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Mechanical Properties of Jute Spun Yarn/PLA Tubular Braided Composite by Pultrusion Molding

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Abstract

Pultrusion is a continuous process with application in the manufacture of fiber-reinforced composite. The thermoplastic pultrusion molding is a manufacturing process in which generated by the resin fiber and reinforcement fibers are pulled through the heat die. The pressure was generated, also the resin fiber start melt and impregnate into the reinforcement fiber. In this investigation study the mechanical properties of jute spun yarn/PLA tubular braided composite by pultrusion molding. The systems for jute spun yarn/PLA braided composite were described in the term of materials design, structure design and processing design. The intermediate materials were prepared by comingle technique. The braiding technique manufactured preform which had jute fiber diagonally oriented at certain angles with the glass fiber inserted into the braiding yarns along the longitudinal direction of braiding structure. The braided preforms were pulled through the heated die where consolidation flow took place due to reduced matrix viscosity. The pultrusion experiments were fabricated the tubular braided composite with varying the structure of braided preform and pultrusion molding condition. The configuration of intermediate material and the molding temperature are influenced to the mechanical properties of jute spun yarn/PLA tubular braided composite. The quality of pultruded composite was evaluated by cross-section observation and mechanical properties evaluated by 4-point bending test.

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1. Introduction

Biodegradable polymers can potentially be combined with plant fibers to produce biodegradable composites materials. The rising concern towards environmental issues has led to increasing interest about polymer composites filled with natural fibers. The use of natural fibers derived from annually renewable resource as reinforcement in thermoplastic matrix composite provide the positive environment benefit with respect to ultimate disposability and raw materials utilization. Polylactic acid (PLA) is produced from renewable resources as well as it is good mechanical properties. After used, PLA can be recycled or alternatively disposed of by incineration or by landfilling [1]. The bio-composites, using natural fibers compounded with polymer matrices, could diminish the impact of plastic waste on the environment [2-4]. Jute fibers are natural fiber superior on light weight, low cost and environmental friendly corresponding to the bio-composite materials. While common composite production methods are unsuitable for mass production. One exception is the pultrusion process, it is possible to maintain a continuous production of straight profile with constant cross-sections. Pultrusion is a manufacturing process in which reinforcing fibers impregnated with matrix are pulled through a die to form composites of a constant cross-section. Generally, the unidirectional fibers are impregnated with low viscosity thermostetting resins before passing through a series of die for shaping and curing during pultrusion process [5-6]. Although thermoset pultrusion is a well known and commercially established manufacturing method, there is less knowledge about the thermoplastic pultrusion. In contrast to thermosets, thermoplastic matrix are generally polymerized, no further chemical reaction are necessary, therefore the processing is reduced to first melting the matrix, then shaping the composite under pressure and finally cooling it to preserve the new shape [7-9].

Thermoplastic resins contain very high melt viscosities, which make in-process melt impregnation of the reinforcement difficult. For this reason, various intermediate materials have been developed to overcome these problems such as micro-braided yarn, commingled yarn and parallel configuration yarn as shown in Figure 1. The schematic of tubular braiding fabric are showed in Figure 2, all fiber bundles are diagonally oriented, and the angle of the fiber bundle to the longitudinal direction can be adjusted freely. Also, the fiber bundle called the middle-end-yarn (MEY) can be inserted into the braiding yarns along the longitudinal direction. For this reason, the braiding technique can control the anisotropic of pultrusion molding. Continuous jute spun yarns reinforced polylactic acid (PLA) resin has been made the unidirectional composite with good impregnation quality and mechanical properties using compression of micro-braided yarns as intermediate materials [10-11]. In the early stage of thermoplastic braided composite by pultrusion molding with various form of materials have been widely studied [12,13-14].

![Fig. 1. Schematic of intermediate material](image-url)
The objective of this study was to establish a development of pultrusion system for jute spun yarn/PLA tubular composite with braiding technique and investigate the effect of configuration of intermediate material and the molding temperature on mechanical properties. Figure 3 shows the schematic of pultrusion process of braided composite in this study. The commingled yarns were used as intermediate materials to prepare the pultrusion preform by braiding technique. The fabrication quality of pultrusion process was evaluated by cross-section observation and mechanical properties evaluated by four-points bending test.

![Figure 2. The schematic of tubular braiding fabric](image)

![Figure 3. The schematic of pultrusion process of braided composite](image)

2. Materials and experiments

2.1 Design concept

In this paper, the designed concept of braided composite by pultrusion molding is described. The designed concept involves the materials design, structure design and processing design as shown in Figure 4. Material designs consisted of interface such as surface treatment on reinforcement fiber, volume fraction and configuration of yarn on intermediate materials. Braiding angle, gap between braiding yarns and filling ratio, are the important parameter of the structure design. Meanwhile, the processing designs were consisted of pultrusion temperature, pulling speed and pulling force.

2.2 Materials

In the previous study, the intermediate materials were prepared by micro-braided yarn and parallel configuration yarns. Successful tubular braided composite realized using glass fiber for middle end yarns in the braided structure. It was found that successful tubular braided composite realized using glass fiber 1,150 tex for middle end yarns in the braided structure. The highest bending strength and modulus were found in the specimen using parallel yarn configuration. Meanwhile, the region of un-impregnation area and macro void are seen both inside and outside the yarns [14].
Following the designed concept in this study, jute fiber tows were comingled with polylactic acid fiber. Figure 5 showed the commingle technique for mix the resin fiber with reinforced fiber. In this experiment, jute fiber tows were comingled with polylactic acid fiber. The jute fibers tow having a fineness of ~400 tex were used as reinforcement fibers. The continuously PLA fibers in a tow configuration were used as resin fiber, having a fineness of ~56 tex. Glass fiber (GF) yarns having a fineness of 1150, 720, 600 and 520 tex were also used as the middle-end-fiber to enhance the strength of braided fabric. The braided fabric preforms for pultrusion was fabricated using 48 braiding yarns (BY) and 24 middle-end-yarns (MEY) in a tubular braiding machine with a 48 carrier (Murata Machinery). The braids were done using braiding ring with diameter of 30 mm and mandrel with diameter of 20 mm, and the braiding angle was 30-38 degree and layer quantities of braided fabric was superposed of 2 layers. Table 1 lists the four different preforms braided with different GF without resin fiber as MEY.

![Fig. 4. Design concept of braided composite by pultrusion molding](image)

![Fig. 5. Comingle technique](image)
Table 1. Lists of the four different braided preforms.

<table>
<thead>
<tr>
<th>Preform No.</th>
<th>Braiding angle (°)</th>
<th>Vf of composite (%)</th>
<th>Vf of Jute (%)</th>
<th>Vf of GF (%)</th>
<th>Filling ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) GF520</td>
<td>38</td>
<td>43.26</td>
<td>33.41</td>
<td>9.85</td>
<td>101</td>
</tr>
<tr>
<td>2) GF600</td>
<td>38</td>
<td>46.22</td>
<td>32.58</td>
<td>13.60</td>
<td>101</td>
</tr>
<tr>
<td>3) GF720</td>
<td>35</td>
<td>46.22</td>
<td>32.58</td>
<td>13.69</td>
<td>101</td>
</tr>
<tr>
<td>4) GF1150</td>
<td>30</td>
<td>52.60</td>
<td>30.81</td>
<td>21.80</td>
<td>104</td>
</tr>
</tbody>
</table>

2.3 Molding

Figure 6 shows the schematic of the tubular pultrusion molding assembly, consisting of the preheater and the pultrusion die. The tubular molding die had outside diameter of 23 mm, inside (mandrel) diameter of 20 mm. The length of the molding die was 270 mm. The preheater had length 500 mm and the entrance side of the die was large and gradually reduced in 50 mm taper region until a constant cross-section of the die. According to the TGA data of jute and PLA (Figure 7), the thermal resistance of the jute degrades at ~ 240 °C and PLA degrades at ~ 320 °C. Meanwhile the melting temperature of PLA was ~ 175 °C. Therefore, the processing window of pultrusion temperature could be ~ 175-240 °C. In this study, the pultrusion temperature was design at 195-235 °C. Prior pultrusion, the preforms were dried at 80°C in convection oven for 2 hours. The preheater was set to 100 °C. The molding die had four separate heating zones and the temperature at each sections of the die was set respectively at 195, 195, 185, 165 °C from entrance side of the die. The temperature of mandrel inside the molding die was set to 165 °C. The braided preforms were pulled through the molding die by a pulling mechanic at a speed of 18 mm/min. Generally, Gf was used as MEY to enhance the strength of braided preform for pultrusion molding. This study will select the preform which use the minimize glass fibers in braided preform to examine the effect of molding temperature. The five specimens were produced by changing the pultrusion temperature in molding die zone1 and zone 2 with constant molding speed. The pultrusion temperature is shown in Table 2. The specimens which showed the best result from experiment with changing the pultrusion temperature is selected to experiment by changing the filling ratio. In here, the filling ratio was defined as the ratio of cross sectional area of material to cross sectional area of molding die [14]. It was defined by equation (1).

\[
\text{Filling ratio} = \frac{\text{Cross-section of materials}}{\text{Cross-section of molding die}} \tag{1}
\]

Cross-section area of materials was given by equation (2) and cross-section area of molding die was given by equation (3).

\[
\text{Cross section of materials} = \left( \frac{A_{BY}}{\cos \theta} \times N_{BY} \right) + \left( A_{MEY} \times N_{MEY} \right) \tag{2}
\]

where \( A_{BY} \) is area of braiding yarn, \( N_{BY} \) is number of braiding yarn, \( A_{MEY} \) is area of middle end yarn and \( N_{MEY} \) is number of middle end yarn
where D is diameter of molding die and d is diameter of mandrel.

After the molding, the specimens were cut and polished in a direction perpendicular to longitudinal direction for the cross-section observation in order to investigate the internal state of the molding with optical microscopic.

\[
\text{Cross section of molding die} = \left(\frac{\pi D^2}{4}\right) - \left(\frac{\pi d^2}{4}\right)
\]  

(3)

Table 2. Pultrusion temperature

<table>
<thead>
<tr>
<th>Preform No.</th>
<th>Pultrusion temperature (°C)</th>
<th>Pulling speed (mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>195</td>
<td>18</td>
</tr>
<tr>
<td>2</td>
<td>205</td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td>215</td>
<td>18</td>
</tr>
<tr>
<td>4</td>
<td>225</td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>235</td>
<td>18</td>
</tr>
</tbody>
</table>

*The temperature is changed in molding die zone 1 and 2*

![Fig. 6. Schematic of the pultrusion system](image)

![Fig. 7. The TGA data of Jute and PLA](image)
2.4 Experiments

The four-point bending test was performed by using the pulley unit and the metal solid bar as shown in the Figure 8. The pulley unit and steel bar are capable of decreasing the stress concentration generated at the point for support and loading nose. The bending test was performed by using an INSTRON universal testing machine with a span length of 300 mm and cross-head speed of 1mm/min.

3. Result and discussion

The plutrusion of preform with GF520 and GF600 was interrupted due to the MEY breakage inside the pultrusion die. The preform with GF720 and GF1150 were fabricated without the problem because the preform had enough strength for pultrusion. The tubular composite jute/PLA with GF 1150 had rougher surface than using GF720. The preform with GF720 was successfully pultruded and had minimized usage of glass fiber and good surface quality as shown in Figure 9. Therefore, it was selected for the experiment with the different pultrusion temperature. As the results from Table 3, specimens No.5 could not be successfully fabricated because the surface of specimens was burned due to high temperature. The specimens with molding temperature of 195, 205, 215 and 225 °C were successfully pultruded. The result from 4-point bending test was shown in Table 3. The highest bending modulus of 9.64 GPa and strength of 29.96 MPa were obtained in specimens No. 2. Meanwhile, specimens No.4 had the lowest modulus and strength because of the temperature was higher than other.

The characteristic of comingled yarn in this study show the higher mechanical properties because the resin fibers were mix with jute spun yarns using blow air. The cross-section photographs of specimens are shown in Figure 10. From the photograph, the dark regions between the fiber bundles indicate macro void and the dark regions inside of fiber bundles indicate un-impregnation area. The relationship between void, un-impregnation and molding temperature are shown in Figure 11. Consequently, it was clarified that void and un-impregnation area was decreased with increasing the molding temperature.

From these results, the impregnation quality was increased when the molding temperature increased because the matrix viscosity was reduced at higher temperature. The matrix resin easily was impregnated into the jute spun yarn and GF. Meanwhile, with increasing molding temperature the modulus and strength were decreased due to the high temperature affected the degradation of jute spun yarns.
The pultrusion of preform with molding temperature 205 °C was selected to experiment with changing the filling ratio 101, 110 and 120% by increase the number of resin fiber in braided preform. All pultruded specimens have braiding angle and same volume fraction of fiber. The pultrusion speed was constant at 18 mm/min. The crossection of the photograph of specimens are shown in Figure 12. The void areas were 7.5, 6.5 and 4.1% respectively and un-impregnation areas were 32.4, 28.3 and 17.6% respectively. It was clarified that void and un-impregnation area was decreased with increasing the filling ratio. The relationship between the filling ratio and mechanical properties are shown in Table 4. From these results, the mechanical properties and impregnation quality was increased with increasing the filling ratio because of rich resin are contained in the composite, also the jute bundles are loosed by comingles technique using blow air and initiated the resin easily impregnate to the reinforcement fiber. Therefore, the molding temperature of 205 °C is the optimum temperature for fabrication the tubular jute spun yarn/PLA braided composite.

Table 3. The result from 4 point bending test of specimens with changing the molding temperature

<table>
<thead>
<tr>
<th>Specimens No.</th>
<th>Pultrusion temperature (°C)</th>
<th>Modulus (GPa)</th>
<th>S.D.</th>
<th>Strength (MPa)</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>195</td>
<td>8.95</td>
<td>0.73</td>
<td>29.04</td>
<td>1.88</td>
</tr>
<tr>
<td>2</td>
<td>205</td>
<td>9.64</td>
<td>0.78</td>
<td>29.96</td>
<td>1.29</td>
</tr>
<tr>
<td>3</td>
<td>215</td>
<td>9.26</td>
<td>0.47</td>
<td>29.00</td>
<td>3.12</td>
</tr>
<tr>
<td>4</td>
<td>225</td>
<td>8.80</td>
<td>1.64</td>
<td>24.52</td>
<td>3.31</td>
</tr>
<tr>
<td>5</td>
<td>235</td>
<td>Unsuccessful</td>
<td></td>
<td>Unsuccessful</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 10. The cross-section observation of specimens
Table 4. The result from 4 point bending test of specimens with changing the filling ratio

<table>
<thead>
<tr>
<th>Preform No.</th>
<th>Filling ratio (%)</th>
<th>Modulus (GPa)</th>
<th>S.D.</th>
<th>Strength (MPa)</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>101</td>
<td>9.64</td>
<td>0.78</td>
<td>29.96</td>
<td>1.29</td>
</tr>
<tr>
<td>2</td>
<td>110</td>
<td>9.84</td>
<td>1.09</td>
<td>30.73</td>
<td>0.96</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>10.40</td>
<td>1.51</td>
<td>31.83</td>
<td>1.59</td>
</tr>
</tbody>
</table>

4. Conclusion

In this study, the processing design of tubular braided composite using jute spun yarns reinforced PLA by pultrusion molding was performed. The comingle technique mixed the resin fiber and jute spun yarn and were used as intermediate materials. The effect of processing design, the molding temperature is effect on the impregnation quality and mechanical properties of tubular braided composite. It was clarified that the impregnation quality increased with increasing the molding. Mean while the temperature increased the mechanical properties decreased because of the deterioration of jute fiber. The structure design, filling ratio is effect on the impregnation quality and mechanical properties. It was clarified that void and un-impregnation area was decreased with increasing the filling ratio. The mechanical properties and impregnation quality was increased with increasing the filling ratio. The pultrusion of jute spun yarn/PLA tubular braided composite in this study is an importance step towards the economically viable production of high performance the bio-composite products with uniform cross-section.
Fig. 12. The cross-section observation of specimens

References