

Development of Direct Three-dimensional Shape Forming Technology of CF RTP by Film Stacking Method

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ABSTRACT

Carbon fiber reinforced plastics greatly contribute to weight reduction of vehicles, but their application has been limited due to high manufacturing cost together with the cost of materials. In order to make this material widely available to motorcycles, we developed a technology that makes it possible to manufacture the parts at low cost by using carbon fiber reinforced thermoplastic as a material. For the molding, a manufacturing method was developed to directly form a three-dimensional shape without using prepregs while adopting a film stacking method in which a stack of thermoplastic resin films and carbon fiber woven fabrics is formed by hot pressing. When this manufacturing method was applied, issues on the exterior appearances of the part were revealed. We successfully solved the issues by devising the temperature settings and shapes of the molds and realized a product without irregularities of fibers while maintaining the required strength. The developed manufacturing method was applied to the parts of the CRF 450 Rally and the practicality of the method was proved.

1. Introduction

Carbon fiber reinforced plastics (CFRP), whose utilization is rapidly expanding in recent years, is a very lightweight and excellent strength material. Therefore, in the field of aerospace, it is used as a structural material replacing metals.

In addition, CFRP has also been demonstrating its features in racing vehicles of automobiles and motorcycles⁽¹⁾. CFRP, from its unique appearance, is a symbol of the superior performances of racing vehicles. Furthermore, it is anticipated that its use will be expanded aiming at weight reduction of the vehicle and the fuel economy enhancement by that⁽²⁾.

However, application of CFRP to mass-produced vehicles has been regarded as hard to achieve due to the high manufacturing cost beyond the price of the material.

The reasons for this includes that molding takes a long time, special equipment is required, and requirements for the storage conditions of materials are severe. In addition, the hurdles against recycling thermosetting resin, which is used as a base material, is also one other factor that makes the material not suitable for mass production.

To solve these problems, we have worked on the development of the technology that enables molding of

Carbon Fiber Reinforced Thermo-Plastic (CF RTP), in which thermoplastic resin is used as base material.

Furthermore, we intended to establish a manufacturing process to directly form deep and complicated three-dimensional shapes using the film stacking method, which is usually used for the forming of two dimensional shapes such as flat plates.

2. Examinations on Production Method and Base Matrix Materials

2.1. Examination on Production Methods

2.1.1. Conventional manufacturing method and associated issues with that

To begin with, we started with the examinations on manufacturing methods. CF RTP can be roughly categorized into two types depending on the length of carbon fibers and the continuous length without break when they are applied. One is a manufacturing method using continuous long fibers such as a woven fabric and the other is a manufacturing method using short discontinuous fibers made by cutting the fibers to a certain length.

The motorcycle part chosen as the subject of our investigation this time is a part that requires structural functionality and, in most of the cases, a superior exterior

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appearance as well. Therefore, in addition to its lightness and strength, the fine appearance featured by the weaves of carbon fibers is regarded as one of the important appealing factors. Therefore, a manufacturing method using a continuous fiber woven fabric having a fabric pattern was examined.

For CFRTP using a continuous fiber woven fabric, a method of press molding a thermoplastic prepreg is widely known. The outline of this production method is shown in Fig. 1. A thermoplastic prepreg, also called a stampable sheet, is a plate-like intermediate material impregnated, in advance, with a thermoplastic resin between multilayered fiber fabric sheets. The prepreg is heated, for example, by infrared heater to soften the resin impregnated in the fiber fabric, and press molding is performed. This method is a manufacturing method aiming at shortening the manufacturing cycle by separating the manufacturing process of the prepreg, in which a resin is impregnated in the fiber fabrics, and the molding process to form the final shape of the product.

There are several methods for producing thermoplastic prepreps, one of which is the film stacking method. The film stacking method is a method of impregnating fibers with a resin by superimposing film-like thermoplastic resin layers and fiber fabric layers in turn and pressing while heating.

The prepreg, in which the multilayered fiber fabric sheets are formed into the shape of a plate, is considerably hard, and the fiber fabric layers regulate the movement of each other. For this reason, the shape-imparting property is bad and it is not suitable for molding parts having complicated shapes often used for motorcycles. In addition, in order to make the surface of the product smooth, the fluidity of the resin must be increased. Therefore, it is necessary to heat the molds.

2.1.2. Direct molding of three-dimensional parts by film stacking method

In order to get better the shape-imparting property, it is desirable that each fiber layer freely moves independently. Therefore, our attention was paid to the material state

during the film stacking method is being applied.

As previously mentioned, in the film stacking method, each layer is independent because the material is in the state just simply laminated of resin layers and fiber fabric layers. In this state, even though a complicated shape with depth is to be molded, it is thought that the fiber fabric layers can be adequately shaped following the shape of the mold.

In addition, since it is unnecessary to prepare a prepreg, it is considered advantageous in terms of cost and thermal deterioration of the resin. Based on the above, we decided to pursue a method of forming a three-dimensional shape directly from the state of raw material being used in the film stacking method. Fig. 2 shows the outline of the process of the manufacturing method that was worked on this time.

First, in the same manner as in the ordinary film stacking method, a plurality of thermoplastic resin films and carbon fiber fabrics are laminated alternately.

Then, the laminated material is set on a heated mold and press molding is performed.

After applying pressure for a predetermined period of time, the mold is cooled, and when the shape is fixed, the product is taken out and molding is completed.

We named this forming process as the “Direct Film Stacking Method” on which we put the meaning that, in this manufacturing method, a three-dimensional shape can be directly formed.

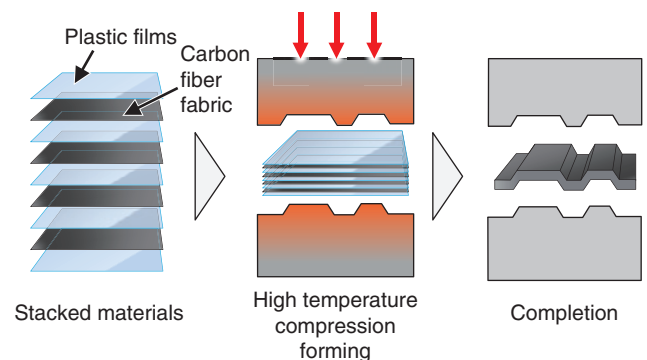


Fig. 2 Process of film stacking direct forming

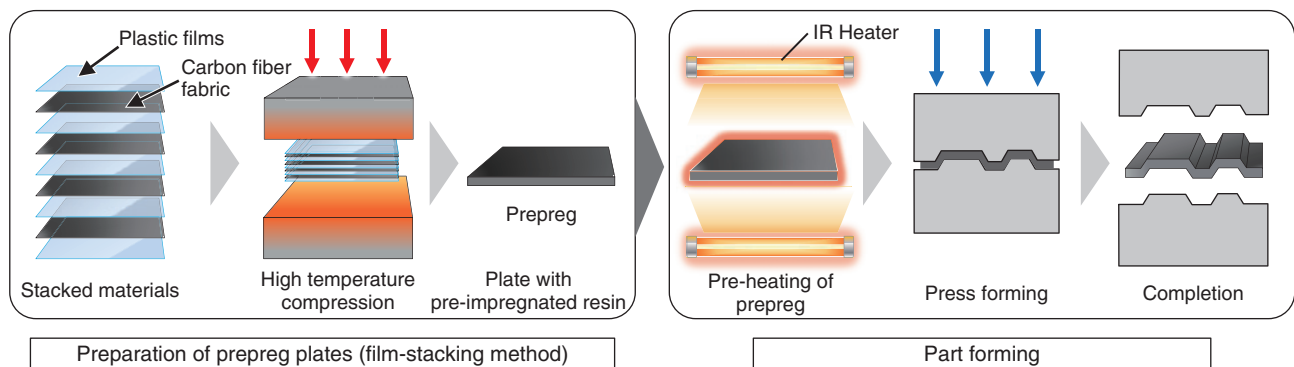


Fig. 1 Part forming using thermoplastic prepreg

Table 1 Comparison of base resins

	PMMA (Polymethyl methacrylate)	PC (Poly- carbonate)	PA6 (Polyamide 6)	PS (Polystyrene)	ABS (Acrylonitrile butadiene styrene)	PVC (Polyvinyl chloride)
Melting point (°C)	180	230	230	215	230	150
Heat deflection temperature (°C)	68	129	67	80	87	54
Flexural strength (MPa)	73	91	127	89	78	64
Tensile strength (MPa)	48	78	78	38	43	42
Stretch at break (%)	2	40	25	5	10	2

Numbers shown in the table are typical ones.

2.2. Selection of Base Matrix Resin

In the direct film stacking method, it is necessary for the thermoplastic resin serving as the base matrix material to take a film form.

For the selection of thermoplastic used as the matrix material, potential options of the material, which are generally available in the form of films, are shown in Table 1.

When applying a material to a vehicle part, it is better to have high physical properties in flexural strength, tensile strength and heat distortion temperature, etc. For elongation, that is, tensile elongation at break, about 5% is required. Therefore, polymethyl methacrylate (PMMA) and polyvinyl chloride (PVC) do not satisfy the requirements.

Furthermore, in addition to the physical properties shown in the table, weathering resistance and flame retardancy must also be considered.

In addition, as mentioned in Section 2.1.1, along with these physical properties, quality of appearance is very important. In order to show the texture of carbon fiber fabric, high transparency is required for the resin used as the base matrix material.

Based on the above considerations, polycarbonate was chosen as the base material. Polycarbonate has the maximum tensile strength of 78 MPa, as shown in the table, and the flexural strength is also the second highest after polyamide. Moreover, among the thermoplastic resins, the transparency is the highest next to polymethyl methacrylate. Furthermore, this material was selected because of one more advantage, which is the wide availability of the raw material in the form of thin films. This is another key condition for establishing a manufacturing method this time.

3. Molding Conditions

3.1. Verification of Molding Conditions using Flat Plate Shape Sample

In verifications of the molding conditions, the most important thing is the degree of resin impregnation. It can be said that the value of the flexural strength is higher when the resin is well impregnated into the fiber fabric. Accordingly, test pieces having a flat plate shape were

prepared and the applied load and the amounts of caused displacements were measured by the three-point flexure test, based on the test conditions defined in JIS K 7074, and the flexural strengths were calculated.

For carbon fiber woven fabric, CO6347B (T300B 3K, twill weave) manufactured by Toray Industries, Inc. is used, and four layers of this fiber fabric and five resin films are alternately laminated. A general pseudo-isotropic lamination of, from the top, 45°, 0/90°, -0/90°, and -45° was applied as the fiber directions. The laminated material is subjected to hot press molding with heated molds, and the degree of impregnation of the resin to the fiber fabrics is confirmed.

Three factors of temperature, pressure, and time are involved in impregnating the resin into the fiber fabrics, but in this paper, the measurement results are presented, specifically, for the molding temperature which affects the resin impregnation the most.

Fig. 3 shows the relationship between the temperature of the mold during molding and the flexural strength of the test piece serving as an index of resin impregnation. As the measurement conditions, the molding pressure was 3.6 MPa and the pressure holding time was 4 minutes.

Polycarbonate is an amorphous thermoplastic resin that does not have a clear melting point, but it is generally considered that its melting point is around 230°C. As the temperature rises above the melting point, the viscosity of the molten resin decreases.

From Fig. 3, it can be seen that the flexural strength is almost proportional to the temperature from 220°C to 280°C. It can be said that, as the molding temperature rises, the viscosity of the resin decreases and impregnation into the fiber fabrics gets better. In addition, it can be seen that there is a difference of two times or more in the flexural strength at the molding temperature of 220°C and 280°C, and that, at the low temperature, impregnation of the resin into the fibers is insufficient.

When observing the cross section of the test piece at this time, it is understood that the test piece formed at 280°C

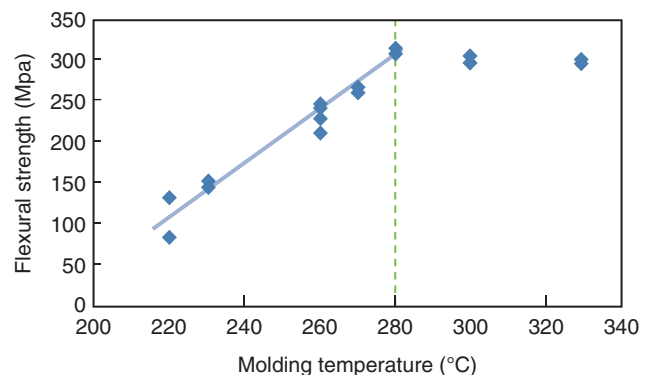


Fig. 3 Relationship between flexural strength and molding temperature

(Fig. 4) is impregnated with the resin deeply into the fiber fabric. In addition, the test piece (Fig. 5) molded at 230°C shows that the resin exists only on the surface of the fiber layer and is not impregnated therein, being left as empty spaces as a result. This is because the temperature of the resin is low and the viscosity is high, making the resin impossible to sufficiently impregnate.

Moreover, the flexural strength shows its peak value at 280°C and, thereafter, gradually decreases with increase of the molding temperature. Regarding the reason for showing this tendency, it is conceivable that the polycarbonate itself is deteriorated due to the heat during molding.

Based on the results shown above, the molding temperature was set at 280°C at which the resin can be sufficiently impregnated into the fiber fabric and the flexural strength becomes maximum.

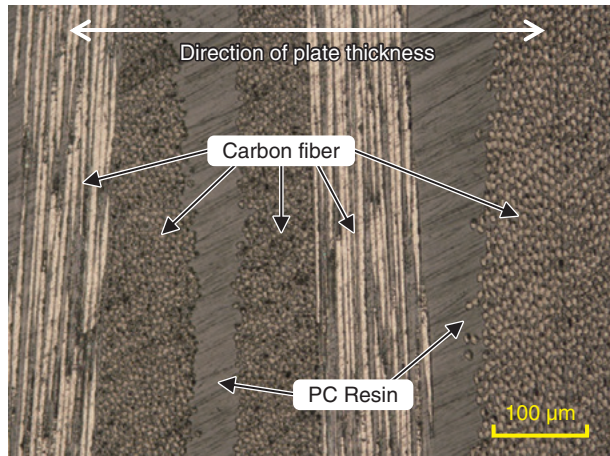


Fig. 4 Cross-sectional view of test piece with good impregnation condition of resin (TP processed at 280°C)

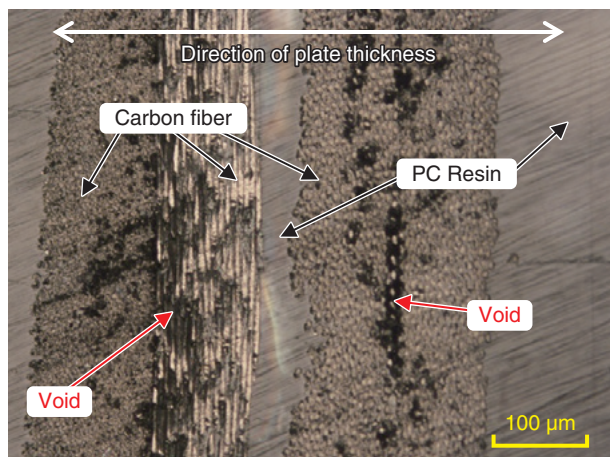


Fig. 5 Cross-sectional view of test piece with poor impregnation condition of resin (TP processed at 230°C)

4. Molding of Three-dimensional Shape

4.1. Three-dimensional Shape Forming

The part to be molded was the rear fender of the CRF 450 Rally, which is one of the motorcycles we produced. In the previous year's model of this vehicle, this part was manufactured using autoclave molding, and it is with the vertical and horizontal dimensions of 600 mm × 200 mm and the depth of about 120 mm. The part has almost vertical walls on the sides, and it also has complexly protruded or dented sections in the front part.

Based on the molding conditions obtained in the tests using test pieces, an actual molding was conducted and a satisfactory molded state was obtained for the horizontally-flat shape portion of the part. However, there were some flawed locations in almost vertical wall sections and in the sections with complicatedly placed protrusions and dents.

4.2. Defects due to Fiber Rupture and Exposure

Among the defects occurred in the molded part of the rear fender, the largest ones were ruptures of the fibers generated in the vertical wall portions on both sides.

Fig. 6 shows the state of the left side of the part. It was confirmed that the fibers in the surface layer were ruptured and the fibers inside were exposed, in the portion indicated by the yellow broken line in the figure. In addition, in the part indicated by the red broken line, it is seen that there are areas where the fiber is broken up throughout the entire layers, exposing the portions composed of only resin. In such a condition, generally anticipated strength as a composite material cannot be exhibited.

Furthermore, in the portion with protrusions and dents complicatedly situated as shown in Fig. 7, it can be seen where there is no surface resin, and the fibers are directly exposed.

In order to know in which step of the molding process the molding defects arises, the behaviors of the base material, when it is under the process of the closure of

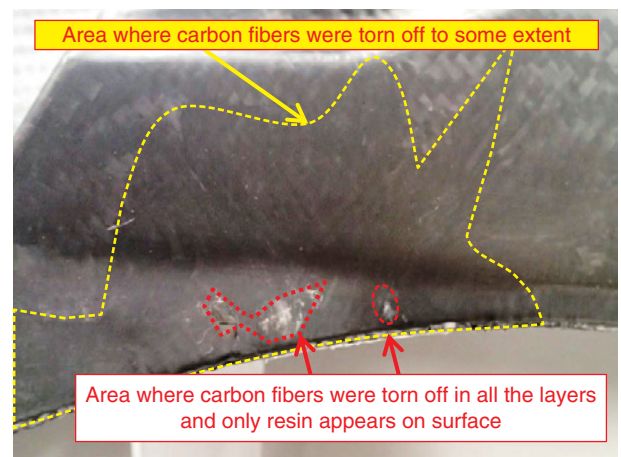


Fig. 6 Breaks of fibers appear on vertical wall section

the upper and the lower molds, were investigated. In this examination, the mold having protrusion is placed lower and the mold having dent is placed on the top. The observation was carried out by stopping the operation of the molds at the desired timing and by cooling down the mold thereafter.

Based on the results of the observation, the process shown below was estimated.

When the upper mold descends after the material is introduced, the resin film begins to melt from the part that touched the upper mold. In the flat part nearly horizontal, since the upper mold descends while contacting in the shape of roughly flat surface, the resin is impregnated into the fiber fabric and molding is performed fitting the mold shape.

On the other hand, in a portion where the inclination of the die wall is close to vertical, the clearance between the upper and lower dies becomes smaller than the thickness of the material at the earlier part of the molding process, and the corner portion of the upper mold touches the material first. As a result, the resin layer of the material surface is pierced by the corner of the die, and, it is considered that, the resin layer does not exist on the surface layer as shown in Fig. 7.

Furthermore, when molding a deep shape as shown in Fig. 6, the movement of the die continues even after the contact of the corner portion of the upper die, as described above, and the upper die further moves downward. Meanwhile, the molten resin has a high viscosity, and acts like an adhesive between the fiber fabrics, and between the fiber fabric and the die surface. Therefore, the fibers are stuck to the mold and torn as the die moves.

These processes are schematically shown in Fig. 8.

The cause of the molding defect is that the resin is melted before the composite layer, which is the raw material, is sufficiently fitted to the shape of the die. Unless the mold temperature is high, the resin film will not be melted to be ruptured. Furthermore, it can be said that the

fibers will not be torn unless the resin melts and sticks to the die.

Accordingly, in order to prevent the resin from melting and tear off before shaping, preliminary shaping with low temperature dies was also examined. However, the material before molding is about twice as thick as the clearance when the mold is closed. Therefore, it is almost impossible to press the material without applying any additional measures. Furthermore, scratches and press marks of fibers are left on the die surface.

By applying preliminary shaping using a plurality of dies, it is possible to realize a method capable of alleviating the above-described defects. However, in this development, we aimed at establishing a method that satisfies both conditions of shaping and resin impregnation with only one set of dies without using multiple dies.

In order to mold with a set of dies, it is necessary to impregnate the resin in one molding process and reduce the thickness of the material. In addition, in order to exhibit the strength as a composite material, it is necessary to realize a material state in which the resin is melted with the die heated to a high temperature and sufficiently impregnated into the fiber fabrics.

Although it is inadequate for the shaping process to set the mold temperature to high temperature, rising temperature is necessary for resin impregnation, and a method to satisfy these requirements simultaneously was investigated.

4.3. Enhancement of External Appearance by Differentiating Die Temperatures

We thought that we would be able to divide the two different processes of part shaping and resin impregnation and assign them individually to the upper and the lower dies.

Specifically, we examined a method of making a difference in temperature between the upper and the lower dies.

The temperature of the upper die is set to be equal to or more than the glass transition point of the resin, and less than the melting point.

By doing this, the resin film can be softened without

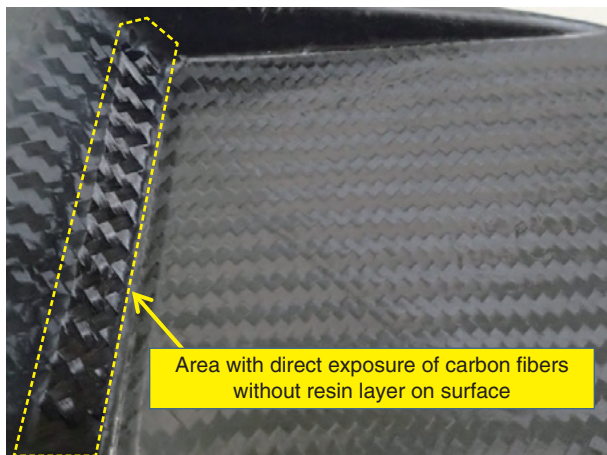


Fig. 7 Area on surface with direct fiber exposure

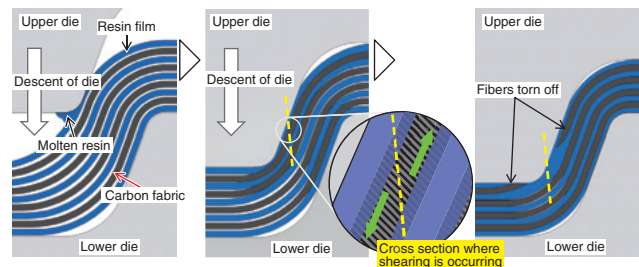


Fig. 8 Schematic views of cross sections of die, which show phenomena occurring while upper die is descending

melting and the base material can be shaped.

On the other hand, the temperature of the lower die is set to be equal to or higher than the melting point of the resin so that the resin film can be melted.

In the case in which those temperatures are set and molding is conducted, the movement of the die and those of layers of resin and fiber fabric can be described schematically as shown in Fig. 9.

The upper die descends while sliding on the surface layer of the resin film without melting it, and presses the material against the lower mold. The material pressed against the die melts from the side that has touched the lower die and is shaped along the die. Since the upper die descends while sliding on the surface of the material, the fibers are less prone to be torn. When the mold is closed, in the material, the resin is impregnated into the fiber fabrics with the heat delivered from the lower die.

The part molded by this method is shown in Fig. 10. No fiber breakage or disorder of weaving is observed in the appearance. Furthermore, it can be evaluated that the direction of the weave is uniform along the part surface shape and that it has an appearance close to that of the one in which the fiber fabrics are manually arranged.

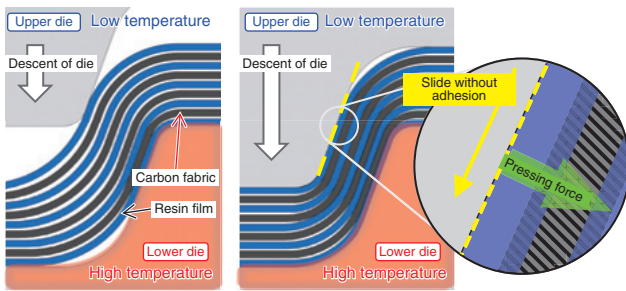


Fig. 9 Phenomena assumed to be happening between upper and lower molds while processing by developed method



Fig. 10 Appearance of vertical wall side surface when processed with developed method

From these results, it was verified that, by setting the upper die to a lower temperature at which the damage of the resin film can be suppressed, and setting the lower mold to a higher temperature at which sufficient resin impregnation to the fiber fabric is obtained, it is possible to eliminate the fiber breakages appearing on the vertical walls and improve the appearance of the product.

4.4. Investigation on Internal State of Material and Enhancement of Quality

To investigate the internal quality of the product molded by the method described in Section 4.3, the cross section was observed by cutting it in the same manner as the flat test plates. Figure 11 shows the cross section of the flat portion of the top surface of the part, and the cross section of the vertical wall portion is shown in Fig. 12.

As shown in Fig. 12, in the part, the resin penetrates deep into the fiber bundles. However, there are sections

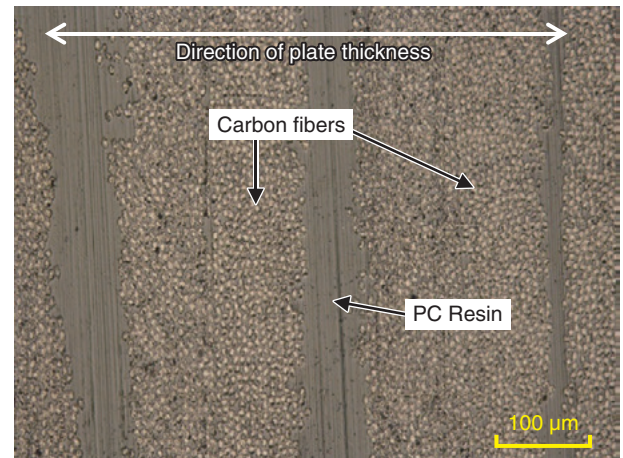


Fig. 11 Cross section of test piece at top flat part of product

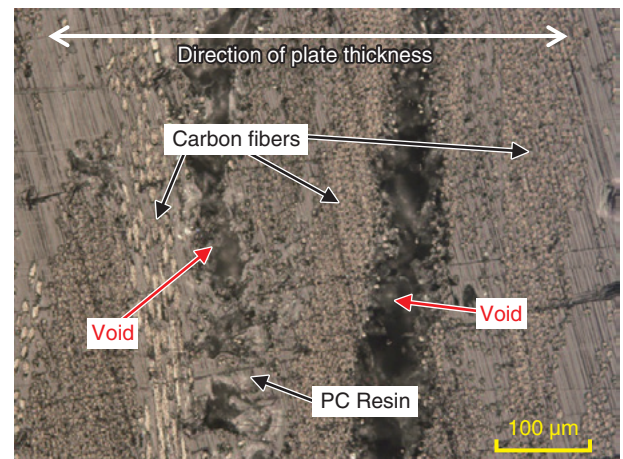


Fig. 12 Cross section of test piece at vertical wall part of product

where large voids are present in the fiber bundles.

It is considered that this was because the temperature of the resin was adequately high and the viscosity was low enough to sufficiently impregnate into the fiber fabric, but, despite of that, the process was stopped halfway.

Another possibility is that the impregnation of the resin had been distributed throughout the fiber bundles, but the material was in the state in which voids had occurred due to the volume reduction of the resin.

4.5. Quality Enhancement of Inner Part of Vertical Walls

Impregnation is a process of injecting the molten resin flows deep into the fiber bundles. In this manufacturing method, a force effective to make the resin flow is generated by the force in the vertical direction applied by the pressing machine. For this reason, to a horizontally flat plane, almost 100% of the force is applied, whereas only a component of the force with corresponding angle is applied to an inclined plane.

A method to take measures against this situation is conceivable in which the molding pressure is set extremely high anticipating the pressure drop due to the high inclination angle. However, even if such a method is schemed, it is not realistic to raise the molding pressure as sufficient as an enough force is generated to be applied to the wall portions substantially vertical.

There are also methods to resolve the issue by using partial dies⁽³⁾.

However, this technique involves an increase in processing time and cost, as compared with the case using a single set of dies, since the number of divisions of the die increases. In addition, when applying this method, there is a possible concern that molten resin enters the gap generated between the divided molds.

Here, we will reconsider the mechanism of causing insufficient impregnation of resin into fiber fabrics. In this method, trimmed portions, which are eventually not used as a finished part, are held in the areas outside the cavity. Therefore, it is impossible to make the space inside the cavity completely closed. In addition, the portions shown in Fig. 12 are located in the vertical wall part, particularly in the areas close to the trim line, in the whole shape of the product.

Therefore, we believed that impregnation into fibers can be promoted if the outflow of resin can be suppressed, and a scheme to narrow the clearance in the vicinity of the vertical wall portion trim line was studied. Specifically, the clearance between the upper and lower dies was narrowed down to the value obtained by summing up the thicknesses of the fiber fabric layers, and, when the upper die is descending, making it suppress the outflow of the resin during the die closure is in process (Fig. 13).

In order to confirm the effect of the scheme, shown in Fig. 13, and the pressure on the other surfaces, a pair of test dies having flat surfaces of different angles was produced. The test die was designed to include a total of five planes

having angles of 30°, 45°, 60°, 88.55° with respect to the horizontal direction, and the scheme shown in Fig. 13 was applied to the portions on the die corresponding to the plane of 88.55°. It is to be noted that, for the plane of 88.55°, the draft angle of 1.45° is secured with respect to 90°. The test part molded by this die had a shape as shown in Fig. 14. The sections shown in red were set so that the dies close completely, and the sections shown in green were set to be left not fully closed. The shape of each plane is rectangular, and it is 220 mm in length and 35 mm in width so that two specimens (100 mm × 30 mm) for flexure test could be cut out. A pressure sensor was placed in the center of each plane perpendicularly to the plane, and pressure changes in the cavity during molding at each plane were measured with the elapsed time. The purpose of the pressure measurement was to compare the pressure of the vertical wall plane with those of the other planes. Therefore, in addition to the vertical wall portion, the pressure at the horizontal plane

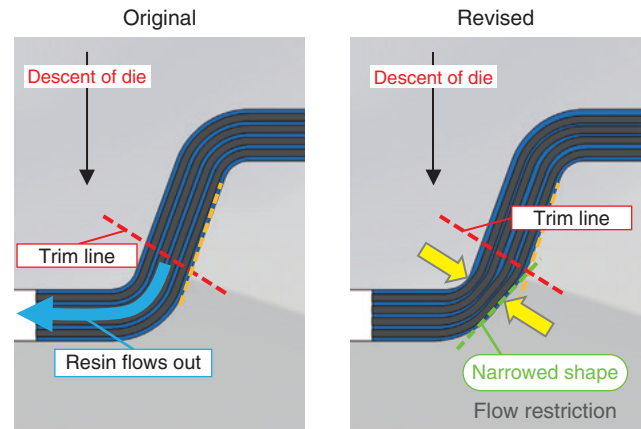


Fig. 13 Revised configuration of die with narrowed shape at resin outlet

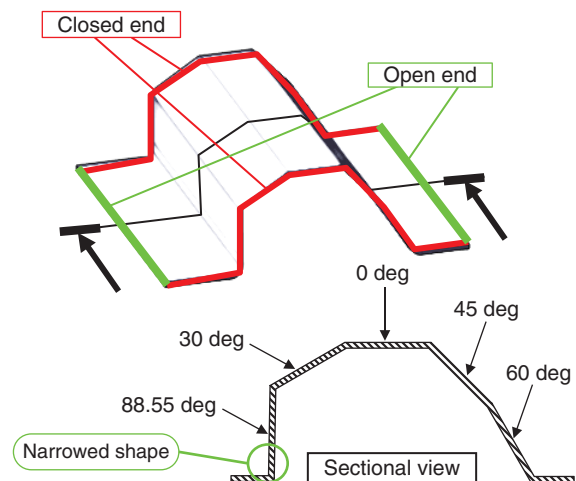


Fig. 14 Cross section of test piece for verification test of developed method

and the pressure at the 45° plane, which has middle angle thereof, was also measured.

Moreover, we also produced dies that do not apply the scheme of Fig. 13 to the plane of 88.55° and verified the effect of the scheme.

The conditions of temperature and pressure are the same as those described in the previous chapter. The changes in the measured pressure to the elapsed time are shown below. Fig. 15 shows the case where this scheme is not applied, and Fig. 16 shows the applied one.

Here, pressure is not detected for about the first 15 seconds because the substance inside is not in contact with the pressure sensor. Immediately thereafter, the sensor comes into contact with the resin which has not yet melted and detects a large pressure. The contacted resin melts according to the temperature of the mold and the pressure rapidly drops. Therefore, the evaluation of the in-cavity pressure was made for the period on and after around 20 seconds in the graph.

First, look at the diagram before applying the scheme (Fig. 15). Regarding the horizontal plane of 0°, with descending of the die, the pressure rises while showing a parabolic graph shape. Regarding the pressure on the

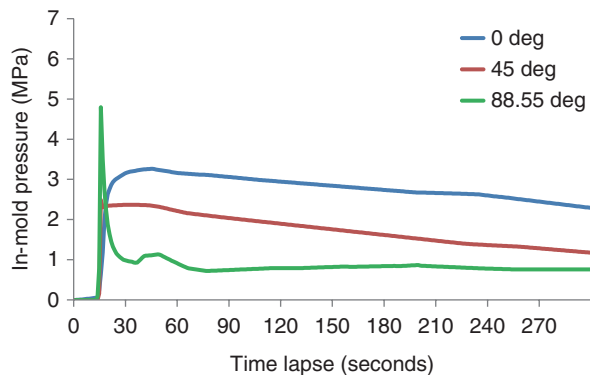


Fig. 15 Pressures in cavity to elapsed time without developed method

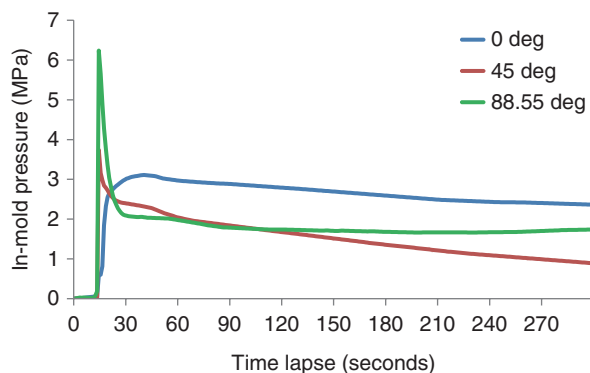


Fig. 16 Pressures in cavity to elapsed time with developed method

plane with the angle of 45°, it is changing at the value corresponding to a component of the force applied to the horizontal plane.

As can be seen in Fig. 15, the pressure in the vertical wall section is only about 1 MPa, after the pressure is stabilized. On the other hand, looking at Fig. 16 that shows the case in which a method was implemented to narrow the outlet of the resin, the pressure of the vertical wall section reaches 2 MPa at around the elapsed time of 30 seconds and that value is maintained thereafter. After about 100 seconds has elapsed, it is found that the pressure is higher than that on the 45° plane. It is considered that, on the 45° plane, the pressure gradually decreases as the outflow of resin progresses.

Further, specimens were cut out from the horizontal plane and the vertical plane of the molded part with the developed method, and flexure tests were carried following the same manner as shown in Section 3.1. The measurement result and section view of each specimen are shown in Fig. 17.

When comparing the flexural strengths of 0°, i.e. horizontal, and 88.55° planes, the difference is as small as 6 to 8 MPa. Moreover, from the state observed in the cross section, it was found that no void, as had been seen in Fig. 12, had occurred. As can be seen from the above results, by narrowing the clearance between the dies in the vicinity of the trim portion and suppressing outflow of the resin to maintain the pressure, impregnation of the resin is promoted, and the internal quality free of voids was able to be secured.

By applying this method in conjunction with the molding method that sets the temperature difference in the upper and lower molds described in Section 4.3, it was possible to realize excellent appearance together with good internal quality of the vertical wall part.

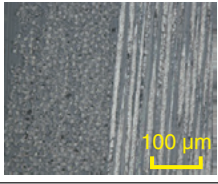
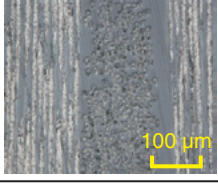
Plane angle (degree)	Number	Flexural strength (MPa)	Cross section
0	#1	313.60	
	#2	304.16	
88.55	#1	305.62	
	#2	298.17	

Fig. 17 Test results and cross sections of test pieces sampled from horizontal and nearly vertical walls

5. Application of the Developed Molding Method to Actual Vehicle Parts

Using this technology, the rear fender (Fig. 19) and the cover of electrical unit installed in the CRF 450 Rally (Fig. 18), which participated in the Dakar Rally in South America in 2016, were made. These parts demonstrated that they were fulfilling the performance and the durability required in the harsh rally of Dakar. These results proofed that the parts manufactured by the developed molding method are compatible even under the applied condition to actual vehicles.



Fig. 18 The CRF450 Rally



Fig. 19 Rear fender of the CRF450 made of CFRTP

6. Conclusions

We studied the molding method of carbon fiber reinforced plastic which can be applied to mass-produced motorcycles. As a result, direct film stacking method, which directly molds without using a prepreg, was established, and the following findings were obtained in the development process.

- (1) By molding having different settings in temperature between the upper and lower dies, it was made possible to shape the base matrix material along the die without breaking either fibers or resin, and, as a result, an excellent appearance was realized.
- (2) In order to increase the impregnation of the resin in the vertical wall, a mold structure with narrowed clearance between the molds of the resin outflow portion was applied. As a consequence, sufficient resin impregnation was realized also on the vertical plane, and the internal quality was enhanced as well.

It is expected that this technology will be widely applied to mass-produced motorcycles in the future. In addition, this method can be widely applied to parts other than of motorcycle, and the future possible deployment will be highly anticipated.

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