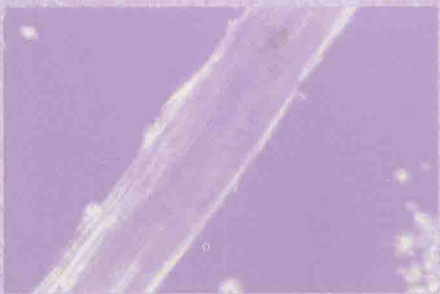
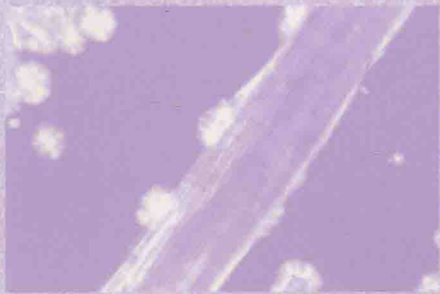
Fifth International Conference on Woodfiber-Plastic Composites


Fifth International Conference on Woodfiber-Plastic Composites

May 26–27, 1999
The Madison Concourse Hotel
Madison, Wisconsin

Sponsored by the USDA Forest Service in cooperation with the American Plastics Council, the University of Wisconsin, the University of Toronto, the Cellulose, Paper, and Textile Division of the American Chemical Society, and the Forest Products Society.

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Preface

This book contains the proceedings of the Fifth International biennial Woodfiber-Plastic Composites Conference held in Madison, Wisconsin, May 26-28, 1999. Hosted by the Forest Products Laboratory, this conference was sponsored by the USDA Forest Service, University of Wisconsin, University of Toronto and Materials and Manufacturing Ontario, American Plastics Council, the Composites Institute, American Chemical Society (Cellulose, Paper and Textile Division), the Society of Plastics Engineers, and the Forest Products Society.

The purpose of this conference was to bring together both technical and applications people to discuss and disseminate data and information in the area of lignocellulosic fiber-thermoplastic composite materials. Fiber reinforced thermoplastic materials is a rapidly growing field and these conferences provide a platform for information exchange on the nature, structure, and properties of these materials.

Interest in this area has grown since the first conference was held. The breadth of the interest in the subject and its worldwide aspect is reflected in conference participation. The total number of registrants for the 1999 conference was 325, with representation from 17 foreign countries. The largest single constituency group was from the manufacturing sector.

The conference covered both fundamental and applied aspects of the fiber-plastic composite field. The fundamental sections covered topics such as fiber and composites, processing and properties, and structural and performance. The application sections covered topics such as worldwide perspectives, processing, and markets and applications. There were keynote presentations on the fundamental principles of polymer composites processing and design; functional fillers for plastics: outlook to the year 2005,;and the changing nature of window materials in North America. This proceedings volume is organized according to papers presented in each of these three sections.

The use of agro-based resources as fillers and reinforcements in thermoplastics dates back almost 40 years, and there are many companies now producing products using these components. Wood flour (particulate) is the most used filler today but interest is growing in using fibers with high aspect ratios as reinforcing fillers. Combining wood flour with thermoplastics without the use of a compatibilizer is also the most used technology today but interest is also growing in the use of compatibilzers with fibers to improve performance of the fiber-thermoplastic composites.

Future research needs identified at the conference included the development of a data base on properties of thermoplastic composites using different levels and types of fillers, improved performance of agro-fiber thermoplastic composites used in adverse environments (water sorption and weathering), improved impact properties, equipment development for more efficient mixing systems while reducing damage to the agro-based resource and faster through put, and developing better compatibilization systems. There was also much discussion on the development of accurate guidelines for mixing, extruding and injection-molding of agro-fiber thermoplastic composites and for the development of standards that can be used by various industries.

It will be interesting to discuss new developments in research, equipment development, and industrial applications at the Sixth International Woodfiber-Plastic Composites Conference planned for 2001.

Roger Rowell

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Applications: Markets and Applications

Moderator: *Robert H. Falk*

Technical Forum Presentations

Opening Plenary Session

Fundamental principles of polymer composites: processing and design

Tim A. Osswald

Abstract

This paper presents some of the basic principles that govern the behavior of polymer composites processing and product performance. The issue of fiber orientation during processing is addressed as well as the influence of the resulting orientation distribution on the mechanical behavior of the final part. The mechanisms that control fiber damage or attrition during extrusion or molding cycles is also covered. The mechanical behavior of the finished product is discussed, including rules of thumb and simple computation schemes used to compute their anisotropic mechanical properties.

Anisotropy development during processing

The mechanical properties and dimensional stability of a molded composite product are strongly dependent upon the anisotropy of the finished part. The anisotropy depends on the orientation of the reinforcing fibers which can either be unidirectional, random, or distributed. A fiber orientation distribution function within the final part is influenced, in turn, by the design of the mold cavity (e.g., type and position of the gate) and by various processing conditions. The amount and type of filler or reinforcing material also has a great influence on the quality of the final part.

In typical injection-molded products fiber, orientation can be divided into seven layers (Fig. 1) (25). The seven layers may be described as follows:

- two thin outer layers with a biaxial orientation, random in the plane of the disk;
- two thick layers next to the outer layers with a main orientation in the flow direction;
- two thin randomly oriented transition layers next to the center core; and
- one thick center layer with a main orientation in the circumferential direction.

There are three mechanisms that lead to high degrees of orientation in injection-molded parts: fountain flow effect, radial flow, and holding pressure-induced flow.

The fountain flow effect (13) is caused by the nonslip condition on the mold walls, which forces material from the center of the part to flow outward to the mold surfaces as shown in Figure 2 (26). The melt that flows inside the cavity freezes upon contact with the cooler mold walls. The melt

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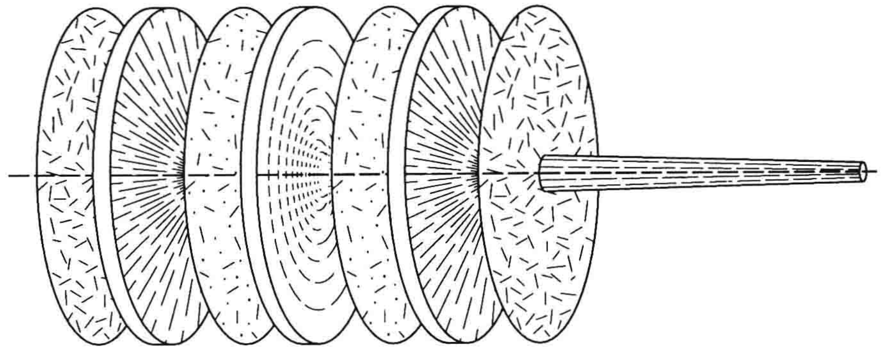


Figure 1. ~ *Filler orientation in seven layers of a centrally injected disk.*

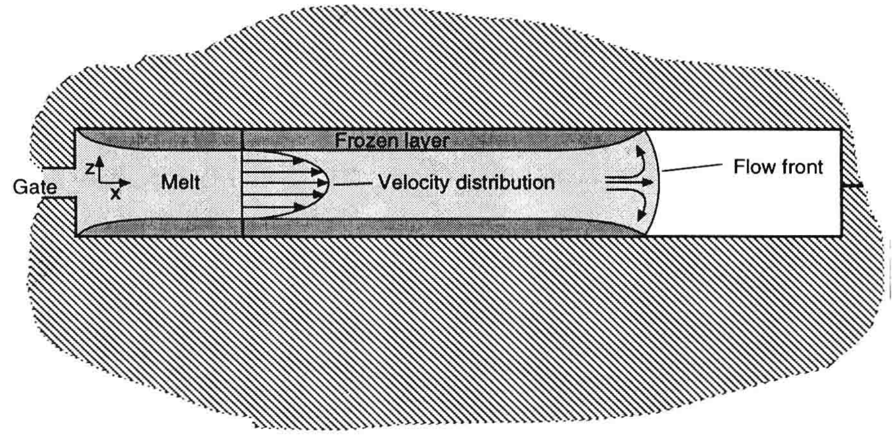


Figure 2. ~ *Flow and solidification mechanisms through the thickness during injection-molding.*

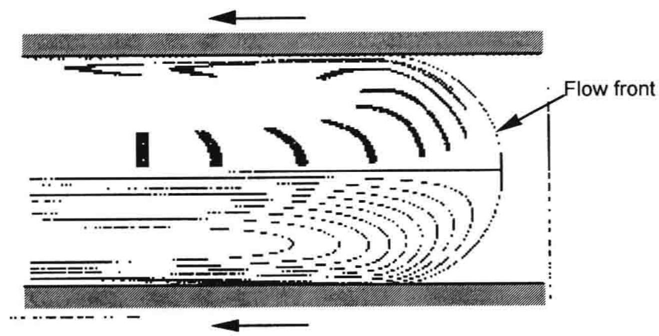


Figure 3. ~ *Deformation history of a fluid element and streamlines for frame of reference that moves with the flow front.*

that subsequently enters the cavity flows between the frozen layers, forcing the melt skin at the front to stretch and unroll onto the cool wall where it freezes instantly. The fibers and molecules that move past the free flow front are oriented in the flow direction and laid on the cooled mold surface, which freezes them into place, though allowing some relaxation of the molecules after solidification. The fountain flow effect has been extensively studied in the past few year using computer simulation (14). Figure 3 (15) presents the predicted shape and position of a tracer relative to the flow front, along with the streamlines for a non-Newtonian, nonisothermal fluid model. The square tracer mark is stretched as it flows past the free flow front, is deposited against the mold wall, pulled upward again, and eventually deformed into a V-shaped geometry. Eventually, the movement of the outer layer is stopped as it cools and solidifies.

Radial flow is the second mechanism that often leads to orientation perpendicular to the flow direction in the central layer of an injection-molded part. This mechanism is schematically represented in Figure 4. As the figure suggests, the material that enters through the gate is transversely stretched while it radially expands and flows away from the gate. This flow is well represented in today's commonly used commercial injection-mold-filling software.

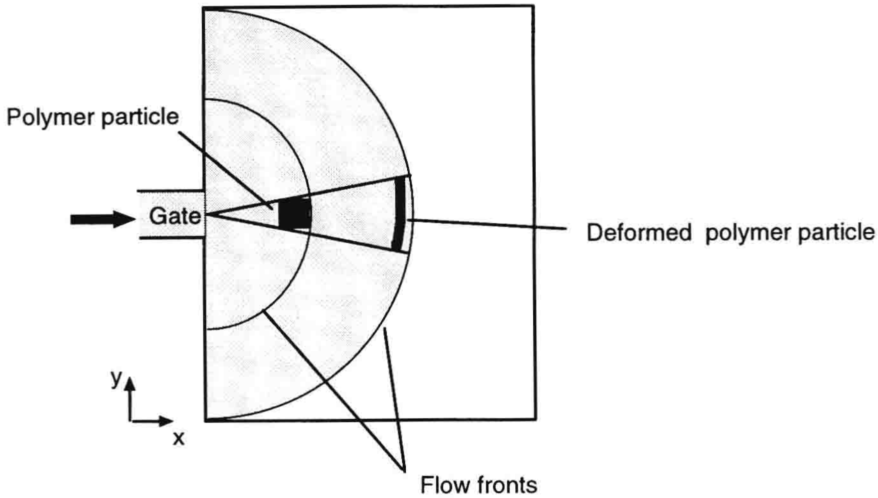


Figure 4. ~ *Deformation of the polymer melt during injection-molding.*

Finally, the flow induced by the holding pressure as the part cools leads to additional orientation in the final part.

Another important polymer composite manufacturing process is compression-molding of thermoplastic and thermoset parts (Fig. 5). During compression-molding of thermoset products, a charge is placed in a heated mold cavity and squeezed until the charge covers the entire mold surface. For example, a sheet-molding compound charge is composed of a polyester resin with about 10 percent by volume calcium carbonate filler and 20 to 50 percent by volume glass fiber content. The fibers are usually 25 mm long and the final part thickness is 1 to 5 mm. Hence, the fiber orientation can be described with a planar orientation distribution function.

To determine the relationship between deformation and final orientation in compression-molded parts, it is common to mold rectangular plates with various degrees of extensional flow (Fig. 6). These plates are molded with a small fraction of their glass fibers impregnated with lead so that they become visible in a radiograph. Figure 7 shows a computer-generated picture from a radiograph, taken from a plate where the initial charge coverage was 33 percent (10,12). Digitizing techniques were applied to the 2,000 fibers visible in Figure 7, resulting in the histogram presented in Figure 8 that depicts the fiber orientation distribution in the plate. Such distribution functions are very common in compression- or

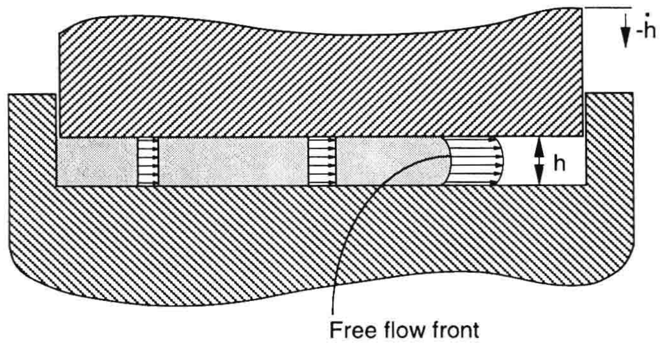
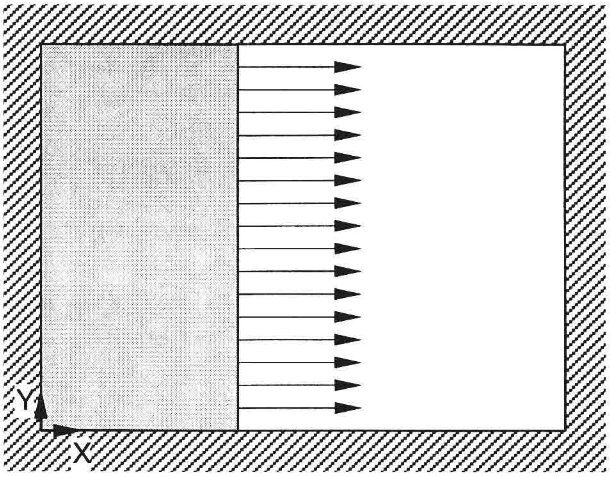


Figure 5. ~ *Velocity distribution during compression-molding with slip between material and mold surface.*

transfer-molded parts and lead to high degrees of anisotropy throughout a part.

Furthermore, under certain circumstances, filler orientation may lead to crack formation (Fig. 9) (25). Here, the part was transfer-molded through two gates which lead to a knitline and the filler orientation shown in (Fig. 9). Knitlines are cracklike regions where few or no fibers bridge across, lowering the strength across that region to that of the matrix material. A better way to mold the part shown in Figure 9 would be to inject the material through a ring-type gate which would result in an orientation distribution mainly in the circumferential direction.

In compression-molding, knitlines are common when multiple charges are placed inside the mold cavity or when charges with re-entrant corners are used (Fig. 10) (2). However, a re-entrant cor-



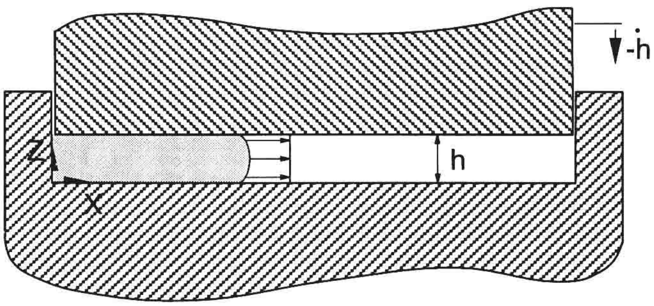


Figure 6. ~ *Schematic of extensional flow during compression-molding.*

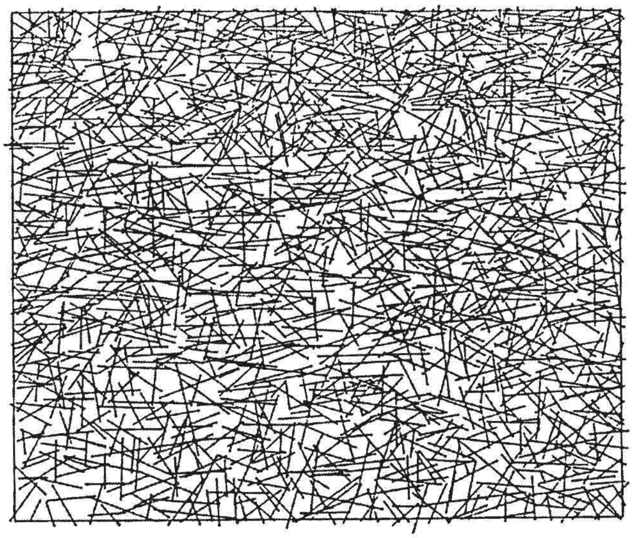


Figure 7. ~ *Computer plot of fibers in a radiograph of a rectangular sheet-molding compound plate.*

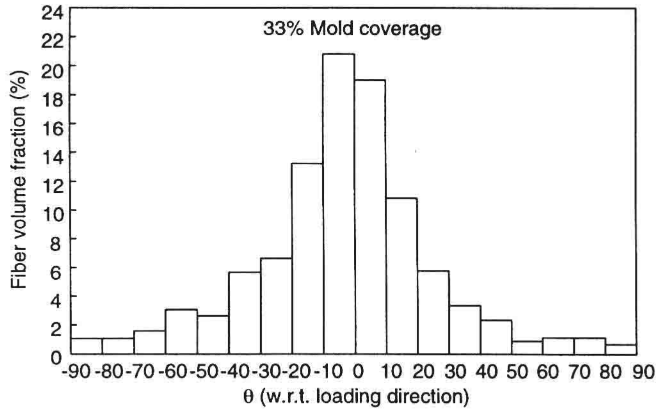


Figure 8. ~ *Measured fiber orientation distribution histogram in a plate with 33 percent initial mold coverage and extensional flow during mold filling.*

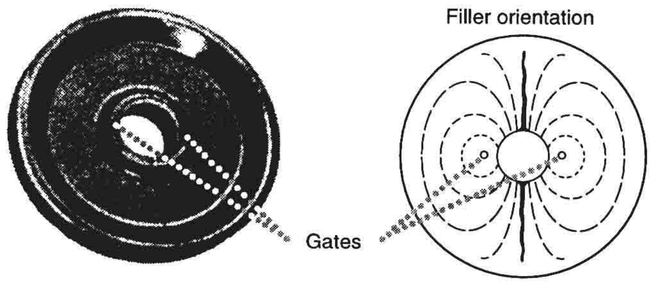


Figure 9. ~ *Formation of knitlines in a fiber-filled thermoset pulley.*

ner does not always imply the formation of a knitline. For example, when squeezing a very thick charge, an equibiaxial deformation results and knitline formation is avoided. On the other hand, a very thin charge will have a friction-dominated flow leading to knitline formation at the beginning of flow. Knitlines may also form when there are large differences in part thickness and when the material flows around thin regions (Fig. 11). Here, a crack forms as the material flows past the thinner section of the body panel. It is interesting to point out that usually the thin region will eventually be removed to create space for headlights, door handles, etc.

Folgar and Tucker (6,7) derived a model for the orientation behavior of fibers in concentrated suspensions. Folgar and Tucker's model for the case of planar flow is as follows:

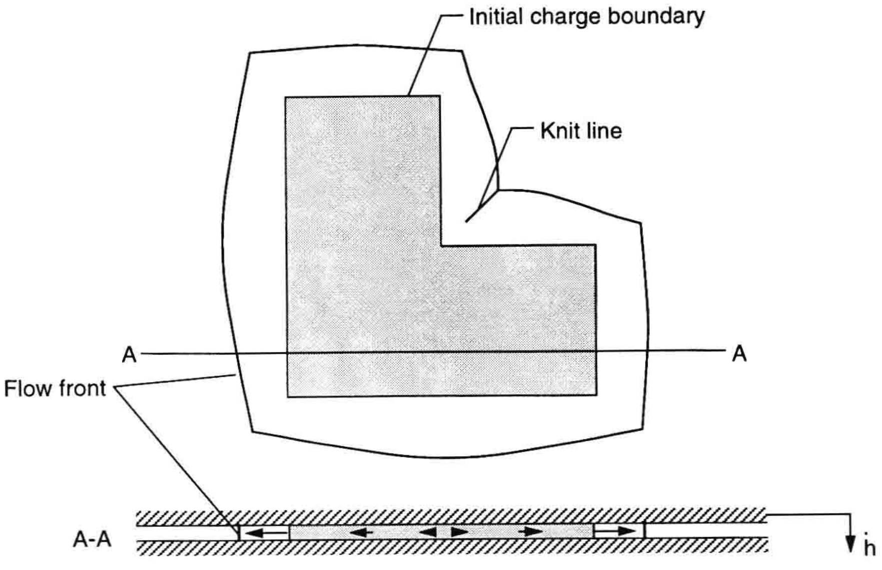


Figure 10. ~ *Knitline formation in an L-shaped charge for a squeeze ratio of 2.*

$$\dot{\phi} = \frac{-C_I \dot{\gamma}}{\psi} \frac{\partial \psi}{\partial \phi} - \cos\phi \sin\phi \frac{\partial v_x}{\partial x} - \sin^2 \phi \frac{\partial v_x}{\partial y} + \cos^2 \phi \frac{\partial v_y}{\partial x} + \sin\phi \cos\phi \frac{\partial v_y}{\partial y} \quad [1]$$

where:

$\dot{\gamma}$ = magnitude of the strain rate tensor

C_I = phenomenological coefficient that models the interactions between the fibers

Folgar and Tucker's interaction coefficient (C_I) varies between 0 and 1, for a fiber without interaction with its neighbors and for a closely packed bed of fibers, respectively. For a fiber-reinforced polyester resin mat with 20 to 50 percent volume fiber content, C_I is usually between 0.03 and 0.06. When Equation [**1**] is substituted into a fiber orientation continuity equation, the transient governing equation for fiber orientation distribution with fiber interaction built in becomes:

$$\frac{\partial \psi}{\partial t} = -C_I \dot{\gamma} \frac{\partial^2 \psi}{\partial \phi^2} - \frac{\partial \psi}{\partial \phi}\left(sc\frac{\partial v_x}{\partial x} - s^2 \frac{\partial v_x}{\partial y} + c^2 \frac{\partial v_y}{\partial x} + sc\frac{\partial v_y}{\partial y}\right) - \psi \frac{\partial}{\partial \phi}\left(sc\frac{\partial v_x}{\partial x} - s^2 \frac{\partial v_x}{\partial y} + c^2 \frac{\partial v_y}{\partial x} + sc\frac{\partial v_y}{\partial y}\right) \quad [2]$$

where:

$s = \sin\phi$

$c = \cos\phi$

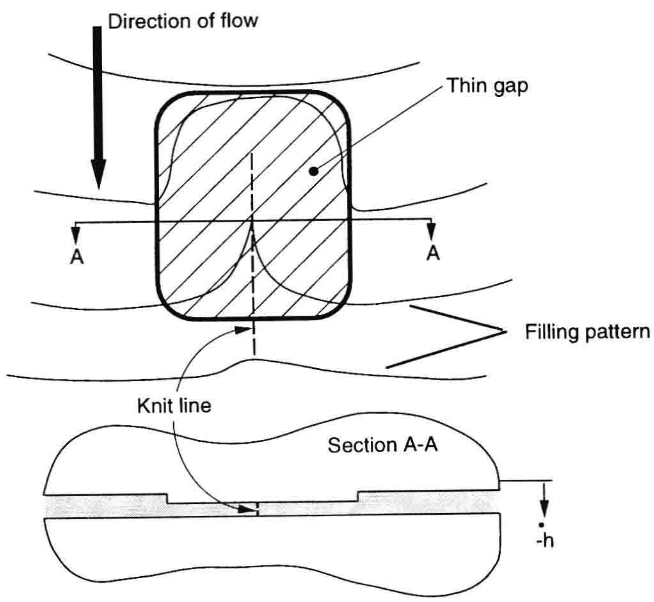


Figure 11. ~ *Schematic of knitline formation as sheet-molding compound is squeezed through a narrow gap during compression-molding.*

The Folgar–Tucker model can easily be solved numerically. The numerical solution of fiber orientation will be discussed using fiber-reinforced thermoset composites as an example.

Today, computer simulation is commonly used to predict mold filling, fiber orientation, thermal history, residual stresses, and warpage in complex parts.

In injection-molding, researchers are making progress on solving three-dimensional orientation for complex realistic applications (5,23). Crochet et al. have solved for the nonisothermal, non-Newtonian filling and fiber orientation in nonplanar injection-molded parts. They used the Hele-Shaw model (9) to simulate the mold filling and Advani and Tucker's tensor representation for the fiber orientation distribution in the final part. They divided the injection-molded part into layers and included the fountain flow effect in the heat transfer and fiber orientation calculations. Figure 12 presents the fixed finite element mesh used to represent a 1- by 40- by 100-mm plate and the filling pattern during molding. Figure 13 presents the isotherms, at the instant of fill, in the three layers of the plate that are shown in Figure 12. Figure 14 shows the fiber orientation distribution for the same layers.

Because planar flow governs the compression process, the models discussed earlier work very well when describing the orientation of the fibers during processing and of the final part. The Folgar-Tucker model in Equation [**2**] is usually solved using the finite difference technique. The velocity gradients in the equation are obtained from mold filling simulation. The initial condition is supplied by fitting ψ_i (t = 0) to the measured initial orientation state. For sheet-molding compound charges, the starting fiber orientation distribution is usually random, or $\psi_i = 1/\pi$.

The model has proven to work well when compared to experiments done with extensional flows described earlier. Figure 15 compares the measured fiber orientation distributions to the calculated distributions using the Folgar-Tucker model for cases with 67, 50, and 33 percent initial charge mold coverage. To illustrate the effect of fiber orientation on material properties of the final part, Figure 16 shows how the fiber orientation presented in Figure 15 affects the stiffness of the plates (4).

The Folgar-Tucker model has been implemented into various commercially available, compression-mold-filling simulation programs. The compression-molding process of a truck fender will be used to illustrate the prediction of fiber orientation distribution in realistic polymer products. The filling pattern must first be computed to com-

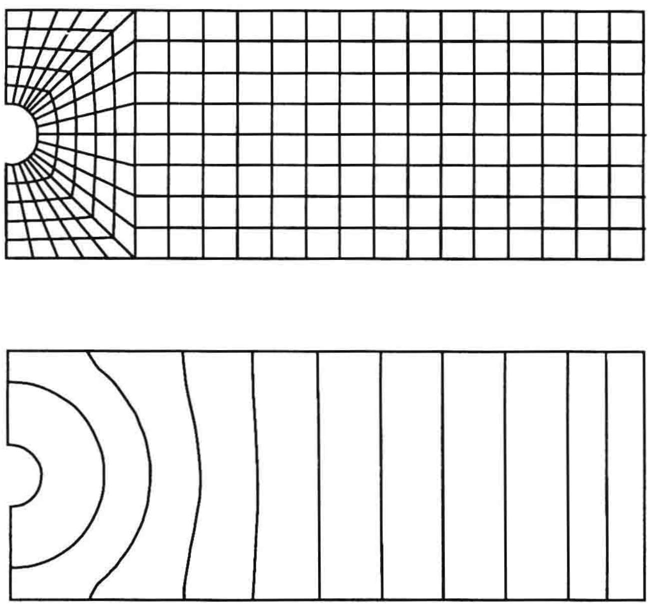


Figure 12. ~ *Fixed finite element mesh used to represent a 1- by 40- by 100-mm plate and temporary mesh adapted to represent the polymer melt at an arbitrary time during filling.*

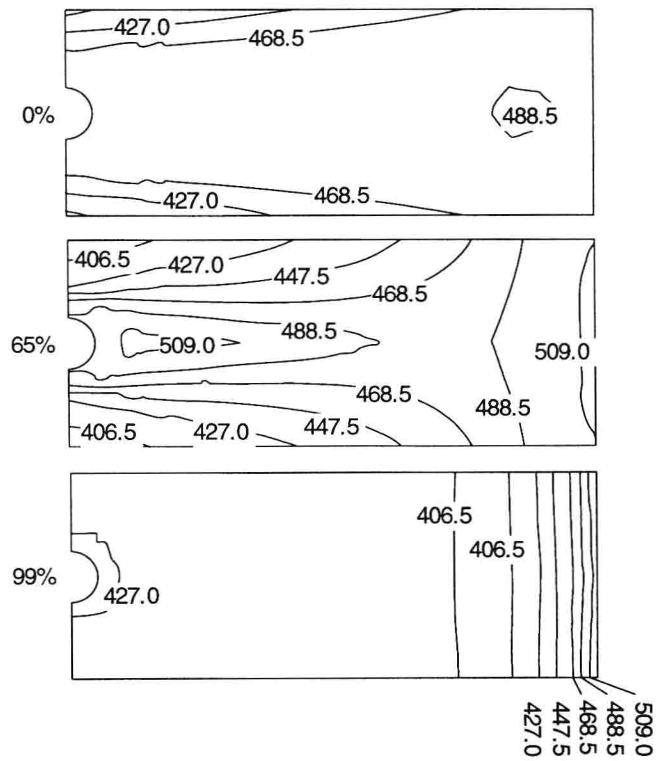


Figure 13. ~ *Isotherms in three layers at 0 (centerline), 0.65, and 0.99 mm, the instant of fill.*