Journal of Metals, Materials and Minerals. Vol.17 No.2 pp.9-16, 2007

Prediction of Tensile Strength for Sandwich Injection Molded Short-Glass-Fiber Reinforced Thermoplastics

Somjate PATCHARAPHUN[1*] and Gunter MENNIG[2]

[1] *Department of Materials Engineering, Faculty of Engineering, Kasetsart University, 10900 Bangkok, Thailand.*
[2] *Institute of Mechanical and Plastics Engineering, Chemnitz University of Technology, 09126 Chemnitz, Germany.*

Received Aug. 1, 2007
Accepted Sept. 19, 2007

Abstract

This present paper provides a modified rule-of-mixtures relationship which allows for the calculation of ultimate tensile strength (UTS) as a function of the area fraction between skin and core layers. The effects of fiber length and fiber orientation within the skin and core layers on the tensile strength of conventional and sandwich injection molded short-glass-fiber reinforced polypropylene have been studied in detail. The present theory is then applied to existing experimental results and the agreement is found to be satisfactory.

Key words : sandwich injection molding, short-fiber reinforced composites, tensile strength, fiber orientation distribution, fiber length distribution.

Introduction

The advantages conferred on polymeric matrices through short-fiber reinforcement are well established.(1-2) During the injection process of short-fiber molded articles, the distributions of fiber length and fiber orientation are governed by various factors. These include the original length and concentration of fibers, the mold design and the processing conditions.(3-6) It is well known that the mechanical properties of injection molded short-fiber composites depend critically on the fiber orientation, fiber length distribution and fiber dispersion in final products.(7-11) Tensile strength is one important property of engineering materials. One of the basic motivations for the use of composite materials as engineering materials is the high tensile strength that can be achieved by incorporating high strength fibers into a matrix since the fibers carry most of the load. Over the last decade, several theoretical models have been proposed in order to predict the modulus and strength of short-fiber composites. One is the laminate analogy, which combines the micro-mechanics of joining different phases with the macro-mechanics of lamination theory. The success of the laminate approximation is strongly dependent upon the assumption of physical volume averaging combined with an ability to estimate the properties of the individual plies, each of which contains uniaxially oriented fibers. This approach has been used successfully to predict strength, modulus, stress-strain behavior.(12-13) and flexural stiffness.(14) The other major approach is the modified rule of mixtures (MROM), which has been mostly used to predict the modulus and strength of short-fiber composite by taking into consideration the effects of fiber length and orientation distribution.(15-20) In general, all of the proposed methods have shown good agreement with experimental results. Although the laminate and MROM methods are usually used to estimate the strength for short-fiber composites, the procedures to estimate the strength of sandwich injection molded parts have not been established.

In this work, the model used for predicting the ultimate tensile strength (UTS) of sandwich injection molded part will be introduced. This predictive method is based on a MROM as a function of the area fraction between skin and core layers (so-called area fraction method). The advantage of this method over the traditional method is that the UTS of sandwich injection molded part, containing different fiber concentration between skin and core material, can be estimated. In order to take into account the influence of fiber length as well as fiber orientation, the fiber

Corresponding author: Dr.-Ing. Somjate Patcharaphun, E-Mail: fengsjpc@ku.ac.th

orientation efficiency factor(f_0) and fiber length efficiency factor (f_l) also can be accommodated.

Background

Microstructure of Conventional and Sandwich Injection Molded Short-fiber Composites

A typical result of fiber orientation in the injection molded short-fiber composites is shown in Figure 1. It can be seen that there are a number of distinct layers within the molding with different fiber alignments. In the skin layer, the fiber orientation is predominately parallel to the flow direction due to the elongational forces developed during fountain flow at the melt front as well as due to the shear flow after the front has passed. In contrast, a random-in-plane alignment of fibers is observed in the core layer due to slower cooling rate and lower shearing.[21]

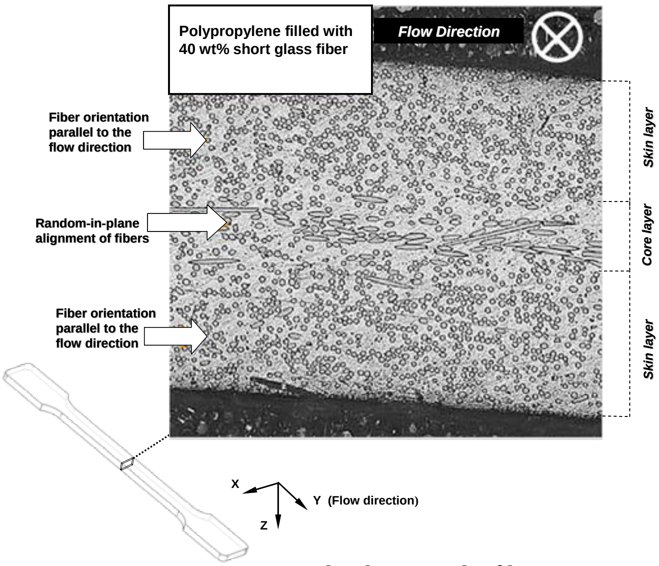

Figure 1. Optical micrographs showing the fiber orientation pattern at the cross-sectional (Z-X plane) area of injection molded short-fiber composites.

Recent work by Patcharaphun and Mennig[22] experimentally studied the fiber orientation distribution in the sandwich injection molded short-fiber composites. It was found that the fibers within the core layer are highly aligned parallel to the local flow direction compared to that of single injection molded parts. This is because the melt flow front of the first injected material develops a parabolic velocity profile. Near the mold wall, the fibers are generally aligned in flow direction due to the high velocity gradient. Prior to the skin material reaching the end of the cavity, the second material is injected to form the core. This material develops a second flow front pushing the skin material ahead of it. The velocity at the center of the core material is higher than the one at the skin flow front, as shown in Figure 2, because the first injected material solidifies as it comes into contact with the cold mold wall. The solidified skin material can act as the second mold wall inside the mold cavity, narrowing the flow channel. Therefore, the higher the velocity gradient of core material, the higher the fiber orientation in the core layer. This results in higher mechanical properties in the flow direction.

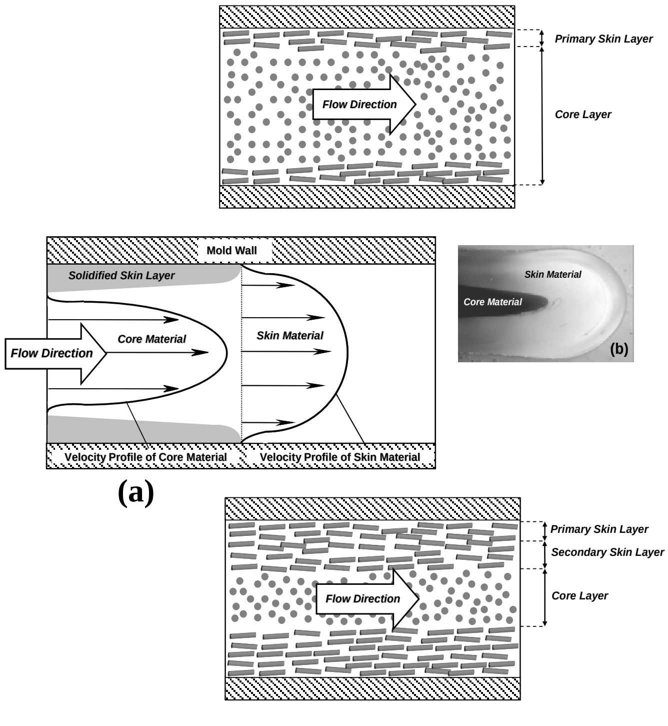

Figure 2. (a)Schematic fiber layer structure in sandwich injection-molded short-fiber reinforced thermoplastics across the thickness of part and (b) Polymer melt flow profile during sandwich injection molding.

Modified rule of Mixtures (MROM)

The modified rule of mixtures is often used to predict the tensile strength of short-fiber composites. The formula of MROM is given by

$$\sigma_{CU} = f_o \, f_l V_f \, \sigma_f + V_m \sigma_m \tag{1}$$

where σ_{CU} and σ_f are the ultimate strength of the composite and fiber, respectively; V_f and V_m denote the volume fraction of the fiber and matrix; σ_m is the stress developed in the matrix; f_o and f_l are the fiber orientation and fiber length efficiency factors, which depend on various parameters such as fiber volume fraction and processing conditions, and are only fitted empirically.(23) By using the Voigt average and dividing the reinforcement into groups of uniaxially aligned fibers, f_o is determined by

$$f_o = \sum_n a_n \cos^4 \varphi_n \tag{2}$$

where a_n is the proportion of fibers making an angle φ_n with respect to the applied load or flow direction. The efficiency of fiber reinforcement for several situations is presented in Table 1, this efficiency is taken to be unity for an oriented fiber composite in the alignment direction, and zero perpendicular to it.

Table 1. Reinforcement efficiency of fiber reinforced composites for several fiber orientations and at various directions of stress application [24]

Fiber Orientation	Stress Direction	Reinforcement Efficiency,(f_θ)
All Fibers parallel	Parallel to fibers Perpendicular to fibers	1 0
Fiber randomly and uniformly distributed within a specific plane	Any direction in the Plane of the fibers	3/8
Fiber randomly and Uniformly distributed within three-dimension in space	Any direction	1/5

If the fiber length (l) is uniform, the fiber length efficiency factor can be obtained from

$$f_l = \frac{l}{2l_c} \qquad \text{for } l < l_c \tag{3}$$

$$f_l = 1 - \frac{l_c}{2l} \qquad \text{for } l \geq l_c \tag{4}$$

where l_c is the critical minimum fiber length. This critical length is given by

$$l_c = \frac{\sigma_f \, d}{2\tau} \tag{5}$$

where d is the fiber's diameter and τ the interfacial shear strength between fiber and matrix. In the case of a strong interfacial bond, τ is limited by the shear strength of the matrix (τ_m). Assuming isotropy of the matrix this results in

$$\tau = \frac{\sigma_m}{\sqrt{3}} \tag{6}$$

If the fiber length is not uniform, the model can be given by

$$\sigma_{CU} = f_o\left[\sum_{l_i \langle l} \frac{V_f\,\sigma_f\,l_i}{2l_c}\right] + f_o\left[\sum_{l_i \rangle l_c} V_f\,\sigma_f\left(1 - \frac{l_c}{2l_i}\right)\right] + V_m\,\sigma_m \tag{7}$$

The first and second terms in this expression represent the contributions of the fiber's length as shorter and longer than l_c, respectively.

Area Fraction Method

The deviation of this model to predict the tensile strength of short-fiber composite can start with considering the total load sustained by the composite (F_C) being equal to the loads carried by longitudinal fibers and transverse (or random) fibers, which was proposed by Akay and Barkley(10) defined as

$$F_C = F_L + F_T \tag{8}$$

From the definition of stress $(F = \sigma A)$ and the expression for F_C, F_L and F_T in term of their respective stresses, the ultimate tensile strength of the composite (σ_{CU}) can be rewritten as:

$$\sigma_{CU}\,A_C = \sigma_{UL}\,A_L + \sigma_{UT}\,A_T \tag{9}$$

or

$$\sigma_{CU} = \sigma_{UL}\left(\frac{A_L}{A_C}\right) + \sigma_{UT}\left(\frac{A_T}{A_C}\right) \tag{10}$$

where $\frac{A_L}{A_C}$ is the area fraction between the skin region and the cross-sectional area of specimen; and $\frac{A_T}{A_C}$ is the area fraction between the core region and the cross-sectional area of specimen.

As to the UTS of the skin region, σ_{UL}, where the fibers near the part surface are generally aligned in the flow direction or tensile axis, is given by:

$$\sigma_{UL} = f_{0_{skin}}\left[\sum_{l_i < l} \frac{V_f\,\sigma_f\,l_i}{2l_c}\right] + f_{0_{skin}}\left[\sum_{l_i > l_c} V_f\,\sigma_f\left(1-\frac{l_c}{2l_i}\right)\right] + V_m\,\sigma_m \tag{11}$$

The UTS of the core region, σ_{UC}, where the fiber orientation is predominately transverse or random to the flow direction, this equation can be written as:

$$\sigma_{UT} = f_{0_{core}}\left[\sum_{l_i < l} \frac{V_f\,\sigma_f\,l_i}{2l_c}\right] + f_{0_{core}}\left[\sum_{l_i > l_c} V_f\,\sigma_f\left(1-\frac{l_c}{2l_i}\right)\right] + V_m\,\sigma_m \tag{12}$$

Therefore, the UTS of short-fiber reinforced composites (σ_{UC}) with respect to the effects of fiber length and fiber orientation can be evaluated using the following equation:

$$\begin{aligned}\sigma_{CU} = &\left[f_{0_{skin}}\left(\sum_{l_i < l} \frac{V_f\,\sigma_f\,l_i}{2l_c}\right) + f_{0_{skin}}\left(\sum_{l_i > l_c} V_f\,\sigma_f\left(1-\frac{l_c}{2l_i}\right)\right) + V_m\,\sigma_m\right]\left(\frac{A_L}{A_C}\right) + \\ &\left[f_{0_{core}}\left(\sum_{l_i < l_c} \frac{V_f\,\sigma_f\,l_i}{2l_c}\right) + f_{0_{core}}\left(\sum_{l_i > l_c} V_f\,\sigma_f\left(1-\frac{l_c}{2l_i}\right)\right) + V_m\,\sigma_m\right]\left(\frac{A_T}{A_C}\right)\end{aligned} \tag{13}$$

where $f_{0_{skin}}$ and $f_{0_{core}}$ are the fiber orientation efficiency factors for the skin and core layers, respectively. The schematic diagram of the cross-sectional area for conventional injection molded composites is depicted in Figure 3a.

Equation (13) can be expressed in terms of the UTS for the sandwich injection moldings as below:

$$\begin{aligned}\sigma_{CU} = &\left[f_{0_{skin}}\left(\sum_{l_i < l} \frac{V_f\,\sigma_f\,l_i}{2l_c}\right) + f_{0_{skin}}\left(\sum_{l_i > l_c} V_f\,\sigma_f\left(1-\frac{l_c}{2l_i}\right)\right) + V_m\,\sigma_m\right]\left(\frac{A_{skin}}{A_C}\right) + \\ &\left[f_{0_{core}}\left(\sum_{l_i < l_c} \frac{V_f\,\sigma_f\,l_i}{2l_c}\right) + f_{0_{core}}\left(\sum_{l_i > l_c} V_f\,\sigma_f\left(1-\frac{l_c}{2l_i}\right)\right) + V_m\,\sigma_m\right]\left(\frac{A_{core}}{A_C}\right)\end{aligned} \tag{14}$$

where A_{skin} and A_{core} are the cross-sectional areas of skin and core materials (see Figure 3b). Equation (13) can also be employed for sandwich injection molded composites, containing different fiber concentration between skin and core material (see Figure 3c). When the skin and core materials filled with 40 and 20 wt% of fiber, for example, the expression can be written as follows:

$$\begin{aligned}\sigma_{CU} = &\left[f_{0_{skin}}\left(\sum_{l_i < l} \frac{V_{f40}\,\sigma_f\,l_i}{2l_c}\right) + f_{0_{skin}}\left(\sum_{l_i > l_c} V_{f40}\,\sigma_f\left(1-\frac{l_c}{2l_i}\right)\right) + V_m\,\sigma_m\right]\left(\frac{A_{skin}}{A_C}\right) + \\ &\left[f_{0_{core}}\left(\sum_{l_i < l_c} \frac{V_{f20}\,\sigma_f\,l_i}{2l_c}\right) + f_{0_{core}}\left(\sum_{l_i > l_c} V_{f20}\,\sigma_f\left(1-\frac{l_c}{2l_i}\right)\right) + V_m\,\sigma_m\right]\left(\frac{A_{core}}{A_C}\right) + \\ &\left[f_{0_{sub.core}}\left(\sum_{l_i < l_c} \frac{V_{f20}\,\sigma_f\,l_i}{2l_c}\right) + f_{0_{sub.core}}\left(\sum_{l_i > l_c} V_{f20}\,\sigma_f\left(1-\frac{l_c}{2l_i}\right)\right) + V_m\,\sigma_m\right]\left(\frac{A_T}{A_C}\right)\end{aligned} \tag{15}$$

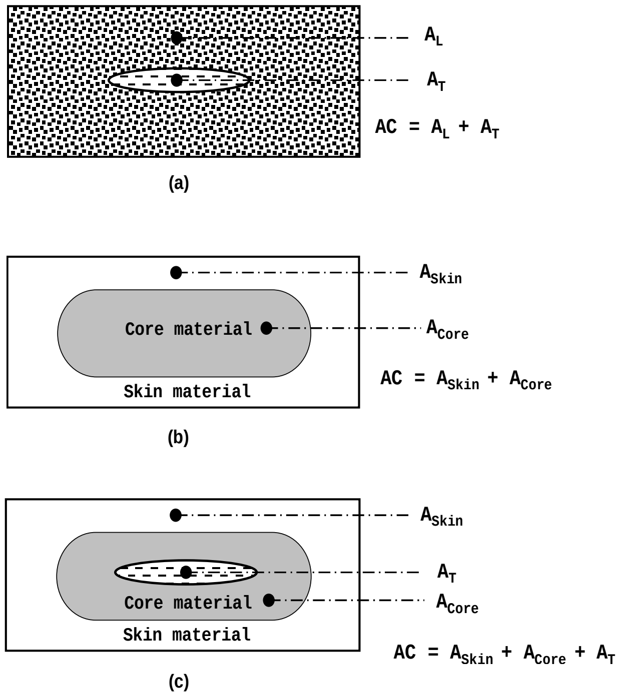

Figure 3. Schematic illustration of the cross-sectional area indicating the skin and core regions: (a) conventional injection molded short-fiber composite, (b) Sandwich injection molded part, and (c) Sandwich injection molded short-fiber composite.

Experimental

The materials used in this study were unfilled polypropylene (PP-H 1100 L), marketed by TARGOR (Germany), and polypropylene filled with 20 and 40 wt% short-glass-fiber (PP32G10-0 and PP34G10-9) supplied in granular form by BUNA (Germany). The test specimens (dumbbell shape) were molded using an ARBURG ALLROUNDER two-component injection molding machine (Model: 320S 500-350), which can be employed for both conventional and sandwich injection molding. The processing parameters used for single and sandwich injection moldings are summarized in Tables 2 and the experimental nomenclatures used for conventional and sandwich molded parts containing different short-glass-fiber contents between skin and core materials are given in Table 3. The details concerning the fiber orientation analysis can be obtained from previous work.[22]

Table 2. Processing parameters

Processing Parameters	Single Molding	Sandwich Molding	
		1st-Injection Unit	2st-Injection Unit
Injection Pressure (bar)	1000	1000	1000
Holding Pressure (bar)	800	-	800
Holding Time (sec)	25	-	25
Back Pressure (bar)	20	20	20
Cooling Time (sec)	40	-	40
Injection Flow Rate (ccm/s)	18.5	18.5	8.8
Screw Speed (m/min)	12	12	12
Injection Volume (ccm), (%)	37(100%)	14.8(40%)	22.2(60%)

Table 3. Experimental nomenclatures

No.	Single Molding		Sample Code
1	PP		PP
2	PP+SGF 20 wt%		SFRPP 20
3	PP+SGF 40 wt%		SFRPP 40
	Sandwich Molding		Sample Code
	Skin Material	Core Material	(Skin/Core)
4	PP+SGF 20 wt%	PP	SFRPP20/PP
5	PP	PP+SGF 20 wt%	PP/SFRPP20
6	PP+SGF 20 wt%	PP+SGF 20 wt%	SFRPP20/SFRPP20
7	PP+SGF 40 wt%	PP	SFRPP40/PP
8	PP	PP+SGF 40 wt%	PP/SFRPP40
9	PP+SGF 40 wt%	PP+SGF 20 wt%	SFRPP40/SFRPP20
10	PP+SGF 40 wt%	PP+SGF 40 wt%	SFRPP40/SFRPP40

The molded tensile specimens were tested on Zwick 1464 mechanical tester at a crosshead speed of 5 mm/min for a sample gage length of 50 mm (DIN EN ISO 527). For each molding condition, five dumbbell-shaped specimens were tested and the average values of the maximum tensile stress were used for analysis. Polarized light microscopy (OLYMPUS model PMG3) and computer aided image analysis (a4i Analysis version 5.1 and Image-Pro Plus) were utilized in order to investigate the area fraction between skin and core region. For the investigation of fiber lengths within the skin and core layer, the microtome technique was employed in order to separate the skin and core layers. Short-glass-fibers were isolated from the composite materials by using an incineration method according to DIN EN 60. Magnified fiber images were then digitized semi-automatically with the help of Image-Pro Plus software running on a personal computer. The fiber length distribution (FLD) was determined as the average fiber length ($\overline{\mu}$) which was calculated from a minimum of 500 length measurements on fibers recovered from the incineration of the specimen sections.

Results and Discussion

The purpose of developing a theoretical model is to explain and predict the experimental results. Additionally, the theoretical model should also allow verification by the existing experimental results. As described in section 2, the critical fiber length (l_c) and the interfacial shear strength between fiber and matrix (τ) can be calculated by Equations (5) and (6) for a composite system if the fiber length distribution, the fiber diameter (d) and the matrix strength (σ_m) are given. The required parameters for predicting the strength of short-fiber reinforced composites are supplied in Tables 4. Since the fiber volume fraction (V_f), the average fiber length ($\overline{\mu}$), the matrix strength (σ_m) and the area fraction between skin and core layer (A_{Skin}/A_{Core}) have been given experimentally, the predicted values of UTS for the conventional and sandwich injection molded composites can be estimated following Equations (13) to (15). The theoretically calculated results, together with the experimentally determined UTS are shown in Figure 4. It can be seen that the model predictions show a reasonable agreement with the experimental values. The calculated results indicate that the UTS increases with the increase of fiber volume fraction (SFRPP20 and SFRPP40) and the UTS of PP sandwich injected with glass fiber reinforced PP (PP/SFRPP and SFRPP/PP) are at an intermediate level between those of PP and glass fiber reinforced PP alone. In addition the predicted results show that the UTS of sandwich injection moldings (SFRPP20/SFRPP20 and SFRPP40/SFRPP40) are higher than that of single injection moldings (SFRPP20 and SFRPP40). This is due to a higher degree of fiber orientation within the core layer (or a higher area fraction of skin layer, $\frac{A_L}{A_C}$) of sandwich injection molded composites,[22] though the fiber length distributions within the core layer of the sandwich moldings are slightly lower than the values obtained for the single injection moldings. However, it should be noted that the predicted UTS results are still higher than experimental ones. The reasons for this are twofold. Firstly, the parameters used in the calculation (σ_f and τ) are given by various independent methods from literature.[24, 25] The conditions of the tests may be different, which would lead to an error in the calculation. It is observed in Equations (2) to (5) that all the orientation measures are independent of the fiber strength. Only the fiber length efficiency factor (f_l) depends on the fiber strength, which is the value known with the least degree of accuracy. Therefore, if σ_f is not known with sufficient accuracy, the absolute value of f_l may be inaccurate. Secondly, the errors may arise due to the consideration of the uniform fiber alignment, flaw-free molding, and both the longitudinal and transverse layers experience the same strain, whereas these assumptions are difficult to obtain in thermoplastic composites.

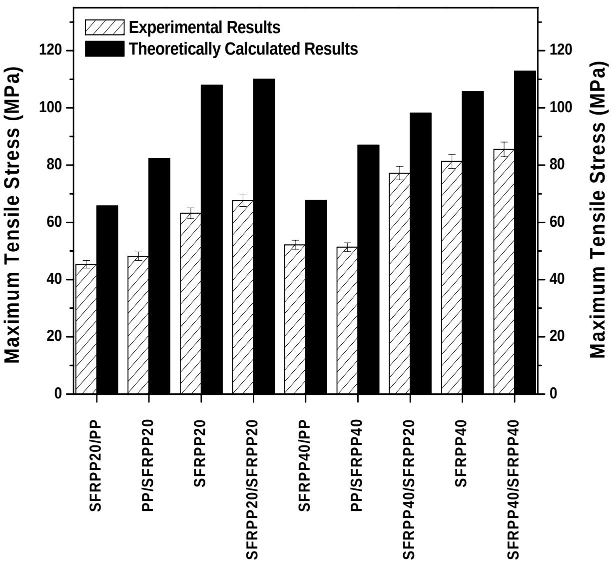

Figure 4. Comparison of experimental and theoretically Calculated UTS results for conventional and sandwich injection molded short-glass-fiber reinforced polypropylene.

Table 4. Parameters used in the theoretical calculation of UTS for single and sandwich injection molded composites

Parameters	Samples									Source
	SFRPP20/PP	PP/SFRPP20	SFRPP20	SFRPP20/SFRPP20	SFRPP40/PP	PP/SFRPP40	SFRPP40/SFRPP20	SFRPP40/SFRPP40	SFRPP40	
σ_m (MPa)	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	Measurement
τ (MPa)	16.45	16.45	16.45	16.45	16.45	16.45	16.45	16.45	16.45	Calculated [24]
σ_f (MPa)	3450	3450	3450	3450	3450	3450	3450	3450	3450	[25]
d (μm)	12	12	12	12	12	12	12	12	12	Measurement
l_c (μm)	1258.36	1258.36	1258.36	1258.36	1258.36	1258.36	1258.36	1258.36	1258.36	Calculated [24]
V_f	0.2	0.2	0.2	0.2	0.4	0.4	0.4/0.2	0.4	0.4	Measurement
V_m	0.8	0.8	0.8	0.8	0.6	0.6	0.6/0.8	0.6	0.6	Measurement
A_L/A_C	-	-	0.913	0.965	-	-	-	0.938	0.834	Measurement
A_T/A_C	-	0.04	0.087	0.035	–	0.063	0.055	0.062	0.166	Measurement
A_{Skin}/A_C	0.44	0.42	-	-	0.41	0.42	0.42	-	-	Measurement
A_{Core}/A_C	0.56	0.54	-	-	0.59	0.517	0.525	-	-	Measurement
μ_{Skin} (μm)	344.05	-	333.04	332.73	190.68	-	193.19	183.15	184.38	Measurement
μ_{Core} (μm)	-	379.81	375.65	370.93	-	224.24	373.68	230.95	232.22	Measurement

Conclusions

In this work the tensile strength of conventional and sandwich injection molded short-fiber composites is derived by an analytical method of modified rule-of-mixtures relationship as a function of the area fraction between skin and core layers. The effects of fiber length and fiber orientation on the UTS have been studied in detail. This model provides the necessary information to determine what fiber length distribution and what fiber orientation distribution are required to achieve a desired composite strength. It should be noted that the predicted results are still higher than the measured ones. This may result from some parameters and assumptions made in the derivation of the equations, which would lead to an error in the calculations.

Acknowledgments

The authors would like to thank TARGOR GmbH and BUNA GmbH, Germany, for the cost-free supply of materials. Financial support from the Faculty of Engineering, Kasetsart University, Thailand, is gratefully acknowledged.

References

1. Bailey, R.S. 1994. Conventional thermoplastics. In : *Handbook of Polymer-Fiber Composites, Polymer Science and Technology Series.* New York : Longman Scientific & Technical.

2. Clegg, D.W. 1994. Recycling of polymer composites. In : *Handbook of Polymer-Fiber Composites, Polymer Science and Technology Series*. New York : Longman Scientific & Technical.

3. Singh, P. and Kamal, M.R. 1989. The effect of processing variables on microstructure of injection molded short-fiber reinforced polypropylene composites. *Polym. Compos.* **10(5)** : 344-351.

4. Gupta, V. B., Mittal, R. K., Sharma, P. K., Mennig, G. and Wolters, J. 1989. Some studies on glass-fiber-reinforced polypropylene; Part I : reduction in fiber length during processing. *Polym.Compos*. **10(1)** : 8-15.

5. Tancrez, J-P., Pabiot, J. and Rietsch, F. 1996. Damage and fracture mechanisms in thermoplastic-matrix composites in relation to processing and structural parameters. *Compos. Sci. Technol*. **56** : 725-731.

6. Barbosa, S.E. and Kenny, J.M. 1999. Analysis of the relationship between processing conditions-fiber orientation-final properties in short-fiber reinforced polypropylene. *J. Reinf. Plast. Compos.* **18(5)** : 413-420.

7. Akay, M. and Barkley, D. 1985. Processing-structure-property interaction in injection molded glass-fiber-reinforced poly-propylene. *Compos. Struct*. **3** : 269-293.

8. Gupta, V.B., Mittal, R.K., Scharma, P K., Mennig, G. and Wolters, J. 1989. Some studies on glass-fiber-reinforced polypropylene; Part II: mechanical properties and their dependence on fiber length, interfacial adhesion, and fiber dispersion. *Polym. Compos*. **10(1)** : 16-27.

9. Franzen, B., Klason, C., Kubat, J. and Kitano, T. 1989. Fiber degradation during processing of short-fiber reinforced thermoplastics, Composites. **20(1)** : 65-76.

10. Akay, M. and Barkley, D. 1991. Fiber orientation and mechanical behavior in reinforced thermoplastic injection moldings. *J. Mater. Sci.* **26(10)** : 2731-2742.

11. Chin-Ping, Fung, Hwang, J.R. and Hsu, C.C. 2003. The effect of injection molding process parameters on the tensile properties of short-glass-fiber reinforced PBT. *Polym.-Plast. Technol. Eng*. **41(1)** : 45-63.

12. Halpin, J.C. and Kardos, J.L. (1978). Strength of discontinuous reinforced composites: Fiber reinforced composites. *Polym. Eng. Sci*. **18(6)** : 496-504.

13. Kardos, J.L. and Halpin, J.C. 1999. Short predicting the strength and toughness of fiber composites. *Macromol. Symp.* **147** : 139-153.

14. Xia, M., Hamada, H. and Maekawa, Z. 1995. Flexural stiffness of injection molded glass fiber reinforced thermoplastics. *Int. Polym. Process*. **10(1)** : 74-81.

15. Fukuda, H. and Chou, T.W. 1982. A probabilitistic theory of the strength of short-fiber composites with variable fiber length and orientation. *J. Mater. Sci*. **17(4)** : 1003-1011.

16. Templeton, P.A. (1990). Strength predictions of injection molding compounds. *J. Reinf. Plast. Compos.* **9(3)** : 210-225.

17. Fu, S.Y. and Lauke, B. 1996. Effects of fiber length and fiber orientation distributions on the tensile strength of short-fiber reinforced polymers. *Compos. Sci. Technol.* **56(10)** : 1179-1190.

18. Fu, S.Y. and Lauke, B. 1998. The elastic modulus of misaligned short-fiber reinforced polymers. *Compos. Sci. Technol.* **58(3-4)** : 389-400.

19. Van Hattum, F.W.J. and Bernardo, C.A. 1999. A model to predict the strength of short-fiber composites. *Polym. Compos*. **20(4)** : 524-533.

20. Thomason, J.L. 2002. Micromechanical parameters from macromechanical measurements on glass reinforced polypropylene. *Compos. Sci. Technol.* **62(10-11)** : 1455-1468.

21. Bay, R.S. and Tucker, C.L. III 1992. Fiber orientation in simple injection molding, Part 1: Theory and numerical methods. *Polym. Compos*. **13(4)** : 332-341.

22. Patcharaphun, S. and Mennig, G. 2005. Properties enhancement of short-glass-fiber reinforced thermoplastics via sandwich injection molding. *Polym. Compos.* **26(6)** : 823-831.

23. Denault, J., Vu-Khanh, T. and Foster, B. 1989. Tensile properties of injection molded long fiber thermoplastic composites. *Polym. Compos.* **10(5)** : 313-321.

24. Miles, I.S. and Rostami, S. 1992. *Multicomponent Polymer Systems, Polymer Science and Technology Sires.* New York : Longman Scientific & Technical.

25. Lee, S. M. 1992 . *Handbook of Composite Reinforcements.* New York : VCH Publishers.