# Thermoforming Technology of Textile Composite Tubes

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**ABSTRACT**

Thermoforming of fiber reinforced thermoplastic (FRTP) braided tubes was studied as a new forming technique. FRTP braided tubes with four plies are fabricated by the pressure bonding method are used in thermoforming. Bulge forming, bending process, pipe fittings and FE analysis are carried out in this study. In bulge forming the composite tube can be expanded up to about two times initial diameter. The suggested bending process can be obtained bent products with various bending radii. In pipe fitting it is possible to fabricate T-shape fitting, cross fitting and two-branch fitting. These results exhibit developed forming processes become useful processes for textile composite tubes.

*Keywords*: Thermoforming, Textile composites, Composite tubes, FEM, Braid

## 1. Introduction

Recently, high speed vehicle such as car, train and so on has required lightweight structure for saving energy and preserving the environment. Fiber reinforced plastics (FRP) with high performance on specific strength and specific stiffness is valuable as engineering materials for solving these problems. In plastic matrix composites, continuous fiber reinforced plastic composite has been used mainly for sport goods and aircraft parts as advanced composite materials. It, however, has not been widely applied to other fields because of high cost more than metal materials.

Nowadays, thermoplastic resins superior to thermosets with respect to thermal resistance and mechanical properties have been developed and produced. They have been used as a matrix of thermoplastic composites as well. Discontinuous fiber reinforced thermoplastic composites have excellent characteristics on forming, compared to ones of metals. For instance, "stampable sheets" have been adopted to many practical situations because such materials have the advantage of mass production and low cost. On the other hand, continuous fiber reinforced thermoplastic composites have poor formability, though they have higher strength than discontinuous ones. Several forming methods have been developed to improve the formability of continuous reinforced thermoplastic composites [1]-[3]. They have already been applied to sheet forming processes so far. Tube forming of the composite components, however, has not been investigated. Therefore, it is necessary to develop suitable forming processes for textile composite tube with thermoplastic matrix.

In this paper, new thermoforming processes for textile composite tubes developed by the authors, bulge forming, bending process and pipe fitting fabrication process, are introduced and explained.

## 2. Thermoforming of textile composite tubes

### 2.1 Bulge forming

Bulge forming process can be basically achieved by the deformation based on kinematics of a cylindrical braid in the theromoforming process under near melting point of matrix. The deformation behavior of the braid is mainly rearrangement of fiber orientation by fisherman's net theory. Consequently, the deformation characteristics including forming limit can be predicted by geometrical calculation. **Fig.1** shows the braid deformation by fiber orientation rearrangement with some assumptions of fisherman's net theory [4]. The geometric relationship between braid diameter and the orientation can be written as follows [4],

$$\frac{D_i}{D_o} = \frac{\sin\theta_i}{\sin\theta_o} \tag{1}$$

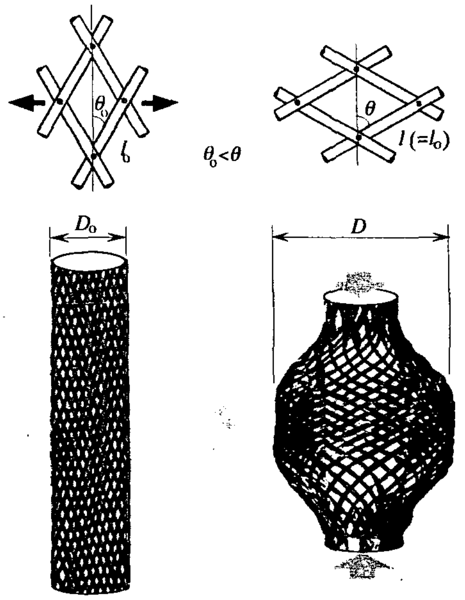
where, $\theta_0$, $\theta$, $D_0$ and D are the fiber orientations and braid diameters before and after deformation, respectively. **Equation 1** indicates that an expansion ratio of the braid depends only on fiber orientations before and after kinematic motion.

**Fig.2** shows the appearances of deformed the textile composite tubes in the case of bulge forming using different spherical dies.

These products are obtained by suitable loading path of axial penetration and internal pressure in the process. In spite of large expanding, the change of thickness at deformed area is small because the deformation mechanism is fisherman's net effect.

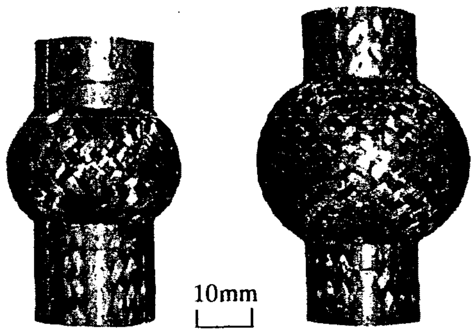
**2.2 Bending process**

A new roll bending process utilizing a local heating and cooling technique was proposed and developed for textile composite tubes in thermoforming [5]. **Fig.3** shows an overview of the bent workpieces with an initial fiber orientation 47° with four different bending radii. The kinematic behavior of reinforcement during the bending process is known to be more complicated than that of axi-symmetric deformation such as bulge forming mentioned above. Nevertheless, for this bending process the forming limit governed by the critical fiber orientation as well as the fiber orientation after bending can be predicted. **Fig.4** shows an example of a three-dimensional bent product. The result shows that




(a) Initial state (b) After deformation

Fig.1 Deformation of braid




(a) Die diameter 30mm (b) Die diameter 38mm

Fig.2 Spherical shape bulge forming ( $\theta_0$=27° )

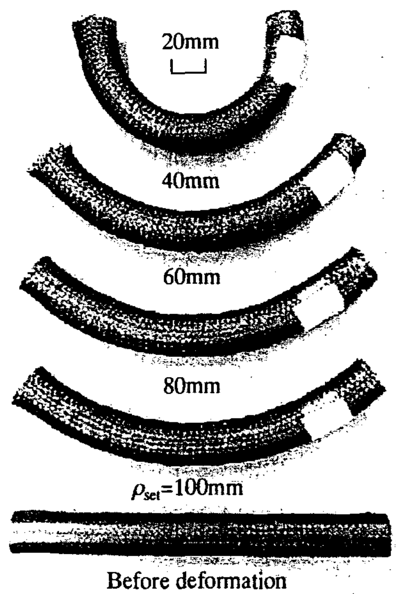



Fig.3 Overview of composite tubes after bending

this bending process has high potential for the flexible bending of braided thermoplastic composite tubes in thermoforming. This roll bending may be able to perform more complicated bending operations such as combined bending radii, three-dimensional and continuous bending.

**2.3 Composite fittings**

In manufacturing process of industrial products, a special part such as joint and fitting is utilized to construct the final product. For composite products, it is very difficult to joint between the composite parts due to a lack of polymer composite fittings compared to metal fittings. From the background, fabrication processes using thermoforming of the textile composite fittings are studied and demonstrated. **Fig.5** shows three kinds of fittings, T-shape fitting, cross fitting and two-branch fitting, produced by thermoforming. From these results, it is found that the complex shape fitting such as cross fitting and two-branch can be produced by thermoforming.

The deformation behavior of braid is very complex compared to bulge forming and bending process. The branch is formed with not only the fisherman's net effect but also with moving yarns along longitudinal direction in every forming [6]. Therefore, fiber orientation after forming is also greatly changed. It is confirmed that moving yarns along longitudinal direction plays an important role in branch forming of pipe fittings.

**3. FEM analysis on thermoforming of textile composite tubes**

For the bulge forming, the basic deformation characteristics and forming limit of the composites can be clarified from the fisherman's net theory expressed in Eq.(1). However, the detailed deformation kinematics of the composite tube has not been clarified enough due to complexity of the fabric behavior with slipping inter yarns. Thus, precise prediction of the forming

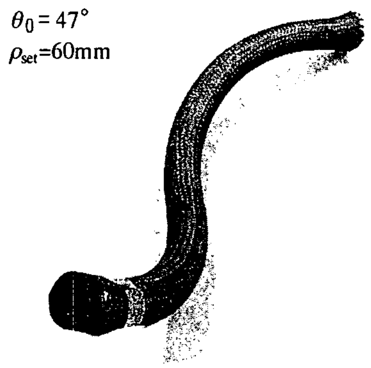
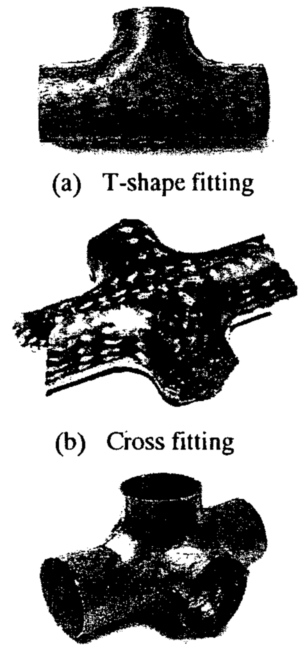



Fig.4 An example of three-dimensional bending



(a) T-shape fitting

(b) Cross fitting

(c) Two-branch fitting

Fig.5 Samples of composite pipe fitting

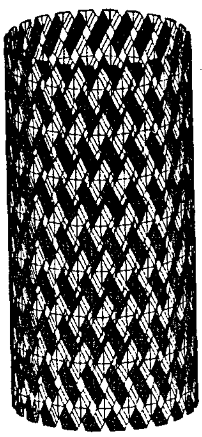
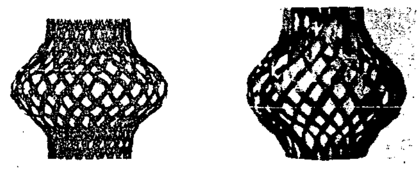
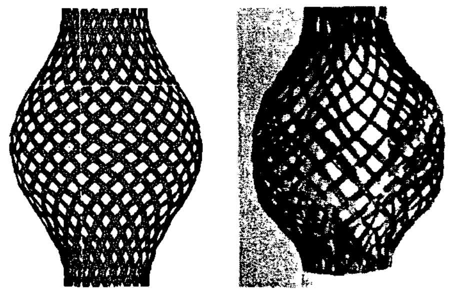


Fig.6 FEM model of braid

characteristics and estimation of the slipping effect needed. As computer and simulation technologies have been progressing more and more, finite element method has been one of the most useful prediction methods to simulate the forming process. FE simulation can predict the deformation behavior of braid taking into accounts a realistic fabric structure and the shear slips inter yarns. **Fig.6** shows the finite element models of the braid used in thermoforming [7]. In a model of the textile composites, the absence of resin matrix is considered because the flow stress of the matrix is small enough to rearrange the fiber orientation during the thermoforming. A dynamic explicit finite element code, LS-DYNA, was used in the analysis of a free bulge forming process with only axial penetration. **Fig.7** shows the effects of the initial fiber orientation on deformation shape of the tube in the free bulging by both-end axial penetration. The deformation shape of the textile tubes is seen to be very susceptible to forming zone length. The simulation results agree well with the experimental results. The results show that the slipping behavior cannot be disregarded and is important forming mechanism.



(a) Braid length 40mm, Penetration 10mm



(b) Braid length 80mm, Penetration 20mm

Fig.7 Effect of forming zone length on deformed shape by both ends penetration

## 4. Conclusion

Thermoforming of textile composite tubes, bulge forming, bending process and pipe fitting process was studied as a new forming technique. For bulge forming, the composite tube can be deformed by applying adequately inner pressure and axial penetration under near melting point of matrix. Roll bending process utilizing a local heating and cooling technique is an effective bending process of thermoforming for textile composite tube. The bending process can be obtained bent products with various bending radii as well. T-shape fitting, cross fitting and two-branch fitting fabricated by thermoforming are demonstrated. These processes proposed by the authors will be able to take advantages as forming process for textile composite tubes. Finite element method is a useful prediction method to simulate the thermoforming process of textile composite tubes.

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