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Interfacial shear strength of glass fiber reinforced polymer composites by the modified rule of mixture and Kelly-Tyson model

Rutchaneekorn Wongpajan[a]*, Suchalinee Mathurosemontri[a], Ryo Takematsu[a], Hu Yong Xu[a], Putinun Uawongsuwan[b], Supaphorn Thumsorn[a], Hiroyuki Hamada[a]

[a]*Kyoto Institute of Technology, Kyoto 606-8585, Japan*
[b]*King Mongkut's University of Technology North Bangkok, Bangkok 10800, Thailand*

Abstract

Four types of commercial grade glass fiber reinforced thermoplastics (GFRP) were used in this study. Polymer matrices included polycarbonate (PC), polyoxymethylene (POM), polypropylene (PP) and polyamide 6 (PA6). The contents of GF were 10%, 20% and 40%. The GFRP were fabricated to dumbbell specimens by injection molding machine. Tensile strength of the GFRP composites was carried out by tensile testing. Theoritical caluculation of interfacial shear strenght was analyzed using a modified rule of hybrid maixture (MRoHM) strength equation according to the orientation and direction of glass fiber reinforcing. The fiber orientation was characterized from the fractured surface observation by scanning electron microscope and optical microscope. The tensile strength of GFRP composites increased with incresing glass fiber contents. However, the declination of tensile strength from the prediction was attributed to the reduction of glass fibers length and fiber orientation in GFRP composites. It is interesting to report that the interfacial shear strength of GFRP composites was calulated according to the MroHM and the Kelly-Tyson model, which the interfacial shear strength of the composites increased with incresing glass fiber contents.

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Keywords: Fiber orientation, Fiber length, prediction, tensile strength

* Corresponding author. Tel.: +81-75-724-7844; fax: +81-75-724-7844
E-mail address: cussu_think@hotmail.com

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1. Introduction

The most important property of short fiber reinforced polymer composites is tensile strength. Several parameters, which control the strength of composite, can be affected by the type and conditions of the fabrication processes. For short fiber reinforced thermoplastic injection molding is the most popular fabrication process because of the high production efficiency [1-4].

The injection-molded process for short fiber reinforced composites has quite complex fiber orientation distributions that vary both through the thickness and at different positions along the composite molding. Fiber orientation can be strongly influenced by processing condition, mold geometry and specimen geometry. Preferentially oriented fiber does not mean the perfect alignment and there should be a fiber orientation distribution with a small average angle of the fibers with the flow direction [1, 5].

It is very important to be able to predict the mechanical properties of a short fiber reinforced composite given the component properties, their geometric size and arrangement. The suitable analytical modeling will not only help in interpreting the experimental results but also optimizing specific applications in many sectors. Moreover, the composite mechanical properties can be inferred with no need of conducting long experiments. Over the last decade, several theoretical models have been proposed in order to predict the strength of short fiber reinforced composites (SFRP). One of the major approaches is the modified rule of mixtures (MRoM), which has been mostly used by taking into consideration the effects of fiber length and orientation distribution. The properties of a hybrid composite depend on the fiber content, fibers length, orientation of fibers, extent of intermingling of fibers, fiber to matrix interface, layering pattern of both fibers and also dependent on the failure strain of individual fibers [5-11].

In this study, aims to develop and validate a predictive capability for tensile strength of short fiber reinforced polymer composites to enable strength predictions in injection molded components. The short glass fiber reinforced polymer composites were made four type have polycarbonate, polyoxymethylene, polypropylene and polyamide were prepared by injection molding of long fiber pellet. The analytical model used for predicting the tensile strength of hybrid injection molded composite will be introduced. The predictive method is based on a modified rule of hybrid mixture (MRoHM) as function of fiber orientation direction, fiber length distribution and tensile strength of the composites are discussed.

2. Theoretical prediction

Tensile strength is one of the most important properties of engineering materials. The important motivation for using composite materials as a class of engineering materials is their high tensile strength that can be achieved by incorporating high strength fibers into polymer matrix. A composite works by taking an applied stress and distributing it on the matrix and predominately, on its reinforcing fibers. It is important to be able to predict the tensile strength of short fiber reinforced polymer composites by using the given component properties, their geometric size and fiber arrangement. The rules of mixture for predicting tensile strength of composite (σ_c^u) can be defined as following equation.

$$\sigma_c^u = V_f \sigma_f + V_m \sigma_m \quad (1)$$

The modified rule of mixtures (MRoM) is also often used to predict the tensile strength of short fiber reinforced composites by assuming a perfect bonding between fibers and matrix. Then equation (1) will be modified as

$$\sigma_c^u = f_o f_l V_f \sigma_f + V_m \sigma_m \quad (2)$$

The well-known Kelly-Tyson model considering the effect of fibers with shorter (sub-critical) and longer (super-critical) than the critical fiber length is given as

$$\sigma_c^u = \sum_{l_i=l_{min}}^{l_c} \frac{l_i}{2l_c} \sigma_f V_{f,i} + \sum_{l_j=l_c}^{l_{max}} \left[1 - \frac{l_c}{2l_j}\right] \sigma_f V_{f,j} + \sigma_m V_m \quad (3)$$

The tensile strength of short fiber reinforced polymers composites depends critically on the fiber orientation, fiber length distribution and fiber dispersion in the final products. Fiber orientation can be measured using an image analyzer system. The direct measurement of the elliptical parameters of each fiber allows the fiber orientation distribution to be measured. The fiber orientation efficiency factor (f_0) can be determined by using the following equation

$$f_o = \sum_n a_n cos^4 \theta_n \quad (4)$$

Where a_n the proportion of fibers making an angle θ_n with respect to the flow direction. Thus the Equation (3) can be modified as the modified Kelly-Tyson model as

$$\sigma_c^u = f_o \left(\sum_{l_i=l_{min}}^{l_c} \frac{l_i}{2l_c} \sigma_f V_{f,i} + \sum_{l_j=l_c}^{l_{max}} \left[1 - \frac{l_c}{2l_j} \right] \sigma_f V_{f,j} \right) + \sigma_m V_m \quad (5)$$

The spatial position of a fiber can be defined by the two Euler angles θ as shown in Fig. 1. θ is defined as the angle that the fiber makes with the injection direction of the plane on which the fiber orientation will be measured. However, the preparation of a specimen for inspection requires the polishing of composites specimen, which is time-consuming process. In this study, the direct observation of fracture surface from SEM micrograph was proposed as the simple method for determines the fiber orientation.

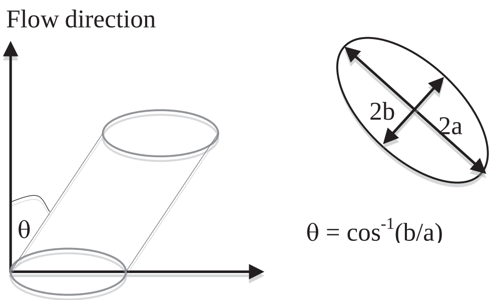

Fig. 1. Determination of the fiber orientation angles θ.

The first and second terms are contributions from fibers with sub-critical length shorter than l_c and fibers with super-critical length longer than l_c, respectively.

The mechanical properties of shot fiber reinforced polymers composites depend on the fiber length distribution (FLD) and the fiber orientation distribution (FOD) in final composite parts. The effects of fiber length distribution on tensile strength of SFRP composites can be described based on the stress build up on different fiber length. The critical fiber length (l_c) is defined as the minimum fiber length necessary to build up the axial fiber stress to the maximum strength of the fiber (σ_f^u) at fiber ends. The variation of fiber axial stress with fiber length for the three cases of $l<l_c$, $l=l_c$ and $l>l_c$. By assuming that the profile of linear stress variation from two fibers ends results from the constant interfacial shear stress (τ), the l_c can be calculated by the following equation

$$l_c = \frac{r_f \sigma_f^u}{\tau} \quad (6)$$

Where τ is interfacial shear stress between fiber and matrix and r_f is fiber radius.

3. Experimental

Glass fiber reinforced thermoplastic resins included polycarbonate (GF-PC) (Grade GSH2020R2 and GSH2040R2), polyoxymethylene (GF-POM) (Grade F40-03 and FG2020) and polyamide 6 (GF-PA6) (Grade 1012F and 1091) were supported by Mitsubishi Engineering Plastics Co., Ltd., Japan. Glass fiber reinforced polypropylene (GF-PP) (Grade J-2012GR and R-250G) was from Prime Polymer Co., Ltd., Japan. The properties of material of composites using for tensile strength calculation are shown in Table 1. Various contents of glass fiber reinforced polymer and specimen designations are tabulated in Table 2. The pellets were dried in an oven at 80 °C for 8 hours before fabricated to dumbbell specimens by injection molding machine (POYUEN UM50, China).

Table 1. Properties of materials of glass fiber reinforced composites.

Polymer matrix	Strength of matrix (MPa)	Strength of glass fiber (MPa)	Diameter of glass fiber (mm)
PC	61	1,500	0.016
POM	56		0.015
PP	27		0.018
PA6	82		0.014

Table 2. Glass fiber contents and specimen designations.

Glass fibers reinforced composite	Code
(PC)(Glass20%)	GFPC20%
(PC)(Glass40%)	GFPC40%
(POM)(Glass10%)	GFPOM10%
(POM)(Glass20%)	GFPOM20%
(PP)(Glass10%)	GFPP10%
(PP)(Glass20%)	GFPP20%
(PA6)(Glass20%)	GFPA620%
(PA6)(Glass40%)	GFPA640%

3.1. Tensile test

Tensile tests was carried out by Instorn universal testing machine (Instron model 4206) with a testing speed of 1 mm/min and a grip distance of 115 mm in accordanced with ASTM D638.

3.2. Scanning electro microscopy

Scanning electron microscopie (SEM:JSM 5200, JEOL, Japan) was conducted to analyze the fiber orientation. The fractured surface of the tensile specimens was mounted on copper stubs and gold coated to avoid electrical charging during examination.

3.3. Fiber length analysis

The specimen was burnt in a furnace at 600 °C for 6 hours to remove the matrix. The remaining fibers were dispersed on a glass slide and examined under an optical microscope. The image analysis software (Image J) was used to measure and record lengths of fibers around 2000 lines counted for each sample ply.

3.4. Fiber orientation analysis

The surface of the specimen was fine polished. The optical microscope and the Image J analysis software were used to examine the pattern of fiber orientation on the specimen surface.

4. Result and discussion

Fig. 2 shows tensile strength of various glass fiber content of glass fiber reinforced polymer composites. It is clearly observed that the presence of glass fiber content increased tensile strength of the composites with regarding to the fiber contents. Tensile strength values of GFRP composites were used for calculated the critical fiber length (l_c) according to equation (5).

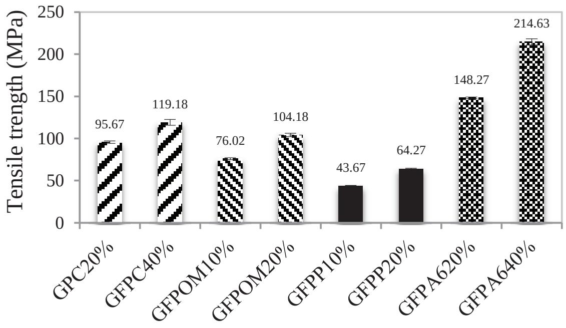

Fig. 2. Tensile strength of glass fiber reinforced composites

4.1. Fiber length analysis

Fig. 3 presents histograms of fiber length distribution of the GFRP composites. The average fibers length decreased with increasing glass fibers contents. It can be indicated that the increasing of glass fiber contents in each kind of matrix of GFRP composites led to a larger damage of glass fiber length, especially at high glass fiber contents, which was due to higher fiber-fiber interaction. Furthermore, the fiber length distribution curves of glass fiber reinforced composite became narrower with increasing of glass fiber content as compared to the lower contents of glass fiber.

4.2. Fiber orientation analysis

The fiber orientation efficiency factor (f_o) of glass fiber reinforced composites was calculated from equation (4). The fiber orientation factor is plotted in Fig. 4. The glass fiber reinforcement effect is obtained in the case of fibers flow direction aligned to the flow direction during processing, which was affected on the tensile strength of the composites. The tensile strength increased as the glass fiber orientation factor increased. From the results, it can be obrerved that the fiber orientation of glass fiber reinforced composites increased as fiber length distribution decreased. It was considered that short glass fibers can be moved along the flow direction better than long fibers.

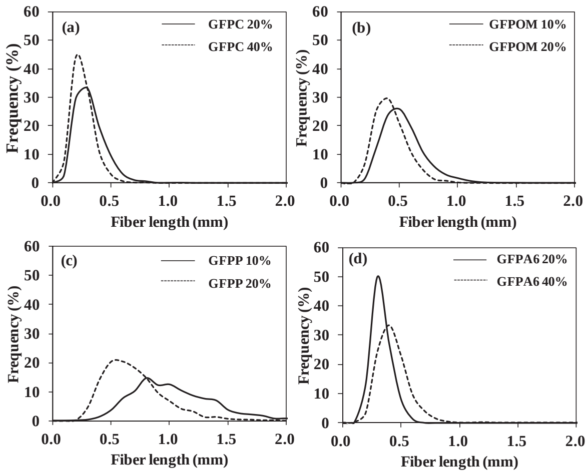

Fig. 3. Fiber length distribution and the number average length of glass fibers reinforced composites (a) PC, (b) POM, (c) PP, (d)PA6.

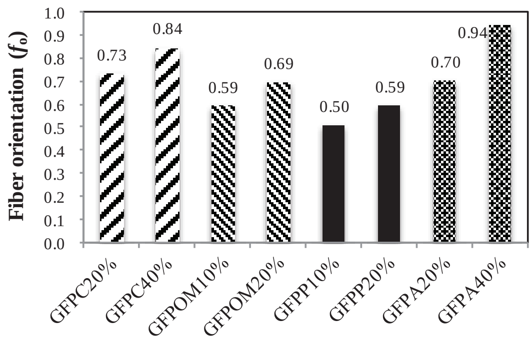

Fig. 4. Fiber orientation factor of each resin.

Figure 5 shows the fracture surface of glass fiber reinforced polymer composites with different polymer matrices (a) PC, (b) POM, (c) PP and (d) PA6 found that the surface of the fiber. matrix is stuck to the skin, demonstrating force collaboration between the matrix and glass fiber.

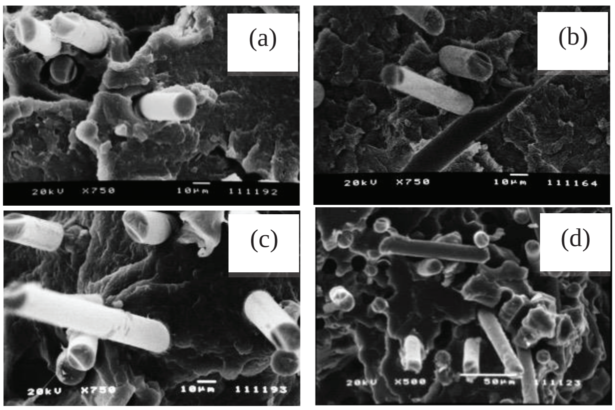

Fig. 5. SEM photographs of fractured surface (a) GFPC20%, (b) GFPOM20%, (c) GFPP20% and (d) GFPA620%.

4.3. Calculation of interfacial strength

The critical fiber length of the glass fiber was calculated by using several fiber orientation factors, which calculated from equation (5). It can be seen that interfacial shear strength agrees well with the experimental result. The interfacial strengths calculeted from equation (6) are summarized in Table 2. The fiber orientation and fiber distribution of glass fiber are strongly depended on the volume fraction of fibers. The interfacial shear strength will be found to comply with the tensile strength. However The average interfacial shear strength values in the range 2-10% error, which may occur in the measurement of the observation.

Table 3. Fiber critical length and interfacial shear strength of glass fiber reinforced polymer composites..

Specimens	lc (mm)	Interfacial shear strength (MPa)
		Theoritical calcultion
GFPC20%	0.34	35.29
GFPC40%	0.31	38.70
GFPOM10%	0.51	21.22
GFPOM20%	0.42	26.78
GFPP10%	0.59	22.87
GFPP20%	0.54	24.77
GF PA620%	0.20	48.42
GF PA640%	0.30	33.54

5. Conclusions

The effect of fiber length distribution and fiber orientation of glass fiber reinforced thermoplastic composites was described. Tensile strength of glass fiber reinforced composites increased as the glass fiber contents increased. The short glass fibers can be moved along the flow direction better than the long fibers. The tensile strength calculated according to the Kelly-Tyson analysis is also used for predicted the interfacial shear strength of short fibers reinforced composites.

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