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Effect of fountain flows on injection-molding-induced morphology

Yutaka Kobayashi, Yasuhiko Otsuki, and Toshitaka Kanai

In injection molding of polypropylene, extensional deformation at the advancing flow front causes high birefringence near the surface.

Polypropylene (PP) is a widely used plastic in the automotive industry that can be easily injection molded. The performance of molded products is affected by the processing-induced sandwich ('skin and core') structure. We have been studying the impact of morphology on the surface properties of injection-molded PP,[1,2] because scratch resistance and paintability are essential requirements for automotive parts. Molten PP injected into a cold tool freezes immediately at the cavity wall. Consequently, crystal morphology forms under transient temperature and flow-rate conditions. Although full control of surface morphology is highly desired to improve the material's surface properties, the mechanism governing the injection-molded surface morphology is not completely understood.

Fountain flows are a fundamental idea in this context because they are relevant to the flow patterns during the filling process in injection molding.[3] Hot molten PP moves forward at the center of the mold cavity. At the advancing flow front, the PP makes a U-turn toward the wall, where it is subject to extensional deformation. Since molten PP freezes immediately when it makes contact with the cold wall, its frozen-in orientation can be observed through birefringence using a polarizing optical microscope (POM). Thus, simulations of birefringence depth profiles from the surface to the core in injection-molded specimens can be studied using viscoelastic-flow analysis. Because of difficulties inherent to these calculations, numerical fluid models are often simplified using the lubrication approximation. This leads to a Hele-Shaw type current and neglects the effect of fountain flows at the flow front.[4] Consequently, a simple shear flow is usually assumed. However, we emphasize the importance of the extensional flow (at the advancing flow front) on the distribution of birefringence in the depth direction. We used a 2D flow (in the flow and gapwise directions) in a rectangular cavity of even thickness to simulate a fundamentally simple flow path. Our aim was to understand the surface-morphology formation mechanism in injection-molded PP, simultaneously using analytical and numerical methods.

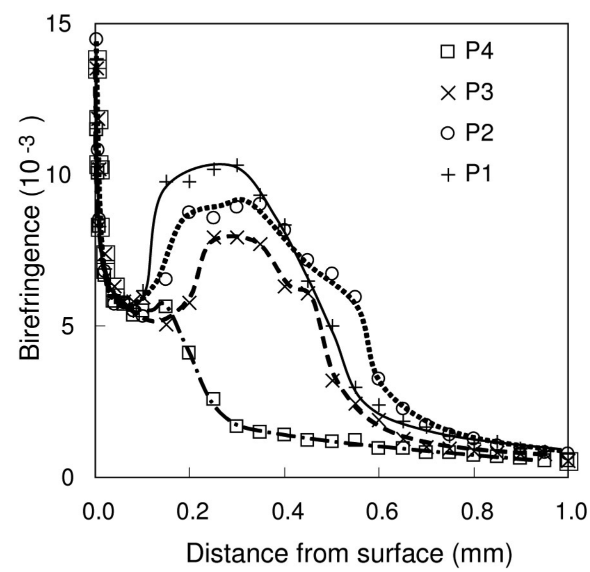

Figure 1. *Birefringence depth profiles. Cross cuts from the gate to the flow end (P1–P4) of an injection-molded plate.*[5]

We numerically track a dimensionless particle in the flow to determine its stress and strain. If the principal axis of stress on the particle becomes parallel to the wall near the surface behind the advancing flow front, extensional deformation is expected to lead to birefringence, although earlier reports have suggested that the molten polymer is largely deformed by the shear stress caused by quenching on the cold cavity wall.

In our analytical approach, we used a blend of PP and ethylene butene rubber (PP/EBR) for injection molding of rectangular plaques (width × length × thickness: 70 × 270 × 3mm^3). We characterized the morphology from the gate to the flow end (P1 to P4) of the plaque using the POM with a Berek compensator at room temperature. Figure 1

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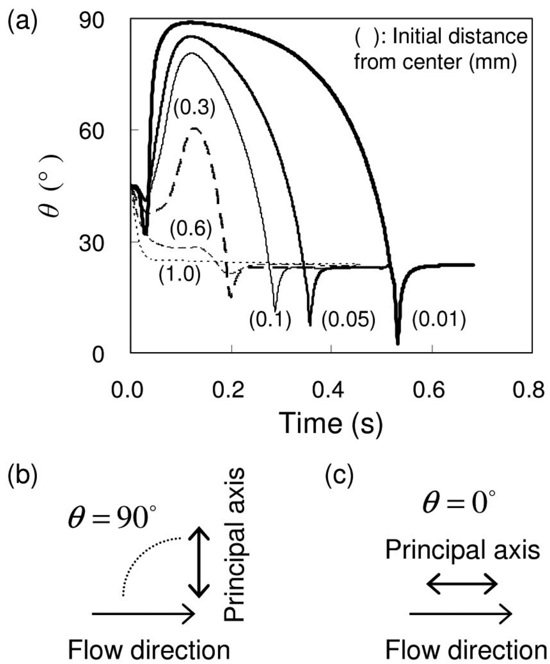

Figure 2. *(a) Changes in angle of the principal axis of stress (θ) for different flow directions as a function of time. (b) and (c) Relationships between the principal axis and the flow direction for $\theta = 90$ and 0°, respectively.*[5]

shows that the birefringence initially decreases strongly with depth and then shows a peak. These features correspond to the frozen and shear-oriented layers, respectively. Although the thicknesses of the shear-oriented layers were different at each position, the strongly decreasing birefringence behavior overlapped near the surface. As a result, surface morphology is formed just behind the advancing flow front without being affected by the post flow.

High birefringence near the surface means that the molecular orientation is retained. To clarify the effect of extensional deformation on the frozen-in orientation, we performed numerical simulations combined with multimode viscoelastic-flow analysis based on the PP/EBR parameters and the molding conditions. We concluded that a particle that was initially near the center in the fluid flowed into the advancing flow front, then traversed to the surface, and finally froze at the mold wall. This particle behavior is the same as the fountain-flow concept. We numerically analyzed the dependence of the angle of the principal axis of stress on the flow direction (see Figure 2). A particle that was initially located at a distance of 0.01mm from the center was stretched in the depth direction in 0.1s—see Figure 2(b)—and the angle (θ) subsequently changed from 90 to 0° during the particle's final U-turn at the flow front (θ was close to zero when it reached the wall). The zero angles suggest that the particle was stretched extensionally in the flow direction: see Figure 2(c). After the particle hit the wall with the maximum deformation rate, it was immediately subjected to shear stress.

In summary, although the surface properties of injection-molded products are important for PP, the surface-morphology formation mechanism is poorly understood. Our study has shown that extensional deformation at the advancing flow front causes high birefringence near the surface. As our next step, we will explore the relationship between crystallization and the flow front.

Author Information

Yutaka Kobayashi
Advanced Composites Inc.
Sidney, OH

Yasuhiko Otsuki
Prime Polymer Co. Ltd.
Sodegaura, Japan

Toshitaka Kanai
Idemitsu Kosan Co. Ltd.
Ichihara, Japan

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