

Development of Gap Mold Technology for RTM of CFRP Parts

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ABSTRACT

A mold structure making it possible to conduct gap resin transfer molding (RTM), a method that reduces the internal pressure of the mold during molding of carbon fiber reinforced plastics (CFRP) parts, using standard hydraulic pressing equipment with no position control function has been developed. Gas springs have been employed in order to maintain the necessary fixed gap in the mold from the vacuum process to the resin injection process. In addition, a specialized seal shape able to withstand both the negative pressure produced during the vacuum process and the positive pressure produced during the resin filling process was also developed. The results of gap RTM using a mold applying these technologies demonstrated that they made it possible to both realize reduced internal mold pressure and produce a good quality molded part even in the case of a large part (a lower dashboard).

1. Introduction

Today, the realization of increased automotive fuel efficiency is an urgent task as a means of responding to environmental issues. The achievement of automotive weight savings is a focus of attention as one method of increasing fuel efficiency. The use of carbon fiber reinforced plastics (CFRP), which are lightweight and high-strength materials, has been taken up as a means of realizing this goal. However, manufacturing costs are high for CFRP parts, not only due to the cost of the materials, but also because the molding cycle time may be from several minutes to several hours. Due to this, the application of CFRP has been restricted to small-lot parts for use in such applications as racing cars and airplanes, in which light weight is demanded even if it entails high costs. In order for the material to be applied in automotive parts, a manufacturing method making it possible to supply parts in high volume at low cost would be necessary⁽¹⁾. Resin transfer molding (RTM), which is capable of continuous molding and offers a variety of choices in terms of shape, provides prospects as one such method.

Figure 1(a) shows an overview of the resin transfer molding process^{(1),(2)}. First, preformed sheet fibers are set in a metal mold. A vacuum is generated in the mold in order to promote resin impregnation and help control the occurrence of air voids. Next, liquid resin is injected into the mold and

impregnated into the fibers. Following heating and curing, the product is removed from the mold. Methods of reducing RTM cycle time in order to reduce costs are available. Increasing the speed of resin injection during the molding process is one such method. However, high-speed injection of resin into a closed mold increases the internal pressure of the mold, making it necessary to employ specialized equipment capable of high-pressure resin injection⁽³⁾. In addition, as parts become larger, the injection pressure increases, and the load required for pressing also increases. As this indicates, the capabilities demanded from injection equipment and pressing equipment increase equipment costs, and it is challenging to realize cost-effectiveness when reducing RTM cycle time.

Against this background, gap RTM has been proposed as a method of reducing the internal pressure of the mold^{(4),(5)} [Fig. 1(b)]. In the gap RTM process, resin is injected with a gap set between the upper and lower molds. The fibers are impregnated with resin during the pressing process, and the entire mold is filled. Even if high-speed injection is performed using this method, the internal pressure of the mold does not increase, and RTM cycle time can therefore be shortened even for large parts. However, it is necessary to control the size of the gap when using this method, and this necessitates the use of high-cost equipment capable of position control, for example servo-press equipment. It was considered that equipment costs could be reduced if it were

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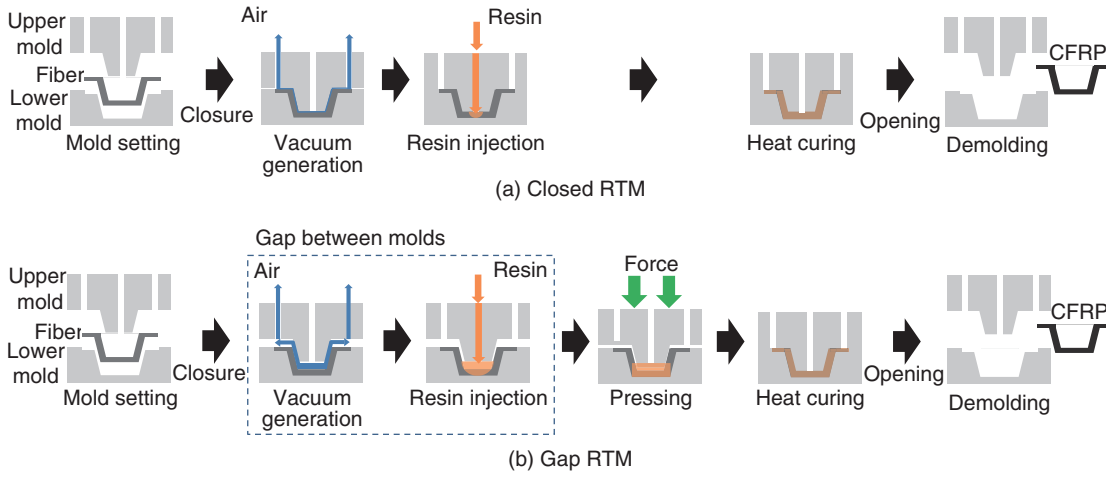


Fig. 1 RTM process

possible to implement gap RTM using hydraulic pressing equipment employed in conventional resin molding.

This paper reports on a mold technology that reduces the internal pressure of the mold during gap RTM by using conventional equipment.

2. Concept of Manufacturing Method

In the conventional RTM process, resin is injected into a mold in which preformed sheet fibers have been set. These fibers resist the flow motion of the resin. The creation of a space for the flow of the resin eases this resistance, reducing the pressure in the mold. Based on this concept, it was considered that the application of gap RTM would make it possible to reduce the resin injection period.

The relationship between resin flow velocity and pressure can be expressed as Eq. (1), based on the Hagen-Poiseuille law, which applies to the flow of viscous fluids through cylindrical pipes of fixed diameter.

$$Q = (\pi a^4) / 8 \times \Delta P / \mu l \quad (1)$$

Q : Flow rate; a : Pipe radius; ΔP : Pressure gradient; μ : Fluid viscosity; l : Pipe length

If the injection flow rate per unit time, Q , is increased in order to reduce molding time, the pressure gradient, ΔP , increases as shown in Eq. (2).

$$\Delta P / l = Q \times \mu \times 8 / \pi a^4 \quad (2)$$

The pressure gradient is proportional to viscosity, μ , and inversely proportional to the pipe radius, a , to the fourth power. Because the cross-sectional area of the flow motion can be increased via the gap between the upper and lower molds in gap RTM, this method can increase injection rate per unit time. This makes it possible to reduce the internal

pressure of the mold and injection time.

In the case of RTM, Darcy's law, as shown in Eq. (3), is almost always applied in studies of resin impregnation.

$$Q = \frac{-kA}{\mu} \frac{\Delta P}{L} \quad (3)$$

Q : Flow rate; k : Permeability; A : Cross-sectional area; ΔP : Pressure gradient; μ : Fluid viscosity; L : Flow distance

Logically, fiber density is zero in the gap section, and this section therefore may not suit the application of Darcy's law. However, taking into consideration the results of studies using, for example, the Navier-Stokes equation in combination with Darcy's law⁽⁶⁾, it can be considered that the permeability value of the gap section employed when Darcy's law is applied is between 1/100th and 1/1000th the value for the fiber section considered from Darcy's law.

During the vacuum generation process, a force equivalent to the vacuum pressure multiplied by the projected area of the mold is exerted in the direction of closure of the mold, and the gap tends to diminish. Due to factors such as the position control function of the hydraulic press machine and the rigidity of the mold affecting the precision of the gap, equipment costs are prone to increase. The research discussed in this paper therefore focused on a mold structure using spring response force.

The study set the target of maintaining any arbitrary gap for the 120 sec necessary for the vacuum process.

In addition, it is necessary for the seals in the molds employed in RTM to possess two performance capabilities: the ability to withstand both the negative pressure generated during the vacuum process, and the positive pressure generated during the resin filling. Conventional RTM is able to respond to both vacuum pressure and resin pressure via a seal structure that displays these performance capabilities

when flattened during pressing [Fig. 2(a)]. In the case of gap RTM, a shear-edge seal structure is conventionally employed⁽⁷⁾ in order to help ensure that seal performance demands are satisfied both when there is and when there is not a gap in the mold [Fig. 2(b)]. A shear-edge structure makes it possible for the seal to satisfy performance demands irrespective of the gap magnitude, but a high level of precision is necessary in the mold in order to help ensure seal performance. In addition, because the area in which the seal can be positioned is restricted to the outer circumference of the mold, the size of the mold increases.

The research discussed in this paper focused on a seal using the same groove structure as the seals employed in conventional RTM, but with a shape making it possible to be employed in gap RTM. Target conditions for the seal were set for two stages: the vacuum process and the pressing process following resin injection. The condition for the vacuum process was the ability to maintain a gap of 5 mm with a mold internal vacuum of 5 kPa or below for 120 sec. This gap magnitude was set with spring-back consideration of the preformed sheet fibers. The condition for the pressing process was the ability to maintain a resin pressure of 8 MPa for 120 sec. This resin pressure represented an upper limit value calculation based on the projected part size and the capacity of the pressing equipment; the time for pressure maintenance was the necessary time for the pressing process.

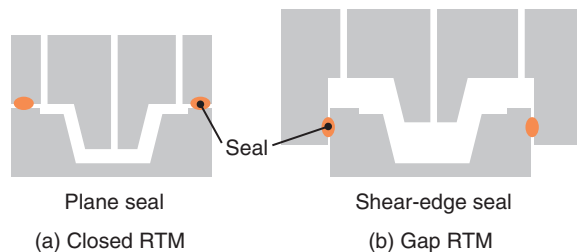


Fig. 2 Difference in seals for closed RTM and gap RTM

3. Stabilization Test of Gap during Vacuum Generation Process

3.1. Test Set-up

Figure 3 shows an image of the gap magnitude and the molding procedure in the gap RTM process. It is necessary for the springs to possess a stroke that will resist the force acting to close the mold during the vacuum process and maintain the gap at a fixed magnitude, and that will allow a gap of 0 mm to be reached when the load exerted by the pressing equipment is applied during the pressing process.

Gas springs were therefore employed. By adjusting the gas sealed inside a gas spring, it is possible to freely set the initial load at which the stroke commences. Multiple gas springs were set in the mold. By setting the sum of their initial loads at a level higher than the force acting to close the mold, it was possible to maintain the gap at a fixed magnitude. In addition, because this method makes it possible to exert a high load despite a compact size, it is suited for application in molds in which space is limited.

For these tests the load-stroke curve for the mold was set as shown in Fig. 4.

3.2. Test Results

The gap maintenance performance of gas springs was verified using an actual RTM mold. Using hydraulic pressing equipment without a position control function, changes in the gap magnitude from a gap of 5 mm were measured when a vacuum was generated in the mold. The results are shown in Fig. 5. When gas springs were not employed, the gap became progressively smaller. After 120 sec of the vacuum process had elapsed, the gap was less than 1 mm, and the mold had completely closed in another approximately 40 sec. This demonstrated that it was not possible to maintain the gap using standard hydraulic pressing equipment. By contrast, when gas springs were employed, a gap of 5 mm was maintained even after 120 sec, demonstrating the gap maintenance performance of gas springs.

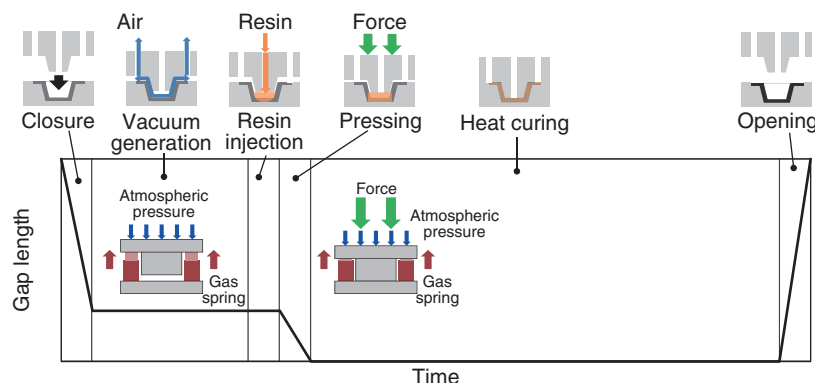


Fig. 3 Gap RTM cycle

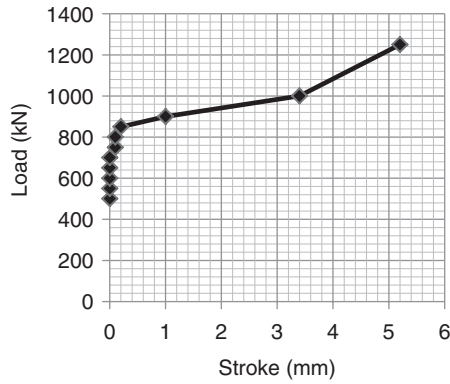


Fig. 4 Relationship between load and stroke for gas spring

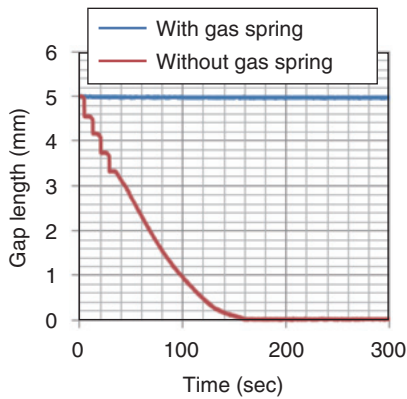


Fig. 5 Relationship between gap length and time during vacuum generation process

4. Proposal of Seal Structure and Test Results

4.1. Test Set-up

Figure 6 shows the concept for the seal shape able to be employed in gap RTM. This seal shape maintains the seal groove shape used in the seals employed in conventional RTM molds. The seal shape used in conventional RTM, (i), does not make contact with the mold at a gap of 5 mm. The seal shape produced when this solid seal is extended by the extent of the gap, (ii), does not fit within the seal groove when the mold is pressed. Given this, O-ring design^{(8), (9)} was used as a reference in proposing a hollow seal shape, (iii), with the aim of realizing a seal that made contact with the upper and lower molds even at a gap of 5 mm, and which progressively deformed under the load during the pressing process, until it finally fitted inside the seal groove. Silicon rubber was employed as the seal material based on considerations of mold releasability and heat resistance. Taking the ability of the seal to deform when the gap magnitude changed into consideration, the hardness of the seal material was set low within the hardness range

demand from O-rings in the JIS standards⁽¹⁰⁾.

Figure 7 shows seal cross-sectional shapes (a) to (c) which were examined during the research. For seal shape (a), a finely pointed shape leading up to the apex was employed to help ensure that the load was received at the apex of the seal and to help prevent the thicker sections at the sides from bulging outwards excessively to the left and right. In seal shape (b), inflection points were employed in order to help ensure that the seal bent in the desired positions when flattened. Seal shape (c) was designed based on different considerations to seal shapes (a) and (b). This shape connects an upper ring designed to maintain a vacuum with a lower square ring designed based on considerations of the ability to set the seal in relation to the groove, and the ability of the upper ring to fit in the groove. In addition, to help ensure the generation of a large repulsion force when the seal is flattened, the seal is designed such that the cross-sectional area increases in density when the upper section is pushed into the lower section.

4.2. Test Results

Figure 8 shows the seals in the direction of flattening with 5 mm and 0 mm gaps. In the case of the 5 mm gap, for all the seals only the hollow sections are deformed, with the seals themselves remaining uncompressed. Even in this state, each of the seal shapes maintained the vacuum in the mold at 5 kPa or below. Performance during the pressing process will be compared next. In the case of seal shape (a), because the hollow section was not flattened into the

		Gap 5 mm	Gap 0 mm
Solid shape	(i) Short type (for RTM)		
	(ii) Long type		
(iii) Hollow shape			

Fig. 6 Seal shape

	(a) Arrow model	(b) Revised arrow model	(c) Two-layer model
Initial shape			

Fig. 7 Hollow seal shape

interior when the seal was deformed, and expanded outside the groove, it was not possible to completely close the mold. Seal shapes (b) and (c) fitted into the groove, and it was possible to completely close the mold. Figure 9 shows results for performance in maintaining resin pressure. Seal shape (b) was unable to withstand the resin pressure, and a resin leak occurred. Seal shape (c) maintained a resin pressure of 8 MPa for 120 sec, which had been set as the target performance.

Figure 10 shows the relationship between the filling rate of the groove by the seal and the surface pressure at the area of contact between the seal and the mold, when the mold gap was varied from 7 mm to 0 mm for seal shapes (b) and (c). The groove filling rate was calculated from the cross-sectional area of the groove and the cross-sectional area of the seal, and the surface pressure at the contact area was measured using pressure-sensitive paper. The groove filling rate for seal shape (b) was around 70% even for a gap of 0 mm, and the seal was unable to withstand resin pressure. By contrast, the groove filling rate for seal shape (c) was close to 90%, and resin pressure was maintained by seal reaction force. Seal shape (c), with an upper and lower two-stage structure that fits into the groove, realizing a high-filling rate and helping to ensure a high-surface pressure, was therefore judged to be the suitable cross-sectional shape.

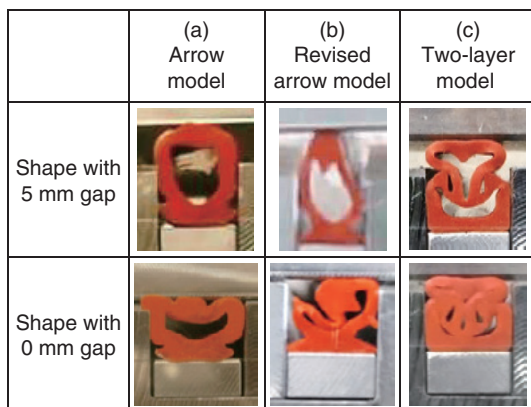


Fig. 8 Comparison of modified seal shapes

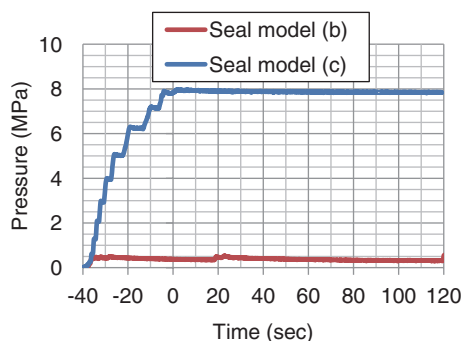


Fig. 9 Results of resin pressure test

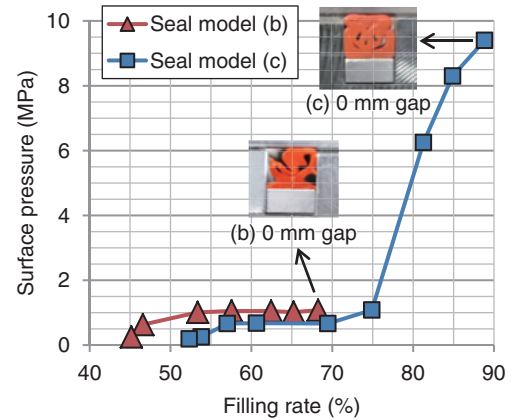


Fig. 10 Filling rate and surface pressure on seal contact area measured using pressure-sensitive paper

5. Molding Test

5.1. Basic Structure of Mold

The developed gap maintenance technology and seal technology were applied in an existing RTM mold (Fig. 11), and gap RTM was conducted using hydraulic pressing equipment without a position control function. The product was a lower dashboard, and the mold size was 1.8 m × 1.2 m. Pressure sensors were positioned in six locations in the mold in order to measure the internal pressure of the mold [Fig. 11(i)-(vi)]. In addition, temperature sensors were positioned in 24 locations inside the mold in order to determine how the resin fills the mold in the resin injection and pressing processes during gap RTM (Fig. 12).

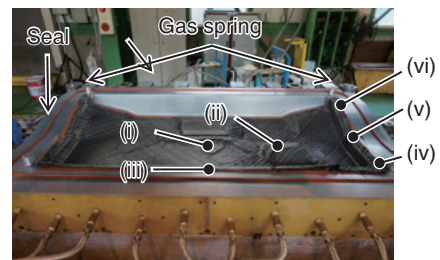


Fig. 11 Mold structure for gap RTM with gas spring, seal, and pressure sensor positions

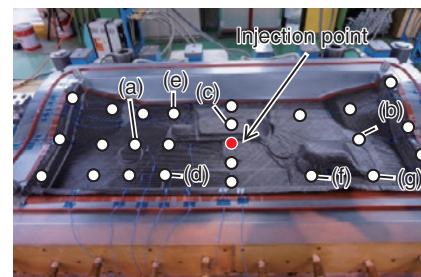


Fig. 12 Thermocouple measurement positions

5.2. Test Results

Changes in the gap magnitude during gap RTM were measured (Fig. 13). The results showed that a gap of 5 mm was maintained from the vacuum process to the resin injection process, and the mold was completely closed in the following pressing process. They additionally showed that the gas springs set in the mold functioned as desired in relation to gap control.

A vacuum gauge positioned in the mold verified that a vacuum of 5 kPa or below was achieved in the mold during the vacuum process. In addition, it was verified that there were no resin leaks to the exterior in the areas around the mold seal groove following molding, as shown in Fig. 14. These results demonstrated that the developed seal displayed adequate function in relation to vacuum pressure and resin pressure even in a large mold.

Taking advantage of the fact that the temperature of the resin and the temperature of the mold differ during molding, the status of resin filling during each process was verified from the responses of the temperature sensors. Figure 15 shows the changes in temperature at each representative measurement position [Fig. 12(a)-(g)]. During the resin injection, the sensors largely responded from positions close to the injection point. Even after the completion of resin injection, the furthest sensor from the point of injection [sensor (g)] does not respond, indicating that the resin has not reached this far. During the following pressing process, all of the sensors

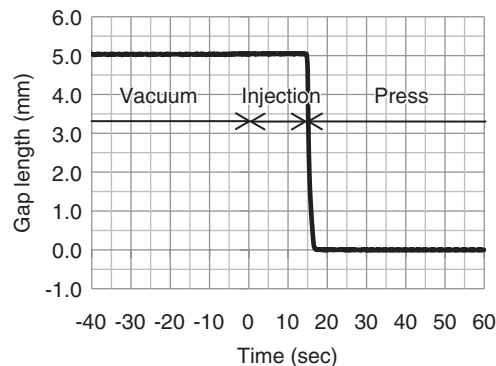


Fig. 13 Gap length in gap RTM process



Fig. 14 Result for gap RTM mold after shot

respond, indicating that the resin has filled the entire mold. Based on the above results, the areas of the mold filled by resin during each process were estimated [Fig. 16(a)].

Figure 16(b) shows an external view of the molded product. The different filling processes have not resulted in any external differences, and the product displays a good finish with no unimpregnated areas.

Figure 17 shows changes in the internal pressure of the mold for gap RTM and conventional RTM using the same mold. During conventional RTM, at a resin injection speed of 80 g/sec, maximum pressure exceeds 7 MPa. In the case of gap RTM, no increase in pressure was observed during the injection process even at an injection speed of 240 g/sec, three times higher. The maximum pressure during the following pressing process is 3.5 MPa, around half that during conventional RTM, and the time necessary for resin filling is also less than half the necessary time during conventional RTM.

Table 1 compares the results of theoretical calculations using Darcy's law and test measurements. As the vertical impregnation process in gap RTM is determined by the speed of the press machine, it was not incorporated in this study, and only the resin injection process was focused on. Table 1 shows the ratios of parameters for gap RTM and RTM, with the ratio of

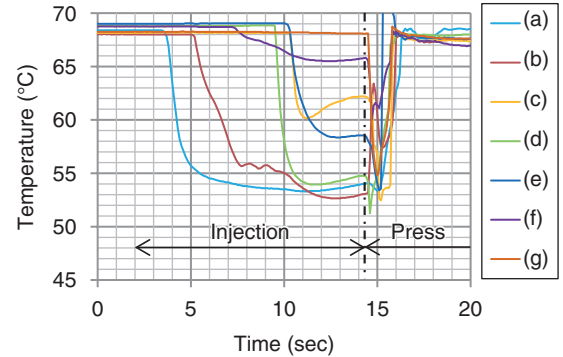


Fig. 15 Results for thermocouple temperature change

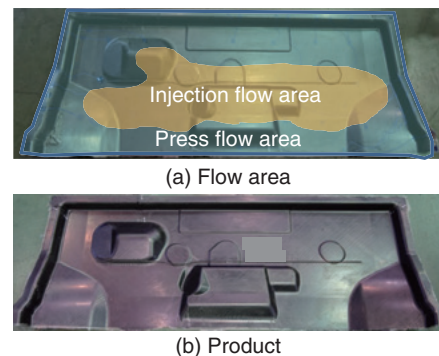


Fig. 16 Lower dashboard produced using gap RTM

Table 1 Comparison of test measurements and theoretical calculations using Darcy's law

	Measured pressure	Calculated pressure	Flow rate	Permeability	Cross-sectional area
Ratio with/without gap	146	100	3	100	3

permeability for the fiber section and space as 100. The same values were set for fluid viscosity and flow distance. A good correlation was obtained between test measurements and calculated values.

These results demonstrate that the developed method reduces the internal pressure of the mold even during high-speed resin injection, and is able to realize high-cycle molding of CFRP parts.

6. Conclusion

A mold structure making it possible to conduct gap RTM using standard hydraulic pressing equipment without a position control function has been developed.

- (1) Positioning gas springs in the mold made it possible to maintain a fixed gap for 120 sec during the vacuum process using standard hydraulic pressing equipment.
- (2) The development of a specialized seal shape made it possible to conduct gap RTM using molds employed in conventional RTM. The developed seal structure was able to maintain an internal vacuum of 5 kPa when the gap was present and a resin pressure of 8 MPa during resin filling for the target 120 sec.

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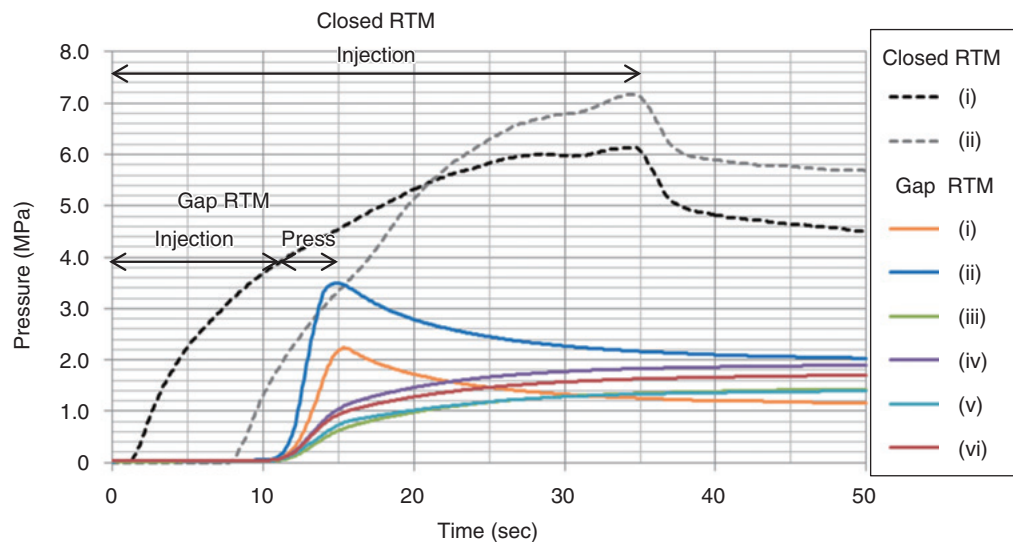


Fig. 17 Pressure profiles for closed RTM process (injection rate: 80 g/sec) and gap RTM process (injection rate: 240 g/sec)

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