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ORIGINAL ARTICLE

# Fiber orientation in melt confluent process for reinforced injection molded part

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**Abstract** Fiber orientation in reinforced polymer parts can greatly affect the appearance and mechanical properties. The fiber orientation process during a confluent process of two or more strands of melt in a mold cavity is discussed. Different from common polymer melts with no reinforced material, a novel model describing the confluent process for fiber-reinforced melt is established. Through finite element simulation, fiber orientation and its accumulation state in different layers of plastic parts are obtained. 3D surface morphologies of the confluent region caused by fiber orientation and distribution are tested in the laboratory, and the relationships between the mold temperature and the appearance of the confluent region are presented as well. By using SEM to observe the fiber orientation induced in different mold temperatures, the effect of the fiber orientation in confluent region process on the impact strength of the resultant parts is discussed. Testing results prove that the established model is effective in explaining the outcome of the confluent process for fiber-reinforced materials.

**Keywords** Fiber-reinforced polymer · Injection molding · Confluent process

## 1 Introduction

Fiber-reinforced polymer products now are widely used in home appliances, automobiles, and medical equipments because of their superior strength, lower linear expansion coefficient, and other desirable mechanical properties relative to common thermoplastics with no reinforced material. However, when the products with short glass fibers are produced by injection molding technology, the melt flow process in the mold cavity is very complex. The fiber orientation, which has a strong influence on product performance, can be easily induced along a given direction [1–4]. In particular, the confluent region on the part surface because of two or more strands of melt meeting in the cavity can strongly affect the product appearance and greatly weaken its mechanical properties. In past studies, the investigations of the confluent process and its effect on part properties were mainly focusing on the polymer melt with no glass fibers. Through experiment, Zhao et al. [5] studied the confluent processes on samples molded by ABS/PMMA, ABS and PP materials. It was demonstrated that, for materials with no fibers, a V-notch shape of the weld mark would be formed on the part surface when two flow fronts met in a mold. There was a critical cavity surface temperature for each plastic material, when the cavity surface temperature reached the critical value, the part surface appearance would reach the optimal level without any weld mark. Kovács et al. [6] analyzed the confluent process of PA 6 material melt; the confluent angle of the melt front was simulated and measured as a function of the flow distance, it could be clearly seen that the meeting angle increased with the flow length, which might be helpful for improving the properties of the confluent region. Park et al. [7] also found that when the mold temperature at the corresponding confluent region was higher than the glass transition temperature of the resin material, the appearance of the confluent region (mainly called weld mark) could be reduced or eliminated. Chen et al. [8, 9] and Kuo et al. [10] also studied the effect of the mold temperature on the tensile strength of the confluent region, and they both revealed that the cross-sectional shape could

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greatly influence the strength. A higher mold temperature was favorable for improving the tensile strength. Many other literatures also addressed that study on the melt confluent process was very important for improving the part performance [11–14].

However, to date, there are still very limited research works about melt confluent process for fiber-reinforced polymer material. A few relevant literatures only give a simple report on the effect of fiber orientation on its mechanical properties. Seldén [15] investigated the influence of injection molding parameters on confluent region strength of different fiber-reinforced polymers with different fiber contents. Results showed that the mold temperature was the greatest factor to affect the strength of the confluent region. The higher the temperature was, the larger the strength was. Using rapid heat cycle molding technology, Wang et al. [16, 17] studied the cavity surface temperature on the tensile strength of 20 % wt glass fiber-reinforced PP (FRPP); it was found that the strength of FRPP reduced slightly and gradually as the cavity surface temperature increased. However, when the cavity surface temperature was higher than 100 °C, the tensile strength of FRPP with confluent region decreased significantly with the increase of the temperature. By using high spatial resolution digital image, Kalus et al. [18] demonstrated the strain profiles in the confluent region and found that the fiber reinforcement provided the confluent region with a higher strength than without reinforcement. The reason was that the fibers reinforced the confluent region by preventing Poisson contraction and necking parallel to the dominating fiber orientation direction at the region. Additionally, many other studies have just addressed the effect of fiber distribution and structure on mechanical properties of the injection part without melt confluent region [19–22].

From the above researches, it can be found that most of the studies focused on the confluent process of polymer melt with no fibers or the effect of the injection parameters on the part tensile strength. For fiber-reinforced polymer melts, there are few studies describing the fiber orientation in melt confluent process and the mechanism of the confluent process and fiber orientation in reinforced melt are still unclear. To obtain high surface quality and enhance the mechanical properties of the fiber-reinforced injection parts, it is very necessary to reveal the mechanism of the confluent process for fiber-reinforced material. In this study, a novel model is established for describing the confluent process of the fiber-reinforced melt. The fiber orientation in the confluent region is discussed by using finite element method and experiments. The effect of the mold temperature on the surface morphologies and mechanical properties are also discussed. Electron microscope (SEM) and white-light interferometry are implemented to explain the confluent mechanism for fiber-reinforced polymer melt.

## 2 Confluent model for fiber-reinforced melt

It has been reported that, for polymer melt with no reinforced material, a V-notch can be easily formed on the region of a part where the separated melt confluent [5, 11]. Figure 1a shows the shape of formed V-notch on the part. It is mainly caused by the residual air or volatilized gas which cannot be eliminated from the mold cavity quickly enough in filling and solidification processes. However, for fiber-reinforced polymer melt, the fibers are easily accumulated at the melt front due to the fountain flow effect in the filling process. When different streams of melt meet each other, the fibers in this region accumulate more and more, and with the continuous flowing process, the fibers can be squeezed to thickness direction as well. This kind of fiber orientation can decrease the shrinkage of the confluent region. Furthermore, as there are much more fibers distributed in this region, the shrinkage can also be decreased in the cooling process compared with other regions with fewer fibers. Therefore, a confluent model for fiber-reinforced polymer melt can be established, which is shown in Fig. 1b. It is quite different from that in Fig. 1a: the V-notch is absent due to the negligible effect of the residual air or gas in the cavity, while a slightly upwardly convex structure similar to "Λ" is exhibited. The upwardly convex structure caused by the different fiber distribution can affect the surface morphologies and mechanical properties of the part which will be studied in the following section.

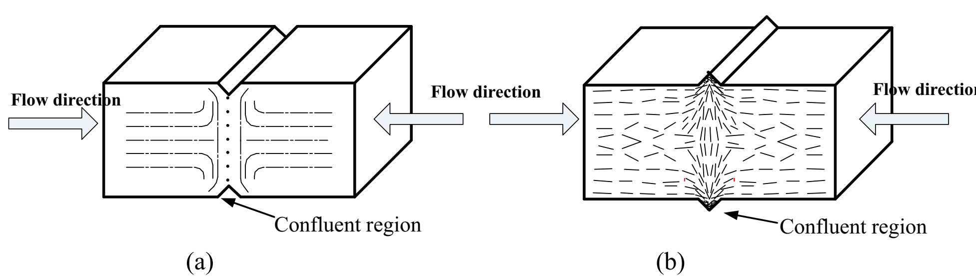
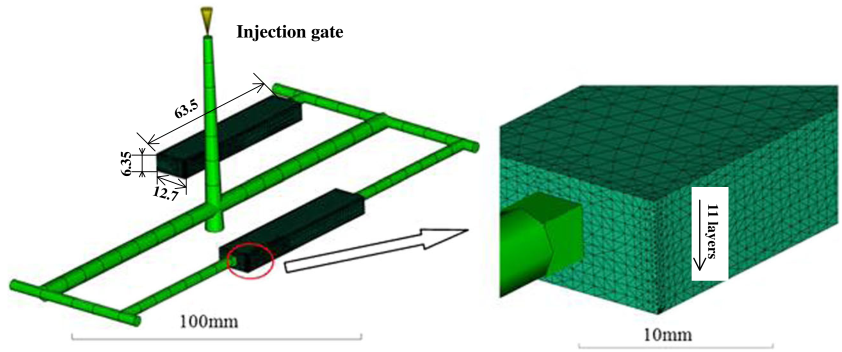



**Fig. 1** Confluent model for polymer melt. **a** Confluent model for non-fiber-reinforced material and **b** confluent model for fiber-reinforced material

**Fig. 2** Simulation model




## 3 Simulation of fiber distribution and experiment

### 3.1 Finite element simulation and analysis of fiber orientation

The commercial software Moldflow is used to analyze the melt filling process and fiber orientation in a mold cavity. A three-dimensional (3D) model including samples with and without confluent region is established. The model is meshed using tetrahedral element, and 11 layers are meshed in the thickness direction. In this way, the distribution of fibers in different layers can be acquired by removing the top layers of the model. Figure 2 shows the meshed model established in the software, and there are 122,661 tetrahedral elements in the model. In the simulation process, the injection parameters are determined according to the practical production process. When the simulation process is finished, the flowing process of the melt and the fiber distribution can be obtained. Figure 3 demonstrates the fiber orientation of the sample with a confluent region in the shear and core layers. It illustrates that, in other than confluent region, the fibers mainly orientate to flow direction in the shearing layer, while they orientate more disorderly in the core layer. The fiber orientation in the confluent region mostly orient to the thickness direction, which is very consistent with the model established in Fig. 1b. The reasons are as follows:

Before the two separated melt streams meet in the mold, the molecular chains and the fibers of the melt flow front are stretched by its fountain flow pattern, leading that the molecular chains and fibers are almost parallel to the flow direction. However, due to a large number of fibers exited, a complicated behavior of the melt and the multi-phase transfer process can be caused. The melt and the fibers interact continually with each other in the flow process, resulting in various orientations of fibers. Usually, the fiber orientation follows two important rules, the shearing flows rule and the stretching flows rule. The former tends to align fibers in the flowing direction, while the latter tends to align fibers in the stretching direction. Accordingly, a layered structure is formed in the thickness direction of the part, as is shown in Fig. 4. The layered structure is influenced by many factors, such as the melt injection speed, injection pressure, mold temperature, melt temperature itself, and so on. When polymer melt flows into the mold cavity, since there is a large temperature difference between the melt and the cavity surface, a frozen layer can be formed on the melt surface. The fibers in this thin layer can't be oriented to a certain direction because of the rapidly cooling rate. In the following flowing process, the melt closed to this outside frozen layer suffers great resistance because of the shell friction, resulting in large shear stress in the melt. Then another layer named as a shearing layer is caused. In this layer, the fibers can tend to highly orientate to the flowing direction as a result of the shear stress effect. Simultaneously, with increasing distance from the frozen surface, the friction

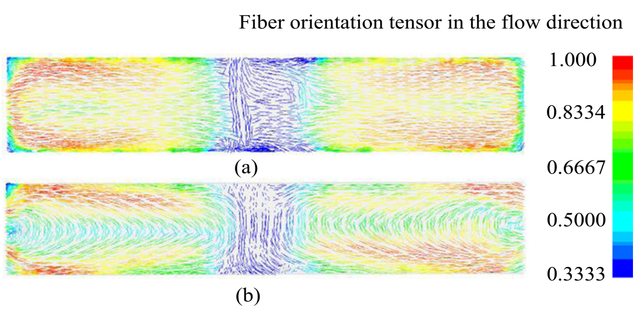



**Fig. 3** Fiber orientation of the sample with confluent region. **a** Fiber orientation of the shear layer and **b** fiber orientation of the core layer

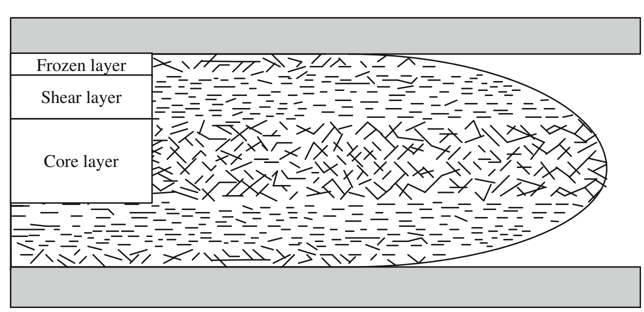



**Fig. 4** Fiber orientation structure of injection part

**Table 1** Injection parameters

| Process parameters | Melt temperature (°C) | Injection speed (%) | Injection time (s) | Packing pressure (MPa) | Packing time (s) |
|---|---|---|---|---|---|
| Values | 235 | 45 | 2 | 55 | 10 |

suffered by the inner melt is decreased gradually. Fibers orientating to the flow direction become fewer and fewer, then the core layer is formed. The fibers in this layer distribute randomly because of relatively long time and high-temperature duration besides the less shear stress effect. When the melt flow fronts with layered structure make contact, the orientations of the molecular chains and the fibers both gradually become perpendicular to the flow direction due to the compression pressure effect. In the packing and cooling stages, the molecular chains relax, tangle, and slowly migrate to the confluent interface. Some fibers simultaneously transfer across the confluent interface as well. The fiber density representing the fibers transferring across the confluent interface is determined by the temperature and the flow rate of the melt flow front. The higher the temperature is, the more easily the fibers transfer across the confluent interface. The influences of the flow rate on the orientation direction and the transfer density are similar to that of the temperature.

### 3.2 Surface morphologies of the parts formed in different mold temperatures

To conveniently study the confluent process of fiber-reinforced injection parts, impact specimens are designed based on the American Society for Testing and Materials (ASTM) standard. The temperatures of the mold cavity surface are set to 55, 70, 80, 100, 115, 125, and 150 °C, respectively, for the injection experiments. Fiber-reinforced ABS with 20 % weight fractions of short glass fibers (20 wt %-GF-ABS) produced by the LG Corporation is used. The injection process parameters are listed in Table 1. Using these parameters and the material, sound samples are produced.

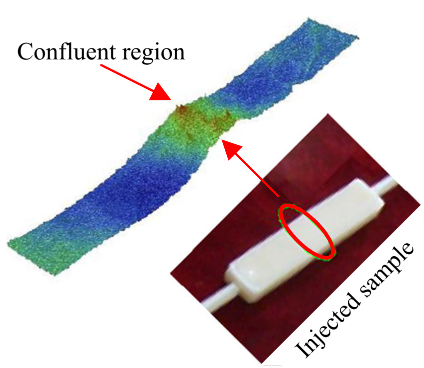



**Fig. 5** Morphology of the confluent region

To verify the established melt confluent model for fiber-reinforced material, the confluent regions of the parts are measured by white-light interferometry (Wyko NT9300). The obtained 3D surface morphology of the confluent region is shown in Fig. 5. It is found that the confluent region is slightly higher in the middle of the sample than elsewhere, in agreement with the model established in Fig. 1b. As shown in Fig. 6, the heights of the confluent region for fiber-reinforced ABS vary in different injected mold temperatures, which generally increase gradually with the increasing temperatures. When the mold temperature reaches to 150 °C, the height reaches to its maximum of approximately 2.0 μm. For mold temperatures below 125 °C, the height increase of the confluent region is not very apparent. However, when the mold temperature reaches 125 °C, the height increases significantly. Previous studies of this paper have shown that the height of the confluent region for the fiber-reinforced polymers is mainly influenced by the fiber orientation and accumulation in the melt flow front. With increasing mold temperature, the melt viscosity decreases, which dramatically reduces the movement resistance of the fibers and facilitates their accumulation in the flow front. The higher the mold temperature is, the more fibers accumulate in the flow front, resulting in larger fiber accumulation density in the confluent region. At the same time, the shrinkage of the melt in cooling stage decreases with the increasing of the fiber accumulation density, leading to a relative higher height of confluent region. When the mold temperature is approximately 125 °C,

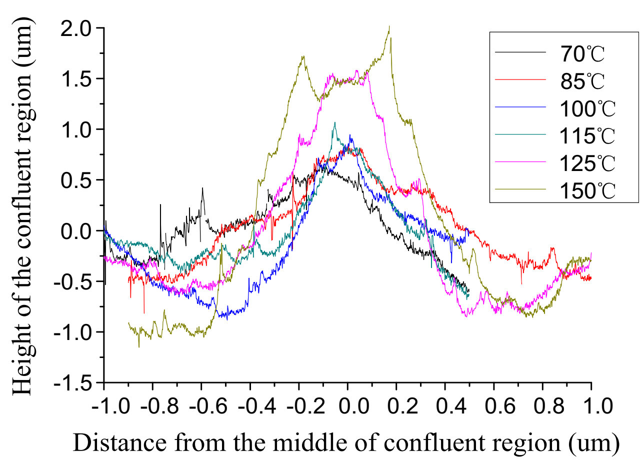



**Fig. 6** Height of the confluent region

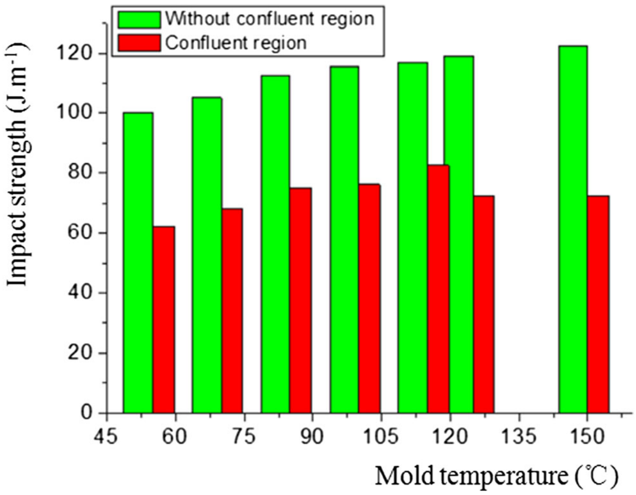



**Fig. 7** Average impact strength for impact samples

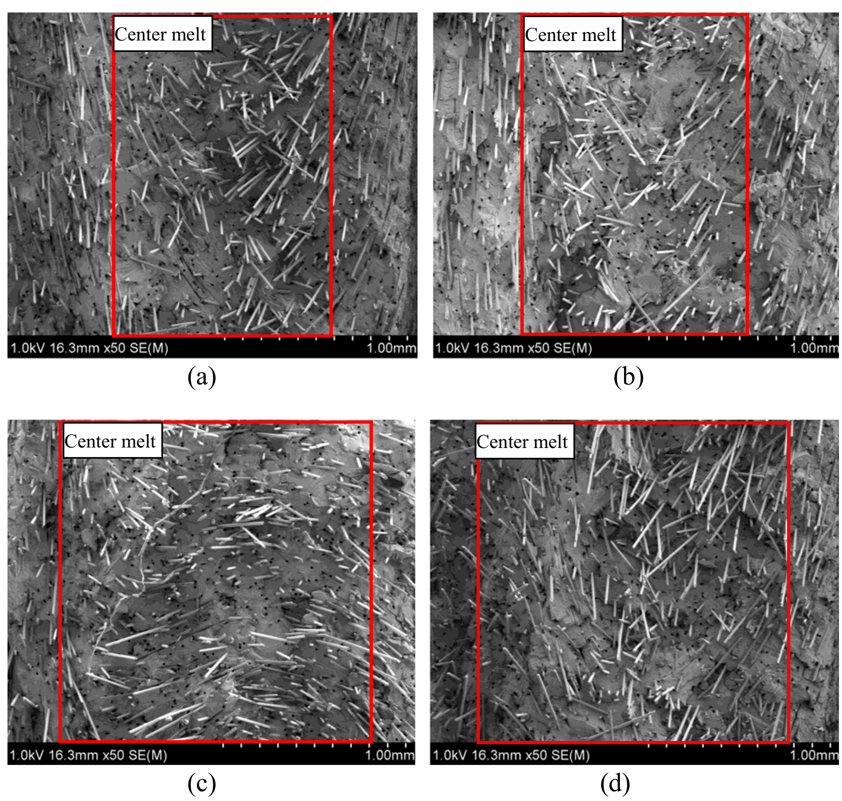
which is higher than the glass transient temperature, a much more increase of the confluent height appears, illustrating that there is a significant change of the melt viscosity and the fiber accumulated density under this temperature.

These analyses prove that the established model in Fig. 1b is effective for fiber-reinforced polymer materials in injection processes, especially for high mold temperature injection processes.

### 3.3 Effect of fiber distribution on part's mechanical properties

The impact strength of the samples is tested based on the ASTM-D256 standard. Ten specimens obtained under the same molding condition are tested and averaged to accurately assess the relationship between the impact strength and the mold cavity temperature. Figure 7 shows the average impact strength of the samples both for confluent region and without confluent region in different mold temperatures. The figure illustrates that in the current mold temperatures, the impact strength of the samples with confluent region first increases and then decreases with increasing mold temperature. In the first stage, the impact strength ranges from 62.2 J m$^{-1}$ at 50 °C to 82.6 J m$^{-1}$ at 115 °C. When the temperature exceeds 115 °C, the strength gradually decreases. The variation of the impact strength is mainly relevant to the fiber orientation and accumulation state in the confluent process. To conveniently explain this phenomenon, the distribution and orientation of the fibers in the confluent region is observed by SEM, which are shown in Fig. 8. The fracture surface of the sample is along with the confluent interface (perpendicularly to melt flow direction). It is found that at different mold temperatures, the distribution and orientation of the fibers are very different. In each picture, fibers at the left and right sides which are close to the cavity wall tend to orient parallel to the confluent region

**Fig. 8** Orientation of the fibers at the confluent interface: **a** mold temperature 55 °C, **b** mold temperature 80 °C, **c** mold temperature 115 °C, **d** mold temperature 125 °C



and others tend to be oriented disorderly. The reasons are as follows:

As we have known that, when the two separated melt streams meet in the mold, the orientations of the fibers gradually become perpendicular to the flow direction. In the following time, some of the fibers could transfer across the confluent interface. Figure 8 shows that fibers close to the cavity wall of the mold mainly tend to orient parallel to the confluent interface, while fibers in the center of the melt tend to be perpendicular to the confluent interface. It is mostly induced by the higher temperature in the melt center compared with that of the cavity wall close by. The figure also denotes that when the mold temperature increases from 55 to 115 °C, the width of the center melt becomes larger and larger, from about one half of the image obtained to about four fifth of that. The number and orientation of the fibers at the confluent region play a very critical role on the impact strength. Much more quantitive analysis of influences of the fiber orientation on the part performance will be discussed in our further research. With the temperature increasing, more fibers become perpendicular to the confluent interface, which means that more fibers can transfer across the confluent interface. As a result, the impact strength is first increased along with the increase of the transferred fibers. It is mainly because that more transferred fibers can improve its combination with the polymer matrix at the interface. Figure 8c shows that when the mold temperature reaches to 115 °C, there are most fibers perpendicular to the confluent interface, meaning that the most fibers can transfer across the interface which cause the largest impact strength. Furthermore, it is expected that since a higher mold temperature can enhance the diffusion of molecular chains by increasing flow front temperature of polymer melt, and hence, lead to a higher bonding at the confluent region interface. This viewpoint is also been clarified in the literature [17]. However, when the fiber accumulation density is too high due to the continuous increasing mold temperature, the volume of the polymer matrix becomes decreasing. As a result, the integration of the polymer matrix with the fibers decreases, meantime, the fibers perpendicular to the confluent interface becomes fewer as Fig. 8d shows. Besides, a much higher mold temperature decreases the molecular chain orientation, which weakens the diffusion and winding of molecular chains and leads to a lower bonding at the weld line interface. Consequently, the impact strength decreases. Figure 7 illustrates that when the cavity temperature increases from 115 to 150 °C, the impact strength decreases from 82.6 to 72.4 J $m^{-1}$, a decrease of approximately 8.2 J $m^{-1}$. Therefore, it is concluded that the impact strength of the confluent region is mostly influenced by the fiber orientation and transferred density in the confluent interface. Suitable mold temperature can improve the confluent strength of the part.

For samples without confluent region, the impact strength increases with the increasing mold temperature. This is also caused by the orientation of the fibers and the polymer molecular chains. With the mold temperature rising, the viscosity of the melt decreases, the shear stress suffered by the fibers and the molecular chains decreased as well. Thus, the orientation of the fibers and the molecular chains are reduced. At the same time, the mold with higher temperature needs longer time to cool, then, the oriented fibers and molecular chains have longer time to disorient because of the released stress. This can also help to reduce the orientation of the fibers and the chains in the flow direction. Therefore, with the mold temperature rising, the impact strength of these samples increases because of the reduced orientation in the flow direction.

## 4 Conclusions

Different from common polymer melt with no reinforced material, the confluent process of the fiber-reinforced polymer melt demonstrates different states. A model is established to describe the confluent process for fiber-reinforced material. Finite simulation and the 3D surface morphologies of the confluent region prove that the established model is very effective. Analysis of the confluent process reveals that the "Λ" structure formed on the surface is mostly due to the fiber accumulation process in the filling stage. The higher the mold temperature is, the more fibers accumulate in the confluent region and the higher of it is.

The fiber transfer density at the confluent interface has a strong influence on its mechanical properties. With increasing mold temperature, more fibers accumulate in the confluent interface, resulting in larger number of fiber transfer across the confluent interface. In the initial stage, the mechanical properties of the injection part improve. However, when the fiber accumulation density is too high, the integration of the polymer matrix with the fibers is inevitably reduced, worsening the mechanical properties of the confluent region.

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