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Tensile properties of short-glass-fiber- and short-carbon-fiber-reinforced polypropylene composites

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Abstract

Composites of polypropylene (PP) reinforced with short glass fibers (SGF) and short carbon fibers (SCF) were prepared with extrusion compounding and injection molding techniques. The tensile properties of these composites were investigated. It was noted that an increase in fiber volume fraction led to a decrease in mean fiber length as observed previously. The relationship between mean fiber length and fiber volume fraction was described by a proper exponential function with an offset. The tensile strength and modulus of SGF/PP and SCF/PP composites were studied taking into account the combined effect of fiber volume fraction and mean fiber length. The results about the composite strength and modulus were interpreted using the modified rule of mixtures equations by introducing two fiber efficiency factors, respectively, for the composite strength and modulus. It was found that for both types of composites the fiber efficiency factors decreased with increasing fiber volume fraction and the more brittle fiber namely carbon fiber corresponded to the lower fiber efficiency factors than glass fiber. Meanwhile, it was noted that the fiber efficiency factor for the composite modulus was much higher than that for the composite strength. Moreover, it was observed that the tensile failure strain of the composites decreased with the increase of fiber volume fraction. An empirical but good relationship of the composite failure strain with fiber volume fraction, fiber length and fiber radius was established.
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Keyword: Short glass fibers

1. Introduction

Short-fiber reinforced polymer (SFRP) composites are very attractive because of their ease of fabrication, economy and superior mechanical properties. Extrusion compounding and injection molding processes are frequently employed to make SFRP composites [1–27]. In general, a high fiber content is required in order to achieve a high performance SFRP composite. Therefore, the effect of fiber content on the mechanical properties of SFRP composites is of particular interest and significance. It is often observed that the increase in fiber content leads to the increase in the strength and modulus [2–6,13,14,17–19,22,25] and also in the toughness if the matrix has a low toughness [7]. However, for injection molded SFRP composites, fiber breakage takes place during processing. Fiber breakage results from fiber–polymer interaction, fiber–fiber interaction, and fiber contact with surfaces of processing equipment [27,28]. Due to the increased fiber–fiber interaction and fiber-equipment wall contact, fiber length decreases with increasing fiber content [2,5,14,19,21, 22,27–30] and this reduction in fiber length then reduces fiber reinforcing efficiency. This is at least partially the reason why the addition of short fibers to a polymer matrix does not lead to a significant increase or brings about a decrease in composite strength [5,6,25,26] and modulus [3–6,13,16,18,19,22,26] and toughness [7]. It has been shown that the mechanical properties such as strength, modulus and toughness increase generally with increasing fiber length [27,29,31–36]. In other words, in general these mechanical properties decrease with decreasing fiber length. Therefore, the effect of fiber content on the mechanical properties of injection molded SFRP composites must be combined with the effect of fiber length and the two competing effects would determine the final mechanical properties of SFRP composites. Moreover, in order to present a quantitative discussion or prediction of the effect of fiber content (fiber volume fraction or weight fraction) on the mechanical properties of SFRP composites, it is necessary to give a proper function to describe the relationship between fiber length and fiber content. In principle, the constants in such a

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Table 1
Mechanical and physical properties of materials at 23°C

Materials	Tensile strength (MPa)	Young's modulus (GPa)	Density (g/cm^3)	Diameter (μm)
Glass fiber	1956[a]	78.51[a]	2.55	13.8
Carbon fiber	3950[a]	238[a]	1.77	7.5
Polypropylene	31.6	1.30	0.903	

[a] Test length = 50 mm.

function can be determined using the known data, in turn the function may be used to predict mean fiber lengths for the cases of unknown fiber contents and hence the composite mechanical properties can be inferred with no need of doing tedious experiments. However, no function has been given previously for describing this relationship. In this work, a proper exponential function with an offset will be given to describe the mean fiber length–fiber volume fraction relationship.

The fiber content has an evident influence on the composite failure strain. It was generally seen that the composite failure strain decreases with the increase of fiber content [2–5,13,14,19,22]. The studies on failure mechanisms [4,20,24,37] showed that under loading of tensile stress, the cracks start at the fiber ends and propagate along the fiber–matrix interface or cross through the matrix and finally the failure takes place. Fiber ends have been shown to substantially concentrate the stress in the adjacent matrix [4], producing stress magnifications of ten or even higher. The effects of these stress concentrations can be relieved only by matrix flow, interface debonding or matrix fracture. Obviously, the failure is closely related to the number of fiber ends and thus to the parameters including fiber volume fraction, fiber length and fiber radius which determine the number of fiber ends. Consequently, there should exist a relationship between composite failure strain and fiber volume fraction, mean fiber length as well as fiber radius. After obtaining this quantitative relationship, the failure strain at any fiber content can then be conjectured. However, such a quantitative relation of composite failure strain containing these parameters has not yet been given previously. This quantitative relation will be established in the present paper.

In the present work, polypropylene (PP) composites reinforced with short glass fibers (SGF) and short carbon fibers (SCF) were prepared by extrusion compounding and injection molding techniques. PP was chosen since it is part of the group of commodity thermoplastics produced in large quantities. The tensile properties of these composites were investigated taking into consideration the combined effect of fiber volume fraction and mean fiber length. The relationship between mean fiber length and fiber volume fraction was described using a proper exponential function with an offset. The results about composite strength and modulus were analyzed using the rule of mixtures equations by introducing two fiber efficiency factors, respectively, for the composite strength and modulus, where the two fiber efficiency factors represent the fiber reinforcing efficiencies for the strength and modulus. Comparison of the fiber reinforcing efficiencies for composite strength and modulus was performed for SGF/PP and SCF/PP composites. The combined effect of fiber volume fraction and mean fiber length on the composite failure strain was also studied. An empirical relationship of composite failure strain with fiber volume fraction, fiber length and fiber radius was established.

Table 2
Formulations investigated

No.	Material type	PP content (% vol.)	GF content (% vol.)	CF content (% vol.)
1	Pure PP	100		
2	SGF/PP	92	8	
3	Composites	84	16	
4		75	25	
5	SCF/PP	92		8
6	Composites	84		16
7		75		25

2. Experimental details

2.1. Materials

The materials employed in this investigation were PP (HOSTALEN PPN 1060 + 2 wt.-% POLYBOND 3150), E-glass fiber rovings (EC 14-300-E 37 300 tex) and carbon fiber rovings (TENAX HTA 5331, 800 tex). The mechanical and physical properties of these materials are listed in Table 1. The compositions of all the specimens are listed in Table 2. No. 1 is neat PP, Nos. 2–4 are SGF/PP composites and Nos. 5–7 are SCF/PP composites.

2.2. Specimen preparation

The composites were prepared by feeding the glass and carbon fiber rovings into the polymer melt using a twin screw extruder. The six heating zones were set to 230, 230, 220, 220, 220 and 220°C and the mass temperatures were 214, 231, 239, 236, 233 and 231°C. The compounded extrudates were immediately quenched in water and cooled in air till ambient temperature. Then the extruded strands were chopped into granules and dried. All the specimens were injection molded into dumbbell-shaped tensile bars under identical conditions using a twin screw injection

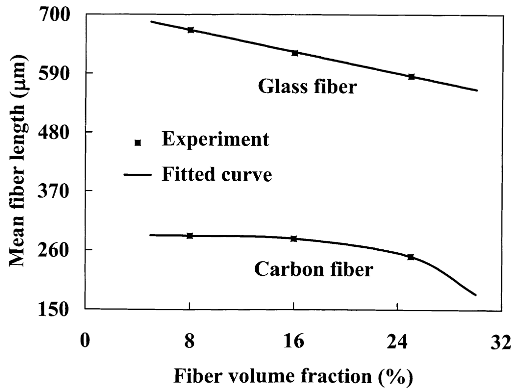

Fig. 1. Mean fiber length versus fiber volume fraction for short-glass-fiber (SGF)-reinforced PP composites and short-carbon-fiber (SCF)-reinforced PP composites.

molding machine with a barrel temperature of 210–230°C. An end-gated mold was used for molding dumbbell-shaped samples according to DIN 53455. The thickness and width of the specimens are 4 and 10 mm, respectively. The fibers in the tensile-bar-shaped specimens were preferentially oriented in the flow direction [9,17,24], that will also be shown in the present study.

2.3. Tensile tests

The tensile properties of specimens were determined using 10 samples for each composition with a Zwick 1456 testing machine at a constant cross-speed of 5 mm/min.

2.4. Measurement of fiber length

Short glass and carbon fibers were first isolated from the composite materials by pyrolysis in a microwave oven for about 10 min at 550°C. An ash of fibrous material was left and some fibers were extracted from the sample ash and dispersed in water in a rectangular glass dish. The dish was then placed on the observation stage of a microscope. Magnified fiber images were transmitted to a large screen, and fiber images were then semi-automatically digitized by software with a computer and fiber length distributions (FLD) were thus determined.

2.5. SEM observations

Prior to scanning electron microscopy (SEM) observations, all fracture surfaces of tensile specimens were sputter-coated with gold. Fractographic studies with SEM were carried out in detail on the fracture surfaces of SGF/PP composites and SCF/PP composites.

2.6. Measurement of mean interfacial shear stress at the maximum fiber pull-out force of glass fiber/PP and carbon fiber/PP samples

Single-glass-fiber/PP and single-carbon-fiber/PP model composites were prepared for single-fiber pull-out tests. A self-made pull-out apparatus [38] has been used to measure fiber displacement and force. The fibers were embedded in the matrix at 230°C under argon atmosphere. The temperature used for embedding the single fibers into the matrix is similar to that for preparing the injection molded samples. Therefore, this method would produce similar interfaces as the injection molding process does. The embedded fiber lengths were from 150 to 300 μm. The pull-out tests were carried out under the same velocity of pulling out the fibers (0.2 μm/s) at ambient temperature. The fiber diameter d_f was measured microscopically. From each force-displacement curve the maximum force F_{max} was determined. This maximum force bears effects of debonding and friction between fiber and matrix as well as geometrical effects of the sample. The shear stress distribution along the interface is not homogeneous [39,40]. That is why an interpretation of the maximum force (F_{max}) normalized by the surface area ($\pi d_f l_e$, where l_e is the embedded fiber length) as interfacial shear strength characterizing adhesion is inappropriate [41], and the normalized stress is defined as the mean interfacial shear stress $\hat{\tau}$ at the maximum fiber pull-out load and is written as:

$$\hat{\tau} = \frac{F_{max}}{\pi d_f l_e} \quad (1)$$

$\hat{\tau}$ provides only a mean value (at the point of maximum applied load) of the strongly inhomogeneous shear stress distribution and cannot be expected to be a physical measure for interfacial adhesion in the sense of a material property. It can be taken as a measure for load transmission ability of a fiber to the matrix for comparison of different material combinations. The mean values of $\hat{\tau}$ of each fiber/polymer system were estimated from 15 to 20 pull-out tests.

3. Results and discussion

3.1. Fiber length

The effects of glass and carbon fiber volume fractions on mean glass and carbon fiber lengths are presented in Fig. 1. Fig. 1 exhibits that the mean glass fiber length decreases with the increase of glass fiber volume fraction as observed previously [2,5,14,19,21,22,27–30]. A similar phenomenon is seen for carbon fiber length, namely the mean carbon fiber length decreases with the increase of carbon fiber volume fraction. These indicate that a higher fiber content leads to a higher damage to fiber length. The increased damage to fiber length for a higher fiber volume fraction is mainly attributed to the higher fiber–fiber interaction. Moreover, it is noted that the mean carbon fiber length is less than the mean glass fiber length. This may be caused by the fact that carbon fibers are more brittle and thus fracture more easily than glass fibers during processing.

The relationship between mean fiber length l_m and fiber volume fraction V_f can be described by a fitting exponential

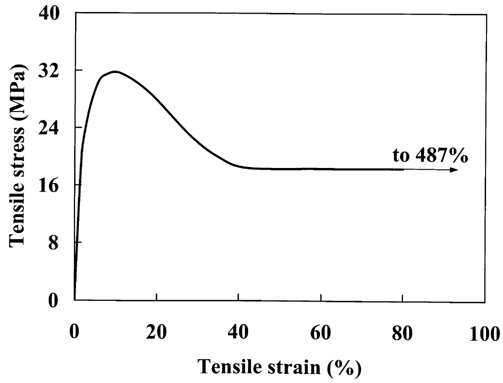

Fig. 2. Typical tensile stress–strain curve for the pure PP matrix material.

function with an offset:

$$l_m = C_1 \exp(C_2 V_f) + C_3 \quad (2)$$

where the absolute value of C_1 is magnification of the exponential function $[\exp(C_2 V_f)]$ in which C_2 is the exponential coefficient. $C_1 + C_3$ is the extrapolated fiber length at $V_f = 0$ (i.e. the relationship of $l_m \sim V_f$ is extrapolated to intersect the l_m axis at $V_f = 0$, see Eq. (2)). C_1 and C_3 have the dimension of length. C_1, C_2 and C_3 are constants for a given fiber/matrix system. And since mean fiber length in practice decreases with increasing fiber volume fraction, then $C_1 < 0$ and C_2 and $C_3 > 0$ hold true.

For SGF/PP composites, the $l_m \sim V_f$ relationship is nearly linear as shown in Fig. 1. Then, C_2 must be small enough so that the exponential function $[\exp(C_2 V_f)]$ can be approximately expanded as $1 + C_2 V_f$. So, from the given experimental data of the mean fiber length at $V_f = 8$ and 25% (or 8 and 16%), we can use Eq. (2) to get $C_1 + C_3 = 0.711$ (mm) and $C_1 C_2 = -0.5$ (mm). For this linear relation it is enough to know the extrapolated fiber length $C_1 + C_3$ and the slope $C_1 C_2$. For SCF/PP composites, we can employ Eq. (2) to estimate C_1, C_2 and C_3 from the given experimental data of the mean fiber length at $V_f = 8$ and 25%. And we get $C_1 = -0.000234$ (mm), $C_2 = 20.482$ and $C_3 = 0.2882$ (mm). The fitted results of $l_m \sim V_f$ are displayed by the solid curves in Fig. 1, showing that the $l_m \sim V_f$ relationships can be fitted very well with Eq. (2). Moreover, Eq. (2) can be easily used to describe the $l_m \sim V_f$ relationship for other systems [2,14,22,28]. For simplicity, this is not presented here.

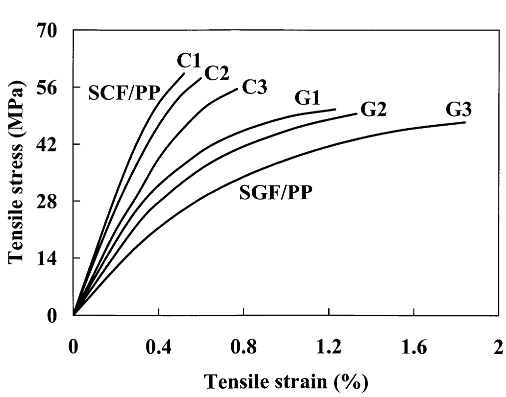

Fig. 3. Typical tensile stress–strain curves for SGF/PP and SCF/PP composites. SGF/PP composites: curve G1-25 vol% glass fibers, curve G2-16 vol% glass fibers and curve G3-8 vol% glass fibers; and SCF/PP composites: curve C1-25 vol% carbon fibers, curve C2-16 vol% carbon fibers and curve C3-8 vol% carbon fibers.

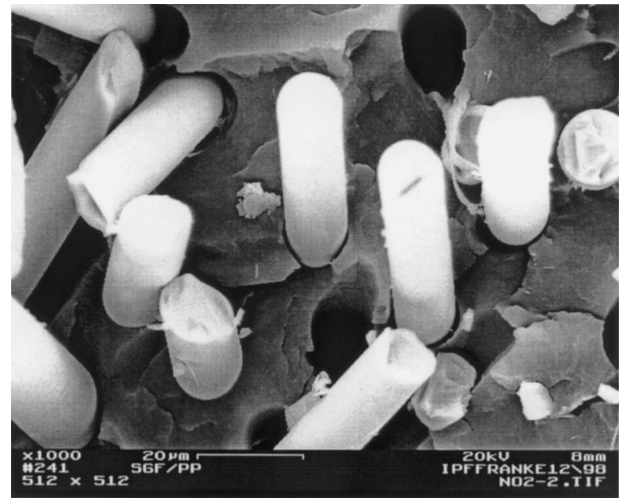

Fig. 4. SEM micrograph of tensile fracture surface of an SGF/PP composite with 25 vol% glass fibers.

3.2. Tensile stress–strain curves

The tensile stress–strain curve of pure PP matrix is shown in Fig. 2. It exhibits that PP shows a ductile type of curve and the strain of failure is about 487%. The tensile stress–strain curves of SGF/PP composites and SCF/PP composites are shown in Fig. 3. It can be seen that SGF/PP composites and SCF/PP composites exhibit a brittle fracture and show linear deformation at lower stresses and nonlinear deformation at higher stresses. The strains of failure for SCF/PP composites are lower than those for SGF/PP composites (see Fig. 3).

3.3. Fractography

All the following micrographs were selected arbitrarily and are typical ones.

The SEM micrographs of the fracture surfaces of SGF/PP composites and SCF/PP composites are shown, respectively, in Figs. 4 and 5. The brittle fracture of the matrix is observed in both SGF/PP and SCF/PP composites, consistent with the brittle nature of the tensile stress–strain curves for the two types of composites shown in Fig. 3, and it can be seen from Figs. 4 and 5 that most fibers are pulled out from the matrix. These can be explained as follows. The critical fiber length (l_c) can be evaluated with the following formula:

$$l_c = \frac{r_f \sigma_{fu}}{\hat{\tau}} \quad (3)$$

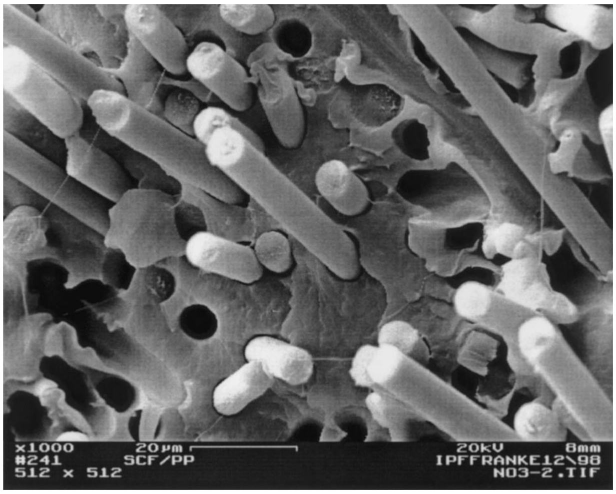

Fig. 5. SEM micrograph of tensile fracture surface of an SCF/PP composite with 25 vol% carbon fibers.

where σ_{fu} is the fiber strength and r_f is the fiber radius. This relation is valid if it is assumed that the interface shear stress is constant along the fiber axis of a fiber embedded in a representative volume element. For elastic behavior of the components, this is not the case. We use here however as an approximation the values of $\hat{\tau}$ determined by the pull-out experiments. The measured mean values of $\hat{\tau}$ for glass/PP and carbon/PP systems are, respectively, 15.2 and 18.2 MPa. Then the critical lengths of glass fibers and carbon fibers can be obtained as 887.92 and 813.87 μm, respectively. It can be seen from Fig. 1 that the mean glass and carbon fiber lengths are much shorter than their corresponding critical lengths. Moreover, the FLD for SGF/PP and SCF/PP composites are presented, respectively, in Figs. 6 and 7, showing that most glass fibers have a length less than their critical length and nearly all carbon fibers are shorter than their critical length. So, most fibers would be pulled out instead of fractured during loading of the composite.

Fig. 8 shows the SEM micrographs of the fracture surfaces of a SGF/PP composite in three different positions across the specimen thickness from one side to middle, and then to another side (Fig. 8(a)–(c)). It can be seen that the fibers are aligned preferentially along the flow direction in the whole specimen thickness. This observation is consistent with the previous ones from fractured surfaces [9,17] and from polished surfaces [24]. For SCF/PP composites, the fibers are also aligned preferentially along the flow direction, see Fig. 9. Moreover, it can be seen that the pull-out lengths of carbon fibers are shorter than those of glass fibers, consistent with the observations in Fig. 1.

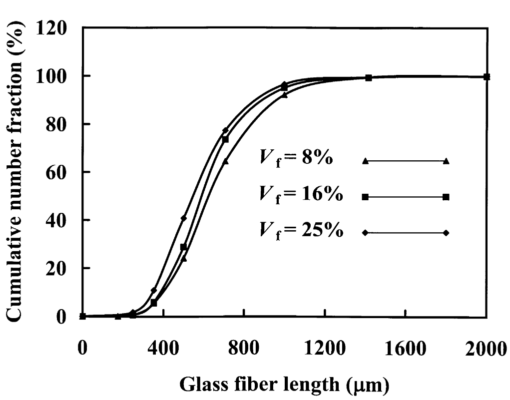

Fig. 6. Glass FLD for SGF/PP composites.

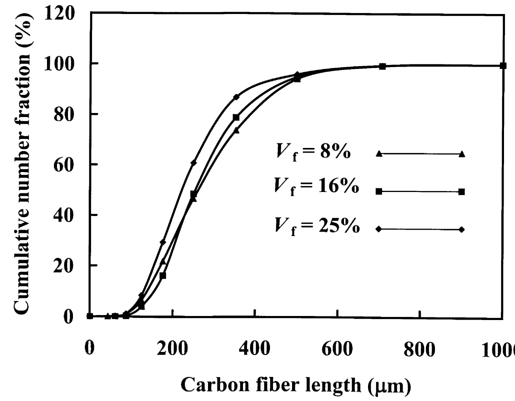

Fig. 7. Carbon FLD for SCF/PP composites.

3.4. Tensile properties

3.4.1. Strength and modulus

Fig. 10 shows the variations of the ultimate tensile strength as a function of fiber volume fraction for SGF/PP and SCF/PP composites. The addition of glass and carbon fibers effectively enhances the ultimate strength (the ultimate strength of pure PP matrix is 31.6 MPa, see Table 1). Moreover, it can be seen that the strengths of SCF/PP composites are higher than those of SGF/PP composites. This is because carbon fibers have a much higher strength than glass fibers. However, the scatter of the data for SCF/PP composites is larger than that for SGF/PP composites. This is because carbon fiber is more brittle than glass fiber. Furthermore, it is observed that as the fiber volume fraction increases, the composite strength increases slightly only. This observation exhibits that the effect of mean fiber length on composite strength is significantly large, so that the combined effect of fiber volume fraction and mean fiber length leads to only a slight increase in the composite strength as the fiber volume fraction increases, namely the decrease in the composite strength caused by the reduction in mean fiber length almost offsets the increase in the composite strength caused by the increase in fiber volume fraction.

The variations of the elastic modulus of SGF/PP and SCF/PP composites as a function of fiber volume fraction are shown in Fig. 11. It can be seen that the modulus for both types of composites increases dramatically with the increase of fiber volume fraction, which is different from the same

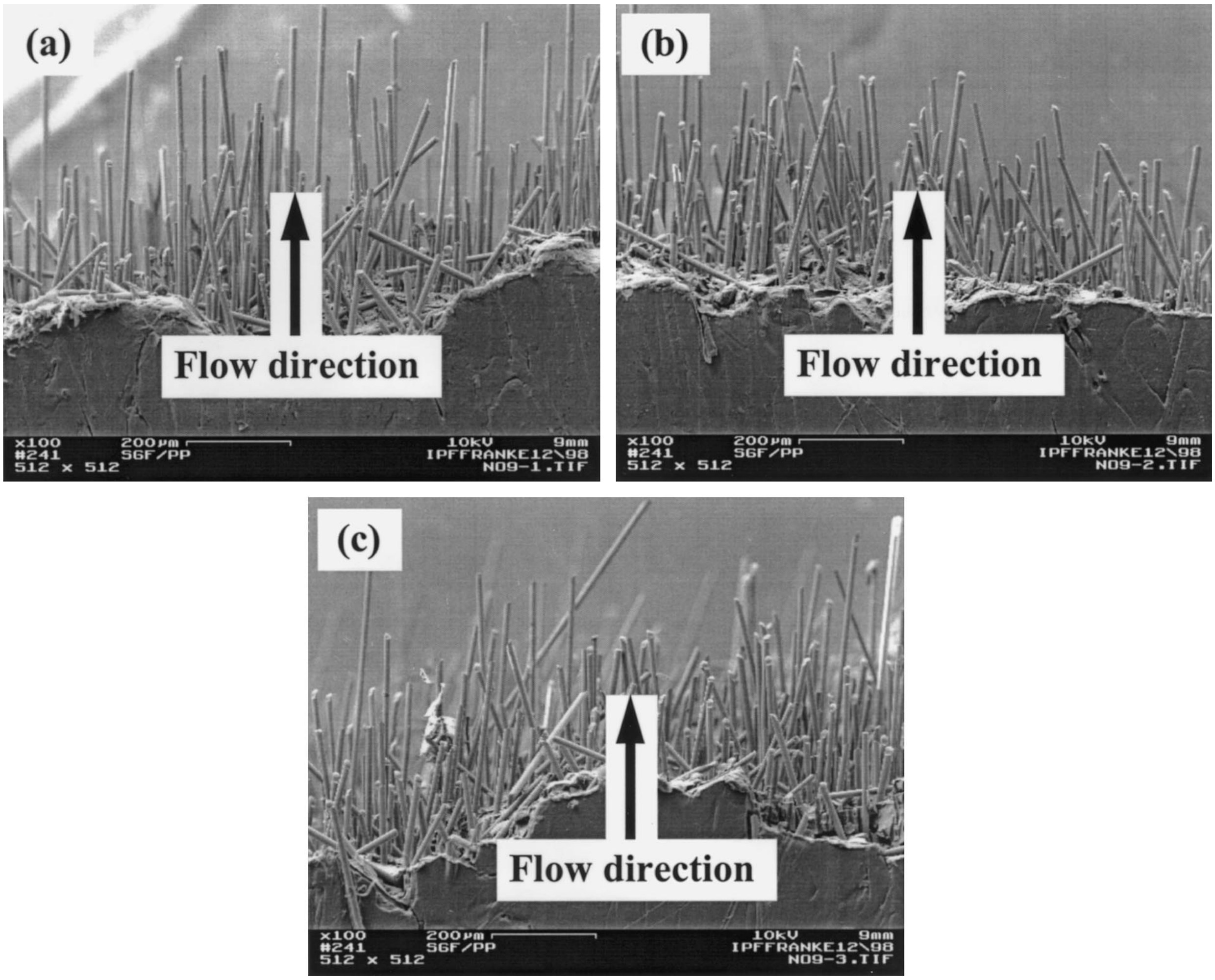

Fig. 8. SEM micrographs of tensile fracture surfaces of an SGF/PP composite with a glass fiber volume fraction of 8 vol%: (a) one side, (b) middle, (c) another side.

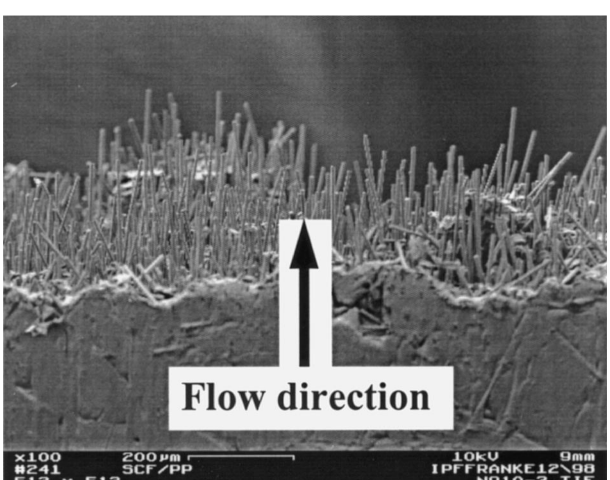

Fig. 9. SEM micrograph of tensile fracture surface of an SCF/PP composite with a carbon fiber volume fraction of 8 vol%.

effect on the composite strength shown in Fig. 10. Obviously, this indicates that the composite modulus is more dependent on fiber volume fraction and less dependent on fiber length than the composite strength does. In other words, the effect of mean fiber length on the modulus must be much smaller than that of fiber volume fraction.

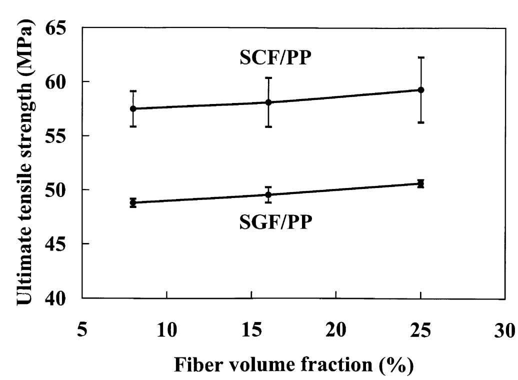

Fig. 10. Ultimate tensile strength versus fiber volume fraction for SGF/PP and SCF/PP composites.

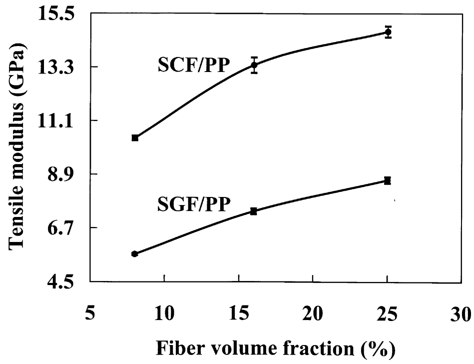

Fig. 11. Tensile modulus versus fiber volume fraction for SGF/PP and SCF/PP composites.

Otherwise, the combined effect of fiber volume fraction and mean fiber length would not lead to a dramatic increase in the composite modulus, namely the increase of the composite modulus caused by the increase of fiber volume fraction would be offset by the increase of the composite modulus caused by the decrease of mean fiber length. Moreover, it can be noted from Fig. 11 that the values of the modulus of SGF/PP composites are lower than those of SCF/PP composites. This is attributed to the fact that carbon fiber has a much higher modulus than glass fiber.

The tensile strength (σ_c) of SFRP composites can be predicted using the modified rule of mixtures equation [31]:

$$\sigma_c = \lambda_\sigma \sigma_{fu} V_f + \sigma_m (1 - V_f) \tag{4}$$

where λ_σ is the fiber efficiency factor for the composite strength taking into account the effects of fiber length and orientation. V_f is the fiber volume fraction. σ_m is the stress of the matrix at the failure of the composite.

Similarly, the tensile modulus (E_c) of SFRP composites can be predicted by the modified rule of mixtures equation [32]:

$$E_c = \lambda_E E_f V_f + E_m (1 - V_f) \tag{5}$$

where λ_E is the fiber efficiency factor for the composite modulus considering the effects of fiber length and orientation. E_f and E_m are the modulus of fiber and matrix, respectively.

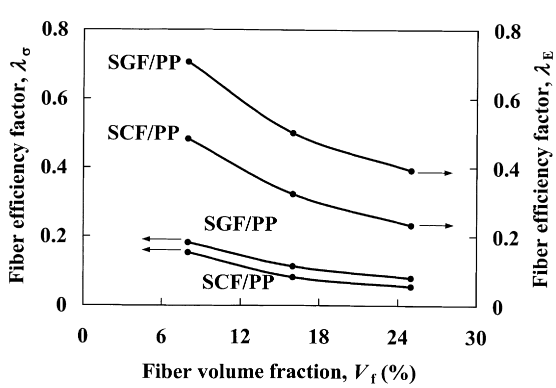

Fig. 12. Fiber efficiency factors for the strength and modulus of SGF/PP and SCF/PP composites as functions of fiber volume fraction.

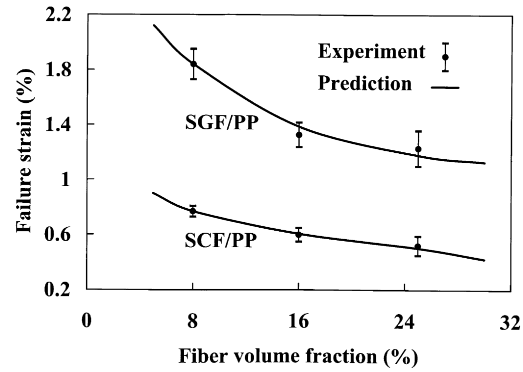

Fig. 13. Composite failure strain versus fiber volume fraction, where $C_s = 0.244$ and $0.208\ \text{mm}^{-1}$, respectively, for SGF/PP composites and SCF/PP composites.

For our cases, the change in fiber orientation can then be neglected since the fibers are preferentially aligned along the flow direction for all specimens and thus the change in fiber length would mainly affect the fiber efficiency factors.

Fig. 12 shows the fiber efficiency factors λ_σ and λ_E versus the fiber volume fraction V_f. It can be seen from Fig. 12 that the fiber efficiency factors decrease with increasing V_f and the factors for SGF/PP composites are higher than those for SCF/PP composites. This is because the fiber efficiency factors decrease with decreasing mean fiber length or mean fiber aspect ratio [31,32]. In addition, it can be easily found that the mean fiber aspect ratios for SGF/PP system are higher than those for SCF/PP system. Moreover, it can be seen that the fiber efficiency factor λ_σ for the strength is much lower than the fiber efficiency factor λ_E for the modulus. This is because the fiber efficiency factor λ_σ for the strength is dependent on both mean fiber length and critical fiber length while the mean fiber length (especially for carbon fiber) is much lower than the critical length and thus, this leads to a relatively low fiber efficiency factor λ_σ for the strength. On the other hand, the modulus is a property of material at low strain and is not very sensitive to the fiber–matrix interface or critical fiber length, so the fiber efficiency factor λ_E for the modulus is relatively high.

3.4.2. Failure strain

The failure strains of short-glass-fiber-reinforced PP composites and short-carbon-fiber-reinforced PP composites are exhibited in Fig. 13. It shows that as the fiber volume fraction increases, the composite failure strain decreases for both SGF/PP and SCF/PP composites. In addition, the failure strains of SGF/PP composites are higher than those of SCF/PP composites. The reduction in the failure strain is caused by an embrittlement effect as the stiffness of the composites is improved (see Fig. 11) when the fiber volume fraction is increased. The cause of this effect has been identified as matrix crack formation at the ends of the reinforcing fibers. Subsequently, as the strain is increased more cracks form progressively at the ends of shorter fibers. Initially this cracking can be accommodated by load transfer to adjacent fibers which "bridge" the cracked region. Final failure occurs when the extent of cracking across the weakest section of a specimen reaches a critical level when the surrounding fibers and matrix can no longer support the increasing load [20,24,37].

As stated above and in Section 1, the failure strain is closely related to fiber ends and thus the number of fiber ends. The number of fiber ends is proportional to fiber volume fraction and is inversely proportional to fiber length and square of fiber radius. The larger the number of fiber ends is, the smaller the failure strain is. So, we can write

$$\epsilon_c \propto \left(\frac{l_m r_f^2}{V_f} \right)^n \tag{6}$$

where n is a constant and will be found to be equal to 1/3. For a given fiber/matrix system, we can introduce a system constant C_S, which is related to fiber–matrix interface and properties of fiber and matrix, then we get

$$\epsilon_c = C_s \left(\frac{l_m r_f^2}{V_f} \right)^n \tag{7}$$

Obviously, both V_f and l_m determine the composite failure strain. As V_f increases, l_m decreases, so it is natural to observe the decrease in composite failure strain. When n is set at 1/3, the predicted results of the composite failure strain versus the fiber volume fraction are very close to the experimental ones for both SGF/PP and SCF/PP systems (see Fig. 13, where $C_s = 0.244$ and $0.208\ \mathrm{mm}^{-1}$, respectively, for SGF/PP and SCF/PP composites). Moreover, it can be easily certified that Eq. (7) also gives good prediction of the $\epsilon_c \sim V_f$ relations for other systems [2,5]. For simplicity, the predicted results are not presented here.

4. Conclusions

The tensile properties of injection molded PP composites reinforced with SGF and SCF have been investigated in detail. The results have shown that mean glass and carbon fiber lengths decrease with increasing fiber volume fractions and the combined effect of fiber volume fraction and fiber length determines the final tensile properties of the composites. Mean fiber length has been described as a function of fiber volume fraction using a proper exponential function with an offset. It has been shown that the composite strength is more dependent on mean fiber length or mean fiber aspect ratio than on fiber volume fraction while the composite modulus is more dependent on fiber volume fraction than on mean fiber length. The fiber efficiency factors, respectively, for composite strength and modulus have been studied for SGF/PP and SCF/PP composites. It was exhibited that the fiber efficiency factors for both strength and modulus decrease with increasing fiber volume fraction and the fiber efficiency factors for SGF/PP composites are higher than those for SCF/PP composites. Moreover, it was displayed that the fiber efficiency factor for composite strength is smaller than that for composite modulus. Finally, an empirical relationship of composite failure strain with fiber volume fraction, mean fiber length and fiber radius has been established.

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