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ScienceDirect
Energy Procedia 89 (2016) 255 – 263
Energy Procedia

CoE on Sustainable Energy System (Thai-Japan), Faculty of Engineering, Rajamangala University of Technology Thanyaburi (RMUTT), Thailand

The effect of processing parameter on mechanical properties of short glass fiber reinforced polyoxymethylene composite by direct fiber feeding injection molding process

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Abstract

This research describes the effect of processing parameters as matrix feeding speed, screw rotational speed and cylinder temperature of direct fiber feeding injection-molded process on properties of short glass fiber reinforced polyoxymethylene composite. The increasing of matrix feeding speed at screw rotational speed of 172 rpm led to the reduction of fiber loading content and increasing of fiber length. Whereas the higher screw rotational speed impacted on the increasing of fiber loading content and fiber length. However, its tensile properties were lower than the molded at screw rotational speed 172 rpm. When fiber loading content over 20 wt.%, tensile strength of both conditions reached the same values because the poor fiber distribution especially at screw rotational speed of 258 rpm. Then Kelly – Tyson's equation was used to predict their tensile strength. It was found that tensile strength at maximum fiber loading content at screw rotational speed of 172 rpm and 258 rpm are lower than the calculated strength values around 28.9 % and 31.8 %, respectively. The effect of cylinder temperature was also elucidated.

Peer-review under responsibility of the organizing committee of the 12th EMSES 2015

Keywords: Polyoxymethylene; Short glass fiber; Direct fiber feeding; Injection molding; Kelly-Tyson

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Peer-review under responsibility of the organizing committee of the 12th EMSES 2015
doi:10.1016/j.egypro.2016.05.033

1. Introduction

Polyoxymethylene (POM) is an engineering thermoplastic, which exhibits good-balance mechanical properties, good creep resistance, excellent thermal stability during molding, low friction coefficient and excellent anti-wear properties [1]-[3]. However, the incorporation of glass fiber into POM can improve its mechanical properties. Nowadays POM and POM composite are used to replace zinc and other metals, which is a part of automobile and machinery. The short glass fiber has been used to reinforce thermoplastic composites. By using this kind of fiber, there are many factors that impact on the mechanical properties of the final products such as interfacial adhesion, fiber length, orientation and distribution, which are determined by the bonding of materials and processing conditions [4]-[8].

In order to reduce fiber breakage problem that has a direct affected on mechanical properties of composite during the molded process. The reduction of fiber length decreases the reinfircing efficiency of fiber [9]-[11]. The original manufacturing was modified to a convenient technique, which has been called a direct fiber feeding (DFF) injection molded process. The short fiber reinforced composite material can be fabricated without the compounded process. The fiber can be guided into the vented area of injection barrel and directly fed into the polymer melt by the shearing motion of injection screw during plasticization process.

The processing parameters of direct fiber feeding injection molding precess as matrix feeding speed (MFS), screw rotational process and cylinder temperature were studied on their effects of fiber length, fiber oreintation, fiber distribution and mechanical properties. The modified Kelly – Tyson's equation was used to calculate fiber critical length and predict tensile strength of GF/POM composite.

2. Experimental

2.1. Materials

The main polymer matrix is POM co-polymer, which was obtained from Mitsubishi Engineering Plastic Co, Ltd., Japan under the trade name of Lupital F40-02. Density of POM co-polymer is 1.41g/cm^3 and melt flow index is 52 g/10 min. Glass fiber grade EX-1658 with 2400 tex, 0.40 wt.% sizing agent for polycarbonate was manufactured by Nippon electric glass Co., Ltd., Japan was selected as reinforcing fiber. The strength of glass fiber is 1,500 MPa.

2.2. Specimen preparation

The dumbbell specimens were carried out through the direct fiber feeding (DFF) technique by 18-tons injection molding machine (Sumitomo: model iM18) with vented barrel. The schematic drawing of DFF injection molding process are shown in Fig.1. Glass fiber roving strand was guided into the vent of devolatilizing unit of the barrel and fed into the melt by the shearing action of the injection screw during plasticization process. Furthermore, the normal feeding hopper of injection molding machine was replaced with the controllable feeding hopper in order to control the fed amount of matrix. The processing conditions as matrix feeding speed, screw rotational speed and cylinder temperature were varied to study their effect on properties of composite materials as shown in Table 1.

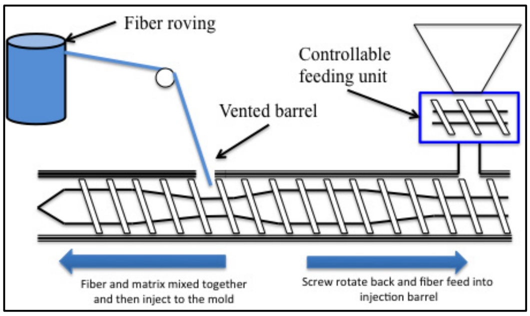


Fig. 1. The schematic drawing of DFF injection molding process.

Table 1. Processing parameters.

<table>
<tr><th rowspan="2">Screw rotational speed (rpm)</th><th rowspan="2">Matrix feeding speed (rpm)</th><th colspan="5">Cylinder temperature (°C) (Nozzle → Hopper)</th><th rowspan="2">Mold temperature (°C)</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th></tr>
<tr><td rowspan="3">172</td><td>40</td><td rowspan="5">200</td><td rowspan="5">190</td><td rowspan="5">180</td><td rowspan="4">170</td><td rowspan="4">170</td><td rowspan="6">40</td></tr>
<tr><td>60</td></tr>
<tr><td>80</td></tr>
<tr><td rowspan="3">258</td><td>40</td></tr>
<tr><td>60</td><td>190</td><td>190</td></tr>
<tr><td>80</td><td>200</td><td>190</td><td>180</td><td>240</td><td>240</td></tr>
</table>

2.3. Mechanical testing

Tensile testing was carried out by an Instron universal testing machine (Instron model 4206) at a crosshead speed of 1 mm/min, according to ASTM D638. At least five specimens were test for each condition.

2.4. Scanning electron microscopy

The fracture surface of tensile testing samples were observed by scanning electron microscope (JEOL : model JSM 5200). The specimens were fixed on aluminum holder and gold sputtered for 6 minutes prior observation.

2.5. Fiber loading content and fiber length determination

The middle part of specimen was cut and burned out in the furnace for 6 hr under the temperature of 600 ^{o}C. The remained glass fiber were measured a weigh and cast on glass slide and observed by optical microscope in order to obtain the distribution of fiber length. The number average fiber length was defined by equation (1)

$$L_n = \frac{\Sigma N_i L_i}{\Sigma N_i} \quad (1)$$

Where N_i is number of fiber at the length L_i

2.6. Fiber orientation measurement

Cross section of dumbbell specimens were cut and polished. After that these polished surfaces were observed by optical microscope for all area in order to measure the angle θ, which is defined as the angle a fiber makes with the flow direction [5]. Fig.2 shows a Definition and determination of the fiber orientation angle θ. through the composite. The orientation of the fiber can define with respect to this section plane by the angle θ_n, which is given by the inverse cosine oft he ratio of the semiminor axis b of this ellipse, to the semimajor axis a as show in equation (2).

$$\theta_n = cos^{-1}(\frac{b}{a}) \quad (2)$$

Then fiber orientation factor [12] can calculate by equation (3).

$$f_0 = a_n cos^4 \theta_n \quad (3)$$

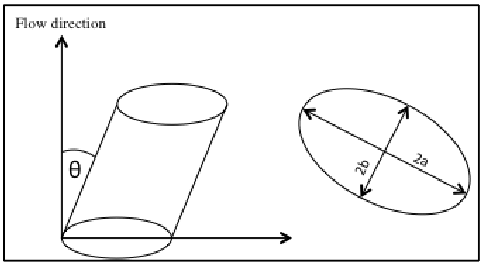


Fig. 2. Definition and determination of the fiber orientation angle θ.

2.7. Critical fiber length determination

The critical fiber length (l_c) of glass fiber reinforced POM/PLA blend composites were calculated by using the modified Kelly – Tyson`s equation [12] that was define by equation (4).

$$\sigma_c^u = f_0[\sum_{l_i=l_{min}}^{l_c}\left(\frac{l_i}{2l_c}\right)\sigma_F^u V_i + \sum_{l_j=l_c}^{l_{max}}\left(1-\frac{l_c}{2l_j}\right)\sigma_F^u V_j] + \sigma_M V_M \quad (4)$$

Where f_0 is fiber orientation efficiency factor, V_i and V_j are volume fraction of fibers of length l_i and l_j, respectively. i and j are subscript and superscript of fiber. σ_F^u is the fiber strength, σ_M is the matrix strength at the fiber failure strain, and V_M is volume fraction of matrix. Moreover, this equation was also used for tensile strength predictionof GF/POM composite material.

3. Results and discussion

3.1. Effect of screw rotational speed and matrix feeding speed on fiber loading content and fiber length distribution

Glass fiber loading content and number average fiber length of GF/POM composites are shown in Table 2. The maximum and minimum fiber loading contents are 36.2 and 11.5 wt.%, respectively. The increasing of MFS led to the deceasing of fiber loading content of both low and high SRS. The using of high SRS shows higher fiber loading content when compare with low screw rotational speed.

However, the increasing of screw rotational speed has affected on the fiber length as well. At 40 and 60 rpm feeding speed, the fiber lengths are longer and almost unchanged at feeding speed of 80 rpm. The higher amount of fiber loading content impacted the fiber breakage when using low feeding speed.

Table 2. Fiber loading content and number average fiber length of GF/POM composite.

Screw rotational speed (rpm)	Matrix feeding speed (rpm)	Fiber loading content (wt.%)	L_n (mm)
172	40	34.1	0.458
	60	20.9	0.597
	80	11.5	0.604
258	40	36.2	0.634
	60	23.3	0.791
	80	13.4	0.628

3.2. Effect of screw rotational speed and matrix feeding speed on mechanical properties

Table 3 shows mechanical properties of GF/POM composite at screw rotational speed of 172 rpm and 258 rpm. At screw rotational speed of 172 rpm, tensile modulus increased with the decreasing of matrix feeding speed because the effect of fiber loading content. Tensile strength also increase until the fiber contents are over 25 wt.%.

In the case of screw rotational speed 258 rpm, its tensile modulus and strength indicate the lower results hen compare with 172 rpm. For tensile modulus, there is only the lowest fiber content that shows the increasing of tensile modulus when screw rotational speed was increased.

Table 3. Fiber loading content and number average fiber length of GF/POM composite.

Screw rotational speed (rpm)	Matrix feeding speed (rpm)	Tensile modulus (GPa)	Tensile strength (MPa)	L_n (mm)
172	40	10.62	70.25	0.458
	60	8.81	70.29	0.597
	80	6.62	63.28	0.604
258	40	9.79	61.56	0.634
	60	8.14	60.29	0.791
	80	6.92	57.82	0.628

As the results show no increase/decrease significantly in tensile strength at matrix feeding speed 40 and 60 rpm, the fiber orientation and fiber distribution are considered the influence of them on the mechanical properties by the observation of SEM micrographs. In general the tensile strength of fiber reinforced composite materials is weak when fibers align in the transverse direction of applied load. It is clear that the glass fiber at feeding speed 40 and 60 rpm (Fig. 3 (c) – (f)) of both screw rotational speed show low directed in the load direction when compared to the fracture surface of GF/POM composited at feeding speed of 80 rpm in Fig. 3 (a) and (b). Moreover, a poor fiber distribution is observed. They reveal an aggregation of glass fiber when matrix feeding speed decreased. They also show the increasing of aggregation when screw rotational speed increased that is a reason of the decreasing of tensile strength when screw rotational speed increased. In other word, the high screw rotational speed has an effect on the dispersion of glass fiber in POM matrix.

As shown in Fig.4, it was clear that facture surface of good fiber dispersion (Fig. 4(a)) and poor fiber dispersion (Fig.4(b)) show the difference of matrix deformation. Matrix deformed as a brittle facture when fiber indicated good dispersion because the melted resin could flow throughout fiber easily. That led to the high efficient transference of applied load from matrix to fiber. While the melted resin could not flow throughout fiber if they still aggregated in the bundle. That impacted on the reduction of load transferable efficiency as the wetting behavior of matrix that shows in Fig.4 (b).

3.3. Strength prediction of GF/POM composite by using modified kelly-tyson's equation

In order to predict tensile strength of composite material, there are many factors that were required including volume fraction of fiber, fiber orientation factor and critical fiber length. Thus, the GF/POM composites, which have the fiber loading content of 11.5 and 13.4 wt.% that were molded by screw rotational speed of 172 rpm and 258 rpm, respectively, were selected to study. Their V_f, L_n, f_0 and l_c value are shown in Table 4. As mentioned before, tensile strength of GF/POM at 172 rpm is higher than the result of 258 rpm because of a better fiber distribution, which were observed by SEM micrographs. Those results were clearly supported by fiber orientation factor. At 172 rpm, its f_0 is higher than 258 rpm. Nevertheless, its l_c is shorter than 258 rpm.

The results of experimental strength at screw rotational speed of 178 rpm and 258 rpm are compared to the calculated strength as shown in Fig.5 and Fig.6, respectively. The calculated strength at172 rpm and 285 rpm are extremely increase when compare at the maximum fiber loading content. Their calculated strength are higher than experimental strength around 18.9% and 31.8% for 172 rpm and 258 rpm. The reinforcing efficiency that was calculated from trend line of tensile strength was used to support the poor reinforcing efficiency of GF/POM composite especially at 258 rpm. The reinforcing efficiency of the calculated and experimental strength at 172 rpm is 1.304 and 1.144, respectively. Whereas the reinforcing efficiency of the calculated and experimental strength at 258 rpm is obviously lower than 172 rpm as 0.970 and 0.627, respectively.

To improve the tensile properties of this composite material, the clear defect that appear in SEM photographs as mention before revealed poor dispersion of glass fiber. Thus, the poorest sample, which was fabricated by using the screw rotational speed of 258 rpm was selected to improve the distribution of glass fiber by vary the cylinder temperature.

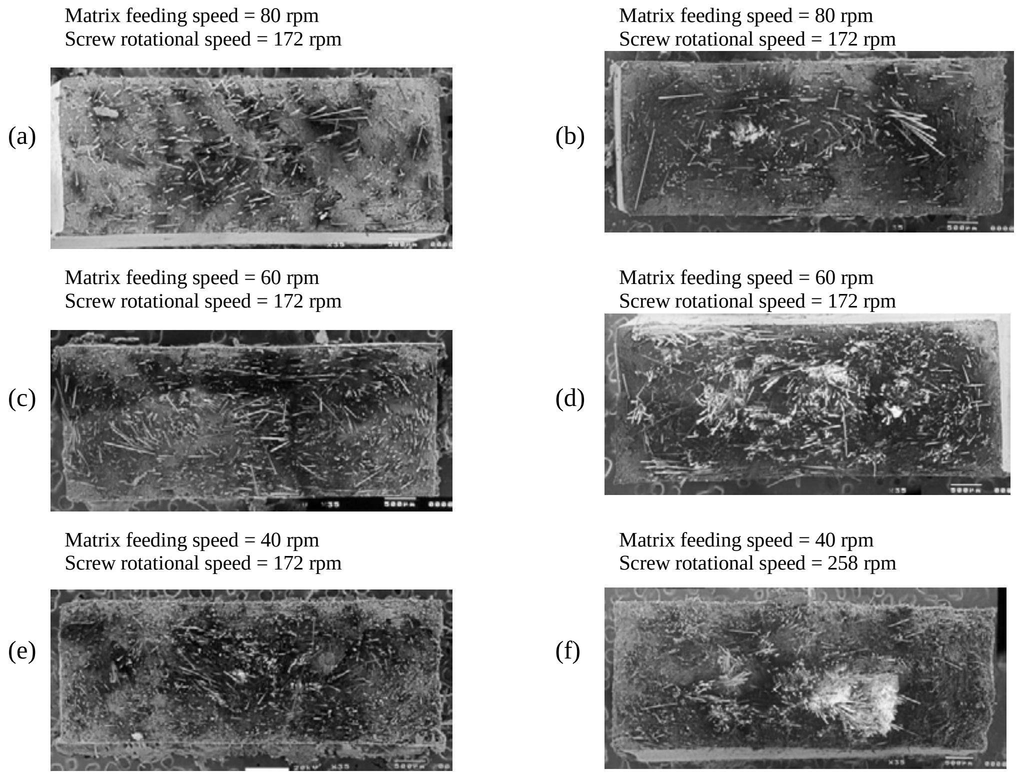


Fig. 3. SEM micrograph of GF/POM composites with different matrix feeding speed and screw rotational speed.

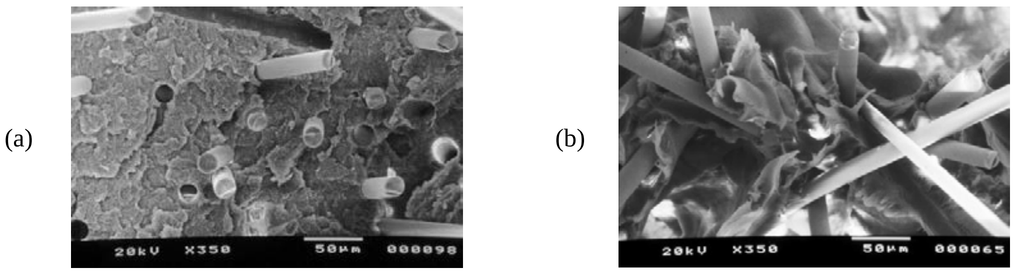


Fig. 4. SEM micrographs of GF/POM composite at high magnification (a) normal fiber distribution area and (b) poor fiber distribution area.

Table 4. Comparison of tensile strength factors between screw rotational speed of 172 rpm and 258 rpm.

Screw rotational speed (rpm)	Wt.%	V_f (%)	σ_C (MPa)	L_n (mm)	f_0	L_c (mm)
172	11.5	6.8	63.3	0.604	0.75	1.048
258	13.4	7.9	57.8	0.628	0.68	1.550

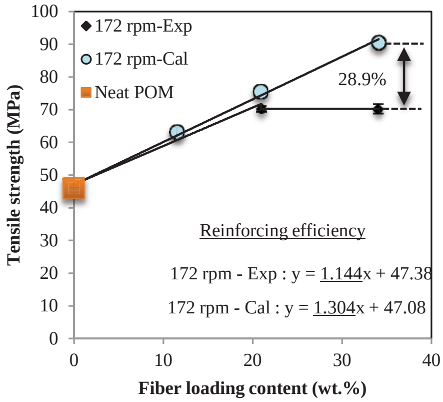


Fig. 5. Comparison of calculated and experimental strength of GF/POM composite at 172 rpm.

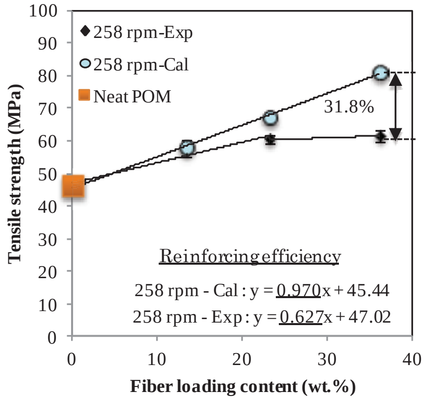


Fig. 6. Comparison of calculated and experimental strength of GF/POM composite at 258 rpm.

3.4. The improvement of fiber distribution of gf/pom composite by using high cylinder temperature

The cylinder temperature of direct injection molded machine were varied from 170 °C to 190 °C and 240 °C at zone 4 and 5. The increasing of cylinder temperature did not impact on fiber length of GF/POM composite, although high processing temperature has an influence on the reduction of viscosity of polymer as shown in Fig.7. The fiber distribution curves of 170 °C, 190 °C and 240 °C show the L_n value in range of 0.49 – 0.63 mm.

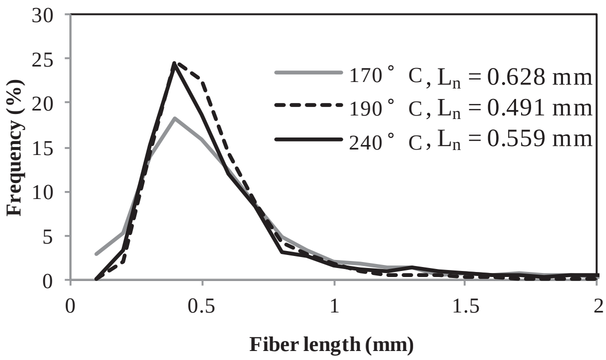


Fig. 7. Fiber length distribution curve of GF/POM composite at different cylinder temperature.

Fig.8 show tensile strength of composite materials at differrent cylinder temparatures those were compared with the calculated strength. Tensile strength increase with increasing of cylinder temperature around 11.9 % at 240 °C. However, the maximum strength is still lower than the calculated strength around 17%. The fiber distribution of glass fiber can be confirmed by polished surface images and marked images of 170 °C and 240 °C in Fig.9 and 10, respectively. It was clear that the fabrication of GF/POM composite at 170 °C reveals the aggregation of glass fiber in a wide area when compared to the cylinder temperature at 240 °C, which indicate a small area of glass fiber bundle. However, the low viscosity of matrix that was affected from higher temperature impacted to spreaded out of fiber to skin area.

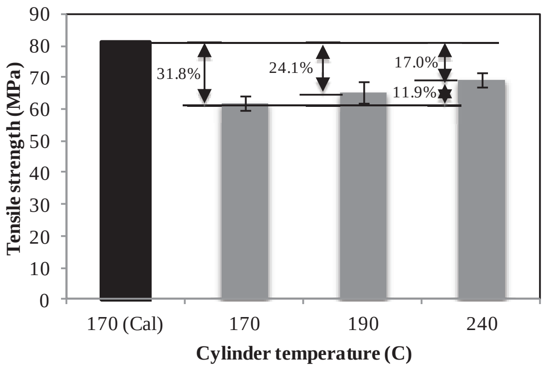


Fig. 8. Tensile strength of GF/POM composite at different cylinder temperature.

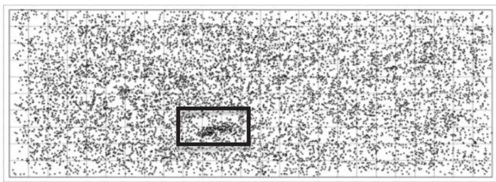
(a)  (b) 

Fig. 9. Cross section image of GF/POM composite at cylinder temperature of 170 °C (a) Polished surface image and (b) Marked image.

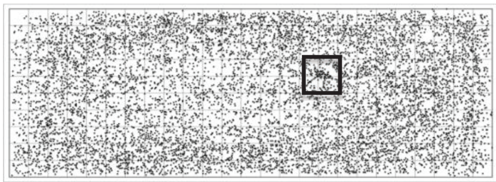
(a)  (b) 

Fig. 10. Cross section image of GF/POM composite at cylinder temperature of 240 °C (a) Polished surface image and (b) Marked image.

4. Conclusion

GF/POM composite was fabricated by direction injection molding technique. The increasing of matrix feeding speed affected the decreasing of fiber loading content. That directly affected on the increasing of fiber length. The increasing of screw rorational speed has an influence on the increasing of fiber loading content and fiber length. Tensile properties of GF/POM composite increased with the increasing of fiber loading content. The higher screw rotational speed showed the declination of tensile properties but at high fiber loading content, tensile strength of both screw rotational speeds were low because poor fiber distribution. However, the defect can be improved by increasing the cylinder temperature.

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