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ORIGINAL ARTICLE

Effect of mold temperature on motion behavior of short glass fibers in injection molding process

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Abstract In injection molding process, the mold temperature can strongly affect the fiber orientation and distribution state in plastic parts. The fiber orientation behavior is discussed, and a model is used to describe the layered structure in injection parts. By studying the injected specimens, the fiber distribution and the layered structure in the part are illustrated and a variation of the fiber distribution along with the increasing of the mold temperatures is also demonstrated. The surface morphologies of the fiber-reinforced specimens at different mold temperatures are analyzed which are used to study the effect of the mold temperature on the fiber motion process of the resultant parts. Results show that in proper mold temperature, the fibers can be completely covered in polymer matrix and the mold temperature can greatly affect the part surface quality.

Keywords Fiber motion behavior · Injection molding · Fiber-reinforced plastic part

1 Introduction

As superior strength, lower linear expansion coefficient and other desirable mechanical properties relative to common thermoplastics with no reinforced material, fiber-reinforced polymer products now are widely used in home appliances, automobiles, and medical equipments. However, when the products with short glass fibers are produced by injection technology, the melt flow process in the mold cavity is very complex. The fiber orientation, which has a strong influence on product performance [1–7], can be easily induced along a given direction. Studies show that the orientation structure in injection part is mainly affected by melt rheological behavior, fiber volume fraction, and process parameters. To date, many studies concerning on the fiber orientation in injection molding process has been done. Jeffery [8] first theoretically studied the motion of ellipsoidal particle suspended in viscous fluid. The model proposed by Jeffery forms the basis for most models that predict the fiber orientation evolution within a composite [9–11]. M. Yamanoi et al [12] investigated the relationship between fiber orientation tensor, aspect ratio, and flexibility. Simulation and experimental results showed the uniaxial extensional viscosity depended on aspect ratio and volume fraction but not on fiber flexibility, while the orientation tensor was independent of aspect ratio, volume fraction, and flexibility. P. Shokri et al. [13] showed that the packing pressure played an important role on fiber orientation in the final products. For long glass fiber orientation, K. J. Meyer et al [14] observed that the fiber orientation mainly depended on the initial conditions of the sprue, gate, and mold. Since the fiber orientation is very important for the product performance, there are also many studies on the optimization of the fiber orientation in injection molding process [15–18]. In general, most of the investigations focus on studying the fiber distribution and structure in an injection process with constant mold temperature. However, engineering applications prove that the fiber orientation is greatly affected by different mold temperatures. In suitable mold temperature, the obtained fiber-reinforced products have a very gloss surface appearance. If the mold temperature is low or improperly determined, the surface of the products becomes very coarse with fibers exposed. It is concluded that the interaction of the polymer matrix and the fibers is very

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complex in the molding process, especially in a high-temperature molding process. Most of the scholars focus on studying the fiber orientation at moderate mold temperature (30–70 °C), although Shigeki et al [19] also investigated the fiber motion at 140 °C. However, the effect of the mold temperature on the fiber motion process was not determined. At present, there are still few studies concerning the effect of mold temperature on the molding characteristics of a fiber reinforced material and present the relationship between the fiber motion process and the mold temperature. This paper examines the fiber orientation behavior in injection molding process and establishes a model for fiber distribution analysis. Specimens produced at different mold temperatures are obtained, and the variation of the fiber distribution in specimens is discussed. By analyzing the surface morphologies of the specimens, the effect of the mold temperature on the fiber motion process is demonstrated.

2 Fiber orientation in injection molding process

In injection molding process, the phase transformation of plastic material from liquid state to solid state is very complicated due to the complex boundary conditions and the transition properties of the material itself. The mechanical properties and molding efficiency of the products are significantly affected by the transformation process. For fiber-reinforced polymer materials, as a lot of fibers exist in the melt, the melt and the fibers interact to each other, leading to a much more complex melt flow behavior and phase transformation. The scattered fibers in a viscous fluid orientate differently with different process parameters. However, it is found that the fiber orientation in the melt generally follows two important rules:

(1) Shear flows tend to align fibers in the flow direction;
(2) Extensional flows tend to align fibers in the elongation direction.

As a result, in different positions of the injected part, the fiber orientations show different structures. Usually, it shows a layered structure in thickness direction of the part [20, 21], and they are mainly affected by the melt filling speed and pressure, the mold temperature, and the material behavior itself. In the filling stage, when the melt at high temperature contacts the mold cavity, the surface melt is rapidly cooled because of the low temperature of the contacting cavity surface. As a result, a frozen layer is formed between the melt and the cavity surface. As the fibers in the frozen layer cannot be oriented in such a short time, they align disorderly in this layer. The inner melt close to this frozen layer would suffer much greater resistance due to the shelled friction during the flowing process and large shear stress is caused. Consequently, the fibers close to the frozen layer can be highly orientated, and the fibers are mostly aligned along the flow direction. This layer of the melt is called “shearing layer.” At the same time, since the melt in the core layer suffers much less friction and the shear stress is also very low, only a few fibers can orientate in the flow direction. Therefore, it can be concluded that in fiber reinforced injection molded parts, three layers, i.e., the “frozen layer (skin layer),” “shearing layer,” and “core layer,” can be formed in the thickness direction. Figure 1 shows a schematic sketch of the three different layers. In the frozen layer, the fibers orientate disorderly due to the influence of the low mold temperature. In the shearing layer, the fibers are highly orientated because of the shear stress effect. The fibers in the core layer have a low orientation in flow direction, but they are easily stretched and tend to align in stretching direction. The thickness of each layer formed in the fiber reinforced products depends on the product geometry, the molding process conditions, and the melt properties.

3 Fiber-reinforced specimen injected at different mold temperatures

To investigate the relationship between the fiber motion process and the mold temperature, the mold cavity temperature is set to 55, 70, 80, 100, 115, and 125 °C, respectively, for injection experiments. Fiber-reinforced acrylonitrile butadiene styrene plastic (ABS) with 20 % weight fractions of short glass fibers (20 wt%-GF-ABS) produced by the LG Corporation is used in our experiments. To reduce the influence of moisture on the molding process and part performance, the material is dried in a drying oven for about 4 hours based on the parameters proposed by the corporation. Accordingly, the injection process parameters used in this study are listed in Table 1. With these parameters, American Society for Testing and Materials (ASTM) standard specimens are produced, as shown in Fig. 2.

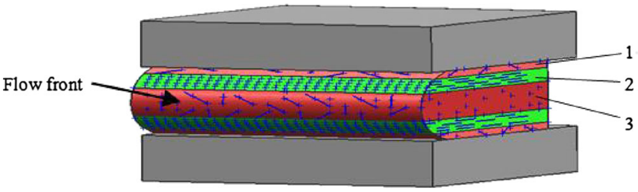

Fig. 1 Fiber orientation structure in injection part: *1* frozen layer, *2* shearing layer, and *3* core layer

Table 1 Injection parameters

Process parameters	Melt temperature (°C)	Injection speed (%)	Injection time (s)	Packing pressure (MPa)	Packing time (s)
Values	235	45	6	55	10

4 Motion process of the fibers in plastic part

4.1 Analysis of fiber orientations

To verify the proposed model (Fig. 1) for fiber orientation structure in plastic part, the specimens injected at the mold temperature of 55 °C are studied.

As the specimens are obtained in same process parameters, the orientation of the fibers is almost the same both for impact and tensile specimen with a single gate. The specimens with two injection gates are used to study the morphologies of the weldline when two separated melt streams meet in the mold, and this will be studied in another paper. Therefore, in the current paper, the middle section of the tensile specimen with a single gate is fractured along with the melt flow direction. The structure of the internal fiber distribution is observed by SEM in our laboratory, as shown in Fig. 3.

It is observed that, when the specimen is fractured in a brittle manner, a lot of fibers in the "frozen layer" are drawn out, leaving many holes in the polymer matrix. Combining the orientations of the left fibers, it can be concluded that the orientation of the fibers is very disordered in this layer. Some fibers are perpendicular to the flow direction of the melt; some fibers are parallel to the flow direction; and there are also some fibers that orient no directionality. In the "shearing layer," the fibers that have been drawn out from the specimen are reduced obviously; most of the fibers orient to the flow direction of the melt. It is mainly caused by the shear stress produced by the friction of the solidified frozen layer. The larger the distance of the melt in the "shearing layer" to the "frozen layer," the less fibers orient to the flow direction. The fibers in the "core layer," i.e., in the center of the specimen in thickness direction, are drawn out of the polymer matrix much more than in the "shearing layer." The number of fibers perpendicular to the fracture cross-section is also increased compared to that of the "shearing layer." However, there are still some fibers orienting to the flow direction, but this kind of orientation is very weak. Along with the increase of the distance from inner melt to the "frozen layer," the friction that the melt subjected to is decreased, and the shear stress is reduced gradually. In the packing stage, the melt in the center could be kept in a high temperature state for a much longer time, and the fibers can move more easily in the "core layer."

From the above analysis, it can be concluded that the fiber orientation obtained experimentally is very close to our model.

4.2 Effect of the mold temperature on motion process of the fibers

To investigate the effect of the mold temperature on the fiber distribution accurately, several specimens are molded at each mold temperature set above. The fractured cross-sections of the specimen along the melt flow direction are observed by SEM. Figure 4 shows the fiber orientations obtained with the mold temperature 70, 80, 100, 115, and 125 °C, respectively.

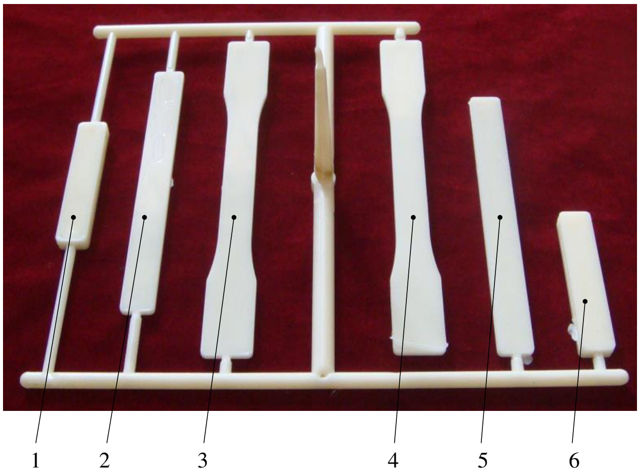

Fig. 2 Standard specimens for ASTM: *1*, *6* specimens for impact test; *2*, *5* specimens for bent test; and *3*, *4* specimens for tensile test

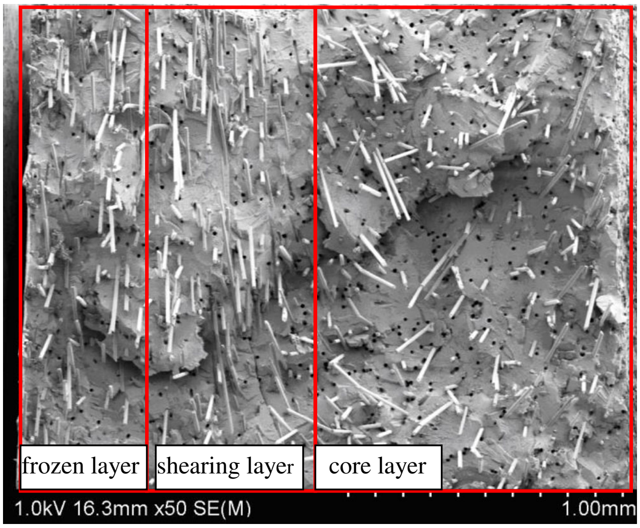

Fig. 3 Fiber orientation in the melt at the mold temperature 55 °C

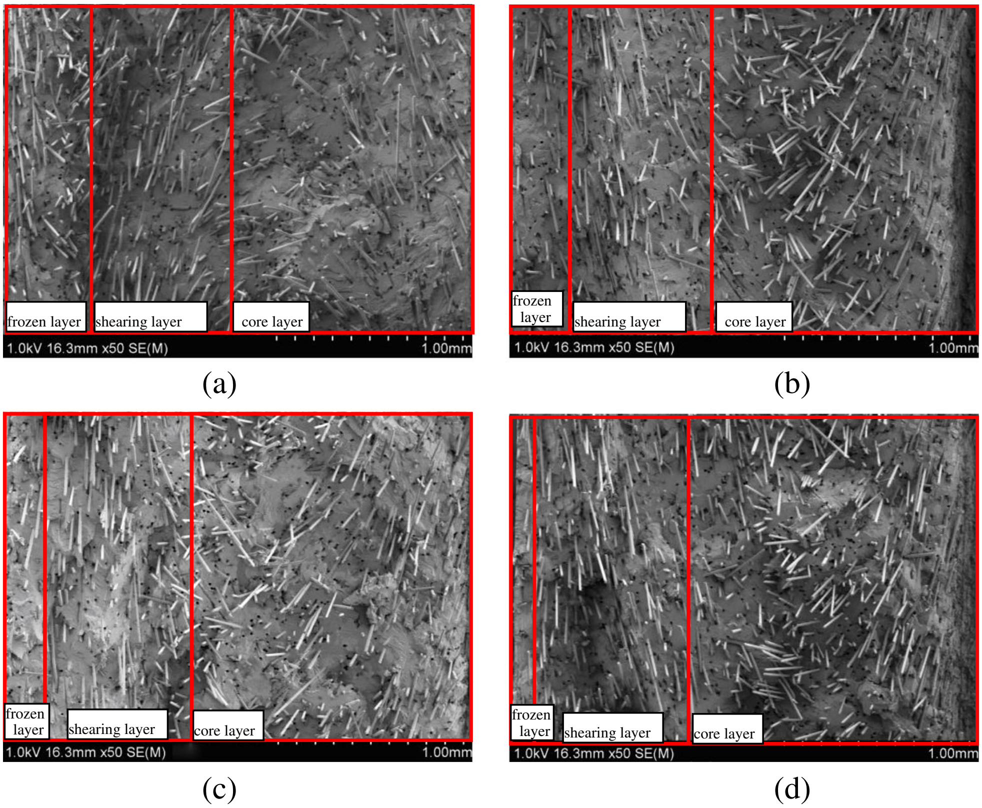

Fig. 4 Fiber orientations at different mold temperatures. **a** Mold temperature 70 °C. **b** Mold temperature 85 °C. **c** Mold temperature 100 °C. **d** Mold temperature 125 °C

Along with the increase of the mold temperature, the viscosity of the melt decreases, while the flow ability of the melt and the motion ability of the fibers increase. At the same time, the temperature difference between the melt and the mold cavity is reduced. Thus, in the filling stage, the skin layer of the melt in contact with the cavity could be frozen in a relatively longer time. At higher mold temperature, the skin layer of the melt would suffer greater resistance due to the cavity surface friction and large shear stress is caused in this layer. Therefore, the fibers tend to orient to the flow direction and the thickness of the frozen layer decreases. From the figures, it is also observed that, along with the decrease of the melt viscosity, the fibers could be covered inside the polymer matrix gradually. When the mold temperature is about 125 °C, the fibers in the skin layer (frozen layer) melt are almost covered by the polymer matrix, and they mostly align in the flow direction. Only few fibers are drawn out when the specimen is fractured in a brittle manner. When the mold temperature is below 85 °C, there is not enough time for the fibers to orient and they are frozen in the skin layer, resulting in exposure of the fibers to the part surface.

To further investigate the effect of mold temperature on the fiber motion process, the surface morphologies and the roughness values (Ra) of the specimens produced at different mold temperatures are determined using a microscope (LEICA DMI3000) in combination with white-light interferometry (Wyko NT9300). Figure 5 shows the obtained morphologies at a magnification of 200 times. Figure 6 illustrates the relationship between the mold temperature and the roughness of the specimens.

From Figs. 5 and 6, it can be concluded that when the mold temperature is lower than 115 ° C, the higher the mold temperature, the better the surface quality of the specimen, resulting in a lower surface roughness value (Ra) of the specimen. When the mold temperature is about 55 °C, the surface of the specimen is rugged and a lot of glass fibers are exposed to the outer surface of the part, leading to fluctuations of the surface height. The surface roughness (Ra) is about 1.44 μm. Under the microscope, the exposed glass fibers present strong light reflection, as shown in Fig. 5a. Figure 5b shows the surface morphology of the specimens produced at the mold temperature of 70 °C. It is found that the surface quality at this temperature is much better than that at 55 °C. The light area is less, demonstrating that the glass fibers exposed to the outer surface of the specimen are reduced. However, there is still a small portion of glass fibers ends exposed. The surface roughness (Ra) induced by the exposed fibers is decreased greatly, and the value is only about 0.28 μm. Figure 5c illustrates that when the mold temperature is increased to 85 °C, there are almost no fibers exposed to the outer surface of the specimen. The surface is relatively glossy, and the quality is obviously improved. The roughness value is maintained at about 0.1 μm.

Fig. 5 Surface morphologies of the injection part at different mold temperatures. **a** Mold temperature 55 °C. **b** Mold temperature 70 °C. **c** Mold temperature 85 °C. **d** Mold temperature 100 °C. **e** Mold temperature 115 °C. **f** Mold temperature 125 °C

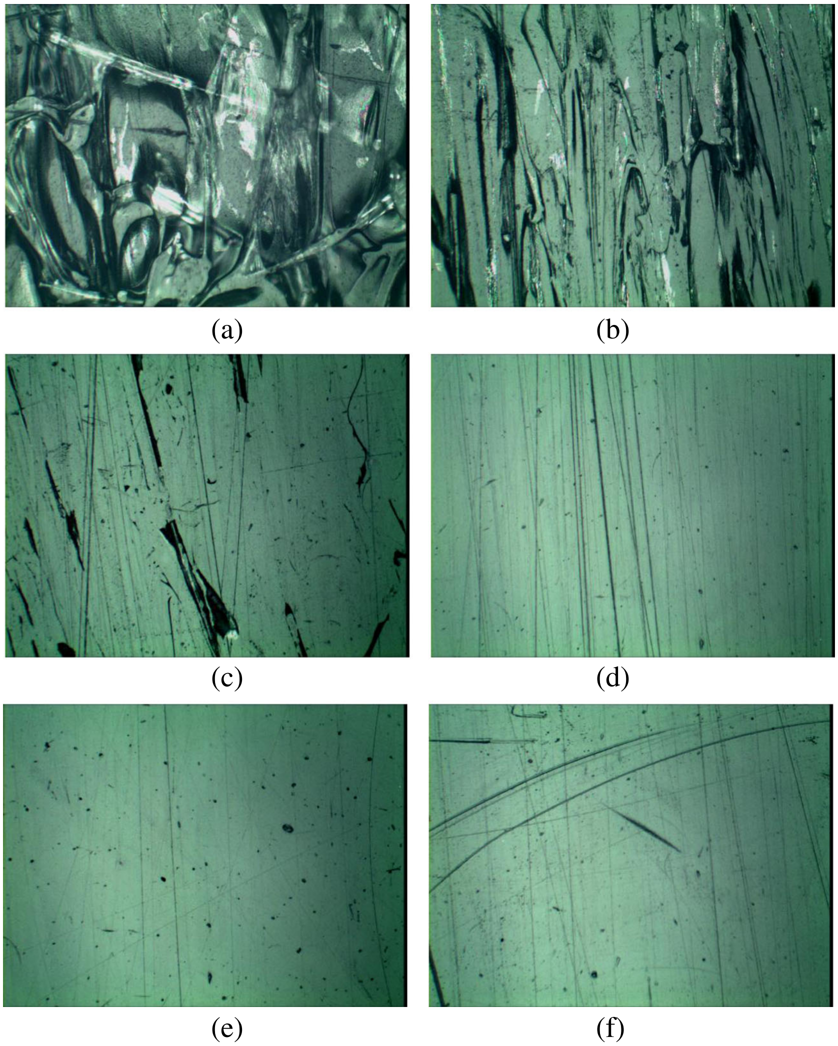

Figure 5d, e, and f shows the surface morphologies obtained at mold temperatures 100, 115, and 125 °C, respectively. It is observed that when the mold temperature is heated to 115 °C, the surface quality of the specimen is the best, and the roughness value is only about Ra=0.03 µm. However, when the temperature continues to increase, the surface quality shows a decreasing trend. From Fig. 5e, f, it can be found that when the mold temperature is increased to 125 °C, the scratches on the specimen surface are much more than at 115 °C. Later studies show that the scratches on the surface of the specimen are caused by cavity surface scratches left on the mold.

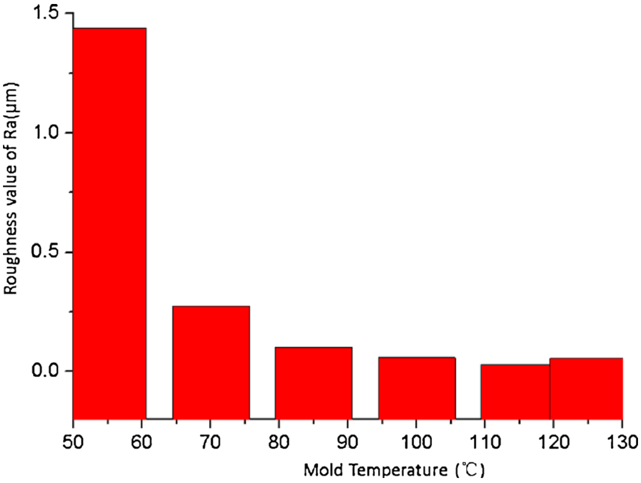

Fig. 6 Relationship between the mold temperature and the roughness

Figures 5 and 6 illustrate that the surface quality of the specimen increases first and then decreases along with the increasing of the mold temperature. It is mainly depended on the flow manner of the fibers and the polymer matrix in the mold cavity. If the polymer melt gets in contact with the cavity surface at low temperature, the surface layer of the melt could be rapidly solidified, inducing a frozen layer on the melt surface. Once the surface layer of the melt solidifies, the melt cannot immerse into the tiny pores on the mold cavity. As a result, it is difficult for the plastic part to replicate the mold cavity surface morphology accurately. Moreover, there is no time for the fibers in the melt to relax and orient to a certain direction, leading to much more fibers floating on the melt surface and exposing to the cavity surface. When the mold temperature increases, on the one hand, the viscosity of melt decreases and the flow and motion ability of the polymer matrix and the fibers increase, on the other hand, the temperature difference between the melt and the mold cavity is decreased. When the melt fills the cavity, the surface layer of the melt in contact with the cavity can be frozen in a relatively longer time, resulting in more time for the fibers to relax and orient to the flow direction. As a result, the fibers can be covered by the polymer matrix completely. The smoothness of the surface can be improved, and the value of the roughness (Ra) is decreased. As the mold temperature is further increased, the surface tension between the melt and the mold surface is reduced with the decreasing of the melt viscosity, and the polymer matrix can immerse in the tiny pores of the mold cavity surface. The fibers can move easily inside the melt and can be completely covered by the polymer matrix. Thus, the surface of the specimen can reflect the mold cavity surface much more accurately. If the cavity surface is polished in a high precision, the surface of the product can be very smooth and glossy. However, if the cavity surface is polished in a relatively low precision, the scratches on the cavity surface could be reflected on the product surface, leading to a worse quality surface on the part.

5 Conclusions

The fiber orientation in fiber-reinforced polymer melt was examined in this study. A model described as “frozen layer,” “shearing layer,” “core layer,” “shearing layer,” and “frozen layer” for the fiber-reinforced polymer melt was presented. The mold temperature effect on the motion process and orientation of the fibers were studied; the conclusions are drawn as follows:

(1) Fibers in the “frozen layer” orientate disorderly due to the influence of the low mold temperature. In the “shearing layer,” the fibers can be highly orientated in the flow direction caused by the shear stress. The fibers in the core layer are easily stretched and tend to align in extensional direction.

(2) With the mold temperature increasing, the fibers tend to orient to the flow direction in the skin layer of the melt and can be covered by the polymer matrix gradually. At low mold temperature, the surface quality of the specimen is very coarse induced by the exposed fibers on the part surface. With mold temperature increasing, the surface quality of the specimen is improved gradually, and there are almost no fibers exposed on the part surface. If the mold temperature is further increased, the polymer melt can get in contact with the mold surface sufficiently, causing the improvement of the melt to replicate the mold surface morphology precisely.

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