EVALUATION OF THE MECHANICAL PROPERTIES OF BRAID-CFRTP PRODUCED BY PULTRUSION

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ABSTRACT

Braids, which have been used to make hoses and pipes, are getting a lot of attention in the field of fiber reinforced plastics (FRP) due to its high reinforcing effect of continuous fibers. For braided composites, pultrusion, known as braid-pultrusion (BP), is often applied, and mainly thermosetting resins have been used for matrix resin. Considering recyclability and productivity, thermoplastic resins are better to be used for matrix. Nevertheless, the thermoplastic resin has the disadvantage of high viscosity, making it difficult to impregnate into the fiber bundle. The unimpregnated area becomes the starting point of fracture, so it is necessary to develop a method to improve the impregnation property. In this study, to improve the impregnation property of the braided composite in BP using a thermoplastic resin, a new pre-impregnation method of resin was developed using a solution in which PA6 was dissolved in HFIP. For comparison, three types of specimens were prepared: two types of specimens were obtained by pultruding the braids once or twice through the die without pre-impregnation, while the third type was pre-impregnated rods pultruded once using the same die. The molded product pre-impregnated with the HFIP solution of PA6 showed the lowest porosity and the highest impregnation ratio, resulting in the highest tensile strength.

Keywords: CFRTP, braid-pultrusion, pre-impregnation, HFIP(Hexafluoro-2-propanol), PA6.

1 INTRODUCTION

In recent years, reduction of CO_2 emission has been required in the fight against global warming. One measure is to replace metal materials with light-weight materials. Carbon fiber reinforced plastics (CFRP) are used in aviation and automobile industries because they have excellent mechanical properties such as high specific strength and high specific rigidity. Among CFRP, carbon fiber reinforced thermoplastic (CFRTP) is expected to be used because it has higher productivity and better recyclability than CFRP which uses thermoset resin as matrix.

Braids that have been used to make hoses and pipes uses continuous fibers which are effective in suppressing crack growth [1], and have a higher reinforcing effect than molded products using filament winding [2]. Hence braiding has been attracting attention in the field of fiber reinforced composite [3], [4]. Braiding is often integrated with the pultrusion process and is known as braid-pultrusion (BP), and a thermosetting resin has been used as a matrix resin. From the perspective of recyclability and producibility, the application of thermoplastic resin is required. In BP, rods are often formed by composing a core fiber that serves as an axis together with a braided fiber that covers the core fiber. When the thermoplastic resin is used for BP, resin impregnation becomes a key technology because of the high viscosity of thermoplastic resin. Typically, to obtain highly impregnated products, intermediate materials such as prepregs are considered to be used. However, it is difficult to adapt intermediate materials to complicated structures such as braids because the intermediate materials are not flexible. On the other hand, powder-attached fibers are flexible but they have a drawback that the powder resin falls off when weaving it into the braids [5]. Therefore, it is required to develop a method to impregnate the resin into the braids after weaving the fiber to the braids. In this study, to improve the impregnation property of the braided composite in BP with a thermoplastic resin, a new pre-impregnation method of resin using a solution in which PA6

WIT Transactions on The Built Environment, Vol 196, © 2020 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/HPSM200091

was dissolved in HFIP (hexafluoro-2-propanol) was developed**.** For comparison, three types of specimens were prepared: two types of specimens were obtained by pultruding the braids once or twice through the mold without pre-impregnation, while the third type was pre-impregnated rods pultruded once using the same die. After pultrusion molding, the mechanical properties of each specimen were evaluated.

2 MATERIALS AND EXPERIMENTAL PROCEDURES

2.1 Braid-pultrusion

PAN-based carbon fiber bundles (Mitsubishi Chemical, Pyrofil, 3K CF) are used as the reinforcing fiber. Eight carbon fiber bundles were manually weaved to a braid on a core fiber bundle that serves as an axis. PA6 (Ube Industries, Ltd. 1015B) was used as the matrix resin, and the braids were used as a reinforcing material while BP was performed using the die shown in Fig. 1. After inserting the braids into the die and filling the tapered portion of the die with resin pellets, the die was heated to the temperature shown in Table 1. The temperature was held for 10 minutes after resin melting and then pultrusion molding was performed. In this study, single pultruted rod (S-rod) in which the braids passed through the die once were molded. Furthermore, double pultruted rod (D-rod) in which the braids passed through the die twice were also molded with the same test condition of S-rod. For more improvement of impregnation of resin, a new molding method using resin solution was used. A solution of PA6 nonwoven fabric (Kuraray, sample) dissolved in HFIP(Hexafluoro-2-propanol) at a ratio of 10 wt.% was prepared. The braids were immersed in the solution and held at a vacuum condition until no air bubbles appeared in the braids. Afterwards, they were kept in a thermostatic bath at 80°C for 2 hours to allow the solvent to evaporate. This process was repeated twice for pre-impregnation of PA6 resin. Using these pre-impregnated braids as reinforcement material, P-S-rod (pre-impregnated single rod) was also molded by passing through the die once.

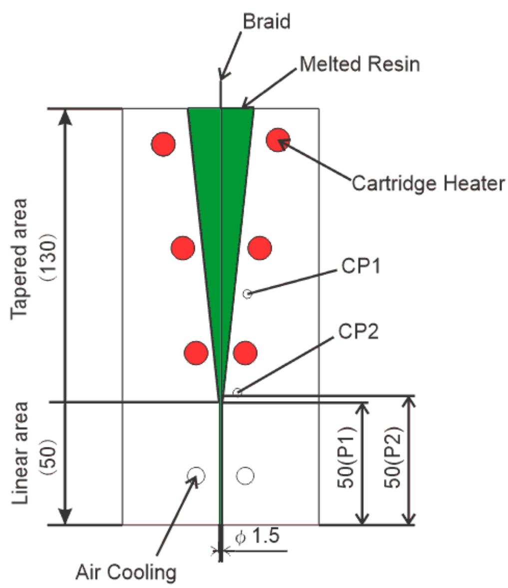

Figure 1: Schematic drawing of the pultrusion die.

Table 1: Thermal condition of the die.

Point	Temperature (C°)
CP1	240
CP2	230

To clarify the impregnation process of P-S-rod, a specimen which was solidified in the middle of the molding was observed by CT scan. Four points were observed by CT scan; specimens before molding, molded product, P1 and P2. Reference point P1 is the point 50 mm away from the die exit, which is the boundary between the straight part and the tapered part and reference point P2 is 3 mm away from P1 in the direction of the taper. The void ratio of molded products was measured with a scanning electron microscope (SEM, JSM-6390LT, JEOL). In this study, voids which are un-impregnated area were defined as the black area on the observed SEM image. The braid angles of each molded product were measured using a digital microscope (Keyence, VHX-5000) as shown in Fig. 2. The average of five points was calculated as the braid angle of the molded product.

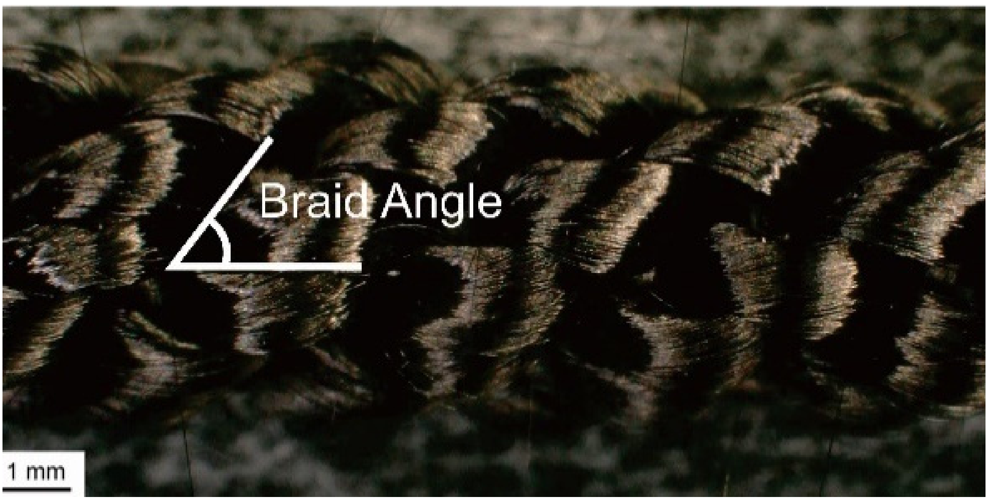

Figure 2: Definition of braid angle.

2.2 Evaluation of the mechanical properties

The mechanical properties of the molded products were evaluated by tensile test using a universal testing machine (Instron 5566). The tensile speed was set at 1 mm/min, and the distance between chucks was 8D (D is the diameter of the molded product) according to JIS Z 2201. In this study, the tensile strength was calculated by dividing the maximum tensile load by the cross-sectional area. Since the outline of the molded product is uneven, the outer circumference was measured at five points and its average value was considered as the diameter of the product. The strains were calculated using the displacement of the chuck.

3 RESULTS AND DISCUSSION

3.1 Resin impregnation

Fig. 3 shows the void ratio of the specimens. P-S-rod showed the lowest void ratio followed by D-rod and P-rod. Fig. 4 shows the cross-sectional image of braids after vacuum pre-impregnation using the HFIP solution with PA6. Even in the center area of the braids, carbon fibers are covered by the resin. This is considered to be the reason that P-S-rod has lowest void ratio. Fig. 5 shows the CT images of the P-S-rod solidified in the die at the molding process. Yellow line in Fig. 5 shows outline of the braid exists. For P1 and molded product, voids shown in P2 as dark spots are not exist. As molding process progress voids exist around center area of the braid shown in P2 are suppressed. Fig. 6 shows the CT images of S-rod and D-rod. At P-S-rod in Fig. 5 and D-rod, voids existing in S-rod were not observed. In P-S-rod, the lowest void ratio was achieved by pre-impregnation.

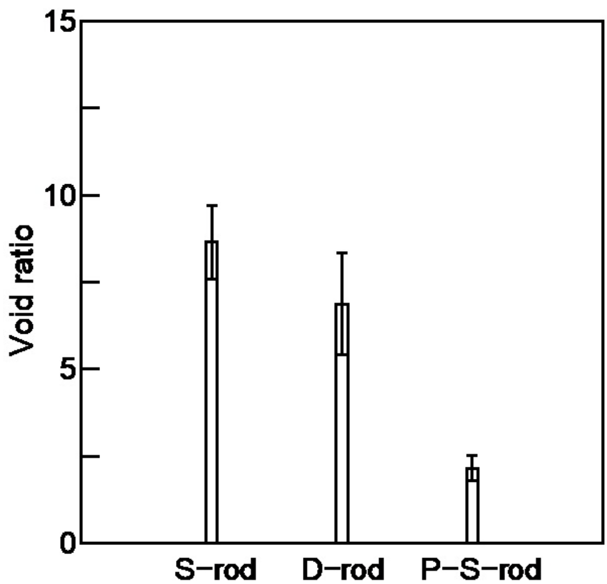

Figure 3: Result of void ratio of the rod (N = 3, means ± SD).

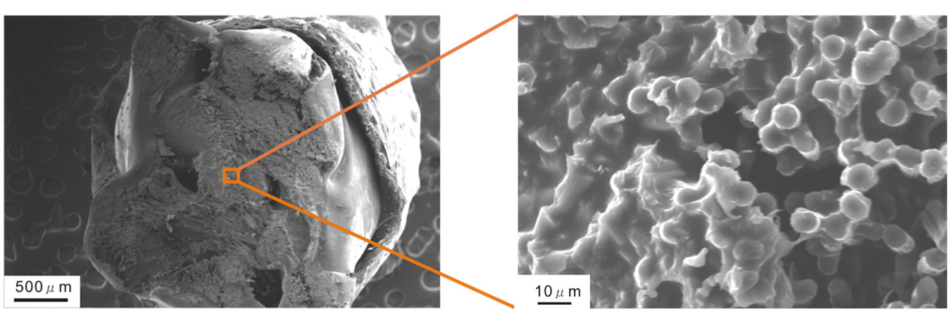

Figure 4: SEM image cross-section of image of pre-impregnation braid.

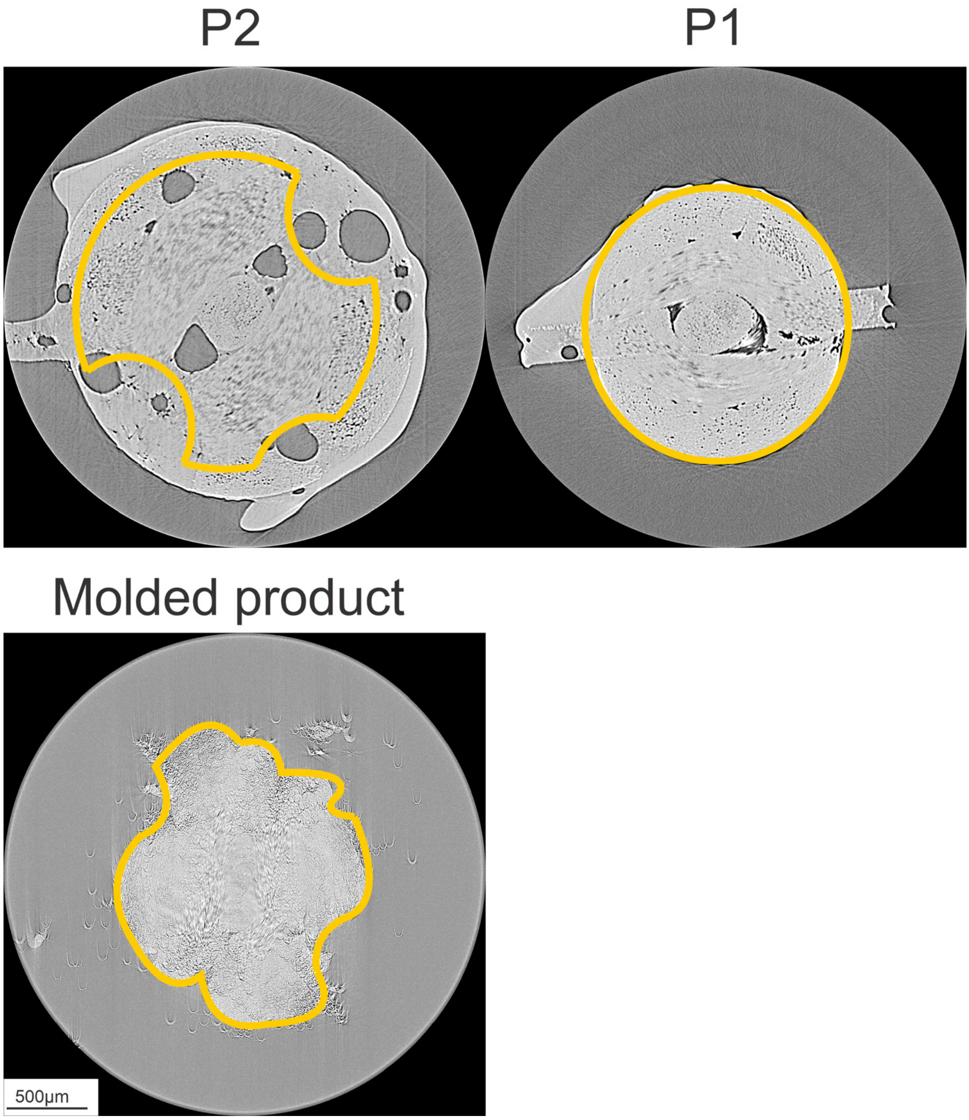

Figure 5: CT images of the P-S-rod solidified in the die.

3.2 Result of the tensile test

The braid angles of the molded products are shown in Fig. 7. D-rod shows a smaller braid angle than S-rod. The braid angle is considered to decrease by passing it through the die twice. Furthermore, it is considered that pre-impregnation does not affect the braid angle, because there was no significant difference between the braid angles of S-rod and P-S-rod.

Fig. 8 shows the stress–strain diagram of each molded product in the tensile test. Fracture occurred after the stress decreased continuously. The tensile strength of each molded product

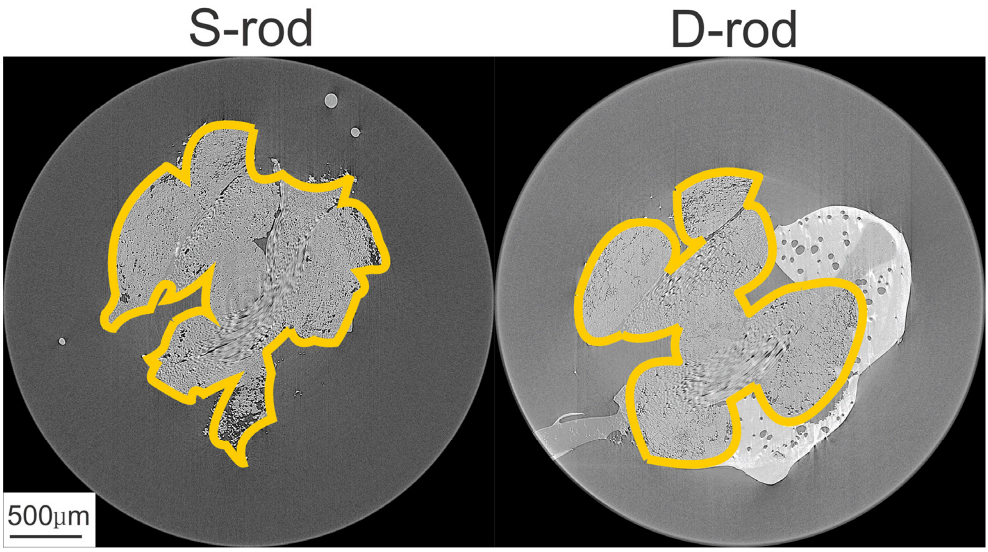

Figure 6: CT images of molded products.

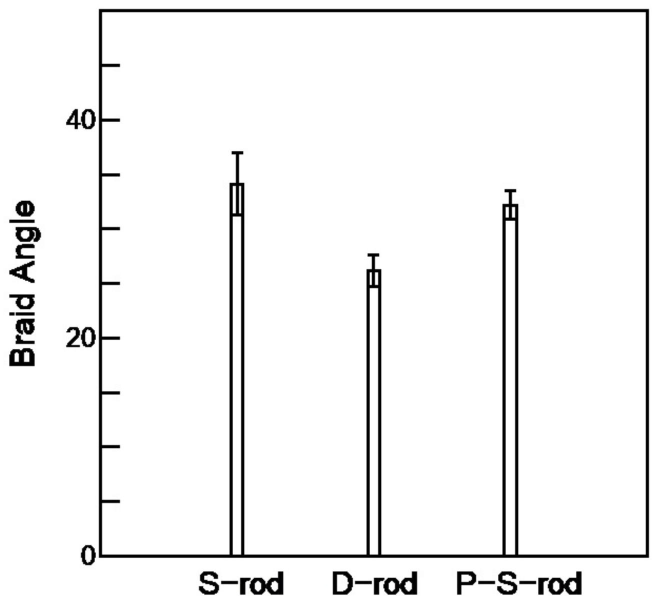

Figure 7: Braid angle of the product (N = 3, means ± SD).

is shown in Fig. 9. P-S-rod showed the highest tensile strength, followed by D-rod and S-rod. In a study of the effect of the braid angle on the mechanical properties of braided composites, it has been reported that the mechanical properties of braided composites depend on the braid angle, and as the braid angle is close to 0 degree, tensile strength becomes higher [6].

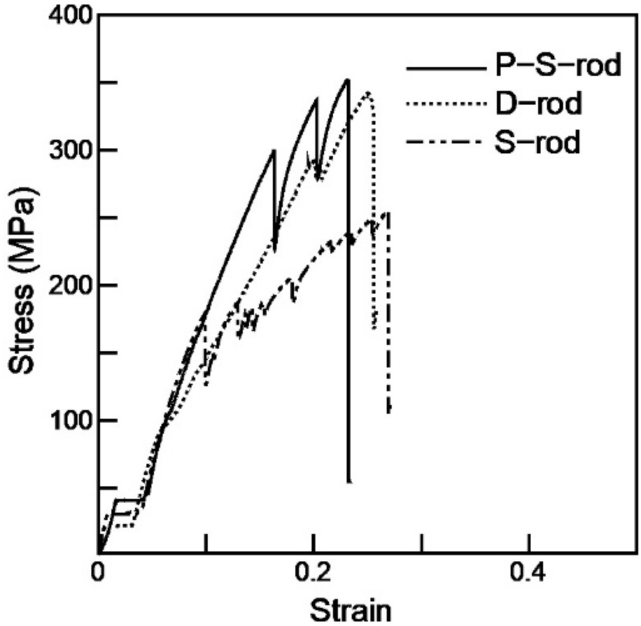

Figure 8: Stress–strain curve of braided rod.

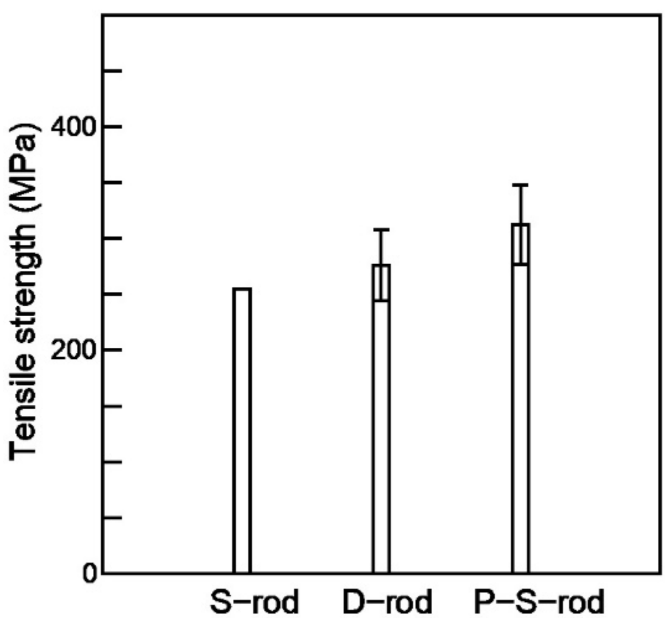

Figure 9: Results of tensile test.

Therefore, considering the braid angles shown in Fig. 7, it was anticipated that the D-rod would have the highest tensile strength of the molded products, followed by P-S-rod and S-rod. However, as shown in Fig. 9, P-S-rod showed the highest tensile strength. This indicates that the better impregnation by pre-impregnation using a solution of PA6 dissolved by HFIP overcomne the reinforcing effet of arrigned fibers.

4 CONCLUSION

To improve the resin impregnation of BP with thermoplastics, a solution which dissolved PA6 by HFIP was prepared and pre-impregnation was performed. Pre-impregnated rods were molded by passing through a die once. For comparison, braided rods without pre-impregnation were molded by passing through the die once or twice. The mechanical properties of the braided rods were evaluated. This investigation yielded the following conclusions.

1. By using a solution of PA6 dissolved in HFIP, the resin penetrated into the inside of the braids and this made the resin adhere to the fibers.
2. Preimpregnation of the braids improved their impregnation and reduced the void ratio. The tensile strength of the pre-impregnated molded product showed the highest tensile strength due to the decreased void ratio.

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