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This paper introduces Porous Mold Process (PMP) as a reliable low-cost manufacturing process of fiber-reinforced composites. PMP using porous aluminum is applied to the vacuum-assisted resin transfer molding (VaRTM) process of carbon fiber reinforced plastics (CFRPs). Experimental evaluation on resin infusion behavior and quality and mechanical properties of the cured plates is performed with varying the dimensions of the plates. The results show that quality and mechanical properties of the cured plates using PMP are satisfactory, stable, and almost independent of plate dimensions. It is concluded that PMP provides a reliable and knowhow-less resin infusion process of composite materials.

Keywords: composite manufacturing; VaRTM; porous mold; mechanical properties

1. Introduction

Carbon fiber reinforced plastics (CFRPs) are widely used as primary structures of civil aircraft. Reductions of manufacturing cost, manufacturing lead time, and development period are significantly demanded for CFRP structures. It is necessary to develop high value-added affordable manufacturing methods enabling us to fabricate CFRP composites with high quality and reliable properties.

In the aerospace industry, autoclave process using CFRP prepregs is widely applied in order to make CFRP structures with high quality and reliable properties. Recently, Out-of-Autoclave (OoA) process has been widely investigated to develop low-cost manufacturing processes.[1,2] One of the representative low-cost processes of CFRP structures is Resin Transfer Molding (RTM) or vacuum-assisted resin transfer molding (VaRTM),[1] in which dry fabric preforms are placed on the mold followed by the resin impregnation using the pressure difference. In these methods, integral production of complex structures with little components is possible using affordable molds and facilities. RTM or VaRTM is suitable for structures with wide variety. However, in the production of in-plane large-scale structures, incomplete resin impregnation and void formations inevitably happen. By reducing the resin viscosity and increasing the inlet and outlet portions, we aim to reduce the void formation. In addition, quality of the fabricated composites strongly depends on the used materials and submaterials, the positions of inlets and outlets, and the resin providing time.[3–5] Numerous trials are required to develop a production method. It is necessary to develop the manufactur-

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ing process to make RTM-based produced structures with more reliable properties and higher quality.

Vacuum Assisted Process (VAP) has been proposed as a reliable VaRTM process.[6,7] Membranes, in which gas permeates but resin does not, are placed between the dry fabric and the vacuum bag during the VaRTM process. This is used for the production of airframe structures. VAP process induces the increase of used sub-materials and working processes, and application to complex structures still remains to be difficult.

The authors proposed Porous Mold Process (PMP), in which porous mold with shape holding and gas permeation functions is used for composite fabrication. PMP was applied to VaRTM process, and experimental feasibility was demonstrated.[8] PMP-based VaRTM process is shown in Figure 1. The mold (e.g. porous aluminum) has enough stiffness for shape holding and porous structures for gas permeation. The resin is impermeable through the porous mold. Expected advantages are: (1) increase of the quality (i.e. reduction of the voids) and the reliability, (2) reduction of the sub-materials (e.g. outlet parts) and working processes, and (3) shortening the development period by making the manufacturing process without know-hows.

In the standard VaRTM process, the suitable resin infusion process and the quality of the fabricated panel depend on the panel geometry and the size. In the present article, the effects of the panel size and thickness on the quality and the mechanical properties of the fabricated CFRP using the PMP-based VaRTM process are experimentally investigated. Effectiveness of the PMP process (quality, reliability, and less know-hows, etc.) is verified through the measurement of thickness variation during resin infusion, fiber and void volume contents of the fabricated samples, and mechanical properties.

2. VaRTM experiment using porous mold

In this study, porous aluminum METAPOR® (average pore diameter: 12 μm, density: 1.9 g/cm^3, pore volume fraction: 16%, binder included) is used as the porous mold with machinability and stiffness. The porous aluminum has open pore structure, and the mold thickness is 10 mm. The porous mold is supported by rigid parts so that flexural deflection is constrained. A magnified image of the surface of METAPOR® is shown in Figure 2.

In order to keep the reusability of the porous mold, it is necessary to prevent the infused resin permeating into the porous mold during the VaRTM process. Based on the preliminary analysis on the resin permeation into porous mold, it is suggested that nanosized pores are

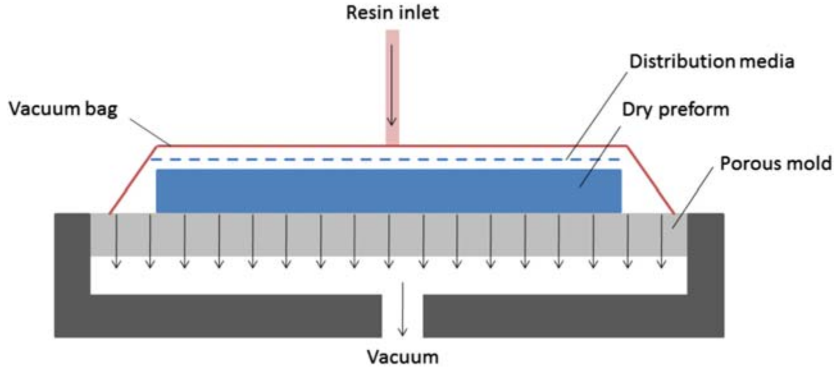


Figure 1. VaRTM process using porous mold.

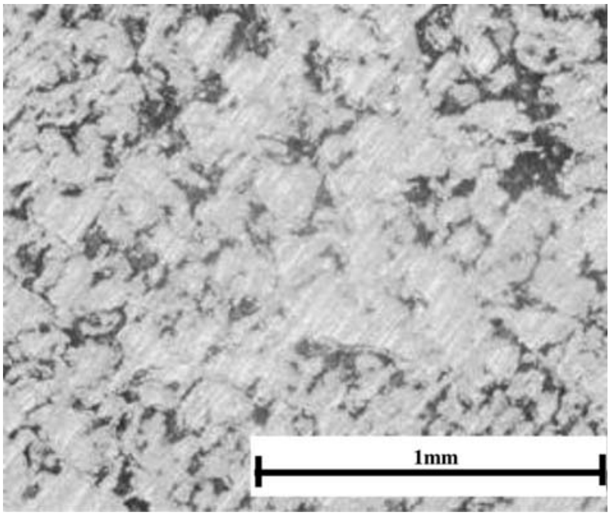


Figure 2. Microscopic image of porous aluminum.

required to prevent the resin permeation when resin with standard viscosity applicable to the VaRTM process is used. In the present experiments, porous films with nanosized pores are placed on the porous mold during the VaRTM process.

Plain-woven carbon fabrics, T700SC-12 K (areal weight of 480 g/cm^2), are used as the dry preform, and epoxy, XNR6815 with XNH6815 hardener (Nagase ChemteX Corporation), is used as the infused resin. Dry preforms are placed with peel ply and distribution media, and they are covered by the vacuum bag film. Resin inlet is connected in the central portion of the preforms. The porous mold is connected to the vacuum pump. Resin is infused into the fabrics by applying the vacuum through the porous mold, and cured at room temperature. The experimental apparatus of resin infusion during the PMP-based VaRTM process is shown in Figure 3. After starting the resin infusion, there is no specific working process. Only waiting for resin cure is required in this process.

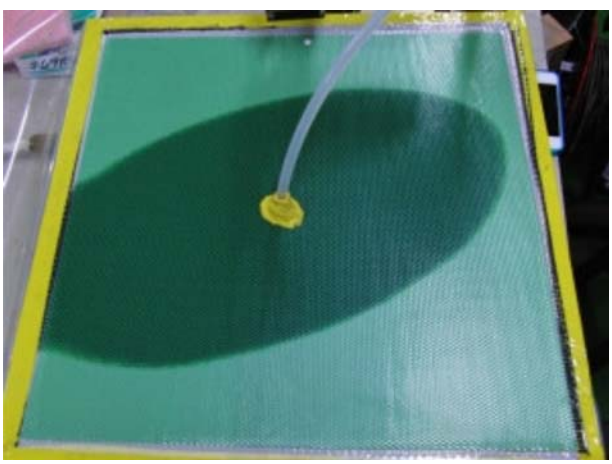


Figure 3. Overview during the resin infusion.

The present study aims at the investigation of the effect of plate dimension on the quality and mechanical properties of fabricated CFRPs using the PMP-based VaRTM process. The dimension of placed dry fabrics is 300 × 300 mm, and the stacked layers vary from 4 to 24 (thickness of the cure plate ranges from 2.2 to 13 mm). In addition, a 450 × 450 mm plate with six dry fabric layers is also fabricated. The resin infusion process is similar independently of plate dimensions (i.e. only waiting for resin cure after resin infusion). During some infusion experiments, thickness change is measured at different positions using laser displacement meters.

It should be noted that the conventional VaRTM process requires the operators to investigate the optimum working process in the resin infusion. Resin flows out from the outlet until the complete resin infusion, and it is necessary to consider the timing to close the vacuum port and other operations to make the composites better. In addition, pressure gradient exists between the inlet and the outlet even after complete infusion in the conventional VaRTM process. This means that thickness depends on the position, and gradually becomes similar until the resin cure. On the other hand, in PMP-based VaRTM process, there is no pressure gradient in the plate when the complete infusion is achieved, and no resin flows out. Thus, no specific operation after starting the resin infusion is required in the PMP-based VaRTM process.

3. Evaluation tests and results

3.1. Resin infusion behavior

Thickness variations during the resin infusion were measured at two positions with the distance from the inlet of 50 and 100 mm in the case of the 300 × 300 mm plate with six fabrics as shown in Figure 4. Owing to the anisotropy of the distribution media, anisotropic resin infusion behavior was observed as shown in Figure 3. When the resin approached the measurement points of thickness change, thickness decreased slightly followed by the monotonic

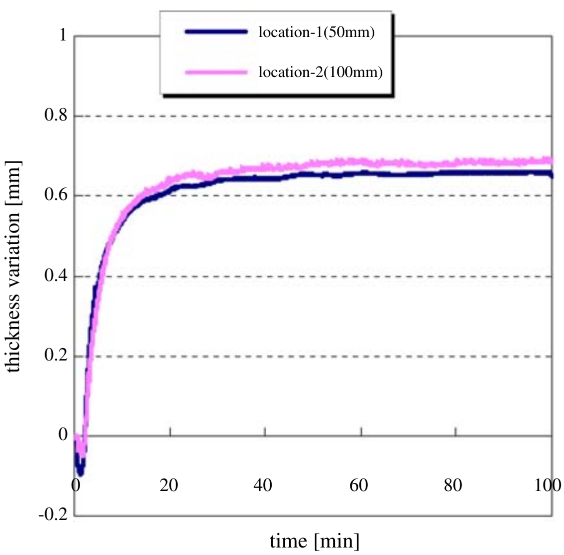


Figure 4. Thickness variation as a function of time of a 300 × 300 specimen consisting of six-ply fabrics.

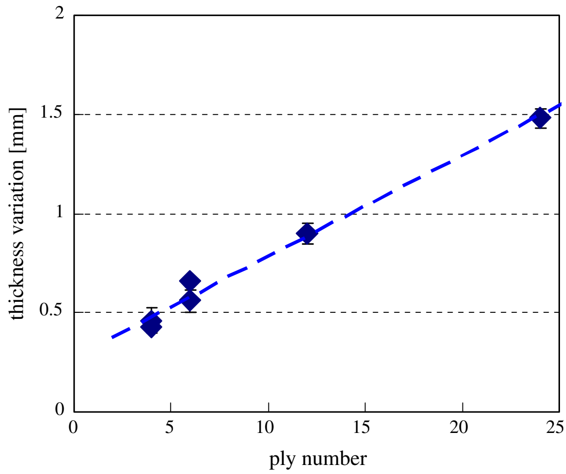


Figure 5. Steady-state thickness variation as a function of ply number.

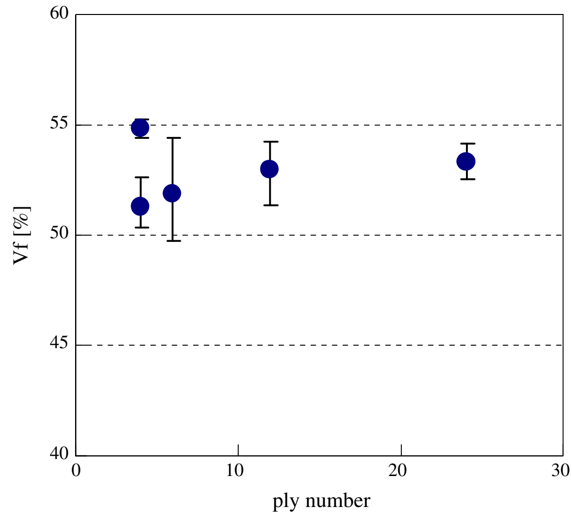
increase of thickness. Thickness decrease may be induced by the compaction of fabrics due to lubrication effect by the resin, and the subsequent thickness increase results from the inner pressure increase due to the resin infusion. In the case of 6-ply fabrics, there was almost no thickness variation beyond 20 min after starting the infusion. The measured thickness change was almost independent of the positions.

In Figure 5, the relationship between the saturated values of thickness variation and the number of fabric layers is plotted in the cases of 300×300 mm plates. Saturated thickness change is proportional to the number of stacked layers. This means that amount of infused resin is proportional to the number of stacked layers. Note that thickness variation includes the effect of distribution media, and the proportional line in Figure 5 does not pass the origin.

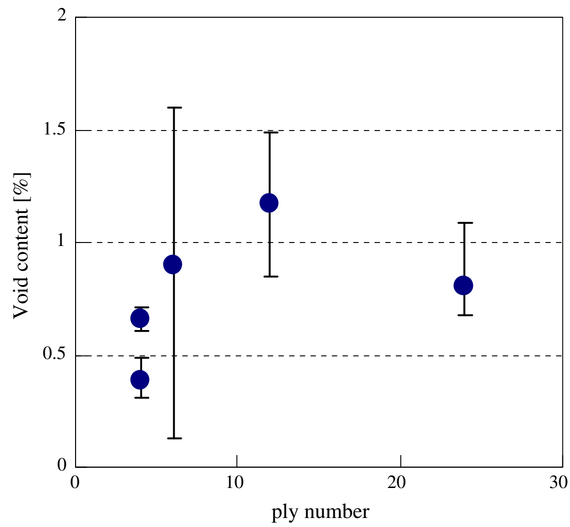
From the results of the measurement of thickness change, it is concluded that resin infusion behavior in PMP-based VaRTM process is very simple. Thickness change is independent of the plate position, and there is no thickness change after enough time passes. In the conventional VaRTM process, complex thickness variations have been observed depending on the timing to close the inlet and the outlet, and thickness of the cured plate varies among the position.[9,10] The present experiment indicated that PMP-based VaRTM process has advantage of simple and stable resin infusion.

When the porous mold is used for VaRTM process, through-thickness pressure gradient is induced during the resin infusion. After the complete resin infusion, it is expected that no in-plane pressure gradient remains. In addition, the CFRP plate (at least lower surface) is overall subjected to low pressure during the infusion and the curing, which may result in void reduction. Although it is necessary to clarify the infusion mechanism of PMP-based VaRTM process in more details, the above-mentioned mechanisms contribute to the stable infusion process and the stable quality of cured CFRPs using the porous mold.

The adverse point of the present simple process is the lack of compaction force after the complete resin infusion, because there is no in-plane pressure gradient inside the bagging when the inlet remains open. This means that high volume fraction cannot be expected when using the present simple process. Modification of the process (e.g. application of close operation of resin inlet, application of the external pressure) will overcome this disadvantage, and is expected in the future study.



(a) Fiber volume fraction



(b) Void content

Figure 6. Effect of ply number on the quality of CFRP specimens.

3.2. Quality evaluation of cured samples

The internal inspection of fabricated samples at representative positions was conducted using X-ray CT scanning. There was no apparent void in the samples. Optical microscopic observations of the cut surfaces also showed no observable voids. It is concluded that all fabricated samples have good quality.

Fiber volume fractions and void contents of the cured samples were evaluated by the burning method. Small samples at the representative positions were cut from the panels. Mass changes due to the matrix loss were measured by the burning method in reference to JIS

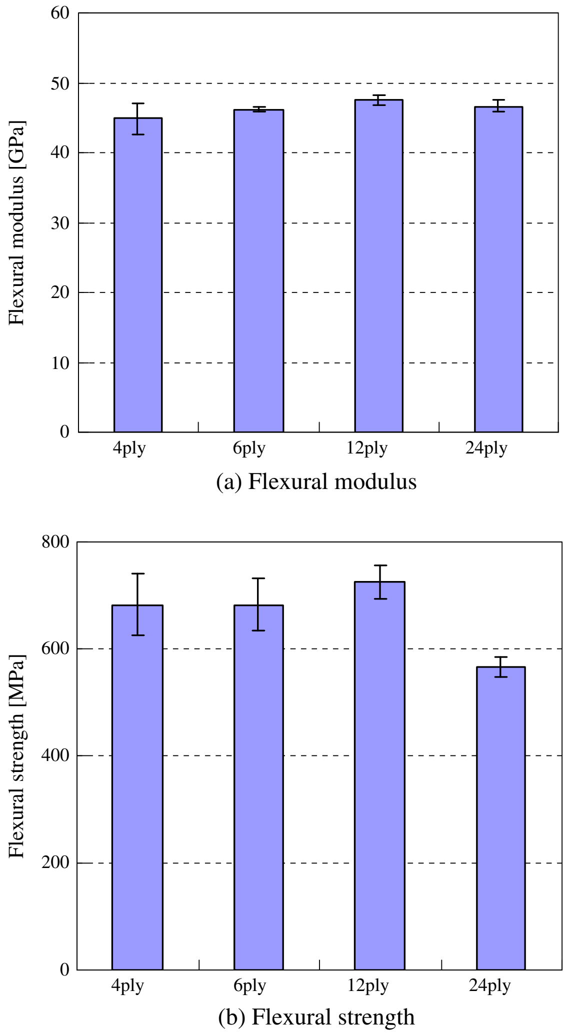


Figure 7. Mechanical properties of CFRP specimens.

K7075 standard. Densities of the cured samples and the constituent materials were also measured, and fiber volume fractions and void contents were evaluated.

Figure 6 shows the measured fiber volume fractions and void contents as a function of the stacked fabric plies in the case of the 300 × 300 mm plates. Similar fiber volume fractions were obtained independently of the plate thickness. All samples exhibited enough small void contents.

In the case of the six-ply 450 × 450 mm plate, the measured fiber volume fraction was about 54% and the void content was 1.5%. This means that the 450 × 450 mm plate has similar quality to the 300 × 300 mm plates.

The thickness of the fabricated plates is about 2.2 mm for four-ply plates, about 6.5 mm for 12-ply plates, and about 13 mm for 24-ply plates. The thickness is proportional to the number of stacked dry fabrics. This result coincides with the experimental measurements of thickness variation during infusion (i.e. thickness variation is proportional to the number of stacked layers, see Figure 5) and the evaluated fiber volume fractions (i.e. fiber volume fraction is almost independent of the number of stacked layers, see Figure 6). It can be concluded that the fabricated CFRP panels using the PMP-based VaRTM process have good quality independently of the plate thickness and size.

3.3. Evaluation of mechanical properties

The fabricated samples were subjected to three-point bending tests in reference to JIS K7074 standard in order to evaluate the mechanical properties. Specimen dimensions and loading conditions (e.g. span length, cross-head speed) were determined based on the standard, and specimens were cut from the fabricated plates. Displacement-controlled bending loads were applied to the specimens using Instron 5582 testing machine. It should be pointed out that 24-ply specimens with 13 mm thickness have short length (as the mother plate has 300×300 mm dimension) compared to the dimension specified in the JIS standard. The span length was set to be 250 mm in the case of 24-ply specimens although this size is out of the standard.

The obtained flexural stiffness and strength are summarized in Figure 7 for the cases of 300×300 mm plates. Flexural stiffness was from 45 to 48 GPa in average independently of specimen thickness. Flexural strength was from 650 to 700 MPa in average for all the specimens except 24-ply specimens. In the case of 24-ply, it is considered that the short span length resulted in low flexural strength compared to other specimens. The experimental results suggest that prepared samples with various thicknesses have similar mechanical properties.

In the case of six-ply 450×450 mm plate, the measured stiffness and strength were 46 GPa and 682 MPa in average, which are similar to the properties of 300×300 mm plates. Therefore, all CFRPs prepared by the PMP-based VaRTM process have similar mechanical properties independently of plate in-plane size, too.

CFRPs prepared by the conventional VaRTM process using the same fibers and epoxy exhibited flexural strength of 638 MPa in average.[11] PMP-based VaRTM process provides CFRPs which have stable quality and better (or at least similar) mechanical properties compared to the conventional VaRTM process.

4. Concluding remarks

The present study proposed the PMP-based VaRTM process, and experimentally investigated the effects of plate thickness and size on the quality and the mechanical properties of fabricated plates.

CFRP plates with varied thickness and in-plane size were fabricated based on the PMP-based VaRTM process. Thickness variation during resin infusion, quality (fiber volume fraction and void content), and flexural properties of cured samples were measured. Results of thickness variation indicated that resin infusion behavior is quite simple and thickness is almost constant in the plate independently of the plate dimension. All cured samples had almost no voids, and measured fiber volume fractions and void contents were almost same among the samples.

The proposed PMP-based VaRTM process is a simple knowhow-less manufacturing process, in which we just wait for resin curing after resin infusion starts. The present experimental demonstration indicated that the quality and the mechanical properties of CFRP prepared by the PMP-based VaRTM process are stable and independent of the locations in the plates and the dimensions of the plates. It is concluded that a low-cost simple manufacturing process was developed for the quality improvement and the reliable quality of FRPs.

Acknowledgment

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