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Development of a Filament-Winding Machine Based on Internal Heating by a High-Temperature Fluid for Composite Vessels

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Pressure vessels made of carbon-fiber-reinforced plastic (CFRP) materials are mainly used for hydrogen storage in fuel-cell vehicles and are manufactured by filament winding (FW). However, the FW method requires the use of an expensive autoclave; furthermore, the fiber strength decreases because of the tension induced in the fibers during lamination, and there is excessive discharge of resin during the fabrication process. To solve these problems, we developed a machine based on the fiber-reinforced plastic (FRP) manufacturing method; in this machine, filament winding is carried out by heating the inner surface of a liner. We fabricated trial CFRP vessels using this machine to show that the CFRP material can be laminated and cured simultaneously. In our method, the quantity of fibers per volume in CFRP increased, and a decrease in a non-bonded area between CFRP layers was observed. Moreover, the vessels produced by the proposed method had higher stiffness and 12–39% higher strength than those fabricated by conventional methods.

1. Prolusion

Fuel-cell vehicles, which are next-generation vehicles, have recently received a great deal of attention because of their potential benefits to the environment. In these vehicles, hydrogen and oxygen are used as fuels; therefore, efficient storage of hydrogen is very important. For this purpose, a method of compressing hydrogen into a high-pressure vessel is required.(1) However, to ensure that the maximum distance a fuel-cell vehicle can travel is comparable to that in the case of a gasoline vehicle, it is necessary to increase the maximum sustainable pressure of the high-pressure vessel used in the

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*Corresponding author: e-mail: tab@tool-a.mech.kyushu-u.ac.jp former and decrease the weight of the vessel. The high cost of manufacturing such high-pressure vessels is one of the main obstacles that prevent the proliferation of fuel-cell vehicles.

High-pressure vessels fabricated from carbon-fiber-reinforced plastic (CFRP) materials are mainly used in fuel-cell vehicles(2) and a lot of studies are under way. These vessels are manufactured by a molding method called filament winding (FW); in this method, resin-impregnated fibers are wound around a liner, and then, the fiber-reinforced plastic (FRP) material is molded by curing the resin.(3) FW has been known as a method that could use the strength of fibers effectively, and it allows weight saving up to 50% in comparison with all metal vessels.(3–5)

A thermosetting resin is generally used for manufacturing vessels by the FW method. The resin is heated and cured in an autoclave (hardening furnace) after winding. However, it is known that the FRP strength decreases to a greater extent than expected because of the occurrence of fiber waviness in the inner FRP layer caused by fiber tension during the lamination of multiple layers.(6–8) In addition, resin-rich layers, which result in the formation of voids and an increase in vessel weight, are formed between the FRP layers owing to the high viscosity of thermosetting resins.(8)

To prevent the occurrence of the waviness, Horide *et al.*(9) proposed a fabrication method in which the fiber tension decreases gradually. However, it is considered that there is a limit of fiber tension as the lamination increases, and the formation of voids cannot be reduced because of the decreased fiber tension.

To solve these problems, we focused on the development of a technique for winding resin-impregnated fibers on a liner heated at a constant temperature. In our method, the resin is heated and cured simultaneously. However, no FW system in which the liner can be heated is commercially available.

We developed an FW machine in which the FRP is cured by heating the liner from the inside. We used this machine to fabricate CFRP vessels for trial purposes and verified its lamination and curing capabilities. In addition, we conducted measurements, observations, and burst tests on these trial vessels and compared the results with those obtained for existing vessels.

2. Purpose of Development

2.1 *Problems encountered when manufacturing composite vessels by the existing FW method*

In the FW method, resin-impregnated fibers are wound under a low tension around a liner, and then, the FRP layers are heated and cured in a hardening furnace (autoclave) after molding the fiber ends. An increase in tension in the fibers results in the collapse of the inner fiber layers. Furthermore, bubbles, from which cracks originate, tend to remain within the FRP layers, and hence, the FRP strength decreases. Moreover, a pressure load cannot be applied uniformly to all the fibers because the fiber tension in the second or outer layer causes loosening of the fibers just below the layer.

Furthermore, because of the cylindrical structure of the vessel, the gas in the vessel gives rise to tensile stress in the FRP layers in the circumferential direction, and this stress is greater in the inner FRP layers than in the outer layers. Hence, the strength of composite pressure vessels is limited by the tensile strength of the innermost FRP layer.

Therefore, the following points are deemed necessary for improving the withstanding pressure of the vessels:

- Removal of bubbles from the FRP layers
- Prevention of loosening of the fibers
- Equalization of stress in the FRP layers with internal pressure

Improving the fiber density is necessary for the removal of bubbles from the FRP layers, and to do so, we must first increase the fiber tension. However, in the existing FW methods, the inner fiber layers collapse upon an increase in fiber tension, and loosening of the fibers is also observed. These issues must be addressed to improve the strength of the vessels.

2.2 *Proposed method*

We propose a method in which lamination and molding of vessels are carried out in such a way that the above-mentioned problems are not encountered. In this method, compressive stress is applied to the inner FRP layers and tensile stress is applied to the outer layers in the circumferential direction. Hence, a uniform stress distribution is obtained when the vessel is pressurized, and the strength of the FRP layers remains unaffected. Therefore, the vessel weight decreases to a considerable extent (Fig. 1).

The proposed method involves the following steps:

(a) Simultaneous layer-by-layer curing of the resin and winding of the resin-impregnated fibers around a liner

(b) Changing the fiber-winding tension in each layer

In step (a), a new layer is laminated on the cured FRP during continuous winding. Therefore, there is no fiber-winding-stress-induced loosening of the fibers in the inner layers, and a load is applied homogeneously to all the fibers. In addition, when steps

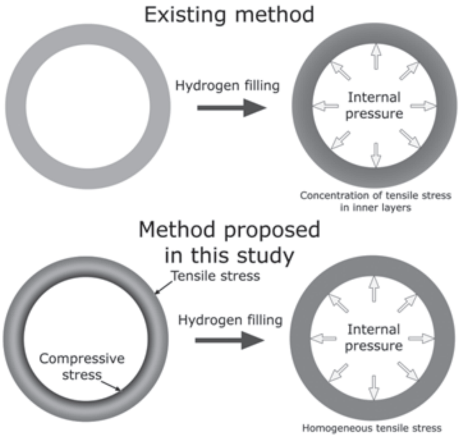

Fig. 1. Schematic representation of the proposed molding method.

(a) and (b) are executed simultaneously, the fibers are subjected to a uniform load and no fiber loosening is observed; this is because the resin is cured simultaneously during winding, even if the reinforced fiber tension gives rise to compressive stress in the FRP layers. Therefore, it is considered that compressive stress is induced in the FRP layers when the fiber tension in each layer is changed. In addition, although V_f (volume fraction of fibers) and the presence of internal defects have a marked effect on the reliability of the FRP, a high fiber tension can be applied because loosening of the fibers does not occur in the inner layers when step (a) is carried out. As a result, V_f increases, and the bubbles in the FRP layer, which are sources of cracks, are removed.

3. Composition of the Developed Machine

3.1 *Overview*

We have developed a machine for the above-mentioned FW. The developed machine is composed of the following components:

- A filament-winding-position controller with a frame construction that can be operated in three dimensions (traverse)
- A liner rotation unit for winding fibers around a liner
- A resin bath for impregnating fibers with the resin
- A heating unit for heating the liner and curing the resin
- A fiber-feeding device for applying a constant tension to the fibers
- A control device (a control panel and a PC)

The schematic of the machine is shown in Fig. 2, and the overall view is shown in Fig. 3. The specifications of this machine are listed in Table 1. The fibers withdrawn from the fiber-feeding device are allowed to pass through a guide aligned along the Z-axis and impregnated with the resin, and then, wound around a rotating liner. For curing the resin during the winding process, a high-temperature fluid is allowed to flow through the liner. Simultaneous control of all the axes can be achieved to control the fiber path.

3.2 *Traverse*

The traverse, which can be operated in three dimensions with the help of an XYZ stage, is a device used to control the fiber-feeding position when fibers are wound onto the liner. The device is controlled by AC servomotors for each axis. Two linear servomotors are used for control along the Y-axis because the span of the supporting section along this axis is long. Ball screws are used in a power transmission mechanism for the X- and Z-axes.

3.3 *Liner rotation unit*

The liner rotation unit is a device used to wind fibers by rotating the liner. It consists of two rotating shafts, a driving device, and a mechanism to connect the liner caps with each rotating shaft. The rotating shafts are hollow, and their edges are joined to the piping in the heating unit via rotatable joints. As a result, it is possible to rotate the liner while injecting and discharging a high-temperature fluid. Servomotors and a pulley are used for driving. To suppress the effect of heat, an air-cooling system that uses compressed air is installed in each bearing.

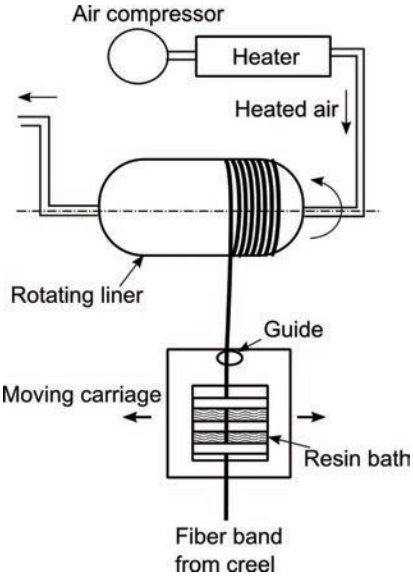

Fig. 2. Schematic of the FW machine.

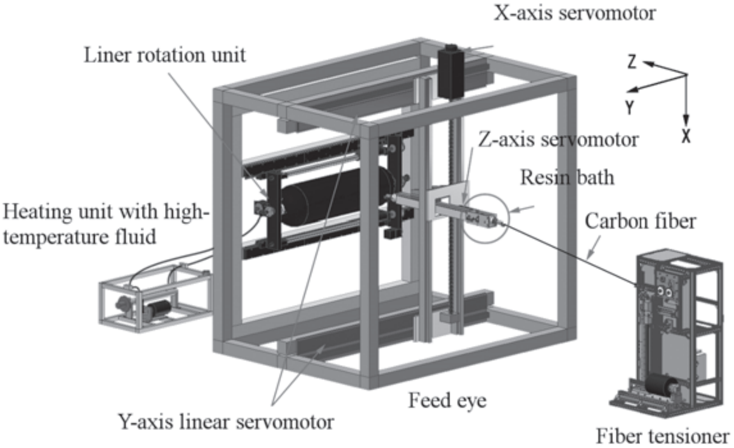

Fig. 3. Composition of the developed machine.

3.4 *Resin bath*

The resin bath is a system for impregnating fibers with the thermosetting resin used as the matrix resin. A roller is immersed in the resin bath. As it rotates, the roller comes in contact with the fibers, so that the fibers are coated with the resin. Excess resin is removed with a spatulate jig after the application process is completed.

Table 1
Specifications of the machine.

‹Traverse specification›	
Overall size	X: 2,895 mm, Y: 2,853 mm, Z: 2,126 mm
Stroke	X: 1,650 mm, Y: 1,650 mm, Z: 500 mm
Maximum velocity	X: 1,700 mm/s, Y: 1,000 mm/s, Z: 1,000 mm/s
Weight	1,600 kg
‹Liner rotation unit specification›	
Maximum velocity	500 rpm
‹Heating unit specification›	
Capacity	5 kW

3.5 *Heating unit*

The heating unit is a device used to heat and solidify the thermosetting resin. Heated fluid is injected into the liner and discharged through the piping. Compressed air is used for the fluid. The fluid temperature, pressure, and flow rate are measured with thermocouples, a digital pressure gauge, and a flow meter, and these are controlled with a thermal regulator, an electropneumatic regulator, and motor valves, respectively.

3.6 *Fiber-feeding device*

The fiber-feeding device is used to apply constant tension to the fibers. Stable tension can be applied with springs, load cells, servomotors, and a control PC, regardless of the change in the speed of drawing the fibers out.

3.7 *Control device*

The control device, which controls various components such as the traverse and rotating shafts, consists of a PC with a built-in board for control and a control board with a power supply unit, a servo amplifier. To identify and control the FW operations necessary for manufacturing the vessels, including hoop winding and helical winding, we have designed software that can be operated on a Windows PC. The degree of device movement can be calculated, and the operation can be provided to the controller by inputting the vessel liner shape data in a graphical user interface (GUI).

4. Verification of Machine Operation and Manufacturing of a Vessel for Trial Purposes

4.1 *Verification of laminating operation*

The laminating operation was verified using helical winding and hoop winding. The hoop winding was carried out by changing the laminating angle continuously after laminating with the helical winding. The conditions after lamination are shown in Figs. 4 and 5. It could be confirmed that uniform lamination was possible with each lamination method.

Fig. 4. Helical winding (16°).

Fig. 5. Hoop winding (laminated continuously after helical winding).

4.2 *Temperature survey of the heated liner*

We heated the liner with compressed air and measured the liner surface temperature. The liner used was made of aluminum alloy, and its outer diameter, axial length, and volume were 400 mm, 382 mm, and 73 L, respectively. The heating conditions used were an air flow rate of 800 NL/min and a preset heater temperature of 250°C. A thermal image analysis device was used to measure the temperature.

The results of the temperature measurement of each point on the liner after 1 h of heating are shown in Fig. 6, a graph of the heating time and the temperature on each measurement point is shown in Fig. 7, and the relationship between the temperature and the curing time of the epoxy resin is shown in Fig. 8. It is understood that the resin is cured within 40 min after lamination as the temperature at each measurement point becomes 80°C or higher after heating for 40 min or longer. Moreover, it is shown that the temperature at each measurement point is almost uniform within the range of ±5°C after the temperature became steady.

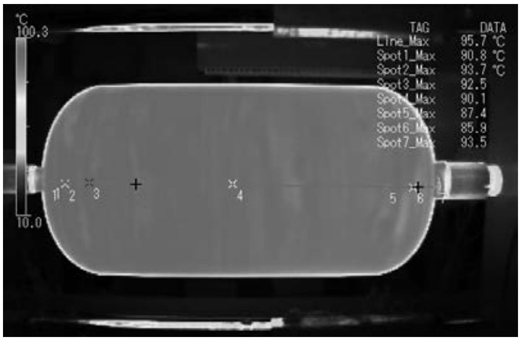

Fig. 6. Temperature at each measurement point on the liner after 1 h of heating.

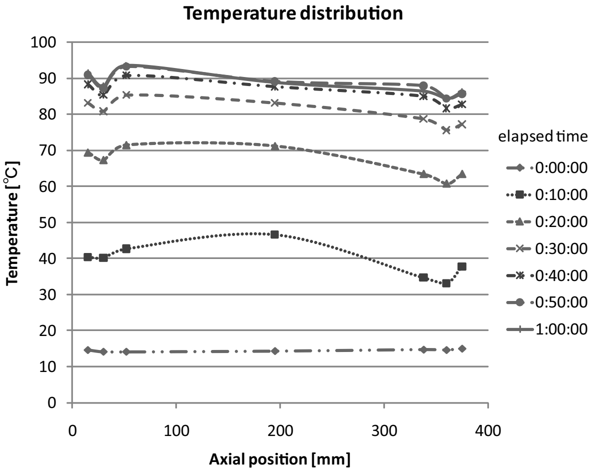

Fig. 7. Relationship between heating time and temperature at each measurement point.

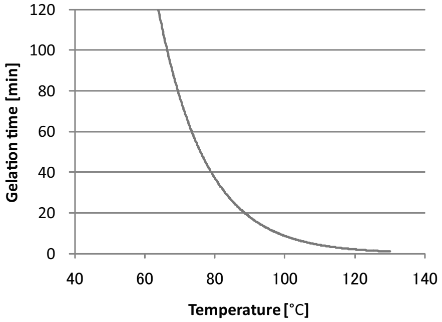

Fig. 8 Relationship between temperature and curing time of the resin used in this study.

4.3 *Production of trial vessels by a combination of various lamination patterns*

We produced a trial CFRP composite vessel consisting of 42 ply by combining helical winding and hoop winding at two or more angles. It was confirmed that the layers could be laminated continuously and that the resin could be cured.

5. Comparison with Existing Manufacturing Method

5.1 *Tensile test*

We measured and compared the incidence of the elastic modulus and V_f by conducting a tensile test on all four CFRP specimens, which were cut out from a trial vessel and from a vessel made by an existing manufacturing method (Fig. 9).

Table 2 shows the results of the tensile test. The V_f value and achievement ratio of elastic modulus of the trial vessel were 1.6 and 4.4% higher than those of an existing

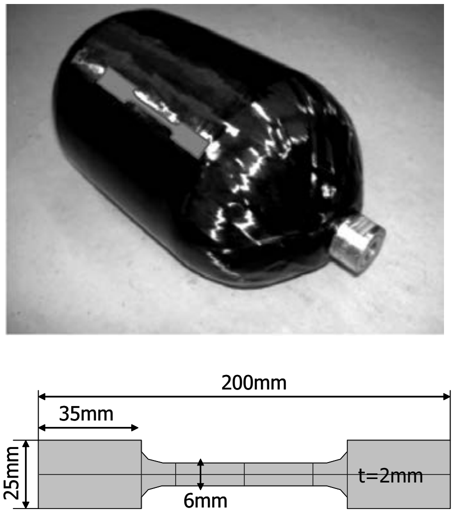

Fig. 9. Specimen for the tensile test.

Table 2
Results of the tensile test.

	Cross-sectional area (mm^2)	V_f (%)	Elastic modulus (GPa)		Achievement ratio of elastic modulus (%)
			Experimental	Calculated	
Trial vessel	13.6	53.6	50.2	64.0	78.4
Existing vessel	13.4	52.0	43.2	58.4	74.0

vessel, respectively. These values affect the deformation tendency of the CFRP and, therefore, the fatigue of the liner can be reduced.

5.2 *Cross-sectional observation*

We observed the normal-to-axial cross sections of the CFRP specimens. The cross section of the CFRP in the trial vessel produced in this study is shown in Fig. 10, and the section of the CFRP in an existing vessel is shown in Fig. 11. The number of voids between the layers in the trial vessel was smaller than that in the case of the existing vessel.

5.3 *Burst test*

We manufactured three CFRP composite vessels for trial purposes using the developed machine, and we conducted a burst test with hydraulic pressure. The specifications of each vessel are shown in Table 3. A graph of the results of the burst test is shown in Fig. 12. In the graph of Fig. 12, the intensity ratio is the standardized value from the burst pressure and the CFRP weight, and the intensity ratio of an existing vessel is assumed to be 100%. Because a different fiber was used in vessel No. 1, the intensity ratio was converted by assuming that the same amount of the same fiber as an existing vessel was used. The intensity ratio of the trial vessel (112–139%) was considerably higher than that of an existing vessel.

6. Conclusions

Lamination of CFRP composite vessels results in a decrease in CFRP strength and an excessive resin accumulation due to fiber tension. To address these problems, we developed a machine that can be used for molding CFRP layers by heating them from the interior of a liner with the help of a high-temperature fluid. Below is a summary of our study.

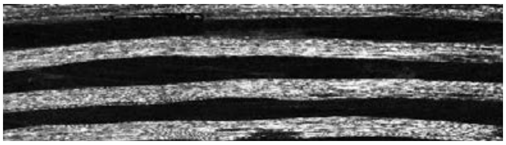

Fig. 10. Axial cross section of CFRP in the trial vessel.

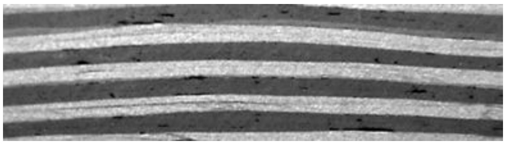

Fig. 11. Axial cross section of CFRP in an existing vessel.

Table 3
Specifications of vessels manufactured for trial purposes.

	No. 1	No. 2	No. 3
Volume	9.3 L		
Fiber	T700SC (σ_B = 5,280 MPa, E = 231 GPa)	MR35E (σ_B = 4,410 MPa, E = 295 GPa)	
Laminated constitution	16.3°×14, 23°×8, 77.1°×2, 85.7°×8, hoop×10	16.3°×10, 18.8°×4, 20.5°×2, 22.1°×2, 23.7°×2, 77.1°×6, 85.7°×6, hoop×12	16.3°×10, 18.8°×4, 22.1°×2, 25.5°×2, 28.8°×2, 77.1°×6, 85.7°×2, hoop×20
Design pressure	191 MPa	179 MPa	183 MPa
Hoop strength ratio vs design pressure	100%	101%	100%
Axial strength ratio vs design pressure	192%	153%	147%

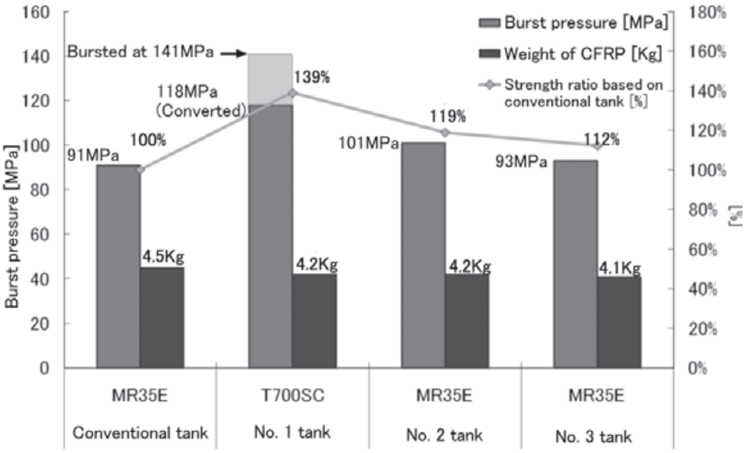

Fig. 12. Results of the burst test.

1. We proposed a method of manufacturing composite vessels to control the internal stress of the CFRP composite and improve the CFRP strength by simultaneous curing during the filament winding process. We developed an FW system with a heating unit that uses a high-temperature fluid. The above-mentioned method is applicable with the FW system.
2. Using the developed machine, we could carry out uniform lamination by a combination of two different lamination patterns (helical and hoop).
3. We conducted a test in which an aluminum-alloy liner was heated by high-temperature air and confirmed that uniform heating was possible.

4. Using our machine, we produced trial CFRP composite vessels by a combination of two or more winding patterns. Simultaneous lamination and curing of the CFRP multilayer could be carried out when heating the liner by the high-temperature fluid.
5. The CFRP characteristics in the case of the trial vessel produced using the developed machine were compared with those in the case of an existing vessel. The results revealed that the V_f value and achievement ratio of elastic modulus of the trial vessel were 1.6 and 4.4% higher than those of the existing vessel, respectively; moreover, there was a decrease in the number of voids between the CFRP layers in the case of the trial vessel.
6. A burst test was carried out to compare the burst pressure of the trial CFRP composite vessel with that of an existing vessel. The intensity ratio of the trial vessel was 112–139%, which was much higher than that of the existing vessel; moreover, the strength of the trial vessel was improved to a considerable extent.

Acknowledgments

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