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Transverse Flow and Process Modeling on the Polymer Composite with 3-Dimensionally Stitched Woven Fabric

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Abstract : In resin infusion process(RIP), the fiber and the resin are in contact with each other for an impregnation step and often results in flow-induced defects such as poor fiber wetting and void formation. Resin flow characteristics in transverse direction and process modeling for woven fabric were studied, and the process modeling was applied to the manufacturing of hybrid composite materials. This study also considered the compressibility of woven fabrics in a series of compression force, and it was fitted well to an elastic model equation. Void formation was varied with the processing conditions in the stage of manufacturing composites using RIP. It was concluded from this study that proper combination of pressure build-up and dynamic heating condition makes important factor for flow-induced composite processing.

Keywords : polymer composite, resin film infiltration, process modeling, wettability.

Introduction

The resin infusion process(RIP) was originally developed for autoclave processing using a vacuum bag/tooling combination for shaping parts. Due to a quite low viscosity of thermosets at elevated temperature before cure, resin infusion into a dry fibrous preform becomes an attractive manufacturing technique especially for 3-D composite structures. In addition, RIP is easily adaptable to the fabrication of either monolithic or honeycomb sandwich structures with various types of matrices. Furthermore RIP, more versatile process involving resin infiltration into a dry fibrous preform, has overcome the problems encountered in conventional Resin Transfer Molding (RTM) such as low fiber content, the need of expensive match molds, long distance for resin to infiltrate out the fibrous preform, and void formation.[1,2]

In transverse flow, compression of the reinforcement occurs with resin flow simultaneously. Therefore, the analysis of flow in transverse direction should be performed carefully. Compression is a common type of deformation happened during many composite processes. In RTM and RIP, the fibrous preform is preplaced in the mold cavity while the mold is open. The resin is injected into the fibrous preform after the mold is closed. In these processes, some compression of the reinforcement occurs when the mold is closed.[3] In addition, the applied pressure compresses fibrous preform as well as facilitates resin infiltration.

A combination of external pressure and resin pressure may also be present in many cases of autoclave processing.[4] In RIP, however, external pressure is transferred to the fibrous preforms and resin layers simultaneously. In addition, the fibrous preforms are compressed and as a result, both porosity and pore structure have changed, which would affect flow permeability and capillary pressure.

The resin flows in the stitched structure composed of woven fabric skins urethane foam core and transversely stitched glass bundles is depicted schematically in Figure 1. Transverse and longitudinal flow are expected when filling the hybrid sandwich structure with resin. The resin flow in the longitudinal direction is known to be faster than that of the transverse direction. Thus, the resin flow through the stitching fibers is faster than that through the fibrous preform. After the resin passes the upper and the lower skin structure, it starts to flow rapidly into the stitched fiber within foaming material.

Transverse or longitudinal flow through woven fabrics is related to physical conditions such as lay-up structure of fiber beds, interfacial properties between fiber and resin, viscosity, compressibility, etc. However, the processing variables are only mechanical pressure and temperature. To investigate the effects of complicated factors into the two processing variables, the precise analysis of the factors and their effects are needed.

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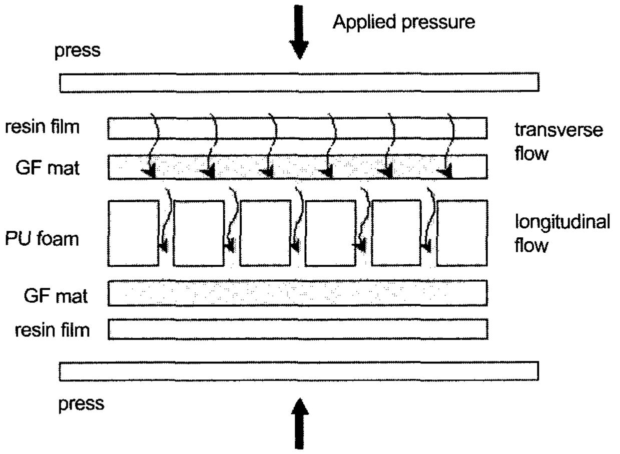

Figure 1. Resin flow path in the hybrid sandwich structure.

In this study, resin flow characteristics in transverse direction were analyzed by the measurements of permeability and capillary pressure. The process modeling was followed by experiments including compression tests and transverse infiltration into woven fabric. The existence of a lot of void in final products is one of the factors lessening properties of the products, so it is important to decrease the void content of the composite. In order to make the overall analysis of the resin infusion process and to examine the effects on transverse resin flow and void formation during processing, the systematic study for the factors affecting processing variables was performed. Finally, the stitched composites of hybrid sandwich structure were manufactured on the basis of modeling using vacuum bag modified RIP.

Theoretical Backgrounds

Transverse Permeability and Capillary Pressure. The resin flow through the fibrous preform can be described by Darcy's law. In resin infiltration experiments, the system consists of two distinct layers: the fibrous preform and the resin layer which may be placed above or below the fibrous preform. Assuming a linear pressure distribution in the fibrous preform, the resin penetration thickness into the fibrous preform may be described as a function of time, and then by rearranging subdivided pressure gradient into applied(P_m) and capillary(P_c) terms, the resin penetration thickness is expressed as:

$$Y_p^2 = \frac{2K_y}{\mu\phi}(\Delta P_m + \Delta P_c)t \tag{1}$$

where, Y_p is the resin penetration thickness in transverse direction, K_y is the transverse permeability, μ is resin viscosity, ϕ is apparent porosity. As shown in equation (1), the permeability can be calculated from the resin penetration thickness as a function of time. Similarly, the capillary pressure can be calculated from the resin penetration thickness.[5,6]

As a first approximation the capillaries between the fibers may be regarded as being cylindrical and uniform in diameter. For a capillary with circular cross section, the pressure difference is a function of the surface tension(γ_{lv}) and the diameter of capillary.[7] The equivalent diameter of the fibrous bed is defined by the cross-sectional area normal to flow divided by the perimeter presented to the fluid. The fibrous preform, however, is usually anisotropic. In addition, the pores of a fibrous preform are different in size and shape. These anisotropic/geometric configurations may be combined in a dimensionless shape or form factor(F), which depends on the flow direction. For one-dimensional resin flow, the capillary pressure is described in a generalized form as follows:

$$\Delta P_c = \frac{F\gamma\cos\theta}{D_f}\frac{(1-\phi)}{\phi} \tag{2}$$

where, D_f is the diameter of filament. For unidirectional fibrous preform, F assumes the value of 4 for resin flow along the fiber direction, while F assumes the value of 2 for flow perpendicular to the fiber alignment. For the complex fiber alignment such as the woven fabric preform, F may be determined only indirectly by measurement of permeability.[6]

Compressibility and Fiber Deformation. There are two distinctive sources of compression in composite lamination process: one is the mechanical pressure applied externally when the mold is closed, the other is the resin pressure applied when the resin infiltrates into the reinforcements. Gutowski *et al.*[4,8-10] proposed a model for the resin flow and fiber deformation in the processing of unidirectional fiber composites. The deformation of parts of fiber between contact points was modeled according to the theory for elastic beams of circular cross section. Thus, one can derive the non-linear stiffness behavior of the fiber mat and, that shows good agreement with experiments. The proposed model equation by Gutowski is expressed as:

$$P = A_s\frac{\left(\sqrt{\frac{V_f}{V_o}}-1\right)}{\left(\sqrt{\frac{1}{V_f}}-\sqrt{\frac{1}{V_a}}\right)^4} \tag{3}$$

where, V_o is the original fiber volume fraction, V_a is the available fiber volume fraction, and A_s is the spring constant. In general, fibers which are misaligned and cross over will result in a lower available fiber volume fraction(V_a).[8]

Several researchers properly identified the compressibility equation in the molding process of fiber reinforcement, and they handled it primarily in an empirical way for convenience. Samarasinghe *et al.* analyzed the consolidation in a simple empirical method.[11] They found out the experimental data for the effective pressure of the fibers and the volume fraction of the liquid were fitted to a logarithmic relation which has been found valid for a large number of normally consolidated soils. Toll and Manson[12] proposed a micromechanical model which yielded the relation for planar fiber networks. They also proposed a more general empirical relation of the power-law type with two empirical constant as follows.

$$P = cV_f^n \tag{4}$$

Equation (4) is proposed on the basis of elastic behavior of fibrous preform and this relation seems to fit the experimental data of compression of layered woven fabric in spite of its simplicity.

Experimental

Materials. Epoxy resin was used to analyze transverse flow. The resin system was formulated same amounts of liquid YD-128 and solid YD-011 epoxy resin(both from Kuk Do Chem. Co.) were mixed 10 phr of dicyandiamide (DICY) as a curing agent. As a reinforcement, WR580A (Hankook Fiber Co.) which is E-glass woven fabric was used. The properties of materials used in this work are listed in Table I.

Permeability and Capillary Pressure. To visualize the resin flow in transverse direction, the mold consisting of a syringe and a piston was made of transparent acryl as shown in Figure 2. Metal mesh plates were placed in the upper and the lower side of woven fabrics, which make good penetration of fluid into fiber mats. Experimental procedure was as follows. Fiber mats were cut into samples of diameter of 5 cm using a sharp-edged punch die made of stainless steel. YD-128 and YD-011(50/50) were mixed together at the elevated temperature. Stacked ten plies of the woven fabrics were placed into the mold, and the heights were adjusted to control porosity. The resin and the apparatus were preheated for 40 min in a convection oven at fixed temperature. After sufficient preheating, the resin was filled into the mold under the constant pressure. The partially impregnated glass fiber mats were taken off to measure the weight of impregnated resin and the depth of penetration was calculated.

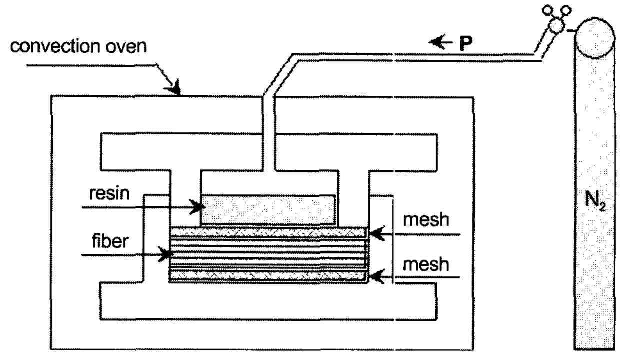

Figure 2. Schematic diagram of equipment for measuring transverse resin flow.

The pressure was controlled by nitrogen gas. Applied pressure was set to 0, 20, 40, 60, and 100 KPa. The porosities of the fiber mats were fixed to 0.25, 0.3, 0.35, and 0.4 by manually placing metal spacers. The low porosity was chosen in order to protect the compression of the fiber mats during flow experiments under applied pressure. Also the pressure range was confirmed as not to change the porosity in the compressibility test. The impregnation was carried out at 100 °C. Transverse permeability and the capillary pressure were measured experimentally.

Compressibility of Woven Fabric. Porosity can be changed during compression of fiber mats. The degree of compressibility of 10 plies and 20 plies of woven fabric with 5 cm diameter was measured. The woven fabric mats were cut into the same size. Since the fabric mats were easily deformed during cutting, a sharp-edged punch die made of stainless steel was used. The compression tests were conducted using universal test machine(UTM), and experiments were performed by three methods. The first one is to measure the thickness and the stress at constant crosshead speed of 0.5 mm/min. The second one is to observe the stress change after compression. The third one is to investigate the effect of interlayer space on the compressibility of fiber mats. This test was performed by the second compression after eliminating the first applied load.

Resin Viscosity and Surface Tension. The viscosity profile as a function of temperature was measured with Brookfield

Table I. The Basic Properties of Matrix Resin and Glass Woven Fabric

	Resin System			Reinforcement	
	YD-128	YD-011	DICY	WR580A	
E.E.W(g/eq)	185~192	450~500	21	22	Filament Diameter (μm)
Viscosity at 25 °C (Pa · s)	12.5	solid	Solid	1150	Roving Tex (g/km)
Specific Gravity at 20 °C	1.16	1.18	-	6.3 × 6.3	Cloth Density (tow/inch)
Melting Temp. (°C)	-	60	202	580	Surface Density (g/m^2)

viscometer. The surface tension of matrix resin was measured by Wilhelmy method, introducing the platinum ring whose contact angle had been already known.[13] The Dynamic Contact Angle Analyzer, DCA322(Cahn Co.) was used to measure the surface tension.

Manufacturing of Composite Specimens. Polymer composites were manufactured by RIP. Resin films with a thickness of 0.3, 0.5, and 1 mm were obtained by using doctor blade in order to control resin ratio to the fiber mats. The two different experimental methods of manufacturing composite specimens were used. The first one is to investigate how many voids exist in the specimen; 6 plies of WR580A woven fabric were used. An autoclave modified hot-press as shown in Figure 3(a) was used on manufacturing the specimens. The lay-up procedure was similar to a conventional autoclave process, except that a resin layer and a fibrous preform were placed separately instead of using prepreg layers. These resin films and fibrous preforms were placed in a vacuum bag composed of releasing film and steel plates as caul plate and tool plate. The vacuum line was installed with a breather mounted on top of the layered part. Since the application of vacuum was critical in eliminating voids in the final composite structures, vacuum pump was used from the beginning of the process. The processing time and the rate of increasing applied pressure were varied to observe the void formation. The distribution of entrapped voids in the final specimen was investigated with a microscopic method.

The second one is the hybrid polymer composite. The hybrid materials composed of glass fiber and PU foam, as shown in Figure 3(b), were placed between the resin films. Specially, PU foam was sandwiched with glass woven fabrics and this sandwich structure was stitched with yarn in order to bind together. The PU foam used in this work has closed-cell structure, which protects impregnating resin into the foam inside. Therefore, stitching fibers could induce resin flow through the stitching hole and improve mechanical properties. The mechanical pressure was applied at the point of increasing viscosity after the sufficient impregnating within woven fabrics and stitching yarns.

Results and Discussion

Analysis of Transverse Flow. The resin penetration length was measured at isothermal condition during flow visualization experiments of epoxy resin system, whose flow direction is transverse to the glass woven fabrics. As the porosity increased, the permeability increased rapidly. The relationship between permeability and porosity is predicted by Kozeny-Carman[14,15] equation as shown in Figure 4. From slope of the line, the Kozeny constant can be determined, which represents the characteristics between the fiber mats and the resin system. Transverse permeability at high porosity is affected by macro pores, while at low porosity this is affected by micro pores. The relatively uniform distribution of pores is formed at low porosity. That is caused by fiber rearrangement at high compression pressure. So, characteristics of fibrous preform are thought to be well defined at the low porosity. In the figure, large deviation was seen at high porosity. Therefore, Kozeny constant was measured at

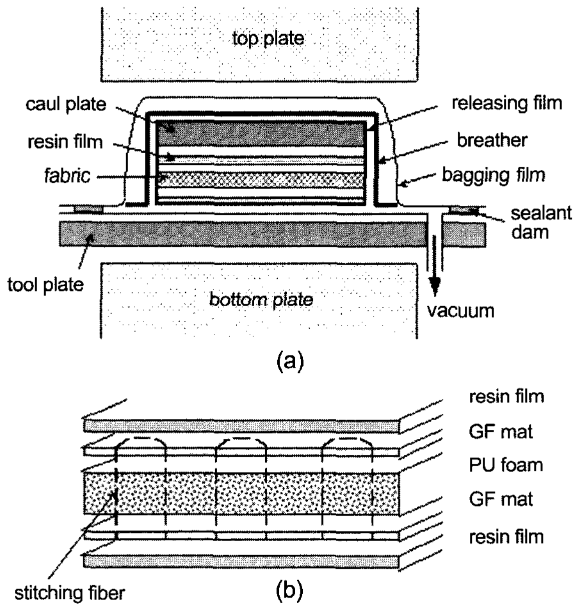

Figure 3. Composite manufacturing by resin infusion process. (a) autoclave modified RIP and (b) stitched hybrid composite.

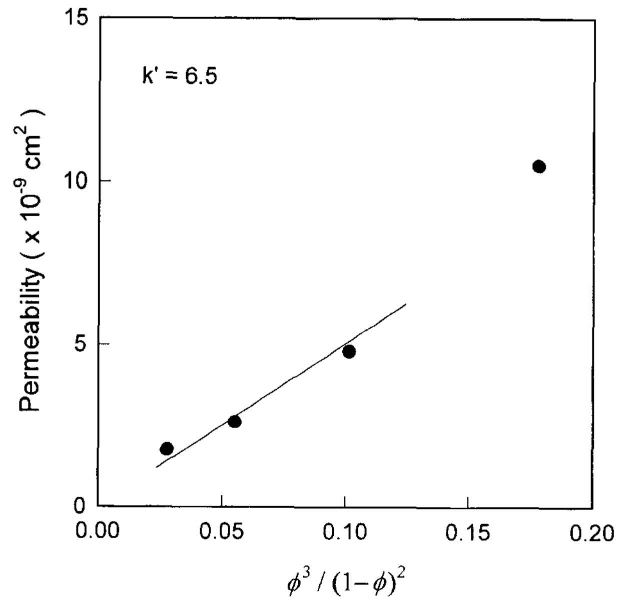

Figure 4. Permeability as a function of porosity showing linearity as predicted by the Kozeny-Carman equation in the range of low porosity.

Table II. Comparison of Kozeny Constant(k) for Fiber Alignment

Flow Direction	Woven	Unidirectional	
	WR580A[a]	Lam & Kardos	Gutowski
Transverse (k_y)	6.5	11	17.9
Longitudinal (k_x)	0.06	0.35~0.68	0.7
k_x / k_y	9×10^{-3}	5×10^{-2}	49×10^{-2}

[a] Based on apparent porosity in woven fabric.

low porosity. Kozeny constant was 6.5, which was reasonable value compared to other investigators' results performed using unidirectional fibers. Kozeny constant is the universal value regardless of the types and the arrangements of fibers, so it could be used to compare the characteristics of woven fabrics with unidirectional fibers. In the previous works,[4,5,11,16] Kozeny constant for transverse flow was from 11 to 18, and for longitudinal flow from 0.35 to 0.7 in case of unidirectional fibers. Woven fabrics have the structure of crossed fiber bundles, so there are macro pores to produce macro flow paths. For this reason, the Kozeny constant is smaller than that of unidirectional fibers and this value should be appreciated to simulate the real system. Characteristic properties of woven fabric used in this experiment are shown in Table II and compared with previous results. First, Kozeny constant is smaller compared to that of unidirectional fibers in longitudinal flow, because permeability is very large due to the geometry having macro pores. Nevertheless, the ratio of longitudinal to transverse Kozeny constants is very small. Then, micro voids could be formed to the transverse direction in impregnation of thick-part products. Therefore, for the optimum design of RIP, it is necessary to arrange the resin film to shorten flow path.

The effect of capillary pressure is thought to be strong due to large amount of micro pores, although the moving distance is short in transverse flow rather than in longitudinal flow. Experimental results showed that the capillary pressure increased as porosity decreases. This capillary pressure affects resin penetration and void formations. It is very difficult to eliminate entrapped voids in the impregnation stage. Thus, the prediction of capillary pressure with porosity change induced by external pressure is very important in the RIP process. In order to obtain the change of capillary pressure with porosity, the proposed equation (2) was used and the results were shown in Figure 5, which showed a linear relationship in the range of measured porosity. The value of slope in the figure is $F\gamma\cos\theta$. From the experiments for the temperature dependence of surface tension and contact angle, the changes in capillary pressure with temperature could be predicted. The surface tension of the resin system was 43 dyne/cm, and the static contact angle was 40 at the experimental temperature. The shape factor calculated from equa-

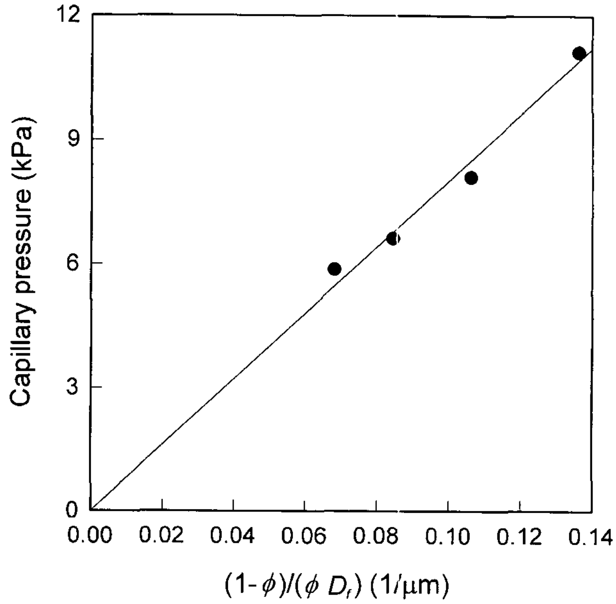

Figure 5. Capillary pressure as a function of porosity showing linearity as a predicted model equation (2).

tion (2) and Figure 5 was 2.4, which was similar to the value of 2 for the unidirectional fiber mats. Ahn *et al.*[6] obtained shape factor of 1.8 in similar experiments using carbon fiber mats. The fiber mat was a dense system composed of 3,000 filaments of 7 μm diameter leading to smaller shape factor than that of unidirectional fibers. However, WR580A woven fabric had loosened woven geometry, which gave us reasonable shape factor of 2.4. From the generalized relationship between porosity and permeability or capillary pressure, the effects of flowing variables in RIP could be predicted.

Analysis of Compressibility. The change in porosity of fibrous preforms induced by mechanical pressure is called compressibility, which is used to predict changes of permeability and capillary pressure by applied pressure during process. In this study, we carried out the experiments to analyze the compressibility, by changing the number of layers, by changing the pressure applying method and by re-compression. Changing the number of layers was used to investigate the effect of interlayer space, and changing the pressure applying method was used in order to compare woven fabrics and unidirectional fibers, and the re-compression was used to investigate the elastic recovery. Figure 6 shows the results of compressibility in case of woven fabric. From this figure, the pressure differences between 10 and 20 plies are relatively large in the first run. However, the pressure differences in re-compression (second run) are so small. It seems that the compression occurs in interlayer space at first, and then uniformly in tows. Moreover, relatively large deviation in pressure at unsteady-state condition, where the thickness of woven fabric decreases linearly with time, was shown in comparison with the deviation at the steady-state condition.

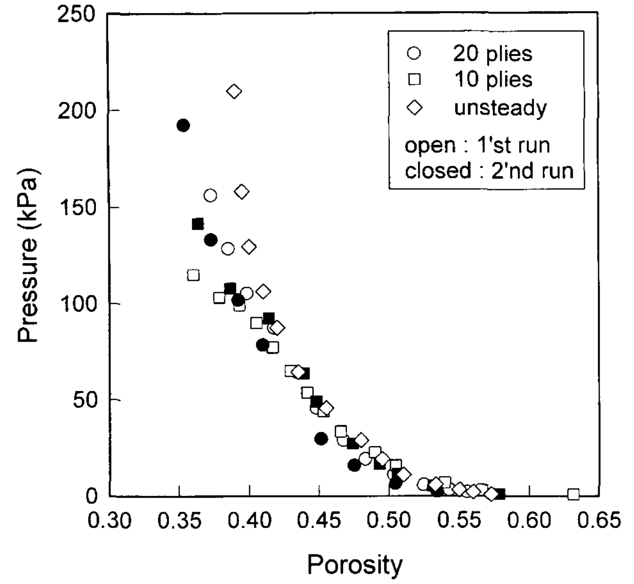

Figure 6. Porosity change as a function of applied pressure in woven fabric.

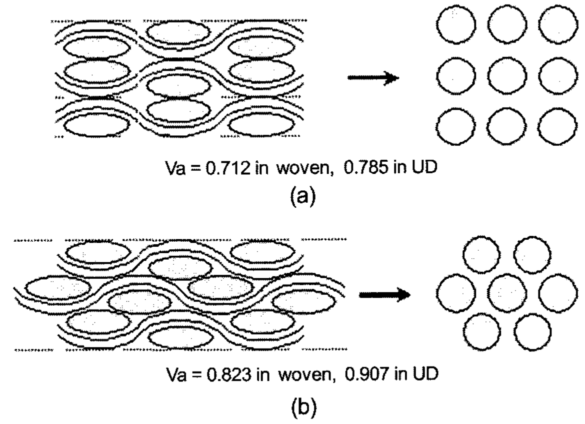

Figure 7. Representation of idealized woven and unidirectional packing. (a) square and (b) hexagonal.

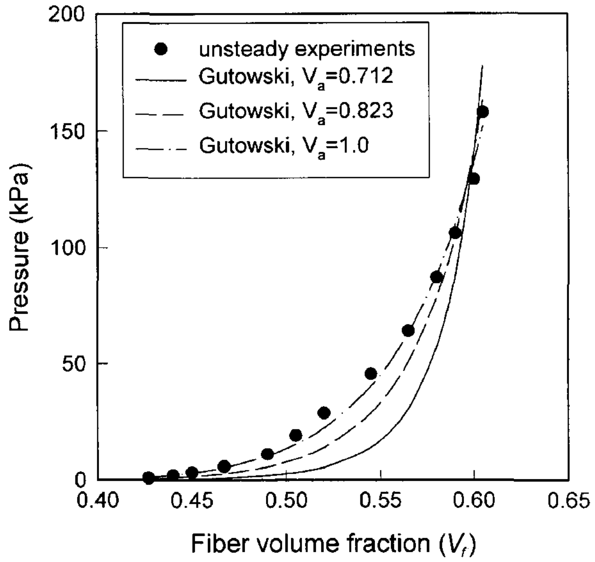

Figure 8. Comparisons of unsteady compression data and model equation applied to woven fabric.

At the initial stage it showed similar results, after that it showed rapid increase of pressure. These results indicate that the compression is applied continuously until the stress relaxation occurred by the interlayer rearrangement. However, these results were very different from those of previous works using unidirectional fibers. In the unidirectional fibers, fiber filaments were slipped to rearrange and the porosity changed rapidly in the initial stage of compression. As the rearrangement comes to hexagonal packing, the fibers can lead to a rapidly increasing load. To apply equation (3) proposed by Gutowski[8,9] for unidirectional fibers to the woven fabrics, V_a' should be assumed. Theoretically, maximum fiber volume fraction of unidirectional system is 0.907 and 0.785 at hexagonal and square packing, respectively. Although the inside status of fiber bundles is locally hexagonal, presence of macro pores between tows reduces the maximum fiber volume fraction obtainable in woven fabrics. At this point, we can give a clear physical meaning for the porosity of woven fabric by following equation.[17]

$$\phi = (\phi_M + \phi_m) - (\phi_M \phi_m) \quad (5)$$

where, ϕ_M is macro porosity, ϕ_m is micro porosity. Figure 7(a) shows the tows in the square position, which is similar to unidirectional system, (b) is similar to hexagonal unidirectional packing. Therefore, the maximum fiber volume fraction has a range between 0.712 and 0.823. Figure 8 shows the results of model equation[8,9] applied to woven fabric. In this figure, V_a is assumed for the three cases, which were proposed from the above results in woven fabric system. The comparison of model equation by Gutowski and experiments showed big differences. Therefore, the maximum fiber volume fraction is smaller than theoretical value, so the Gutowski equation cannot be applied to woven fabric systems.

Woven fabrics are the systems showing perfect elasticity as shown in Figure 6. In addition, the woven fabric shows that the fiber slippage hardly occurs due to cross-weaving structure, so general elastic model was used to decide experimental variables. To linearize the experimental results, natural logarithm was used. As a result of many investigations, our experimental results agreed with the equation (4), and the compressibility was expressed as follows

$$P_m = 1512 V_f^{14} \quad (6)$$

Conclusively, it was confirmed that the woven fabrics showed elastic behaviors which are attributed to cross-weaving structure of fiber bundles.

Process Modeling. Only pressure and temperature, which are dependent on time, are processing variables in RIP. However, it is impossible to analyze process without understanding mutual effects of factors affecting impregnation stage. The effects of processing variables were considered to have three categories as follows. The first is the mechanical pressure, which changes the porosity of fabric layers leading to the changes of capillary pressure and permeability. The second is temperature, which changes the viscosity of resin, so surface tension and contact angle are changed. These also affect permeability and capillary pressure. The third is the combined effects of temperature and pressure.

In isothermal condition, permeability and capillary pressure can be predicted by the model equation stated above. Permeability, which is a main factor governing macroflow, decreases while capillary pressure increases as porosity decreases. However, as porosity decreases, the filling time increases. From this point, it is necessary to maintain high permeability by increasing porosity rather than increasing capillary pressure in case of constant inlet pressure.

As mechanical pressure change becomes linear in isothermal condition, each processing variable and their effects were investigated. Figure 9 shows porosity, permeability, capillary pressure, and penetration length with time, at the pressure increasing rate of 0.1 atm/min. The value is predicted by equation (1), (2), (6). Porosity and permeability decreased with time. However, capillary pressure increased to become a sufficient driving force for the stage of impregnation. Penetration length was linearly increased at initial stage, and the slope was lowered as the compression progressed. When increased mechanical pressure makes the porosity reach the critical value, permeability was lowered to prevent the resin from penetrating in spite of increased capillary pressure. This means there is a critical penetration length.

To analyze the temperature effect, viscosity change with temperature before curing was fitted using Arrhenius type equation with two empirical constants. From the experimental results, the equation of viscosity profile is as follows.

$$\eta(Pa\ .s) = 5.63\times 10^{-5}\exp\left(\frac{39920}{T}\right) \tag{7}$$

Temperature dependence of capillary pressure is analyzed using equation (2). The change of surface tension with varying temperature is expressed by Guggenheim equation[18] derived for low molecular weight liquids and has been also found to be applicable to polymers.

$$\gamma = \gamma_o\left(1-\frac{T}{T_c}\right)^{11/9} \tag{8}$$

where γ_o is the surface tension at 0 K, and T_c is the critical

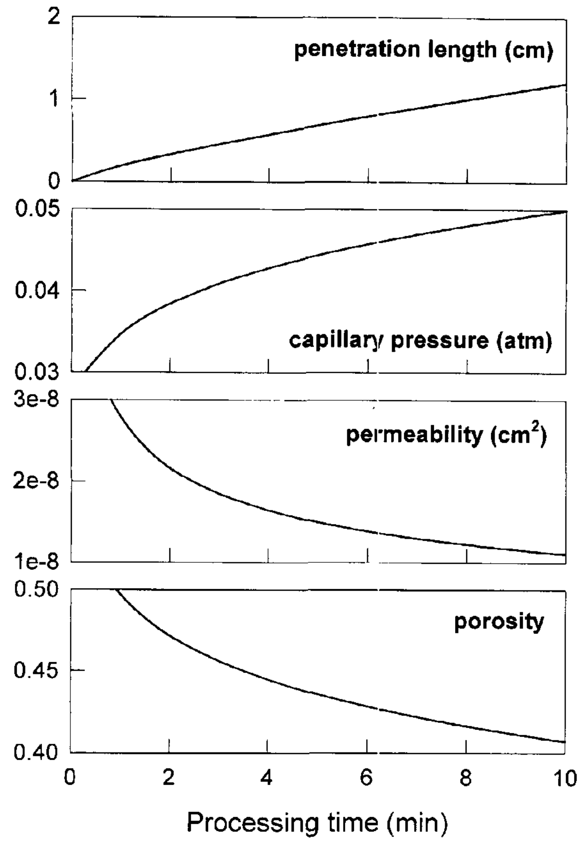

Figure 9. Predictions according to process model for increasing rate of 0.1 atm/min of applied pressure at constant temperature.

temperature. Obtained parameters were γ_o = 91.3 dyne/cm, T_c = 807.7 K, showing the similar values to the experimental results. The variation of contact angle(θ) according to temperature depends on the relative magnitudes of surface entropy of two phases. In general, at ordinary temperature range, the values of $-d\theta/dT$ is quite small, about 0.05 deg/°C.[18] Therefore, temperature dependence of contact angle can be negligible in this section. Figure 10 shows viscosity, surface tension, capillary pressure, and penetration length at constant pressure and constant porosity with the dynamic heating rate of 5 °C/min. The value is predicted by combined equation (1) to (8). Penetration length increased linearly. However, there are differences in penetration length between Figure 9 and Figure 10 after initial stage. Probably this is due to decreased viscosity with increased permeability under dynamic heating condition. Penetration length with time using model equation is shown in Figure 11, when mechanical pressure was applied under non-isothermal state. Penetration length increased rapidly at initial time, and then linearly increased at the latter period. Nevertheless, comparing with Figure 10, at constant pressure under heating condition, the penetration length was shorter, possibly by the decreased permeability with increased pressure. Consequently, it is very important to control pressure and temperature so as to impregnate easily in transverse direction. From the facts described above, this study showed that process modeling for the actual manufacturing process was possible from the analysis of effects of processing variables on flow behaviors. In addition, overall process optimization to produce void-free final products would be expected.

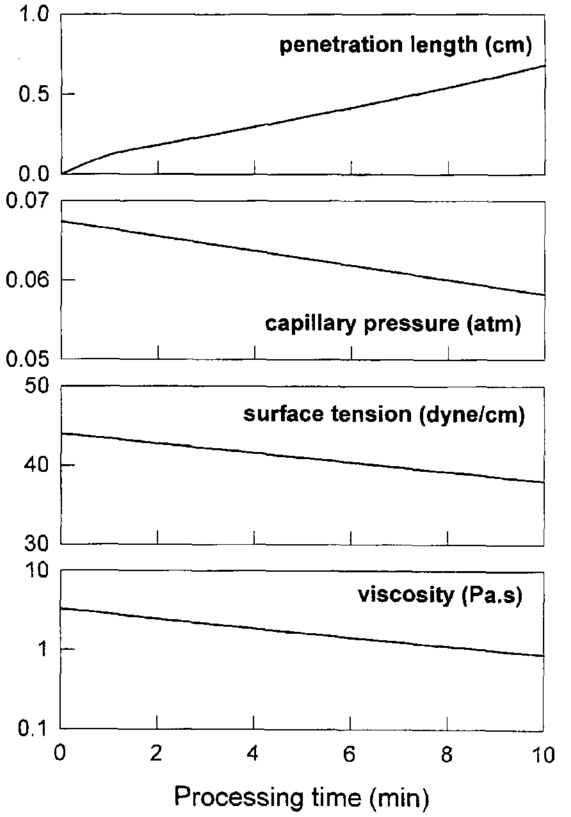

Figure 10. Predictions according to process model for increasing rate of 5 °C/min of temperature at constant applied pressure of 20 kPa, porosity of 0.35.

Manufacturing of Composites. Composite specimens with epoxy resin and glass woven fabric were prepared using RIP. Resin films and glass woven fabrics were mounted in a vacuum bag composed of lay-up structures, which was similar to a conventional autoclave process. The molded structure was placed in the programmable hot press. Initial resin amount was 47 wt%, which is the excess amount compared to the general process. Heating rate was 5 °C/min and the system was maintained for 2 hrs after reaching 180 °C. Resin is impregnated into fabrics with decreasing viscosity as temperature rises. The effects of pressurizing point and the increasing rate of pressure were analyzed. The pressurizing points were 80 °C and 120 °C, and the increasing rate was varied. Cross-sectional areas of cured composite were observed to find out the degree of impregnation and entrapped void. For the specimen pressurized at 80 °C with slow increasing rate, large amount of resin was squeezed out so as not to fill the macro pores at surface of fabrics. In addition, there were macro voids between tows in the fabrics as shown in Figure 12. Viscosity and capillary pressure directly affect the resin flow, the latter plays a greater role in micro pores than in macro pores. This means that resin fills inside the tows of the fabrics faster than the macro pores between tows. When the external pressure is applied at low viscosity, impregnated resin is squeezed out. And the volume shrinkage occurs as cure reaction progresses, so macro voids were formed between tows. For the specimens pressurized at 120 °C,

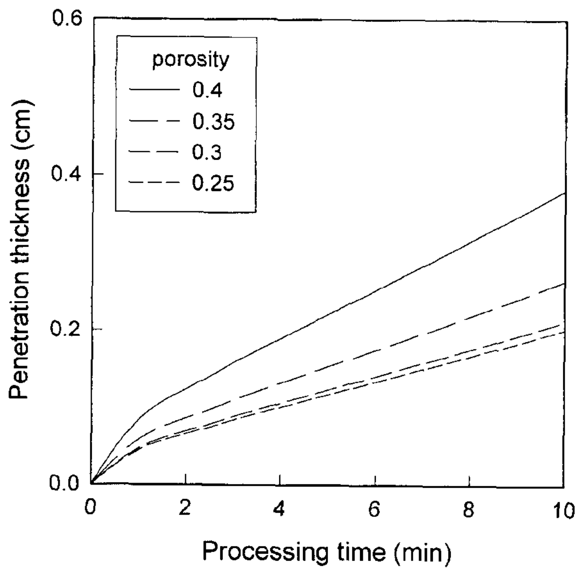

Figure 11. Predicted penetration thickness as a function of time for dynamic heating condition at constant pressure.

Figure 12. Photographs of cross-section for the woven fabric composites.

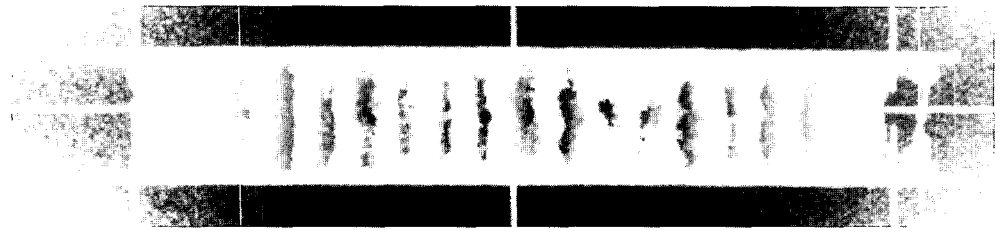

Figure 13. Photograph of stitched hybrid composite after extracting PU foam.

however, resins were filled in micro pores as well as in macro pores. At 120 °C, the viscosity increases slowly with progress of cure reaction, and the pressure was applied slowly to prevent the squeezing out of the resin. From these results, it was confirmed that the applying time of the pressure should be controlled to reach its maximum pressure at the gel point of resin.

Sandwich structures were prepared with inserting PU foam having thickness 3 cm into the layer of glass woven fabric. They were stitched with strands of glass yarn through the transverse direction. Since the foam structure was not impregnated with resin, stitching was introduced in order to induce resin flow and to improve mechanical property. This stitching was known to create a complex resin flow mechanism in the composite processing. Therefore, the investigation of the resin flow in this special structure was necessary to provide a better understanding of infusion phenomena into the fibrous preform during RIP. Two strings of stitching fiber bundle were used. Sufficient impregnation was carried out at low viscosity range, and it was pressurized to get void-free products. From the process modeling as mentioned above, the processing variables such as applied pressure and temperature were controlled in manufacturing of stitched sandwich structure. In the experiment, it was observed that the resin flows well both side of the laminated structure; transverse flow in upper and lower glass woven fabric, longitudinal flow in stitching fiber bundles. The resin was impregnated well at the structure of stitched fibers as shown in Figure 13. This sandwich form can be used in building structure such as container wall parts, whose properties should be light and stiff. Mechanical properties can be controlled by stitching density and enhanced material properties are also achieved by using this structure. In addition, stitched sandwich structure may be substituted with honeycomb structure. Conclusively, it was found that the resin flow characteristics and process modeling could be applied to design of manufacturing process using RIP with improved properties and void-free structural composites.

Conclusions

Resin flow characteristics in transverse direction and process modeling for woven fabric were studied, and the process modeling was applied to the manufacturing of hybrid composite materials. The results may be summarized as follows:

The change of permeability with porosity called Kozeny constant for the woven fabric showed smaller value than that of unidirectional aligned fiber. It was considered that the differences of Kozeny constants were due to the structure of woven fabric containing macro pores. For the capillary pressure, there was a linear relationship for the range of measured porosity from which the form factor in woven fabric system was determined. The results of compressibility for the woven fabrics were found to fit well to an elastic model equation.

When the mechanical pressure was increased at constant rate under isothermal condition, the permeability became so small that the resin cannot penetrate the woven fabrics. However, penetration length increased linearly with time because of decrease of resin viscosity in dynamic heating condition. Consequently, the optimization of real process could be designed by using process modeling, and quality of final product could be controlled. Void formation was varied with the processing conditions in the stage of manufacturing composites using RIP. The pressing condition and the heating condition are important for the good impregnation of resin and the manufacture of void-free product. Especially, it was shown that longitudinal and transverse flow analysis and process modeling could be applied directly to the manufacture of hybrid products with foam materials and stitching fibers.

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