Development of pultrusion system for continuous fiber reinforced thermoplastic composite tube with braiding technique

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ABSTRACT: Pultrusion process is one of the composite production methods that have been used for mass production of uniform profiles. However, there are two problems that are commonly found in pultrusion products; one of which is its anisotropic mechanical properties. This anisotropicity stems from the alignment of reinforcements in the longitudinal direction during the pultrusion process. The other problem is the difficulty in recycling since thermosetting resins are typically used as the matrix resin for these composites. Therefore, a combination of braiding and pultrusion techniques as well as the usage of thermoplastic resins to produce continuous fiber reinforced thermoplastic composite profiles was proposed. In this study, L-shape pultrusion of thermoplastic composite was fabricated with braiding technique. Relationship between molding speed and impregnation state, mechanical property of the composites was discussed.

KEYWORDS: Pultrusion, continuous fiber reinforced thermoplastic composite, braided composite,

INTRODUCTION

Pultrusion is one of the most common methods for continuous fabrication of fiber reinforced plastic (FRP) with uniform cross sections. Generally, unidirectional fibers are impregnated with low viscosity thermosetting resins before passing through a series of dies for shaping and curing during the pultrusion process. This would provide the composite with a preferential load bearing capacity only in the longitudinal direction while this capacity reduces significantly in other loading directions. Additionally, the usage of thermosetting resin impedes the possibility of recycling. Therefore, to solve these problems, a combination of pultrusion and braiding technologies to produce continuous fiber reinforced thermoplastic composites was proposed.

Due to the high viscosity of thermoplastic resins, impregnation of the resin into the reinforcement fibers could be challenging. Various methods to improve the impregnation have been proposed, including the development of various intermediate materials such as pre-impregnated tape, powder impregnated yarn, commingled yarn and micro-braided yarn as shown in Fig. 1. In this study, the usage of the intermediate material for pultrusion process, which was composed of matrix resin fiber bundles and the reinforcing fiber, was considered [1].

Braided fabric which is one of the textile techniques was used in this study. The braided fabric is one of the old traditional techniques in Japan. The schematic drawing of braided tube was shown in Fig. 2. One of the features is that the all fiber bundles are continuously oriented, so that the excellent mechanical properties were expected. Other characteristic is capability of changing the “braiding angle”. In the braided fabric, 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-fiber (MEF) can be inserted into the braiding yarns along the longitudinal direction. For this reason, the braiding technique can control the anisotropic of pultrusion molding. The purpose of this study is to investigate the molding condition of the pultrusion molding for the braiding composites with thermoplastic resin. Temperature measurement of the inside molding, cross-sectional observation and tensile test were performed. From these results, the effect of molding conditions on the inside and surface state of the molding and the mechanical properties was discussed.

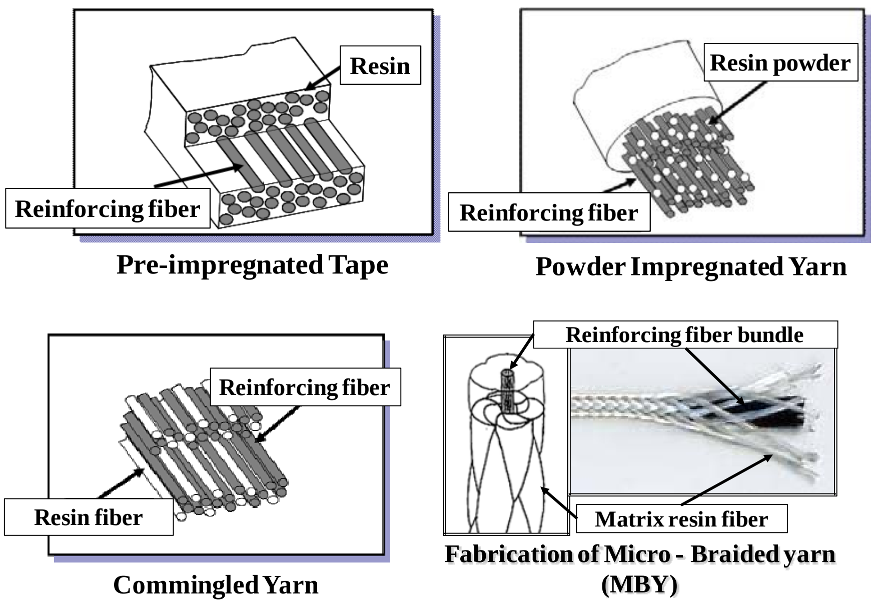

Fig. 1 Schematic of intermediate material

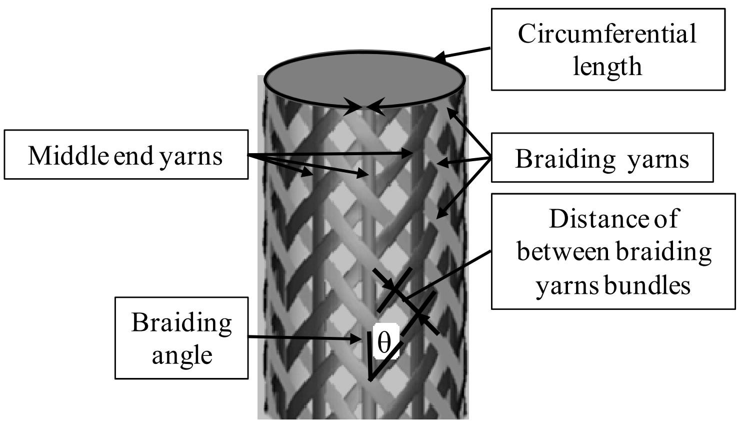

Fig.2 Schematic of braiding

EXPERIMENTS

Materials

Carbon fibers (T700-50C 12000 and 6000 filaments, Toray Co,.Ltd) were used as the reinforcement while the PA66 resin fiber bundles (1120tex, melting temperature:265 ^{o}C) were used as the matrix resin. Carbon fibers (T700-50C 12000 filaments) and PA66 were commingled and used as the braiding yarns. Carbon fibers (T700-50C 6000filaments) without resin fibers were used as middle end yarns. The volume fraction of carbon fibers in the intermediate material was about 50%. In this study, tubular braided fabric was fabricated with 48 braiding yarns and 24 middle-end yarns. Two layers of tubular braided fabric with 50^{o} of the braiding angle were stacked. These fabrics were flattened and taken into the hot die with L-shape hole. The resin fibers of the braided fabric were melted and impregnated with reinforcing fibers i.e. carbon fibers in the hot die. As a result, four-layered braided composites with L-shaped cross section were molded.

Pultrusion System

A molding die and a preheating die were prepared for pultrusion molding in this study. The braided fabrics were pre-heated in the preheating die up to near melting temperature of resin fiber for easier impregnation. The molding die had the L-shaped molding hole, and L-shaped molding with cross-sectional shape of 30mm and 30mm and the thickness of 3mm can be produced. The length of the molding die was 470mm, which was separated into six parts. The temperature at each part of the die can be precisely controlled during pultrusion. The temperature at each sections of the die was set respectively at 290, 290, 290, 280, 270, 260^{o}C from entrance side in this study. The temperature of the preheating die was set 255^{o}C.
In this study, the processing condition for pultrusion is shown in Table 1. Three types of specimens were produced by changing the molding speed at 46, 94 and 106mm/min with and without the air cooler. The air cooler with constant flow by compressed air was set up at exit side of the molding die to get cool moldings.

Table 1 Type of specimens

Sample name	(a)	(b)	(c)
Measured speed (mm/min)	46	94	103
Air cooler	OFF	ON	ON

TESTING METHOD

To measure the thermal distribution inside of molding during pultrusion, thermocouples were inserted into braided fabrics. After the molding, the specimens were cut and polished in a direction perpendicular to longitudinal direction for the cross-sectional observation in order to investigate the internal state of the moldings with optical microscopy. Tensile test was performed by using INSTRON universal testing machine (model 4206) to investigate mechanical properties. The tensile specimens were obtained by cut the molding into 200mm in longitudinal direction and 20mm in transverse direction from the flat part. The span length was 100mm and the crosshead speed was 1mm/min. Strain was measured by strain gage attached on the center of the specimen.

RESULT AND CONCLUSION

Temperature measurement and Cross-sectional observation

The relationship for each specimen between the temperature of room, surface and inside of molding, and the position from entrance of die are shown in Figs.3(a)-(c) respectively. During the preheating area, the difference of temperature between surface and inside of molding for (a) was lower than that of (b) and (c), and the difference increased with an increase in molding speed. The temperature of the surface and the inside of each molding became almost the same value in the molding die, and both temperatures were up to the sufficient temperature around 295 degrees for the impregnation of the matrix resin. Cross marks in each figure are the beginning and end points indicating the area in which the temperature reached 295 degrees. The molding time in this area for each specimen(T_a, T_b, and T_c, respectively) were 612sec, 300sec, and 162sec, these were called Maximum temperature Holding time (Mt-Ht) in this study. Mt-Ht decreased with an increase in molding speed. After the molding die, the temperature of each specimen was lower in order of (b), (c), and (a). This could be because of cooling effect for (b) and (c), and the molding speed faster in (c) than (b).
The cross sectional photographs of each specimen are shown in Fig.4. In these photographs, the dark regions at the center of the fiber bundles and between the fiber bundles could be seen. The dark regions of the former indicate un-impregnated region. The area of un-impregnated region increased with an increase in molding speed from these photos qualitatively. The dark regions between the fiber bundles could be seen much more and the surface became worse condition in (a) and (c) than (b). The thickness of each molding was bigger than the dimension of die especially for (a) and (c). The thickness of (a), (b) and (c) were 3.8mm, 3.2mm and 3.6mm, respectively. It seems that these gaps between fiber bundles depend on the existence of the air cooler. If the melting resin cannot be fixed by unsatisfactory air cooling, the molding pressure released at after molding region. Therefore, the gaps seemed to be generated.
Consequently, from these results, it was clarified that Mt-Ht decreased and the un-impregnated regions increased with increasing molding speed. Moreover, the molding state such as gaps between fiber bundles and surface roughness depend on cooling effect at after molding region.

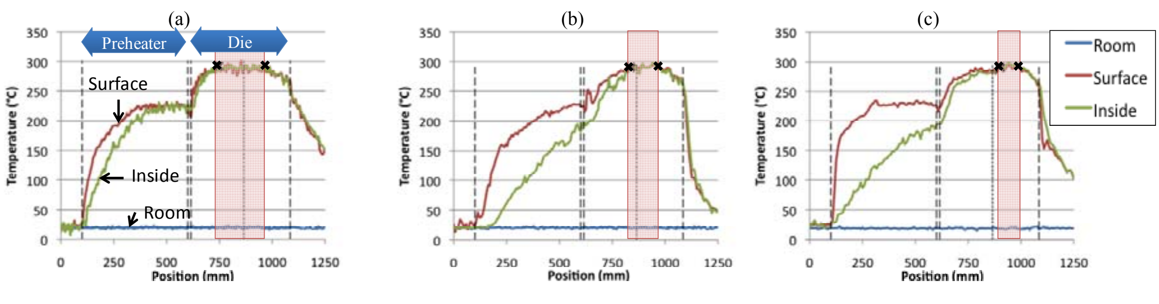

Fig. 3 Results of temperature profile measurement

(a) (b) (c)

Fig.4 Cross section of specimens

Tensile test

The modulus and strength are shown in Table 2. Modulus of each specimen was almost the same despite of the difference of molding speed and the existence of the air cooler. Theoretical achievement ratio obtained from experimental modulus divided by theoretical modulus calculated by laminate theory was investigated. These values were almost the same and close to 100%. The strength was the highest in (b) with the fewest un-impregnated region and the gaps between fiber bundles, and was about 10~15 percent higher value compared with the others.

Table 2 Type of specimens

Sample name	Modulus (GPa)	Strength (MPa)	Achievement ratio(%)
(a)	27.7	303	91
(b)	28.4	349	93
(c)	28.4	317	93

CONCLUSION

In this study, braided fabrics reinforced thermoplastic pultrusion molding was performed. The effect of molding conditions such as the molding speed and the cooling effects after molding on the molding state and the mechanical properties were investigated. It was clarified that the un-impregnated regions in the fiber bundles and the gaps between fiber bundles increased with increasing the molding speed. The air cooling prevented from the release of the molding pressure.

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