Thermoforming of Textile Composite Pipe Fittings

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Thermoforming of braided thermoplastic composite tubes was carried out in order to clarify the mechanism of the thermoforming process for pipe fittings such as T-shape fittings, cross fittings and two-branch fittings. The composite tube was made of a cowoven braid that consists of a carbon braid and polyamide resin, and 4-ply tubes with initial fiber orientations of 18° and 26° are used in the experiment. The branch is formed with not only the fisherman's net effect but also with moving yarns along the longitudinal direction in every forming process. The results show that the deformation behavior of the braid is very complex. Therefore, fiber orientation through forming is also greatly changed. Wall thickness at the branch decreases with increasing branch height. From these results, it is found that a fitting with complex shape can be produced by thermoforming. T-shape fittings, cross fittings and two-branch fittings are achieved by this process. It is confirmed that moving yarns along the longitudinal direction plays an important role in branch forming of pipe fittings.

Key Words: Composite Material, Textile, Composite Tube, Thermoforming, Braid, Fitting

1. Introduction

Recently, high-speed vehicles such as cars and trains require lightweight structures to save energy and preserve the environment. Fiber reinforced plastics (FRP) with high performance of specific strength and specific stiffness are valuable engineering materials for solving these problems. However, constructing structural components of complete of polymer composites is difficult because the methods of joining composite parts are not perfect. Polymer composite fittings are not popular compared to metallic fittings. Conventionally, polymer composite fittings are fabricated by filament winding(9) or braiding(9). These processes require a mandrel with a complex shape as a template on which reinforcement can be wound. In these processes, there is no easy way to remove the component from the mandrel making cycle-time reduction the most important technological issue. Furthermore, conventional composite fittings are made of thermoset composites; a composite fitting with thermoplastic matrix has not yet been developed in practice.

Thermoplastic composites have several advantages over thermoset composites. In particular, a unique characteristic of thermoplastic composites is thermof ormability. In sheet forming, thermoforming processes for thermoplastic composite have been developed(3,8). However, thermoforming for composite tubes has not been reported, except in our previous studies(8,9).

This paper deals with the applicability of the thermoforming process to the fitting forming process of a braided thermoplastic composite tube. In this study, the internal pressure method is adopted in the pipe fitting forming process of T-shape fittings, cross fittings and two-branch fittings.
2. Experiment

2.1 Materials

The material used is the cowoven braid which consists of polyamide (PA, specific gravity 1.19, glass transition temperature 80-120°C, melting point approximately 230°C) and carbon fiber. A fiber reinforced thermoplastic (FRTP) braided tube with 4-ply braids was fabricated by the internal pressure bonding method. The composite tube is cut to 100 mm length and is used in the experiment. The outer diameter of the fabricated tube is 20 mm and the inner diameter is about 18 mm. Initial fiber orientations are about 18° and 26°. Table 1 shows the specifications of braided composite tubes fabricated as test specimens.

2.2 Experimental procedure of fitting forming

Figure 1 shows the T-fitting forming process for braided composite tubes. A silicon tube was inserted into a composite tube as a test specimen. The test specimen is set into the molding die with the fitting shape. After heating, the internal air pressure was applied through the pressure medium (the silicon tube) to the test specimen and the pressure is kept constant during the forming process. After cooling, the fitting produced is removed from the die. The fabrication procedure of a two-branch fitting is similar to the T-fitting forming process. Figure 2 shows a die for a two-branch fitting. Table 2 shows the T-fitting forming conditions.

2.3 Measurements

To determine the suitable forming conditions of a fitting, branch height was measured under different internal pressures and forming temperatures. To clarify the deformation characteristics in forming, branch height \( h \), axial reduction \( \Delta L \) and thickness \( t \), shown in Fig. 3, were also measured after forming. In addition, axial reduction of the tube, thickness and fiber orientation were measured at 16 points along the circumference.

3. Experimental Results in T-Fitting Forming

3.1 Effect of forming conditions on branch height

Figure 4 shows the effect of forming conditions on branch height for different initial fiber orientations of composite tubes. For both 18° and 26° fiber orientated
composite tubes, the branch height increases with increasing internal pressure and forming temperature. The branch height can be up to 20 mm; the height is the same as the tube diameter. On comparing the 18° and 26° composite tubes, it is seen that the former can attain higher branch forming under the same forming conditions. However, in the case of high internal pressure above 0.5 MPa, the silicon tube used as the pressure medium often ruptured. Thus, the suitable forming conditions in the experiment are determined to be internal pressure of 0.4 MPa and forming temperature of 240°C.

3.2 Fitting products

Figure 5 shows an overview of a T-fitting product with a branch height of 13 mm fabricated under the suitable forming conditions mentioned above. Although the branch height is insufficient for enough in practical application, the T-fitting shape is obtained without undesirable deformation on the outside surface. Figure 5(b) shows the inside surface of the fitting produced. A wrinkle occurred on the inside surface of the tube. The inside-wrinkle phenomenon could not be prevented under all fitting forming conditions.

Figure 6 shows a successful product with a branch height of 20 mm. The result implies that the braided composite tube can be deformed to a T-fitting shape. However, the top area of the branch is considerably thin, because there are few yarns at the top, as shown in Fig. 6. The same tendency of the thickness distribution was also observed for the product with a branch height of 13 mm.

3.3 Axial reduction of tube

Figure 7 shows the axial reduction distribution of a tube after fitting forming. The axial reduction is not uniform and there is some reduction along the circumference. For the fiber orientation of 18°, the axial reduction at the lower side of the tube is larger than that at the upper side. In the case of 26°, the tendency is opposite that in case of 18 degrees. It is suggested that the kinematics of the braid affects the axial reduction of the tube fitting produced.

3.4 Wall thickness distribution

Figure 8 shows the thickness distribution along the circumference after forming. The thickness at S=0 mm, i.e. at the center (Fig. 3) is thinner compared to the initial thickness. The wall thickness at the branch decreases during the forming process. In particular, the wall near the top of the branch is extremely thin. On the other hand, the thickness at the upper side in the case of S=25 mm increases substantially. Conversely, the thickness at the lower side of the tube (S=25 mm) negligibly changes.

3.5 Fiber orientation

Figure 9 shows the fiber orientation distribution.
Fig. 7 Axial reduction distribution of a tube ($h_{net}=13$ mm)

Fig. 8 Thickness along circumferential after T-fitting forming ($\theta_0=18^\circ$, $h_{net}=13$ mm)

after forming. The fiber orientation after forming becomes larger than in the initial state over the entire area. However, the fiber orientation after forming is not uniform in the circumference. The fiber orientation at the bottom area of the tube of $S=25$ mm negligibly changes. In the case of an initial fiber orientation of 26°, fiber orientation after forming at near $a=100^\circ$ ($S=25$ mm) becomes large. These results indicate that the branch can be formed with not only the fisherman's net effect$^{(6)}$ but also with moving yarns along the longitudinal direction in every forming process. The results imply that the deformation behavior of the braid is complex.

4. Experimental Results in Two-Branch Fitting Forming

4.1 Fitting products
Figure 10 shows an overview of a two-branch fitting product before trimming and after trimming. The result indicates that a component with complex shape such as that in two-branch fitting, can also be produced by this thermoforming process.

4.2 Axial reduction of tube
Figure 11 shows the axial reduction of the tube in two-branch fitting forming. The axial reduction is again nonuniform along the circumference, as in the case of the T-fitting. In the case of an initial fiber orientation of 26°, axial reduction is very large. In particular, the reduction at the lower side of the tube is larger than that in the case of an initial fiber orientation of 18°. The area at $a=180^\circ$ corresponds to the bottom area of a ravine between the two branches. The amount of axial reduction is the largest in this area. The constituent yarns of both branches coincide
Fig. 10 Overview of two-branch fitting produced by the present method

Fig. 12 Yarn alignment of two-branch fitting after forming

Fig. 11 Axial reduction distribution of two-branch fitting

4.3 Fiber orientation

Figure 14 shows the fiber orientation distribution after two-branch fitting forming. The fiber orientation angle increases during the forming process and becomes the largest at the branch. The variation in fiber orientation during this process is relatively large,
4.4 Applicability to fitting forming of textile composites

Generally, utilizing the braid as a reinforcement of a composite is difficult for an asymmetric deformation process. The present forming process, however, enables braided composite tubes to deform into a complex fitting shape such as a T-fitting, two-branch fitting and cross fitting, as shown in Fig. 15. It is confirmed that the yarns moving along the longitudinal direction played an important role in branch formation in pipe fittings in the experiments. Therefore, as long as yarn movement, as well as the Fisherman’s net effect, takes place, any complex fitting and component can be produced by this thermoforming process.

5. Conclusion

In this study, thermoforming of the braided thermoplastic composite tubes was performed in order to clarify the thermoforming mechanism for various pipe fittings. As a result, it was found that the branch can be formed with not only the fisherman’s net effect but also with yarn movement along longitudinal direction during forming.

The experimental results show that the deformation behavior of a braid is fairly complex, and consequently, the fiber orientation after forming is greatly changed. The branch height of up to 20 mm was achieved in T-shape fitting and two-branch fitting experiments.

The thermoforming process will be applicable to the manufacture of fittings with complex shapes, including two-branch fittings. T-shape fittings and two-branch fittings are achieved by this process. It was clarified that yarns moving along the longitudinal direction play the most important role in branch forming in pipe fittings.

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References