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Study on Effects of Short Glass Fiber Reinforcement on the Mechanical and Thermal Properties of PC/ABS Composites

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ABSTRACT: This article mainly investigated the length distributions of the alkali-free short glass fibers in specimens and their effect on the mechanical and thermal properties of the composites. The results show that the initial length, addition level and feed way of the fibers have obvious effects on the length distributions of fibers in specimens, and thereby the mechanical and thermal properties of the composites. The main-direction feed way has an intense shear action on the fibers in specimens. With the increase of the fiber content, the reinforcing effect of fibers on the tensile strength, flexural strength and flexural modulus of the composites is increased, while the impact strength is decreased first and then tends to be stable, and the strength factor (*F*) of the tensile strength to weld line is significantly reduced. The longer the fiber lengths in specimens are, the more obvious the reinforcing and toughening effects are. To some extent, with the increase of the fiber content, the storage modulus (E') and loss modulus (E'') of the specimens are increased, but the loss factor (Tan δ) is reduced. The effect of the fiber initial lengths on the heat-degradation of composites is smaller than that of the fiber content. Meanwhile, adding fibers can improve the thermal stability of the composites, and this law is also confirmed by the heat deflection temperature (HDT) test. © 2014 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2014**, *131*, 40697.

KEYWORDS: blends; fibers; mechanical properties; thermal properties

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INTRODUCTION

Traditionally, in addition to implementing a specified function, the most important purpose of the inorganic fillers modified plastics is to reduce the cost of raw materials. However, with the extension of the plastics application fields, the realization of specified functions of plastics becomes the most important task for the fillers modification, where the alkali-free short glass fiber reinforced thermoplastics (SGFRP) is one of the typical representatives. SGFRP have many advantages, such as high specific strength and stiffness, good corrosion resistance and weatherability, excellent thermal stability and durability, strong design ability and low-cost.[1–6] The studies on SGFRP have received wide attention. For example, Yoo et al.[7] and Abdulmajeed et al.[8] investigated the morphology and mechanical properties of reinforced composites with large ratio glass fiber. Dejak et al.[9] and Bumm et al.[10] studied the breakup and adhesion of fibers in specimens with the increase of fiber content by using different simulations methods.

The blends dominated mainly by PC (polycarbonate) and ABS (acrylonitrile-butadiene-styrene) are important engineering materials, which have good molding flow properties, high HDT and thermal stability, excellent comprehensive mechanical properties and a certain flame retardancy. PC/ABS blends have been widely applied in automobile, appliance, electrical apparatus, defense industry and others.[11–17]

PC/ABS melt presents a pseudo-plastic flow characteristic of the shear-thinning and their composites show a strong nonlinear behavior under the impact and compression.[17,18] Meanwhile, although there is certain compatibility between PC and ABS, the further modification of compatibility is still needed to obtain higher performance of PC/ABS blends. The related studies have found that some additives (EVA-*g*-MAH, SMA, etc.) can improve the compatibility between PC and ABS, thereby improve the impact performance and elongation of materials.[18,19] The researches from Din and Hashemi[2] and Hashemi and coworkers.[20–23] showed that when the reinforcing fibers are added into composites, the tensile strength, flexural strength, tensile modulus, and flexural modulus of the plastic parts are improved at different degrees, and elongation, work of fracture are decreased. Meanwhile, the weld line strength factor will be reduced due to the orientation of the fillers near the weld line. In addition, Yin et al.[20] studied the thermal properties of PC/ABS blends. They gave the thermal-dynamic behavior of composite systems under variable loads and the phase transformation temperature by testing the storage modulus E' and loss modulus E''. It was also reported that the determination of the glass transition temperature for the small ratio compositions in PC/ABS blends is always a challenge. Yazdi et al.[15] successfully determined the double glass transition temperature about PC/ABS blends by using both dilatometer and dilatometer probe in the thermal mechanical analysis (TMA).

Although studies on glass fiber reinforced polymers have always been concerned and investigation on PC/ABS blends have also been deep developed, the previous researchers paid more attention to the effect of fiber content on properties of composites, and the studies about alkali-free short glass fiber reinforced PC/ABS composites are also just in the beginning stage. However, the higher requirements are put forward for the properties of PC/ABS blends as the extension of application demands and the gradual innovation of design philosophy. Especially, the demands for high strength, high stiffness and low-cost have become the main bottleneck for PC/ABS blends to develop in the structural parts area. The modification of the alkali-free short glass fiber reinforcement just makes up the disadvantages of PC/ABS blends as the structural parts materials, and it becomes an important development direction for PC/ABS modification.

This article will investigate the effects of the initial length, addition level and feed way of the fibers on the distributions of the glass fiber lengths in specimens, and further systematically study the effect of the fiber length distributions in specimens on the mechanical and thermal properties of the composites.

EXPERIMENTS

Materials

PC (2405) was supplied by Bayer (Germany). ABS (8391) was purchased from Shanghai Gaoqiao branch, China Petrochemical (China). Glass fibers with 3.0 mm and 4.5 mm in length were selected from Chongqing Composites and Zhejiang Tongxiang Jushi Group (China), respectively. Lubricant (EBS) was prepared by Kepong (Malaysia).

Performance Testing and Characterization

All materials were sufficiently dried at a suitable temperature. PC and ABS were mixed by weight percent of 7 : 3. The fibers with the different lengths were added by 10, 20, and 30% in weight by using different feed ways in a twin-screw extruder with a ratio of length to diameter, $L/D = 40$, respectively. Two feed ways for fibers are considered, including the main-direction feed way and the lateral feed way. The schematic view of these two feed ways is shown in Figure 1. Thus, the blends were prepared by melt blending, cooling, and repelletized in a SHJ-30 twin-screw extruder. the melting temperature were respectively controlled at 180, 230, 240, 245, 245, 240°C from section one to section six of the twin-screw extruder. The temperature of the extruder's nozzle was specified as 230°C. The screw configuration was arranged as "transport section—strong shear section—transport section—shear section—shear section—transport section" from section one to section six of the twin-screw extruder, and then the extruded granules were dried at 90°C for 8 h.

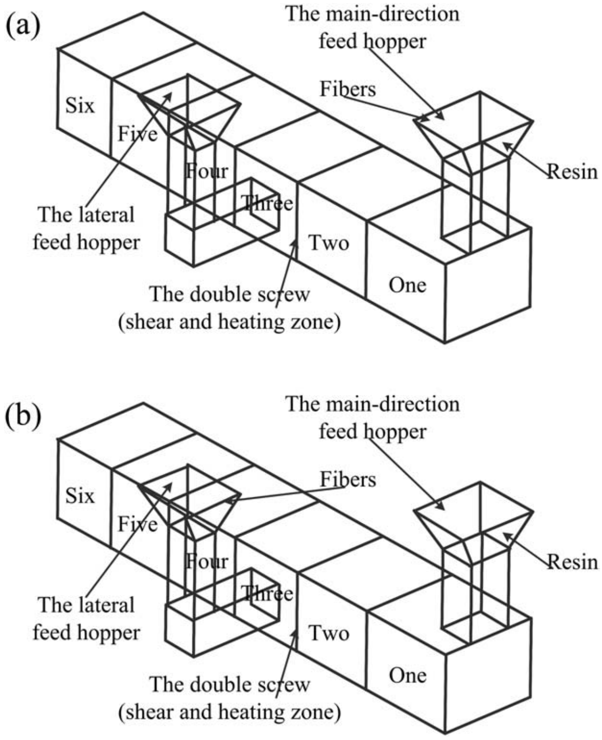

Figure 1. Schematic view for different feed ways: (a) the main-direction feed way and (b) the lateral feed way.

The dried granules were molded in an XL-680 injection molding machine to get standard specimens for test at a temperature range of 230–250°C.

Strength Test. The strength test was carried out by using a CMT2404 universal testing machine. The crosshead speed of the machine was selected as 5.0 mm/min in tension strength test and 2.0 mm/min in flexural strength test, respectively. Meanwhile, the standard specimens with dumbbell shape and a gauge of 50.0 mm were selected for the tensile test and their sizes were 165.0 × 12.7 × 3.2 mm in length × width × depth. The specimens for the flexural test have a flat rectangular parallelepiped shape with the sizes of 127.0 × 13.0 × 3.2 mm in length × width × depth. The specimens for the tensile test included two forms: one with single-gate and the other with double-gate. The specimens with double-gate were used to get the weld line at the middle location of the tension gauge. For each test, at least five specimens were tested and measured.

Impact Test. A XC-5.5D electronic impact testing machine was used for the Izod impact test. The impact energy of 2.75 J and the impact velocity of 3.50 m/s were selected. The specimens for the impact test have a flat rectangular parallelepiped shape with the sizes of 65.0 × 12.7 × 6.4 mm in length × width × depth. A standard A-notch in the thickness direction of the specimens was processed for the use of the Izod impact test.

Table I. Ash Experiment Schedules of the Fiber Length Distributions in Specimens

Schedules	Fiber length L_f (mm)	Fiber content W_f (wt %)	Feed way
1	3.0	20	Lateral feed
2	4.5	10	Lateral feed
3	4.5	20	Lateral feed
4	4.5	20	Main-direction feed

DMA Test. DMA test was performed by using a DMA 242 dynamic thermal mechanical analysis instrument. The specimens were heated at a heating speed of 5°C/min from 25°C to 180°C. A double cantilever mode was used for the test, and the test frequency is 1 Hz. The specimens for DMA test were processed from the flexural specimens, whose sizes are 32.0 × 13.0 × 3.2 mm in length × width × depth.

Heat Deflection Temperature (HDT) Test. A XRW-300M heat deformation and VICAT temperature tester was adopted for the test of heat deflection temperature. The heating rate was selected as 120.0°C/h and the magnitude of deflection was specified as 0.42 mm. The specimens for HDT test with the required sizes were also processed from the flexural specimens, and the sizes are 80.0 × 13.0 × 3.2 mm in length × width × depth.

Thermogravimetry Analysis (TGA). TGA test was carried out on a SDT Q600 thermogravimetry analysis instrument with the heating rate of 10°C/min from 25°C to 600°C in argon.

Ash Test. Table I gives the ash experiment schedules of the fiber length distributions in specimens. Three flexural specimens were burned simultaneously for each ash experimental schedule. The specimens were burned in a muffle furnace at 600°C for 2–4 h, ensuring full combustion and evaporation of the resin composition. Then, the remaining fibers were randomly scattered on the conductive adhesives and observed in a scanning electron microscope (SEM) to determine their lengths. The multiple micrographs were obtained for each ash experimental schedule and all measurable lengths on each micrograph were recorded. Finally, 600–700 fibers were counted from SEM micrographs for three specimens of each ash experimental schedule by using software named as "image-proPlus". Representative SEM micrographs under the lateral feed way and the main-direction feed way were shown in Figure 2, respectively.

RESULTS AND DISCUSSION

Distributions of the Fiber Lengths in Specimens

In the SGFRP injection molding products, the glass fibers as reinforcing framework materials play a role of undergoing the structural stress. The distributions of the fiber lengths in the plastic parts directly affect the ability of fibers reinforcement. In both the extrusion and the injection molding process, the extrusion and injection process parameters and the crew combination mode affect the fiber lengths in the plastic parts. In addition, the initial length, addition level and feed way of the fibers also have significant effects on the final distributions of fiber lengths in the plastic parts.

In this article, the fiber length distributions in specimens were determined by using the ash test. In the ash experiment schedules, the effects of the initial length, addition level and feed way of the fibers on the fiber length distributions in specimens were considered respectively. Finally, the frequency distributions of the fiber lengths in specimens were plotted. Figure 3 gave the statistical results of distributions of the fiber lengths in specimens for different experiment schedules. By comparing the results of the different schedules in Figure 3, the following results can be obtained:

1. For the different initial fiber lengths, fiber contents or feed ways, the fiber lengths in specimens are all concentrated

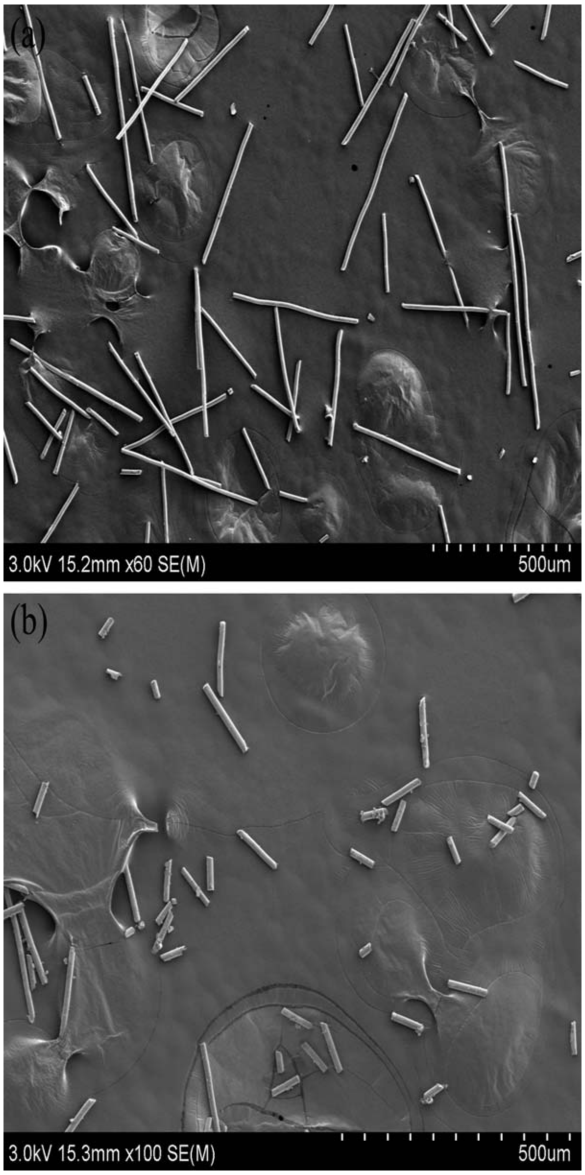

Figure 2. Representative SEM micrographs under different feed ways: (a) the lateral feed way, $W_f = 20$ wt %, $L_f = 4.5$ mm and (b) the main-direction feed way, $W_f = 20$ wt %, $L_f = 4.5$ mm.

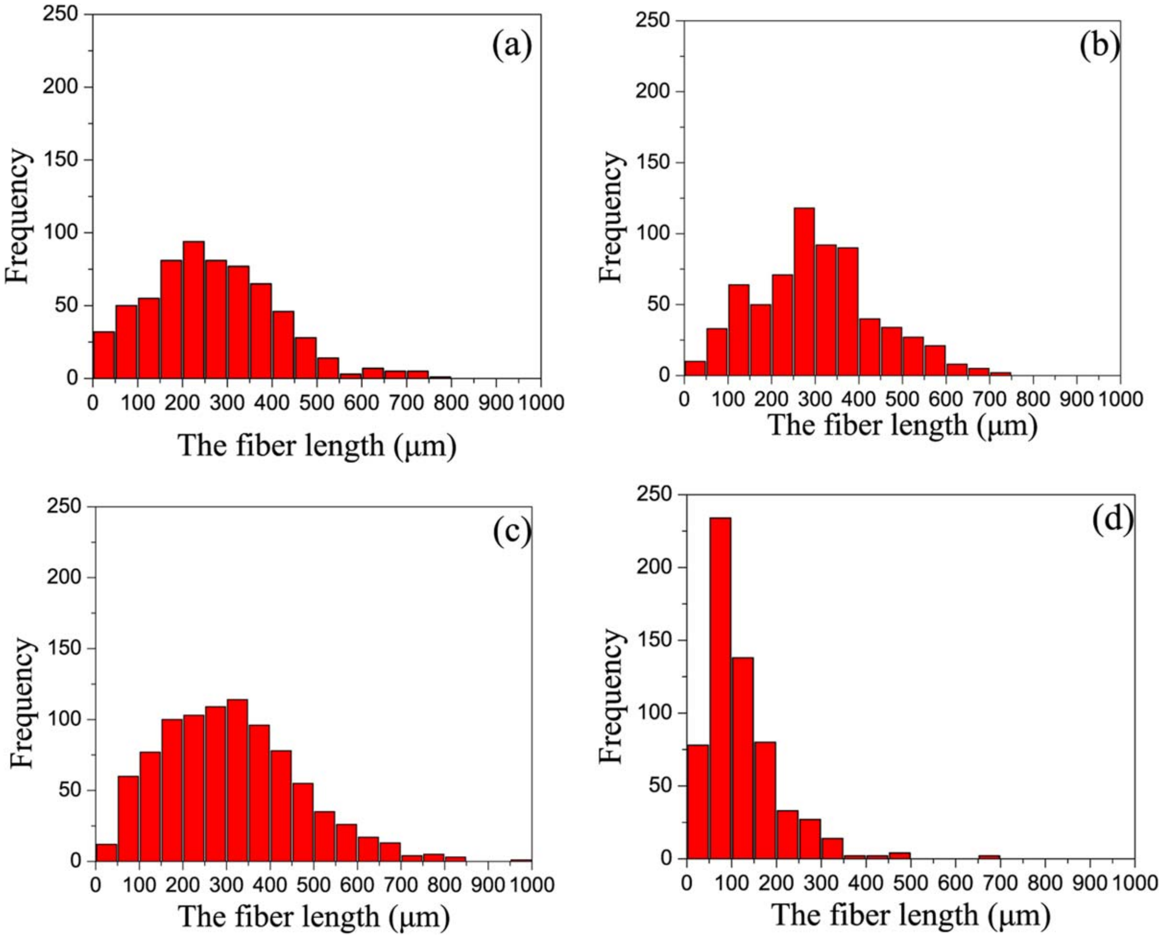

Figure 3. Distributions of the fiber lengths in specimens for different experimental schedules: (a) schedule 1; (b) schedule 2; (c) schedule 3; and (d) schedule 4. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

within 0.10–0.80 mm after intensive shear action in the extrusion and injection molding processes.

2. It can be observed from Figure 3(a,c) that the length of the final fibers in specimens molded by using the initial fibers with long length is a little bit longer than that by using the initial fibers with short length. For the specimens obtained by adding glass fibers with the initial length of 3.0 mm, the length distributions in specimens are concentrated in 0.15–0.40 mm, accounting for 61.80% in the total statistics. The fibers in the length of 0.20–0.25 mm are the most, accounting for 14.60% in the total statistics. However, for the case of 4.5 mm, the length distributions in specimens are concentrated in 0.10–0.40 mm, accounting for 72.90% in the total statistics. The fibers in the length of 0.25–0.30 mm are the most, accounting for 17.70% in the total statistics.

   The phenomenon may be because that, for the same shear rate in the extrusion and injection molding process, the fibers with the initial lengths of 3.0 mm and 4.5 mm are subjected to the almost same shear with respect to the pitch of screw (the pitch of screw in the molding process is in the range of 6–12 mm). Therefore, for the studied short glass fibers, the longer the initial fiber lengths are, the more the ratio of fibers that remain long lengths is. However, it should be indicated that the above law may be unsuitable for the fibers with longer length than the studied fiber lengths.
3. By comparing Figure 3(b,c), it can be seen that the distribution proportion range in which the final fiber lengths in specimens are concentrated becomes wider with the increase of the glass fiber content, the area of concentrating distribution moves toward to the left of the figure. This indicates that the fiber lengths in the concentrating distribution area become short. When the glass fibers are added according to 10 wt %, the fibers being smaller than 0.25 mm in length in specimens occupy 34.30% in the total statistics. For the case of 20 wt %, the fibers being smaller than 0.25 mm in length in specimens rise up to 38.80% in the total statistics. With the increase of the glass fiber content, the ratio of resin decreases and the degree that the fibers are “protected” by the resin in the extrusion and injection molding process reduces.[2] Thus, the amount of fibers with disordered arrangement increases and the damage degree that the fibers undergo in the molding process is also raises.
4. As can be seen from Figure 3(c,d), the fiber length distributions in specimens are concentrated in 0.05–0.15 mm for the main-direction feed way, accounting for about 60.60%

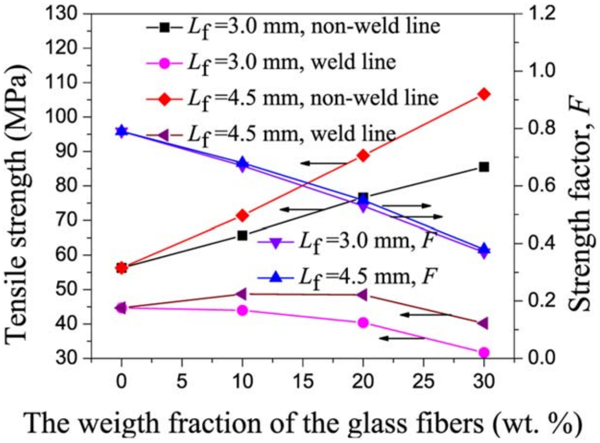

Figure 4. Tensile strength and weld line strength factor versus the weight fraction of glass fibers. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

in the total statistics. For the lateral feed way, the fiber length distributions in specimens are concentrated in 0.10–0.40 mm, accounting for 72.90% in the total statistics. As shown in Figure 2 corresponding to ash experimental schedule 3 and 4, the fibers obtained by the main-direction feed way are apparently cut to shorter than those by the lateral feed way.

In comparison with the lateral feed way, when the main-direction feed way is adopted, the initial fibers are subject to longer shear action of the screw. Therefore, the chance that the fibers are cut is also increased. Especially, the second strong shear zone in the screw shown in Figure 1 provides severe shear effect on the fibers.

Effects of Fibers on the Mechanical Properties of Composites

Effects of Fibers on Composite Strengths. The performances of SGFRP depend on the fiber content to a large extent. As can be seen from the Figures 4 and 5, with the increase of the fiber content within a studied range of 0–30 wt %, the proportion of the reinforcing framework undergoing structural stress in composites is increased, so that the mechanical properties and dimensional stability of the composites are improved and the energy that the plastic parts need to absorb when they are failed (for example, fibers are pulled out and/or abrupt from matrix) increases. Therefore, the tensile strength, flexural strength and flexural modulus are all increased by different degrees.

1. The effect degree of the fiber content on the tensile strength is far less than that on the flexural strength, and the ratio of the flexural strength to tensile strength (modulus of rupture) is concentrated in 1.59–1.73 within the studied fiber content range. When the fiber content is small, the tensile and flexural specimens both approach the ductile failure, but the flexural specimen absorbs more energy than that of the tensile specimen absorbs since it generates plastic yield at cross-section edge before ultimate failure is occurred. Meanwhile, when the glass fiber content is large, the specimens under two loading modes both generate brittle fracture. In this time, the tensile strength value can be considered as the mean of the overall stress on the cross-section since the whole cross-section of the tensile specimen is subject to a relatively uniform stress. Whereas, the stress distribution on the cross-section of the flexural specimen is non-uniform and the maximum flexural stress appears at its outer surface, meanwhile, the number of the defects is lower and their sizes are smaller in the outer surface of the specimen than those in the internal. So the measured maximum stress when the flexural specimen fails in bending is higher than that in tension. This phenomenon is similar to the research result by Din and Hashemi[2] in the study of the ultimate strength of the short glass fiber reinforced PC/ABS.

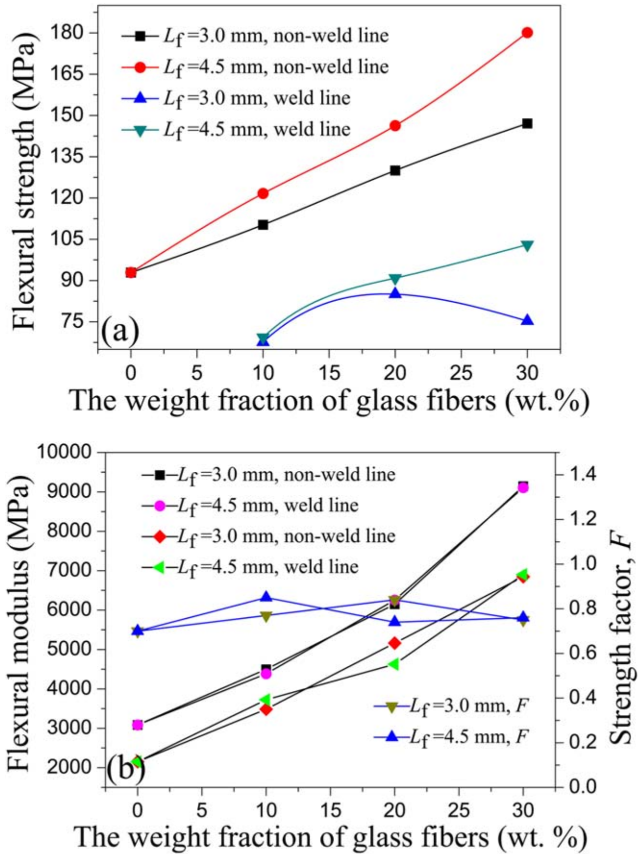

Figure 5. Relationship between the flexural properties and the weight fraction of glass fibers: (a) flexural strength and (b) flexural modulus. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

2. It is noteworthy that the effect of the fibers with the initial length of 4.5 mm on the flexural modulus is not obvious in comparison with that of fibers with the initial length of 3.0 mm. This may be because that the difference of the final fiber lengths in above two kinds of specimens is relatively small and the test results characterized by the deflection are not sensitive. However, the influences of the two kinds of different initial fiber lengths on the tensile strength and flexural strength are both relatively prominent.
3. The weld line is the weakest location and the source of failure on the molded plastic parts. Therefore it is necessary to investigate the impact of the fibers on the weld line. The

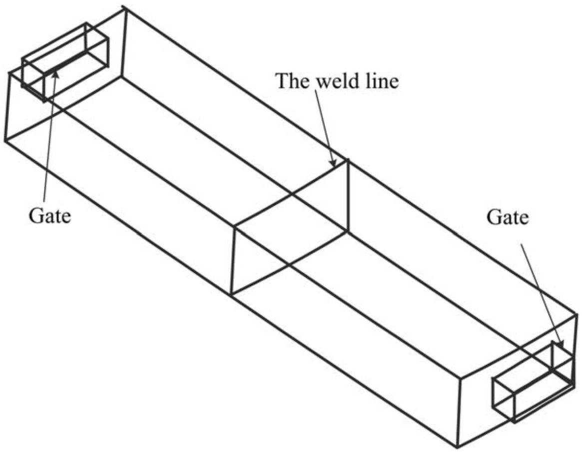

Figure 6. Schematic plot of the weld line for double gate sample.

schematic plot of the weld line is given in Figure 6. To compare the difference between the specimens with weld line and those without weld line, the strength factor to weld line, *F*, is defined as a measurement index. The lower the *F* value is, the greater the effect of the weld line on the specimen quality is. The strength factor to weld line, *F*, is defined as:

$$F = F_w / F_o$$

where F_w is the measured item of the specimens with weld line, F_o is the measured item of the specimens without weld line.It can be seen from Figures 4 and 5 that, no matter how long the fiber length is, the value of the strength factor is all reduced with the increase of the fiber content. This phenomenon implies that the negative effect of the weld line on the specimen quality increases with the increase of the fiber content. This is because that the fibers in specimens generate orientation along the melt flow direction in the injection molding process. at the position away from the weld line, the fiber distribution orientation tends to the loading direction in tension, whereas the distribution orientation of the fibers in the vicinity of the weld line is inclined to parallel with the weld line, namely, the fiber orientation is perpendicular to or at an angle with the loading

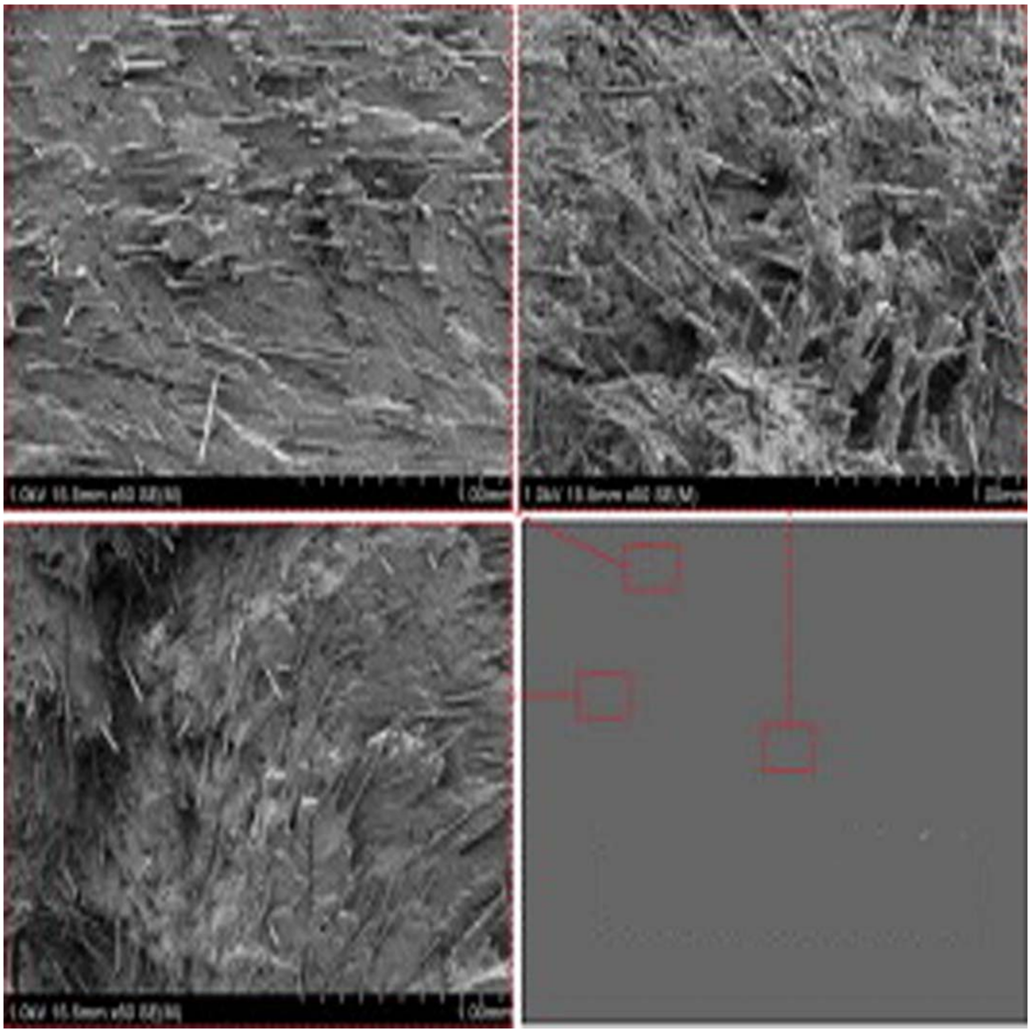

Figure 7. The orientation of the reinforced fibers at the weld line interface.[24] [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table II. Effects of the Different Fiber Feed Ways on Mechanical Properties of the Specimens

	Tensile strength MPa		Strength factor of tensile strength to weld line	Flexural strength MPa		Strength factor of flexural strength to weld line	Flexural modulus MPa		Strength factor of flexural modulus to weld line
Schedules	Nonweld line	Weld line		Nonweld line	Weld line		Nonweld line	Weld line	
L_f =3.0 mm Lateral feed	76.63	40.37	0.53	130.00	85.04	0.65	6148.86	5161.85	0.84
L_f =4.5 mm Lateral feed	88.80	48.44	0.55	146.30	90.88	0.62	6254.98	4627.26	0.74
L_f =4.5 mm Main-direction feed	42.80	40.29	0.94	127.51	71.99	0.56	5398.12	4524.04	0.84

direction in tension. The arrangement feature of fibers in specimens during filling process of resin melt has been confirmed by Wang et al. in our research group using experimental and simulation methods.[24,25] A SEM images about fiber arrangement at the weld line interface is cited from the reference 24 for proving the above discussions, and it is shown in Figure 7. This above case will cause a phenomenon that the number of the overlapping fibers at the weld line is smaller than that in other positions on the specimens when the two melt encounter,[2] this finally leads to the strength difference between the weld line and the other positions on the specimens. The more the fiber content is, the more significant the performance improvement in the positions away from the weld line is, but the performance improvement in the location with weld line is not obvious. Therefore, as the fiber content is increased, the performance difference between the specimens with and without weld line gradually becomes large. For example, when the addition level of the fibers with the initial length of 3.0 mm is up from 0 to 30 wt %, the strength factor of tensile strength to weld line will decrease from 0.79 to 0.37, the reduction ratio is about 53.16%.

4. According to the discussion in section 3.1, the feed ways of the fibers (the main-direction feed way and the lateral feed way) have a significant effect on the final fiber lengths in specimens. Table II lists the comparative results of the mechanical properties of the specimens for the different feed ways and different initial fiber lengths, where the fiber content is 20 wt %.

It can be observed from Table II that in comparison with the lateral feed way, the properties of the specimens obtained by using the main-direction feed way are lowered obviously. The effect of the feed ways on the specimen strengths is higher than that of the fiber initial lengths. The main reason for this phenomenon is that the difference of the fiber initial lengths is relatively small, and the main-direction feed way greatly reduces the final fiber lengths in specimens, so that the length for most of the fibers in specimens is smaller than a required “critical length” in which the resin can be reinforced by fibers. When the plastic parts are subject to an external load, due to the relatively large difference between the elastic modulus of the fibers and plastic matrix, the composites generate a nonuniform elastic deformation throughout the whole specimen, and the tensile and shear stress of the fibers along the axial direction exhibit an uneven distribution. When the fiber length in specimens exceeds the critical length, the maximum stress at the central position of the fiber length may reach the rupture strength and the fiber may be abrupt. Contrarily, when the fiber length in specimens is smaller than the critical length, the fiber is not abrupt but is pulled out from the matrix. In other word, when the lengths of the fibers in specimens are smaller than the critical length, the fibers cannot play a full role in reinforcing the composite materials.

Figure 8 gives the SEM micrographs of the tensile fracture with the different feed ways. It shows that the more number of fibers are pulled out on the tensile fracture of the specimens obtained by the main-direction feed way than those by the lateral feed way. So the tensile strength of the specimens obtained by using the main-direction feed way are lower than that by the lateral feed way.

It can also be seen from Table II that, the tensile strength factor to weld line is more improved by using the main-direction feed way than the lateral feed way. In the main-direction feed way, the fibers are cut to very short, and the more number of fibers are obtained than that in the lateral feed way under the same fiber content. The more number of fibers increase the cross-distribution degree of the fibers at the weld line. The orientation consistency of the fibers is then reduced, and the isotropic property of the specimens is increased. On the contrary, in the lateral feed way, the number of the fibers is relatively less than that in the main-direction feed way and the orientation consistency of the fibers is increased. This will increase the anisotropy of specimen properties. So, from the point of getting isotropic property of the specimens, the better fiber orientation refers to higher degree of disordered arrangement of the fibers. Therefore, in the main-direction feed way, the weld line has small effect on the tensile strength of the specimens.

Effects of Fibers on the Impact Properties. Figure 9 shows the effect of the fiber content on the impact strength of the specimens. The impact strength is decreased as the fiber content

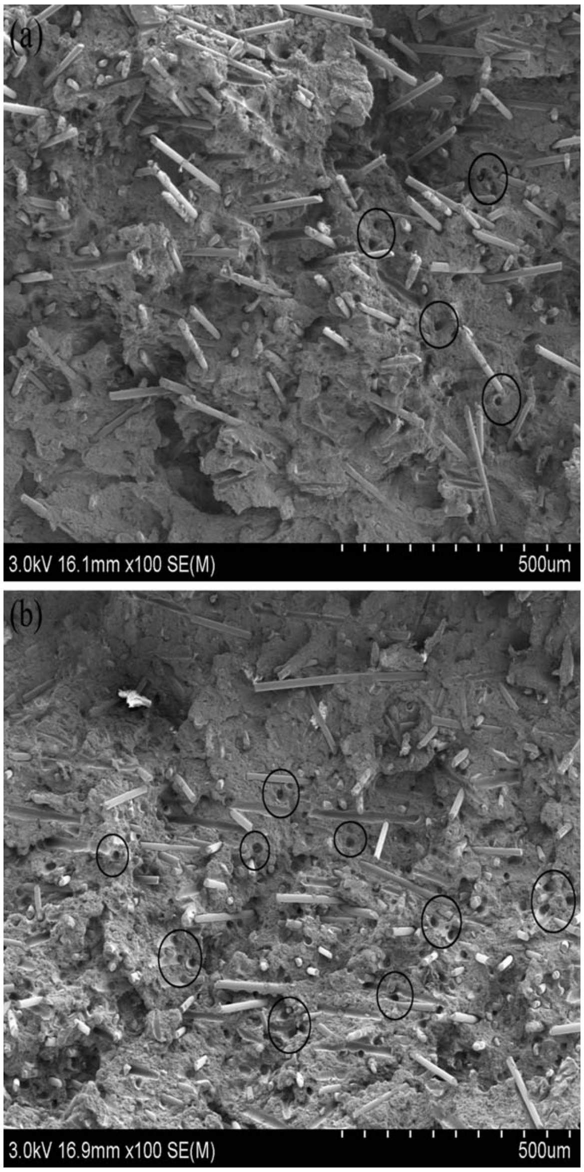

Figure 8. Comparison of tensile fracture with different feed ways: (a) the lateral feed way and (b) the main-direction feed way.

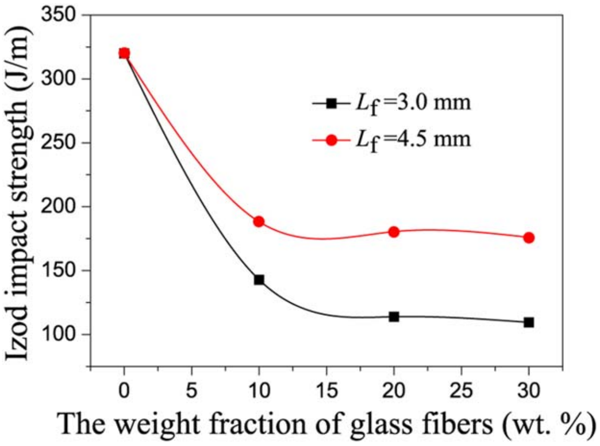

Figure 9. Relationship curve between Izod impact strength and the weight fraction of glass fibers. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

increases. Whereas, the decreased margin of the impact strength for the specimens molded with longer initial glass fibers is significantly less than that with the shorter initial fibers.

As the content is less than 13 wt %, the impact strength is obviously decreased with the increase of the fiber content. This is because that the increase of the fiber content reduces the uniformity and continuity of matrix materials, and increases the possibility of the stress concentration and brittleness of the matrix materials, which results in the decreasing of the impact strength of the specimens. However, when the glass fiber content is larger than 13 wt %, the impact strength of the specimens remains almost unchanged with the increase of the fiber content. This implies that the fiber content has no longer effect on the impact strength of the specimens as the fiber content is up to a critical value. In this study, the critical fiber content is about 13 wt %. This may be because that the isotropic trend of the fiber distributions increases with the increase of the fiber content, the proportion of the crossly distributed fibers will increase, and these crossly distributed fibers will form an arrangement similar to "three-dimensional network," This network will achieve a equilibrium with the above introduced reduction of the uniformity and continuity of matrix materials. In this case, the fluctuation of the energy absorbed for specimen impact failure is small as the fiber content continued increases. Therefore, when the glass fiber content is larger than 13 wt %, the impact strength of the specimens is no longer changed. Figure 10 shows the staggered arrangements of fibers on the impact fracture.

As discussed in section 3.1 of this article, when the initial fiber lengths are relatively long, the proportion of relatively long glass fibers remained in the molded specimens is increased. Since the consumed power for pulling out long fibers from the matrix is more than that for pulling out short fibers, the impact strength

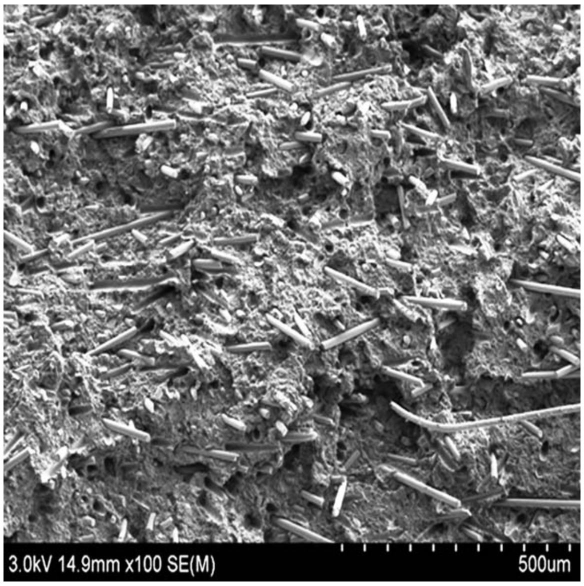

Figure 10. Staggered arrangements of fibers on the impact fracture.

of the specimens molded with long initial fibers is higher than that with short initial fibers. In addition, since the stress concentration at the fiber ends easily occurs, the ends often become the initial points of the cracks. When the fiber length is long, the number of the fiber ends and the corresponding crack initial points are both decreased under the same fiber content, so the impact strength of composites obtained by adding long fibers is relatively larger than that by adding short fibers with the same fiber content.

Effects of Fibers on the Thermal Properties of Composites

Effects of Fibers on Dynamic Mechanical Thermal Properties of Composites. DMA test is a technology describing the relationships among dynamic modulus, mechanical loss, and temperature in the temperature range controlled by the program and under the action of variable loads. When a certain heating rate and the variable loads with a given frequency are adopted, the storage modulus E', the loss modulus E'' and the loss factor Tan δ can be obtained. Tan δ is a ratio of the loss modulus to the storage modulus, (E''/E'). Compared with the static test method, DMA test is closer to the actual usage situation of the products, and it is an effective method to study the relaxation behavior of polymers.

It can be seen from Figure 11(a) that the critical transition temperature T_g and T_f have little change. T_g is a critical transition temperature from the glassy state to the elastomeric state, and T_f is the critical transition temperature from the elastomeric state to the viscous flow state. When the glass fiber content increases from 0 to 10 wt %, the E' value substantially increases. This is because that the proportion of the stiffness portion in specimens rises, and the resistance of the polymer macromolecular chains motion near the interface layers between the fibers and the resin matrix is increased. But, when the fiber content is up to 20 wt %, although the E' is still greater than that of the content of 0 wt %, its value is obviously less than that of the content of 10 wt %. This phenomenon may be because that when the fiber proportion in specimens is larger than a certain value between 10 and 20 wt % and the specimens generate deformation, the energy transformed to potential energy will be correspondingly reduced and the E' value exhibits a decreasing trend.

As shown in Figure 11(b) that, when the fiber content is increased, the change of the E'' peak is corresponded to that of the storage modulus, the flow properties and molding performance of the specimens decrease, and the E'' peak values become large within a certain range of content. Moreover, the loss modulus curves of the three kinds of composites all have two peaks feature. This is because that the composite compositions include not only the rigidity portion, but also the toughness portion. Near 93–94°C, the polystyrene chain segments in polymers start to move and a lot of energy is consumed. At this time, the first peak of the E'' curve appears. When the temperature is about 123–124°C, the other compositions in the composites reach to the glass transition temperature and start to move into the high elastomeric state. At this time, the E'' reaches the maximum value, its second peak value appears, and this peak is much higher than the first.

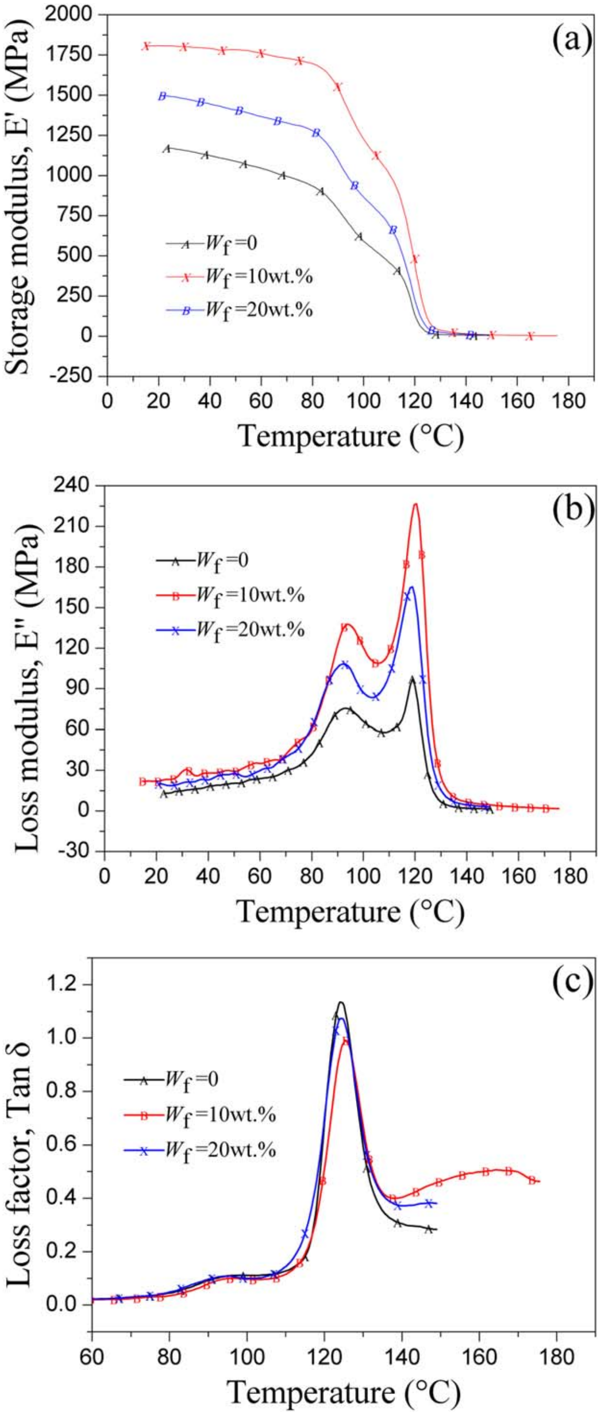

Figure 11. Relationship curves among the storage modulus E', loss modulus E'', loss factor tan δ and the temperature: (a) storage modulus; (b) loss modulus; and (c) loss factor. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

According to the above definition of Tan δ, Tan δ can reflects the internal friction of the polymers. The higher the value of Tan δ is, the greater the internal friction which the molecular chains of polymers in moving process is subject to is. Therefore, the larger the Tan δ value is, the worse the interface strength between the resin matrix and the glass fibers is. This phenomenon finally results in the poor mechanical properties of

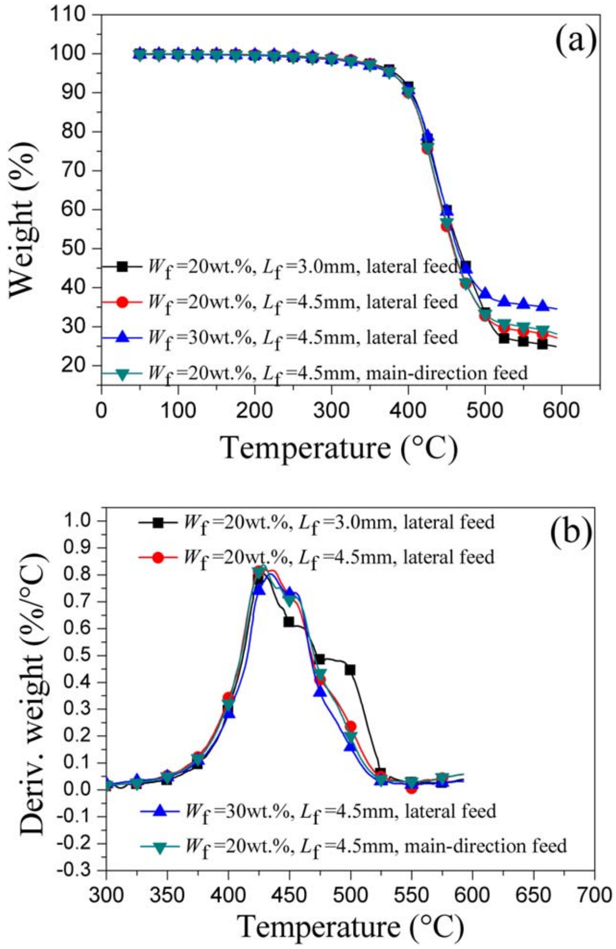

Figure 12. Thermogravimetry analysis curves of the different specimens: (a) TGA and (b) DTG. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

composites. As can be seen from the Figure 11(c), the peak values of the Tan δ in the fiber reinforced polymers are less than those of the resin matrix. This implies that the molecular chains in the fiber reinforced polymers need more energy to move, namely, the specimens obtained from the fiber reinforced composites require more energy before phase transformation. At the macro level, it is indicated that the tensile strength, flexural strength and flexural modulus in the fiber reinforced composites are all increased by the different degrees in comparison with the resin matrix. This is consistent with the conclusion in section 3.2.1.

Effects of Fibers on Thermogravimetry of Composites. Thermogravimetry analysis (TGA) is a method measuring the dependence relationship of the specimen mass and temperature under the programmed temperature. The first order of derivative of TGA curve to temperature, dW/dT, represents the mass change rate, called as "Derivative thermogravimetry curve (DTG)".

Figure 12(a) and Table III show that when the temperature is less than 325°C, the composite mass and T_{onset} (a temperature at which the composites begin to be thermal degradation) for different experimental schedules are hardly changed. When the temperature is in the range of 325–500°C, the mass of composites for all experimental schedules is obviously reduced, whereas, the amount of the mass loss is almost irrelevant with the initial length, addition level, and feed way of the glass fibers. As the temperature exceeds 500°C, the mass loss of composites is obviously slowed down with the increase of temperature. It can be also observed that the T_{end} (a temperature at which the mass loss ends) for the fiber content of 30 wt % is slightly lower than that for the fiber content of 20 wt %. But the effects of the fiber initial length and feed way on the T_{end} is very small. Therefore, the effect of the fiber content on the T_{end} is greater than that of the glass fiber length. By comparing the residue after the mass loss, the mass loss of composites in adding short glass fibers is greater than that in adding long fibers, and the mass loss of composites with low fiber content is larger than that with high fiber content. When the fiber initial length and addition level are both constant, there is almost no any effect of the feed way on the mass loss.

The reasons of the above phenomenon are because that the thermal decomposition temperature of the glass fibers is up to thousands of Celsius, and only the resin has mass loss in heating process of the fiber reinforced polymers. So no matter how the experiment schedules of adding fibers are adopted, the T_{onset} is nearly unchanged. In the case of the same fiber content, since the number of the short glass fiber is more than that of the long fibers, the action that the short fibers induce thermal degradation is greater than that of the long fibers before the charring protection of PC phase in polymers, so the residue after the mass loss for the composites with shorter fibers is less than that with longer fibers. However, in the main-direction feed way, parts of fibers are cut too short due to the strong shear action, and the action of promoting thermal degradation is reduced significantly, so that the residue after the mass loss of composites is almost unchanged. Meanwhile, with the continuous increase of the fiber content, the action that the fibers induce the thermal degradation promotes the action for the PC charring reaction, and the continuous mass loss of composites is prevented. Therefore, with the increase of the fiber content, the T_{end} is lowered, and the residue of composites after the mass loss is increased.

It is observed from Figure 12(b) and Table III that the $T_{\max}$ (a temperature at which the rate of composites mass loss reaches

Table III. Results Statistics of the Thermogravimetry Test

Experimental schedules	T_{onset} °C	$T_{\max}$ °C	The residue %
W_f =20 wt %, L_f = 3.0 mm, Later feed	387.50	428.28	24.93
W_f = 20 wt %, L_f = 4.5 mm, Later feed	387.00	436.60	27.35
W_f = 30 wt %, L_f = 4.5 mm, Later feed	387.30	435.09	34.68
W_f = 20 wt %, L_f = 4.5 mm, Main-direction feed	387.10	429.33	28.38

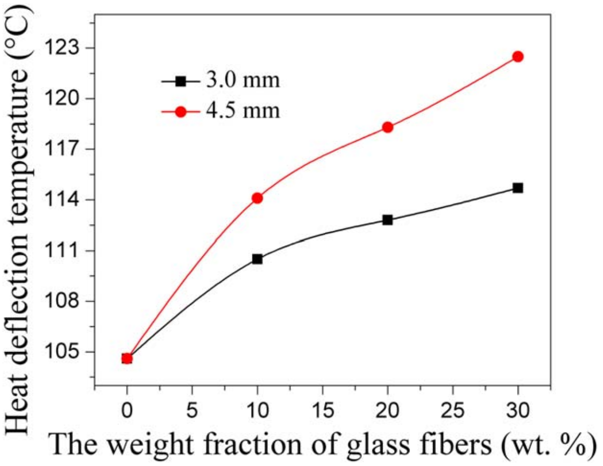

Figure 13. Relationship curve between the heat deflection temperature and the weight fraction of glass fibers. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

maximum) is slightly increased with the increase of the fiber initial length. When the initial length of the glass fiber increases from 3.0 mm to 4.5 mm, the T_{max} increases from 428.3°C to 436.6°C. But the effect of the fiber content on the T_{max} is very little.

Effects of Fibers on the Heat Deflection Temperature of the Plastic Parts. As shown in Figure 13 that the HDT value of the specimens is gradually increased with the increase of the fiber content. It is indicated that the higher fiber content is beneficial to improve the thermal stability of composites. Meanwhile, the longer glass fibers are useful for improving the HDT and thermal stability of composites than that of the short fibers. For the specified magnitude of deflection, 0.42 mm, when the glass fiber content increases from 0 to 30 wt %, the HDT of the specimens obtained with the glass length of 3.0 mm increases from 104.6°C to 114.7°C, but the HDT of the specimens obtained with the glass length of 4.5 mm increases form 104.6°C to 122.5°C. It is obvious that the application temperature range of polymer products is increased.

CONCLUSIONS

1. The initial length, content and feed way of the fibers all have a significant effect on the final fiber lengths in the plastic parts, where the effect of the feed way is the most evident among them.
2. With the increase of the fiber content, the strengths of composites are increased and the impact property of the composite is reduced. However, when the fiber content is sufficient to form a cross-distribution similar to "three-dimensional network" in the plastic parts, the impact property is almost kept constant with the continue increase of the fiber content. In addition, the longer lengths of the initial glass fibers are, the better the reinforcing and toughening effects of the fibers on the plastic parts are.
3. As the fiber content is increased, the reinforcing effect of the fibers on the positions away from weld line is relatively obvious. However, since the fibers near the weld line tend to be parallel with the weld line due to the orientation effect, the increase of the tensile stress near the weld line is limited. Therefore, the strength factor of the tensile strength to weld line is decreased with the increase of the glass fiber content.
4. When the glass fiber content is increased within a certain range of the fiber content, the storage modulus E' and the loss modulus E'' are both increased, and the loss factor Tan δ is reduced. However, when the fiber content is larger than a certain value between 10 and 20 wt %, the energy transformed to potential energy may be correspondingly reduced, so that the E' value exhibits a decreasing trend.
5. With the increase of the fiber content, the effects of the initial length, fiber content, and feed way of the fibers on the T_{onset} are little, whereas, the T_{end} is slightly decreased and the residue after the mass loss is increased. Meanwhile, the addition of the fibers increases the thermal stability of the composites system and enlarges the application temperature range of the plastic parts.

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