiber suspension. The frontal region of each disk was cut out and mounted in acrylic and observed in the *rz*-plane under an optical microscope at 5X zoom level. Fig. 2 shows the images of the advancing front of the

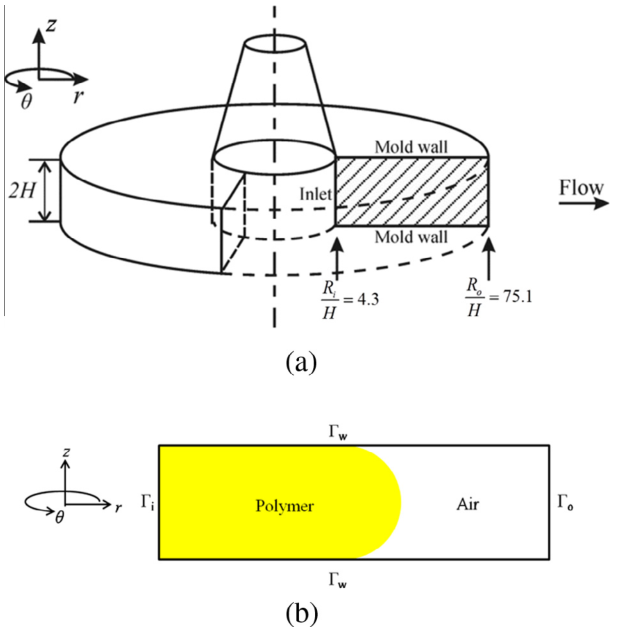

Fig. 1. Center-gated disk with dimensions normalized by the half thickness H of the disk (a) and the simulation domain and boundaries (b).