A Study on the Analysis and Prediction of the Anisotropy of Injection Molded GF/PA66

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Abstract. In recent years, short glass fiber reinforced PA66 composites (GF/PA) have been considered to be certain significant to promote the development of "automotive lightweight". At current study, the mechanical properties of injection molded GF/PA were investigated both in axial and off-axis directions. In addition, the fiber volume fraction (vf) and the residual length as well as the distribution of glass fiber (GF) after injection molding were investigated particularly to evaluate the interfacial property based on SEM observation and Kelly-Tyson model equation. It is found that the composites have a trend with a slight increase in the critical fiber length and decreased interfacial shear strength with an increase of vf.

1. Introduction

Researchers have shown that reducing vehicle weight is the most effective way to save energy today: a 1/10 reduction in vehicle weight increases the fuel efficiency by 6% to 8% [1]. So that Plastic and fiber reinforced plastics were realized in application in vehicles instead of metallic parts [2-3].

In recent decades, researchers have done a lot of researches on the mechanical properties of injection molded GF/PA. Thomason et al. [4] reported that the notched impact strength of injection-molded GF/PA composite samples would be affected by fiber length and content. M. De Monte et al. [5] studied the anisotropy of injection molded PA66-GF35 at room temperature (23°C) and high temperature (130°C) under pull-down pressure and cyclic loading. Shao-Yun Fu [6] studied the joint effect of fiber average length and fiber content on the mechanical properties of the material, and gave the empirical equation of failure strain on the influence parameters. Researchers found that in addition to the strength of glass fiber and PA66 itself, the main factors affecting the performance of GF/PA include the ratio of length to diameter, mass fraction, length distribution, orientation distribution of glass fiber, and the interface between PA66 resin and glass fiber [7].

The objective of this work was to study the off-axis mechanical properties of injection molded GF/PA66 composites. The effects of fiber orientation angles, fiber lengths, glass fiber contents on the mechanical properties of the composites were investigated. Prediction and discussion on the off-axis mechanical properties of composites were carried out.
2. Experiments
The materials used in this project were provided by Shanghai Key point Quality Inspection Technology Service Co., Ltd. The materials tested are GF35/PA66 and GF50/PA66, short glass fiber reinforced composites with glass fiber mass fraction of 35% and 50%, respectively which were prepared by injection molding. The molded plate GF/PA has a size with a width of 150 mm, a length of 220 mm and a thickness of 4 mm. The melt flow direction is shown in Figure 1a. According to the ISO standard, the specimens required for the mechanical test were cut out in the 0°, 30°, 45°, 60° and 90° directions on the sample plate, as shown in Figure 1b.

The tensile tests were carried out in accordance with the ISO-527.2-2012 standard on an Instron (55R 4206, Instron Co., Ltd., USA) at least 5 times for each type and the cross-section of the damaged specimen were observed by scanning electron microscopy (SEM).

The fractured specimen after the tensile test was cut into three-part sample sections (Figure 2). The SEM observation of the fracture section test, $v_f$ and the fiber length distribution test, and the fiber orientation distribution test were carried out. The $v_f$ of No. 2 part of the failed sample as shown in Figure 2 was determined. In details, the damaged sample section  was placed in a dry crucible, and then placed in a muffle furnace and baked at 600 ºC for 6 hours. The difference of mass before and after burning test was used to do the calculation of $v_f$ of GF. The length of the fiber was measured by means of an optical microscope (VAB-100-1), PS software (Adobe Photoshop CC 2015.5), and ImageJ (Image J v1.8.0) software. In the test, the weight average length was chosen as the average residual fiber length $L_w$. The testing process of fiber orientation factor $f_0$ the damaged sample section  is shown in figure 3. The fiber orientation factor $f_0$ is calculated with the equation (1,2).

$$\theta_n = \cos^{-1} \frac{b}{a} \quad (1)$$
$$f_0 = \sum a_n \cos^4 \theta_n \quad (2)$$

Where, $\theta_n$ is the angle between the axial direction of the fiber and the flow direction of the melt. $a$ is long axis of the ellipse, and $b$ is short axis of the ellipse. $a_n$ is the ratio of the number of fibers at an angle $\theta_n$.

3. Discussion
The off-axis tensile stress-strain curves were shown in Figures 4. The tensile modulus of GF50 / PA66 is significantly higher than that of GF35 / PA66 in each off-axis sample. It indicates that the content of GF has a certain influence on the tensile modulus of the composite. However, there is no significant increase in the tensile strength of the material, indicating that there are other factors affected the reinforcement in tensile strength. The tensile modulus and tensile strength of GF/PA66 composites decrease rapidly with the off-axis angle increasing from 0° to 30°. When the off-axis angle is bigger than 45°, the tensile modulus and tensile strength of the material tend to be stable no matter of the increasing of off-axis angle further more. The difference in tensile properties of the samples with different off-axis angles indicates that the injection molded short glass fiber reinforced PA66 matrix composite exhibit anisotropic mechanical properties, and the anisotropic mechanical properties is considered because of the multi-effects with orientation of the glass fibers in the injection direction as well as the distribution relative to the impregnation situation and interfacial strength.
Figure 1. The cutting direction of samples.

Figure 2. Cutting diagram of failed specimen.

Figure 3. Determination of fiber orientation.

Figure 4. Tensile stress-strain curves of GF35/PA66 and GF50/PA66.

The fracture sections of tested GF35/PA66 and GF50/PA66 tensile samples were observed by SEM at 35 times and 1000 times at 15.0 kV, as shown in Figures 5 and 6. Obviously, samples with different off-axis angles have significantly different alignment directions as shown in Figures 5 and 6 (a, c, e). From Figures 5 and 6 (b, d, f), it can be seen that the surface of the drawn fiber is covered with resin, indicating that the fiber has good hygroscopicity, which has a positive effect to the mechanical properties of the material.

The values of $v_f$ of GF in the GF35/PA66 and GF50/PA66 composites are 19.63% and 31.01%, respectively, according to the measurements in burning tests.

It can be seen from the Figure 7 that the length of glass fiber in GF35/PA66 and GF50/PA66 is mainly distributed at 0.20 mm and 0.15 mm. The average fiber lengths are 0.26mm (GF35/PA66) and 0.24mm (GF50/PA66), respectively. Compared to the original length of the glass fiber (1 mm), the residual fiber average length of GF35/PA66 and GF50/PA66 after injection molding decreased by 74% and 76%. Therefore, the injection molding process resulted in a significant reduction in glass fiber length.

As shown in Figure 8, the orientation factor decreases as the off-axis angle of the fiber increases; when the off-axis angle is the same, the increase in the fiber content leads to an increase in the orientation factor of the fiber slightly. As mentioned in the fiber length measurement test, the weight average fiber length of GF50/PA66 is similar or a little shorter than that of GF35/PA66, therefore it is considered that short fibers are more likely to be arranged along the flow direction of the melt than long fibers.
4. Calculation and prediction of mechanical properties

The strength of the interface bond strength is related to the strength of the energy transfer between the interfaces [8]. The calculation equation of the interface shear strength $\tau_f$ is as shown in equation (3).

$$\tau_f = \frac{\sigma_f d}{2l_c}$$  \hspace{1cm} (3)

Where $\sigma_f$ and $d$ is the tensile breaking strength and the diameter of the fiber, respectively, and $l_c$ is the critical fiber length. In this test, $\sigma_f = 1500$ MPa and $d = 13.8$ μm are known. The value of the critical fiber length $l_c$ can be obtained by the modified Kelly-Tyson model equation (4) [9].

$$\sigma_c = f_0 \sigma_f \left[ \left( \sum_{i=l_{min}}^{l_c} \left( \frac{l_i}{2l_c} \right) \nu_{f,i} \right) + \left( \sum_{i=l_{max}}^{l_c} \left( 1 - \frac{l_c}{2l_f} \right) \nu_{f,j} \right) + \sigma_m (1 - \nu_f) \right]$$  \hspace{1cm} (4)

$\sigma_c$ is the ultimate tensile strength of the composite, $\sigma_m$ is the ultimate tensile strength of the resin, $f_0$ is the fiber orientation factor, $V_f$ is the fiber volume fraction, $l_i$ and $l_j$ are the fiber lengths shorter than and longer than the $l_c$ part, respectively. The parameter values obtained by the test are brought into the equation to obtain the theoretical value of the interfacial shear strength, as listed in Table 1.

It is thought that an increase in the $\nu_f$ brought a necessity of larger value for the critical fiber length and a reduced interface shearing strength. Therefore, the tensile strength of GF50/PA66 material is not significantly improved compared to GF35/PA66 material.
This test only predicted for GF35/PA66 composites. According to the previous test, the following engineering parameters were obtained. The engineering elastic constants of GF35/PA66 are listed in Table 2.

For anisotropic elastic materials, the tensile modulus in tension satisfies the following equation [10]:

\[
\frac{1}{E_\theta} = \frac{m^4}{E_L} + \left(\frac{1 - 2\nu}{G}\right) m^2 n^2 + \frac{n^4}{E_T} \tag{5}
\]

Where \(m\) and \(n\) are the cosine \(\cos \theta\) and sine \(\sin \theta\) of the off-axis angle of the sample, \(E_\theta\) is the initial tensile modulus, \(E_L\) and \(E_T\) are the tensile modulus of the 0° sample and the 90° sample, \(G\) is the shear modulus and \(\nu\) is Poisson's ratio.

**Table 1.** Calculation result of interfacial shear strength of 0° specimens.

| Sample      | \(\sigma_c\) (MPa) | \(\sigma_m\) (MPa) | \(\sigma_f\) (MPa) | \(f_0\) (%) | \(l_c\) (mm) | \(\tau_f\) (MPa) |
|-------------|-------------------|--------------------|--------------------|-------------|--------------|-----------------|
| GF35/PA66   | 169.48            | 82.7               | 1500               | 0.77        | 0.20         | 48.99           |
| GF50/PA66   | 175.58            | 82.7               | 1500               | 0.81        | 0.27         | 35.71           |

**Table 2.** Elastic constant of GF35/PA66.

| Elastic constant | 23°C (GPa) | CV (%) |
|-----------------|------------|--------|
| \(E_L\)         | 10.15      | 1.02   |
| \(E_T\)         | 5.99       | 2.41   |
| \(G\)           | 2.36       | 3.12   |
| \(\nu\)         | 0.38       | —      |

**Figure 9.** Prediction of Off-axis tensile modulus of GF35/PA66.

The off-axis tensile modulus prediction curve obtained by substituting the parameters in Table 2 into Equation 5, as shown in Figure 9. It is considered that the tensile modulus calculated by the engineering elastic constant is consistent with the change trend of the experimental value with high degree of coincidence. Comparing the deviation of the predicted modulus of GF35/PA66 in the normal temperature and high temperature environment with respect to the experimental value, as listed in Table 3, it was found that there was a slight deviation at the moderate off-axis angle (45° and 60°), but the predicted values of the remaining angles were very close to the test value. This method can also predict the tensile modulus at other off-axis angles, so it has strong practicability in engineering applications.

**5. Conclusions**

When the off-axis angle is increased from 0° to 30°, the mechanical properties are greatly reduced. While at the case that the off-axis angle is greater than 30°, the downward trend of the mechanical properties of the material is weaker. The difference in off-axis mechanical properties is caused by the arrangement of the fibers in different orientations, and the flow characteristics of the material during injection molding are responsible for the orientation of the fibers. The fiber orientations of samples with different off-axis angles are quite different. Prediction of off-axis tensile modulus: The off-axis tensile modulus predicted by the tensile modulus equation of the anisotropic elastomer is in good agreement with the experimental value.
References

[1] Zhang L 2018 Current situation analysis and development suggestion of engineering plastics industry in China New Chemical Materials. 46 16-22

[2] Friedrich K and Almajid A A 2013 Manufacturing Aspects of Advanced Polymer Composites for Automotive Applications Appl Compos Mater. 20 107-128

[3] Bendemra H, Compston P and Djukic L 2014 Automotive composites manufacturing in Asia: challenges and opportunities AutoCRC 3rd Technical Conference

[4] Thomason J L 2008 The influence of fibre length, diameter and concentration on the strength and strain to failure of glass fibre-reinforced polyamide 6,6 Compos Part A-Appl S. 39 1618-1624

[5] Monte M D, Moosbrugger E and Quaresimin M 2010 Influence of temperature and thickness on the off-axis behaviour of short glass fibre reinforced polyamide 6.6 – cyclic loading Compos Part A-Appl S. 41 859-871

[6] Fu S Y, Lauke B 1996 Effects of fiber length and fiber orientation distributions on the tensile strength of short-fiber-reinforced polymers Compos Sci Technol. 56 1179-1190

[7] Bao Y D 2017 Properties of glass fiber reinforced PA66 twill weave composite Southeast University

[8] Hassan A, Yahya R, Rafiq M I M, et al 2011 Interfacial shear strength and tensile properties of injection-molded, short- and long-glass fiber-reinforced polyamide 6,6 composites J Reinf Plast Comp. 30 1233-1242

[9] Kelly A 1965 Tensile properties of fiber-reinforced metal: Copper/tungsten and copper / molybdenum J Mech Phys Solids. 13 329-350

[10] Chawla K K 1987 Composite materials / science and engineering Compos. 20 286-286