MECHANICAL PROPERTIES OF THERMOPLASTIC PULTRUSION PRODUCTS WITH BRAIDING TECHNIQUE

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Abstract

In this study, continuous fiber reinforced thermoplastic composites with pultrusion technique using micro-braided yarn (CF/PA66) were fabricated. We made three kinds of pultrusion products, one was unidirectional composites, another was unidirectional composites with braided yarn at around the unidirectional one and the other was 3 layers braided composite. 3-point bending test and cross sectional observation by optical microscope were performed.

Unidirectional pultrusion composite had the highest bending modulus and strength. From the cross sectional observation after fracture, different fracture mechanisms were observed on each specimen. In the case of unidirectional composites, fracture was fiber fracture. In the case of 3 layers braided composites, main fracture was delamination between carbon fiber bundles.

1 Introduction

Pultrusion process is one of the composite production methods to be suitable for mass production and by using this process a continuous production of specimens with uniform cross sections is maintained. The pultrusion of continuous fiber reinforced thermosetting composites is a well developed manufacturing method in widespread use. On the other hand, there are few reports of pultrusion for thermoplastic composites. Compared with thermo-setting composites, continuous fiber reinforced thermoplastic composites have a number of advantages such as high fracture toughness, recyclability and possibility to re-melt and reprocess. Thermoplastics as matrices, however, have the drawback of their high melt viscosity so that it is difficult to impregnate resin into dry fiber structures.

In order to overcome this problem, various intermediate materials have been developed, for example, pre-impregnated tape, powder impregnated yarn, commingled yarn and micro-braided yarn. Their common features are the short matrix flow paths to improve the impregnation into the reinforcing fibers. Pre-impregnated tape is suitable for high-speed manufacturing. It is enough just to heat the surface above the melting point of resin and then to consolidate the tapes into the required shape. However, pre-impregnated tape has less draping characteristics and it is not possible to fabricate complex shaped parts or to realize braided or knitted reinforcements. In powder impregnated yarn, the polymer is added in the form of powder directly in the fiber tows. Each polymer powder grain can impregnate into the fibers by flowing parallel to them, which results in relatively high impregnation speeds due to the high permeability parallel to the fibers. But, it is difficult to control the dispersion of the powder and also it is necessary to avoid the polymer powder falling out of the bundles. In commingled yarns, thermoplastic resin fibers are mingled with reinforcing fibers. In the manufacturing process, the yarns are as easy to handle as usual dry fiber bundles. Therefore, it is easy to fabricate textile forms such as woven, knitted and braided fabrics. By heating and pressing commingled yarns, thermoplastic resin fibers are melted and impregnated into reinforcing fiber bundles. However, the damage of reinforcing fiber bundle usually occurs during the spreading process of the fiber bundles and also further textile processing.

Micro-braided yarn is fabricated using only tubular braiding machine and other processes are not necessary. In micro-braided yarn, the reinforcing fiber bundle is straightly inserted in the center of braided fabric and the matrix resin fiber bundles are braided around the reinforcing fibers as shown Fig.1.

The thermoplastic resin fibers would be melted by heat to become the matrix for FRP. Since the resin fibers are directly in contact with the reinforcing fibers, the melted thermoplastic resin could easily impregnate into the reinforcing fibers. Moreover, reinforcement fiber bundles suffer no damage during micro-braided process and provide better protection for further processing such as producing textile preforms.

In this study, continuous fiber reinforced thermoplastic composites with pultrusion technique using micro-braided yarn (CF/PA66) was fabricated. Finally we made three kinds of pultrusion products, one was unidirectional composite, another was 3-layer braided composites and the other was unidirectional-braided composites, which consist of the unidirectional yarns and braided yarn around the unidirectional one. 3-point bending test and cross sectional observation by optical microscope were performed.

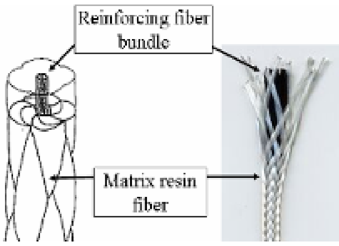


Fig.1 Micro braided yarn.

2 Materials

A carbon fiber bundle (UT500 F301, 12000filaments, TOHO TENAX Co., Ltd.) as reinforcement and the PA66 resin fiber bundles (470dtex, TORAY Co., Ltd.) as matrix were used to make Micro-braided Yarn (CF/PA66). 16 PA66 resin bundles were braided around a carbon fiber bundle by using the tubular braiding machine. The volume fraction of carbon fiber was about 39%.

3 Pultrusion

3.1 Pultrusion Machine

Pultrusion machine was mainly made up of mold, cooling equipment and drawing roll as shown in Fig.2. The length of mold is 200mm, and the shape is circular rod (diameter = 10mm, in entrance R = 40mm). The mold can control temperature separately at front and rear sections. The cooling equipment has three sections, in which water flow volume can be controlled separately. In this study, water cooling was not used.

3.2 Structure of Pultrusion Product & Processing

In the case of unidirectional composites, 90 Micro-braided yarns were used. On the other hand, in the case of unidirectional-braided composites, 24 Micro-braided yarns were used as braided yarn. The braided angle was about 15 degree to longitudinal direction. 50 Micro-braided yarns were used as straight yarn inside of the braided yarn. Therefore total 74 Micro-braided yarns were used. In the case of 3 layers braided composites, 24 Micro-braided yarns were braided to make braided preform. And then, 24 Micro-braided yarns were also braided on the 1st layer, this is 2nd layer. Finally we got the 3 layers braided preform. Braiding angle of this preform was also about 15 degree to longitudinal direction on each layer.

The processing condition for pultrusion was shown in Table 1. The same condition was used on fabrication of all composites. The schematic drawings of each structure were shown in Fig.2. The carbon fiber volume fractions of unidirectional, unidirectional-braided and 3 layer braided composite were 76.6%, 65.4% and 54.3%, respectively.

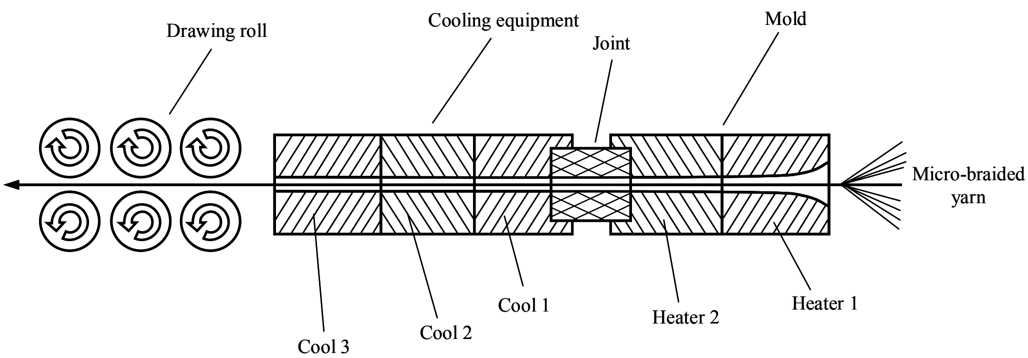
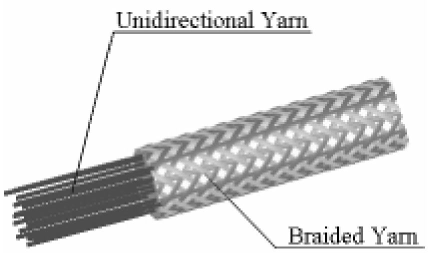


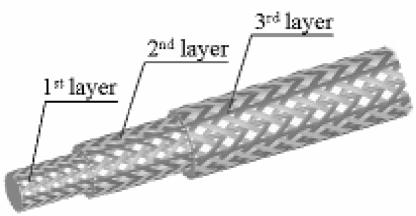
Fig.2 Schematic drawing of pultrusion machine.

Table 1 Process condition.

	Speed (mm/min.)	Cool 3 (°C)	Cool 2 (°C)	Cool 1 (°C)	Joint (°C)	Heater 2 (°C)	Heater 1 (°C)
Set Value	6.7	-	-	-	-	305	270
Actual Valure	6.7	-	74	87	199	305	273



(a)



(b)

Fig.3 Schematic drawing of structure for braided pultrusion products; (a) unidirectional-braided structure, (b) 3 layers braided structure.

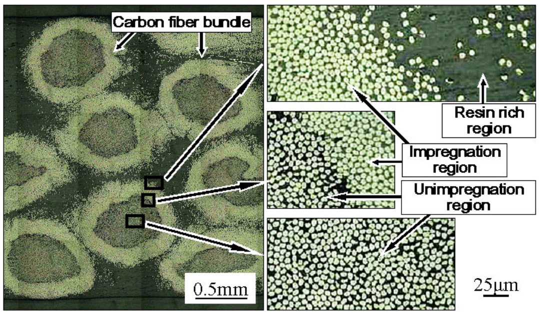
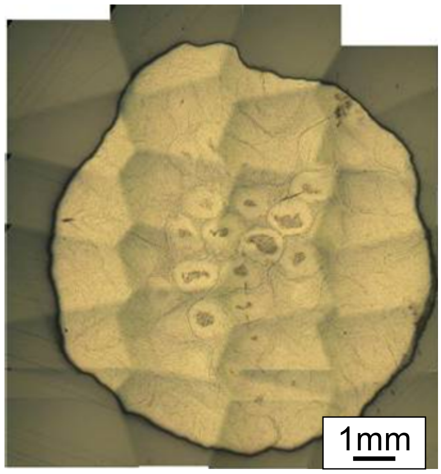


Fig.4 Typical cross section of unidirectional composite using Micro-braided yarn.

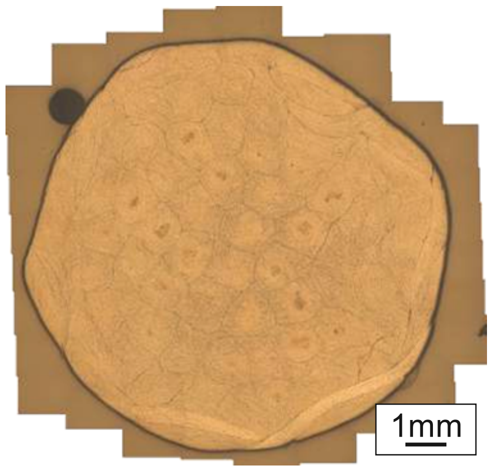
3.3 Cross Sectional Observation

To observe the impregnation state of PA66 into carbon fiber bundle, cross sections of the specimens were observed with optical microscope. The cut specimens were embedded by thermosetting resin, and then it was polished by polisher. Typical cross sections of the specimen were shown in Fig.4. In the cross section, the black region at the center of fiber bundle contained voids and can be regarded as unimpregnated region. The region between carbon fiber bundles in the photograph is known as resin rich regions. In order to evaluate the impregnation state, the unimpregnated ratio (UR) was defined as area of unimpregnated region divided by total area of specimen.

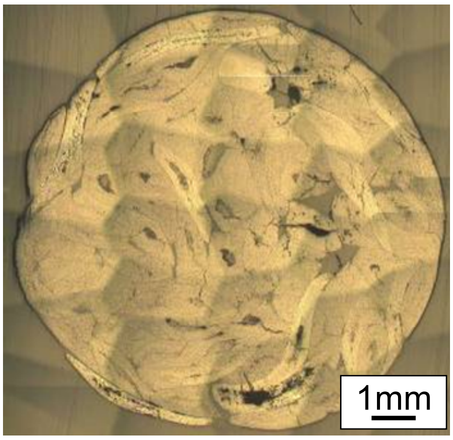
The photographs of cross sections at each specimen were shown in Fig.5. The unimpregnated regions were observed in all cross sections. Especially, in the case of 3 layers braided composites, resin rich region and void were also observed. The unimpregnated ratios of each specimen were shown in Table 2. 3 layers braided composite had the highest unimpregnated ratio.



(a)



(b)



(c)

Fig.5 Cross section, (a) unidirectional composites, (b) unidirectional-braided composites, (c) 3 layers braided composites.

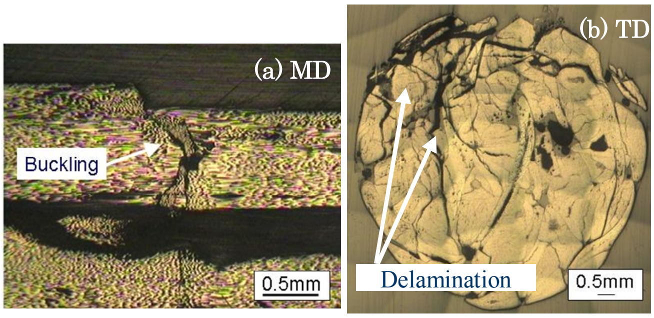
4 Bending Test

The specimen size was 8 to 8.5 mm in diameter for 3-point bending test. The span length was about 130mm. 3-point bending test was performed using INSTRON Universal Testing Machine (Model 4206) at crosshead speed of 1.0mm/min. After bending test, fracture surface was observed.

The result of bending test was shown in Table 2. From Table 2, it was clear that both the modulus and the strength of unidirectional composites were higher than those of unidirectional-braided and 3 layers braided composites. The reason of this tendency is not only effect of volume fraction but also fracture mechanism. In the case of unidirectional composite, the buckling occurred at the compression side of the specimen as shown in Fig.6 (a); this photograph is along the machine direction (MD). On the other hand, in the case of braided composite, the delamination between carbon fiber bundles occurred as shown in Fig.6 (b); this photograph is transverse direction (TD) to machine direction. It was considered that this difference in fracture mechanism cause the decrease in mechanical properties. Another considerable reason for decrease in mechanical properties is unimpregnated ratio. In our previous study, we found the critical value of that ratio; if that ratio is under the critical value, unimpregnated region doesn't affect the crack propagation. The critical value is 2.3% in the case of CF/PA66 material system. Unimpregnated ratio of 3 layers braided composite was 3.2%, which is above the critical value 2.3%. Hence, it was suggested that unimpregnated region would affect the bending properties. In the case of unidirectional-braided composites, both the modulus and strength showed the middle value. Because unidirectional Micro braided yarns enter in the braided yarns, bending modulus becomes high. However, initial fracture is delamination because of braided yarns in outer layer. On this account, it is thought that bending strength deteriorated.

Table 2 Bending properties.

	Bending modulus (GPa)	Bending strength (MPa)	Vf (%)	UR (%)
Uni	118	778	76.6	1.7
Uni-Braid	118	682	65.2	0.8
Braid	79	450	54.3	3.2



(a) (b)

Fig.6 Aspects of cross section, (a) unidirectional composites (Machine Direction; MD), (b) 3 layers braided composites (Transverse Direction; TD).

5 Future Works

In this report, braided rod composites were fabricated. The Micro-braided yarns were put straightly along the MD in order to increase the mechanical properties compare with the only braided products.

There are several advantages in braided rod. For example, we can control the mechanical properties by controlling braiding angle. However, the fabrication process was not continuous way. Our future work is to fabricate braided composite by connecting the braiding machine to pultrusion machine. We called this process Braiding Pultrusion Molding for Thermoplastics "BPM-TP".