

Technology for High-speed Manufacturing of High-pressure Hydrogen Tank by 14-axis Simultaneous Control Filament Winding Machine

Koei FUJIKI¹Kenta UMETSU, Ph.D.¹Kosuke TATSUSHIMA¹Andreas REIMANN²Masaru NAKANISHI¹

ABSTRACT

In the interest of reducing the cost of high-pressure hydrogen tanks, a 14-axis simultaneous control filament winding system was developed that shortens the filament winding process time and stabilizes tank pressure strength.

To accelerate the process, a mechanism capable of high-speed helical tumble winding was adopted, speeding up the process to approximately five times the conventional carbon fiber feeding speed. With the increased speed, a reservoir was implemented to keep the machine's band path distance constant at all times, allowing for reduced band tension fluctuations in winding. In addition, feed rollers capable of widening tow prepreg for feeding at a stable bandwidth were developed, along with a control method for the rollers, to help enhance carbon fiber reinforced plastic laminate quality. Upon studying the cost reduction effects of the increased speed, the machine was configured for dual head filament winding.

As a result, process time was reduced by approximately 80% compared with the conventional process, and the effectiveness of the machine was confirmed to reduce variance in pressure resistance for the high-pressure hydrogen tanks.

1. Introduction

The spread of fuel cell vehicles (FCVs) using hydrogen as fuel is expected to help in achieving a carbon-free society. An important component of FCVs is their high-pressure hydrogen tanks. For FCVs to spread in the future, it will be important to build manufacturing technologies that reduce costs with stable production quality in order to help guarantee the safety of high-pressure hydrogen tanks.

Vehicle high-pressure hydrogen tanks are dominated by 70-MPa type 4 vessels⁽¹⁾. As seen in the sectional view in Fig. 1, type 4 tanks comprise a plastic liner to seal in the enclosed hydrogen gas, a boss for device connection, and a multiple layer laminate of carbon fiber reinforced plastic (CFRP) to reinforce the outer surface of the liner. The CFRP layer is molded through filament winding (FW), a process that involves winding and then thermosetting a band of carbon fibers impregnated with an epoxy resin onto the resin liner. Given the high-pressure resistance and durability required of high-pressure hydrogen tanks, the liner is wound with dozens of layers of CFRP. The filament

winding process takes time, which greatly affects the cost of hydrogen tanks⁽²⁾.

In order to help enhance productivity, Honda has jointly developed a new high-speed multi-axis filament winding machine with high degrees of freedom together with Roth Composite Machinery. This machine is capable of world-

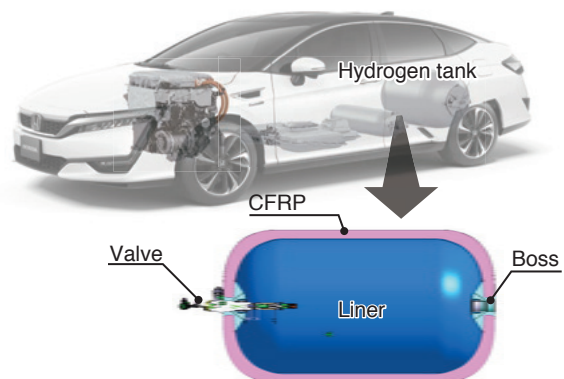


Fig. 1 Type 4 high-pressure hydrogen tank

¹ Innovative Research Excellence

E-mail: koei_fujiki@jp.honda

² Roth Composite Machinery GmbH

class filament winding speeds, reducing winding time by approximately 80% from the conventional process for filament winding machines. In addition, the process achieves a stable CFRP laminate quality, which can be an issue for high-speed filament winding. Therefore, the technology will be introduced here.

2. Development Goals for High-speed Filament Winding Machine

Figure 2 shows the methods used for winding the carbon fiber bands in filament winding for high-pressure hydrogen tanks. Hoop winding is used to wrap the cylinder to help ensure strength around the tank circumference, and helical winding is used to reinforce the tank dome. Helical winding is classified into high- and low-helical winding according to the winding angle. A currently popular filament winding machine is shown in Fig. 3. In low-helical winding, the band feeding speed fluctuates as the delivery head needs to reciprocate in the Y-axis direction of the filament winding machine in the figure. The band winding tension fluctuates due to acceleration and deceleration of the band, and large changes in tension will impact tank pressure strength. Thus, the inability to speed up low-helical winding is one issue in the filament winding process. As shown in Fig. 4, low-helical winding takes up approximately three-quarters of the total molding time.

Another issue in the filament winding process is with wet filament winding, in which the carbon fiber band is impregnated with epoxy resin before winding. Using this

method, the resin can be scattered when winding at high speed, or resin flow can occur in the CFRP layers when spinning the tank⁽³⁾. By contrast, high-speed winding is possible with dry filament winding, which uses tow prepreg, a tow (carbon fiber bundle) that comes preimpregnated with high-viscosity epoxy resin. However, to date, dry filament winding has presented issues in maintaining uniform tow prepreg bandwidth and thickness during tank winding, making it a challenge to achieve a uniform CFRP laminate quality. Where this has resulted in decreased pressure strength, measures such as winding more CFRP layers were necessary.

Thus, speeding up the filament winding process for high-pressure hydrogen tanks requires the following two technologies:

- (1) Faster low-helical winding with more stable tensioning
- (2) High-speed tow prepreg delivery and high-quality lamination

In response, the machine answers these two technical needs with the following three new technological developments:

- (1) A 14-axis simultaneous control high-speed filament winding machine capable of high-speed low-helical winding
- (2) Simultaneous multiple-filament winding technology for multiple tow prepreps, compatible with a new control high-speed filament winding machine
- (3) Bandwidth stabilization technology for tow prepreps

Each development will be described in order in the sections to follow.

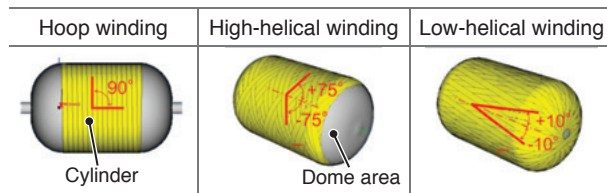


Fig. 2 Various filament winding methods

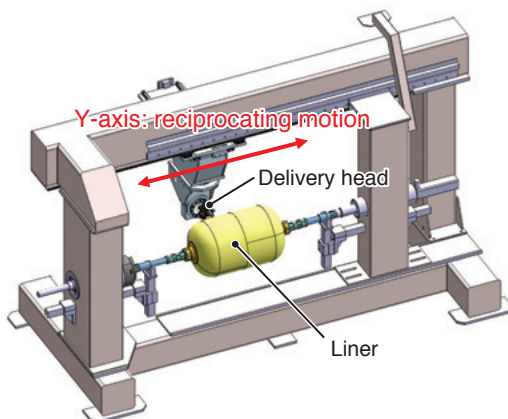


Fig. 3 Conventional FW machine

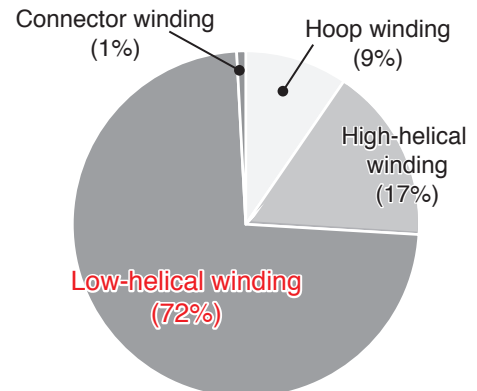


Fig. 4 Proportions of total FW time by winding method

3. Development of 14-axis Simultaneous Control Filament Winding Machine

3.1. Development of High-speed Helical Tumble Winding

3.1.1. Machine mechanism enabling tumble winding

The filament winding machine jointly developed with Roth Composite Machinery is shown in Fig. 5. The

machine has a high degree of freedom thanks to the 14-axis system outlined in Table 1. The machine has two creel stands for delivery from bobbin-shaped tow preregs, with tow prepreg fed from the stands along two band paths. Each band path is controlled by the system across 6 axes (Y-axis, Z-axis, U-axis, V-axis, W-axis, and I-axis).

The liner mounted to the filament winding machine adds a tumble axis (C-axis) to the rotation axis (X-axis) on conventional machines, allowing it to rotate on two axes. As shown in Fig. 6, low-helical winding allows for band winding while tumbled, with the band winding speed kept constant by maintaining a constant C-axis speed. However, even at a constant band winding speed, operating the delivery head will make the band path distance fluctuate, in turn fluctuating the band feed speed in the band path, as shown in Fig. 7. Fluctuations in the band feed speed may cause tension fluctuations, which impact tank pressure strength. Therefore, in order to keep tension constant throughout the filament winding process, the band path distance needs to be kept constant.

Table 1 Functions of each axis of FW machine

Axis	Function	Number of axes
C-axis	Mandrel tumble	1
X-axis	Mandrel drive	1
Y-axis	Horizontal carriage	2
Z-axis	Horizontal cross carriage	2
U-axis	Rotating pay-out eye	2
V-axis	Horizontal swivel axis	2
W-axis	Vertical carriage	2
I-axis	Reservoir	2

In the newly developed filament winding machine, reservoirs (I-axis) have been installed in between the tank winder and creel stands to maintain a constant band path distance (Fig. 8). This machine mechanism reduces band tension fluctuation, as shown in Fig. 9, allowing revolutionary high-speed helical tumble winding.

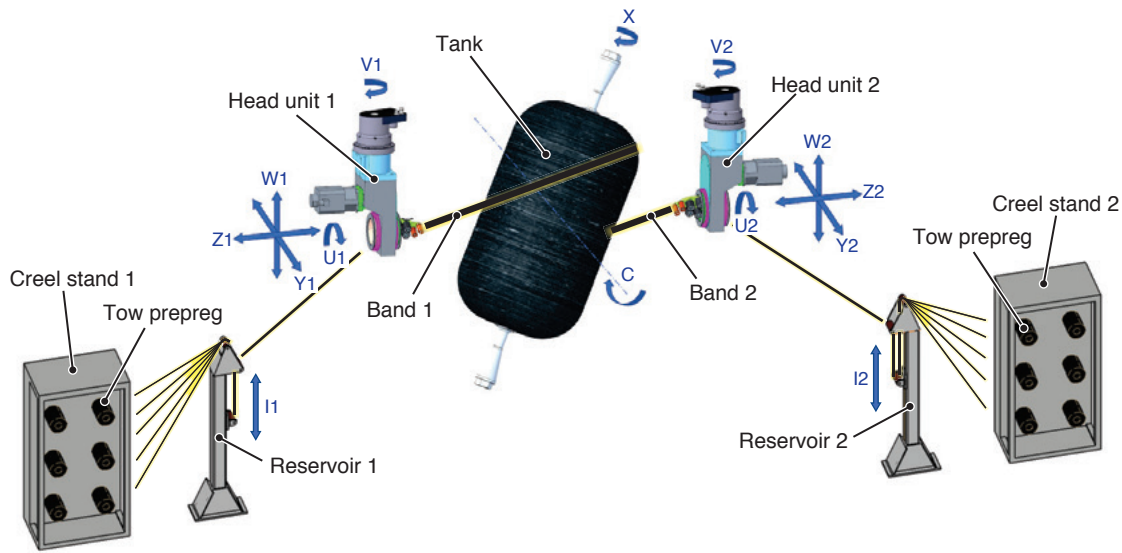


Fig. 5 14-axis simultaneous control FW machine

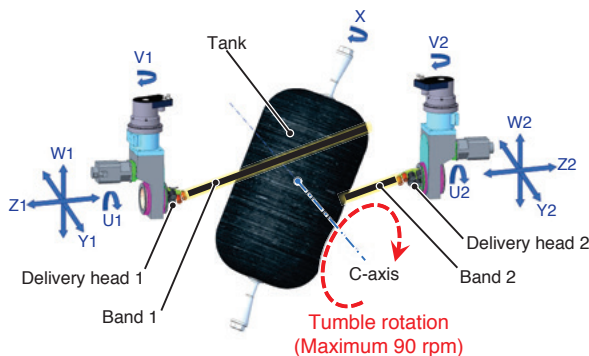


Fig. 6 High-speed helical tumble winding

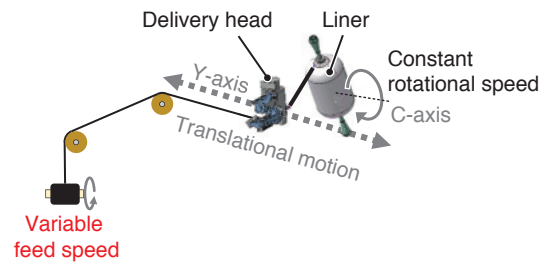


Fig. 7 Velocity change due to change in band path distance

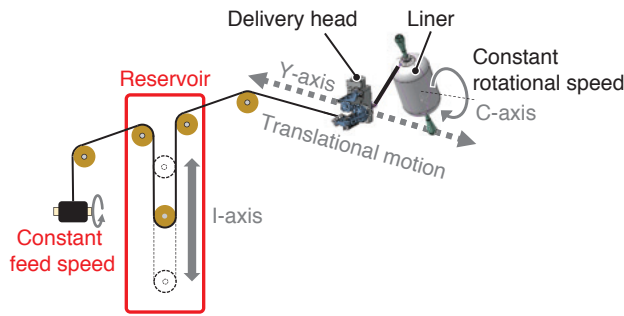


Fig. 8 Reservoir installed in FW machine

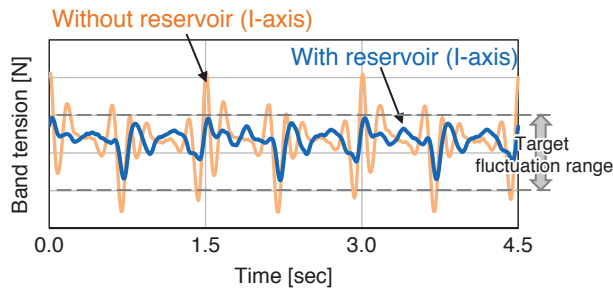


Fig. 9 Effect of reservoir on band tension stability

3.1.2. Reservoir control (I-axis) and higher winding speed

Helical winding in the machine is accelerated by high-speed rotation along the tumble axis (C-axis). The machine needs to feed the band along the band path at speeds corresponding to the liner rotational speed under high-speed tumbled rotation. The control method using the reservoir (I-axis) described above is important to achieving high-speed delivery at a stable tension. In the feedback control initially assumed, maintaining steady control was not easy. The band path distance fluctuated greatly at high speeds, and there was no control designed to respond to those fluctuations. Thus, an additional control was implemented to employ feed-forward control. A Honda proprietary computational algorithm estimates band path fluctuation to high precision, and I-axis motion is configured to correspond with the estimated fluctuation. With this, the fluctuations in tension were kept to no greater than the fluctuations for helical winding on a conventional filament winding machine for high-speed helical tumble winding at rotation speeds of up to 90 rpm. Band feeding speeds for helical winding on the developed filament winding machine are approximately five times conventional band feeding speeds.

3.2. Multi-filament Winding

3.2.1. Examination of number of delivery heads

To further reduce the time required for the filament winding process, a multi-filament process was examined. Simultaneous feed of bands from multiple locations can

shorten filament winding time. However, multi-filament winding creates constraints on the CFRP laminate design.

Multi-filament winding impacts CFRP laminate design as follows. In CFRP laminate design, the filament winding parameters considered are the number of cycles and coverage rate. The number of cycles is how many cycles the band is wound around the liner to form one layer. The coverage rate is the ratio of the total surface area of actual band as wrapped relative to the total surface area of the tank cylinder. If there are gaps between bands and the entire cylinder is not covered, the coverage rate will be less than 100%. Coverage rates of less than 100% decrease tank pressure strength. Therefore, in CFRP laminate design, the number of cycles needed to keep the coverage rate of each layer at 100% or higher is determined. In the interests of reducing CFRP weight and shortening filament winding process time, preferably, the minimum number of cycles to achieve a 100% coverage rate will be selected. As the number of cycles for multi-filament winding is multiplied by the number of band feeds, this limits the number of cycles that can be selected in the laminate design and can be an issue that the minimum number of cycles to achieve a 100% coverage rate cannot be selected. Thus, multi-filament winding can lead to increased CFRP weight.

With that, CFRP laminate designs were performed with between one and four band delivery heads, calculating the CFRP weight and process time for each case. The results are given in Fig. 10. In the calculations, the number of cycles needed to achieve a 100% coverage rate was determined for each number of delivery heads. With the CFRP weight of a single head as the baseline, CFRP weight increased by 2% with two heads and by 10% with four heads.

Figure 10 also shows the relationship between the number of delivery heads and time required for the filament winding process. The time required for filament winding was estimated for the CFRP weight at each number of delivery heads as calculated above, then calculating the rate of reduction in process time compared with a single head. It was found that process time could be reduced by 44% using two heads, and by 65% using four heads.

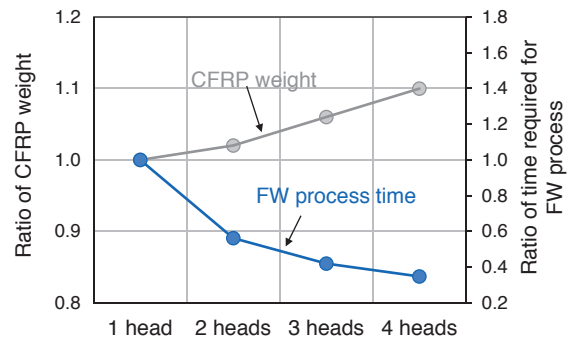


Fig. 10 Effect of the number of delivery heads on CFRP weight and FW process time

Based on the estimates of CFRP laminate weight and filament winding process time from using multi-filament winding, the impacts on hydrogen tank cost were examined. Figure 11 shows the cumulative estimated CFRP material costs and filament winding manufacturing costs per hydrogen tank for each number of delivery heads. At three or more delivery heads, the cost reductions from shortening filament winding time are outweighed by cost increases due to increased CFRP weight, meaning that cost is lowest at two heads. Therefore, the newly developed filament winding machine was configured for dual head filament winding.

3.2.2. Dual head filament winding machine enabled for tumbling

To perform high-speed helical tumble winding from dual bands, the two band delivery heads 1 and 2 need to be arranged on opposing sides and operated in point symmetry with the tank in the center, as shown in Fig. 6. This arrangement is effective in reducing head interference and band crossing during filament winding. With tumble winding speed five times faster than conventional speeds and the dual heads, the combination allows for high-speed helical winding at approximately 10 times the speed of conventional filament winding machines, and high-speed helical tumble winding is still stable even with the dual heads.

3.3. High-quality Lamination of Tow Prepregs

3.3.1. Tow prepreg widener mechanism

In the development of a 14-axis simultaneous control filament winding machine to enable high-speed filament winding, it is also important that the tow prepregs used for high-speed feeding are laminated at a high quality. High-quality lamination requires that the tow prepreg be widened before winding. However, the filament winding process in which the tow prepreg is used applies tension to the tow prepreg, making the filament bundle shrink in width. Comprising high-viscosity epoxy resin, bundles will keep their shape once shrunk, and thus widening a tow prepreg once shrunk is no simple task. For this reason, a tow prepreg

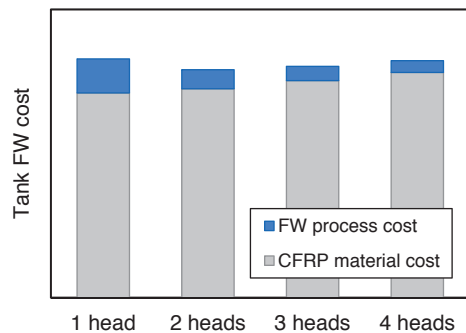


Fig. 11 CFRP material cost and FW process cost by number of delivery heads

widener mechanism with the following characteristics was installed in the band feed port of the filament winding machine⁽⁴⁾:

- (1) Heaters inserted in the rollers to heat the roller surface
- (2) Roller surfaces given multiple convex ridges at equal intervals in the axial direction
- (3) Multiple rollers equipped in the feed direction

Each of these characteristics is shown in Fig. 12.

First, in order to stabilize and widen the tow prepreg, the roller surfaces are heated to heat the tow prepreg as it contacts the rollers. This reduces the viscosity of the epoxy resin, lowering the holding strength of the filament. Multiple rollers are installed to help ensure more contact time with the rollers even with high-speed feeding and heat the tow prepreg to the required temperature. Next, surface pressure is applied to the entire tow prepreg by the axially convex roller surface to widen the prepreg. With the narrow interval between convex ridges on the rollers, the convex ridges are able to apply continuous surface pressure to the filament bundle before it shrinks in width, thereby suppressing band shrinkage in the width direction.

Using the widener mechanism as described here widened tow prepregs by more than 50% compared with their width before passing through the widener mechanism.

3.3.2. Stable control for tow prepreg bandwidth

In order to wind the expanded tow prepreg around the liner at a stable bandwidth without it shrinking, the position and attitude of the band feed port are controlled. If the band is twisted at a distance from the feed port to the liner winding point, the band will shrink. Thus, it is necessary to match the sectional attitude of the band at the liner winding point with the sectional posture at the feed port. Especially in helical winding, the band sectional attitude will change dynamically on the curved surface of the dome. To accommodate the dynamic changes of the curved surface, the band feed port requires two degrees of freedom for translational motion and three degrees of freedom for rotational motion. The band feed for this machine has a mechanism that allows motion in the above five degrees

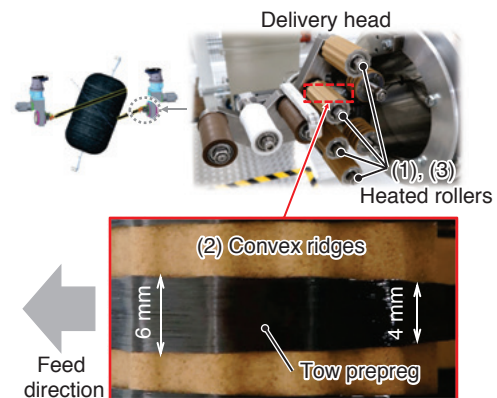


Fig. 12 Tow prepreg widener mechanism

of freedom. By controlling the position and attitude of the band feed port through the five degrees of freedom while winding the tow prepreg, the high-quality dome shown in Fig. 13 was successfully laminated at a stable bandwidth.

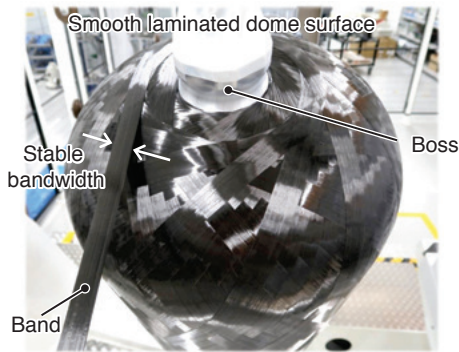


Fig. 13 Lamination quality at dome

4. Reductions in Filament Winding Process Time

Due to the high-speed helical tumble winding and dual heads, the time required for the filament winding process to manufacture a high-pressure hydrogen tank with the 14-axis simultaneous control filament winding machine was reduced by approximately 80% compared with a conventional filament winding machine. Table 2 shows the size, volume, and CFRP weight of filament-wound tanks and filament winding time with the new machine. Tank A is a high-pressure hydrogen tank shorter in length and larger in outer diameter, assuming installation behind the rear seatback of the FCV. Tank B is greater than 1 m in length with a smaller outer diameter, assuming applications for installation in the center tunnel of FCVs or for commercial FCVs. For both tank sizes, the CFRP filament winding speed was 1.69 kg/min.

5. Verification Results for Tank Pressure Strength

Table 3 gives a comparison of burst pressure stabilities between two 120-L tanks: the first manufactured by a conventional filament winding machine using wet filament winding, and the second manufactured by the developed high-speed filament winding machine using dry filament winding with tow prepreps. Stability was evaluated using the coefficient of variation (standard deviation/average) as an index. The same lot of carbon fiber was used to manufacture the two tanks.

By using filament winding tension-fluctuation control technology, a tow prepreg widener mechanism, and feeds with stable bandwidth, pressure strength (burst pressure) variation was reduced to one-fifth compared with conventional manufacturing methods.

Table 2 Results for high-speed FW production

	Tank A	Tank B
Tank length [mm]	915	1120
Tank diameter [mm]	530	435
Tank volume [L]	120	102
CFRP weight [kg]	48.9	42.2
FW process time [min]	29	25
Average FW speed [CFRP kg/min]	1.69 (0.26)	1.69 (0.31)

() : Conventional Wet-FW speed

Table 3 Results of burst pressure stability of 120 L tanks

	Conventional FW (Wet-FW)	High-speed FW (Dry-FW)
Coefficient of variation of burst pressure (standard deviation / average)	0.059	0.012

6. Conclusions

In this paper, we described a 14-axis simultaneous control filament winding machine enabling high-speed helical tumble winding with dual delivery heads in the interest of achieving high-speed filament winding manufacturing and high-quality lamination for high-pressure hydrogen tanks.

- (1) We introduced the structure of a newly developed 14-axis simultaneous control filament winding machine capable of high-speed helical tumble winding with dual delivery heads.
- (2) High-speed filament winding tension-stabilization technology, tow prepreg widening technology, and band feed port control technology were applied to the machine for stable lamination.
- (3) The machine reduced the time required for the filament winding process by approximately 80%, achieving world-class filament winding speeds.
- (4) This development also confirmed that variances in tank pressure strength due to manufacturing impacts could be reduced to one-fifth the conventional values.

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■ Author ■



Koei FUJIKI



Kosuke TATSUSHIMA



Masaru NAKANISHI



Kenta UMETSU



Andreas REIMANN