Commingled Yarn 을 이용한 열가소성 복합재료의 Filament Winding 공정에 관한 연구

A Study on the Filament Winding Process Using Thermoplastic Commingled Yarn

김선경*, 김공민**, 이우일***

Abstract

복합재료의 성형 공정 중 하나인 Filament Winding 공정에 열가소성 기지재료인 폴리프로필렌(Polypropylene)과 강화섬유인 유리섬유로 이루어진 Commingled Yarn 을 이용한 연구를 수행하였다. 함침 과정을 해석하기 위한 계산모델을 제시하였다. 그리고 위의 모델링을 해석하는 데 필요한 복합재료 내의 온도 분포를 수치해석을 통해 계산하였고 실험을 통해 이를 검증하였다. 온도계산 결과를 함침도 예측에 이용하였다. 모델링을 통해 Filament Winding 공정의 주요 공정 변수를 찾아내었고 제시한 모델을 검증하기 위해 직접 Filament Winding 실험 장치를 제작하여 제품을 생산하고 모델과 비교하였다. 제작된 시편으로부터 함침도를 계산하는 방법을 제시하였다. 그 결과 함침도에 관해서 실험 결과가 모델과 그 경향이 뚜렷이 일치함을 확인하였다.

Keyword : commingled yarn, filament winding process, degree of impregnation

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Introduction

Recently, thermoplastic filament winding process is getting attentions of many researchers. Carpenter and Colton came up with deformation and flow models for filament winding process using APC-2 in consideration of the roller compaction force and the mandrel angular speed with experimental investigation [1]. Kim et al. performed thermal analysis for tape laying process using APC-2 with both experimental and numerical methods [2]. Romagna et al. investigated experimentally the effect of preheating in the thermoplastic filament winding process [3].

In thermoplastic composite manufacturing processes, resin impregnation into fibers is difficult to achieve due to higher viscosity. Thus, in a thermoplastic filament winding, prepreg such as APC-2 has been widely used despite high price of that material. The consolidation between laminates has been the main issue of thermoplastic filament winding process. The degree of consolidation can be controlled by the thermal energy transfer rate during the bonding process. Furthermore, the temperature of the molten spot is to be below the degradation temperature. However, other thermoplastic composite manufacturing processes utilizes various materials including powder-impregnated fiber bundles and commingled yarn. In this case,

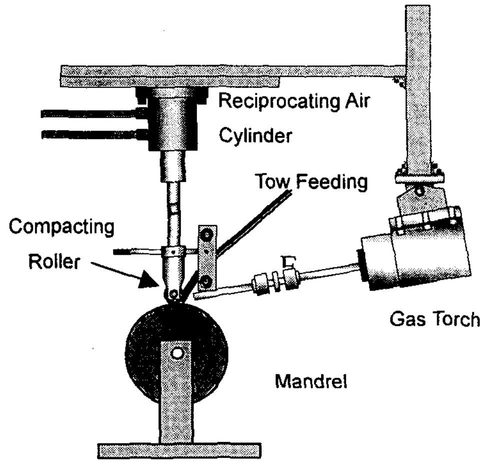

Figure 1 Experimental Apparatus for Filament Winding Process.

the impregnation holds fundamental importance. This study considers thermoplastic filament winding process using commingled yarn. Commingled yarn is flexible, preservable, and easy to handle in comparison with thermoplastic prepreg. Furthermore, forming of complicated shape with large curvature is possible. Above all, the moderate price of commingled yarn is attractive.

In the present study, winding of commingled yarn involving polypropylene resin and glass fiber on a cylindrical mandrel is investigated. The area where the incoming filament begins to contact with the substrate is heated during the winding by a nitrogen gas torch. Such heating method is efficient and inexpensive for in situ consolidation. Because the energy is concentrated on the welding region, overall residual stress and warpage can be minimized. Thus, local heating by gas torch is widely used for thermoplastic winding and lay-up processes. This study is focused on establishing the numerical models for the filament winding process using commingled yarn. The models include the contact model, the flow model, the thermal model, and the impregnation model. Furthermore, the model is examined with experimental data for a few test cases. For the experimental investigation, laboratory size filament winding machine with two axes is built. The ultimate objective of this work is to address the optimal process window by predicting the dimension of the product and the degree of impregnation accurately.

Model

Contact time

In the course of the filament winding process, the molten region is pressurized by the compaction force of the roller. While the roller contacts with the incoming tow, pressure develops in the molten region, and impregnation proceeds. Regarding commingle yarn as a thin strip, the thickness of the strip changes after the compaction point. The cushion nip concept suggested by Carpenter and Colton is considered [1]. As illustrated in Fig.2, the thickness decreases from h_i to h_f. With the use of this geometric relation and the linear velocity V at the contact point, height h and the time derivative of height $\dot{h}$ can be expressed in terms of h_i, h_f, V, and radius R as follows.

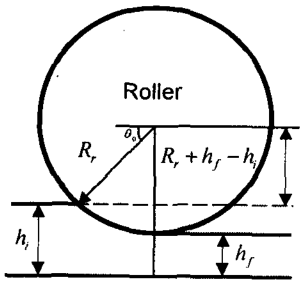

Figure 2 Geometrical Description of Contact Model.

$$h = R_r + h_f - R_f \sin(Vt/R_f + \theta_o) \quad (1)$$

$$\dot{h} = -V \cos(Vt/R_r + \theta_o) \quad (2)$$

where $\theta_o = \sin^{-1}\left(\frac{R_r + h_f - h_i}{R_r}\right)$

As a result, the contact time t_c is of the form

$$t_c = \frac{2R_r}{V}\left(\frac{\pi}{2} - \theta_o\right) \quad (3)$$

Here, the linear velocity is controllable and the thickness can be measured. Because impregnation and consolidation is induced by the compaction force, the contact time is required for the subsequent models.

Pressure profile

During the process the pressure profile inside

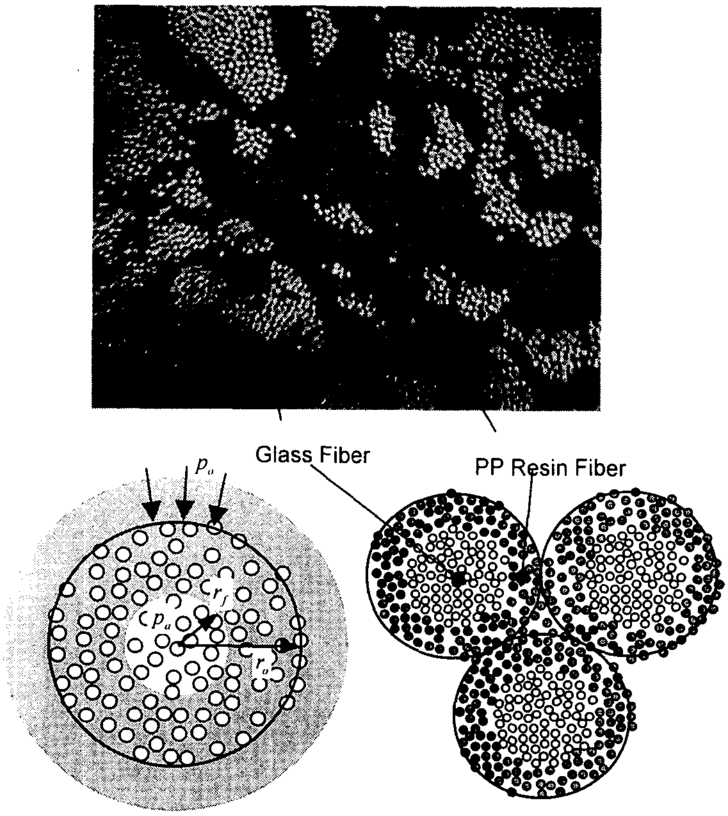

Figure 3 Circular unit cell model and microscopic flow inside unit

the composite can be approximated to a parabolic function along the fiber direction [12]. The maximum pressure occurs beneath the compaction roller. Besides, the atmospheric pressure is imposed on the start and end points of contact between the composite and the compaction roller. The pressure profile combined with the temperature distribution can be utilized for the impregnation model.

Impregnation Model

Figure 3 shows the magnified view of commingled yarn used in this work. The bright and dim portion is charged by glass fiber and the polypropylene fiber, respectively. Impregnation is the procedure that the molten matrix (polypropylene) soaks into the glass fiber bundle. The conventional material used for the thermoplastic filament winding is the prepreg that already is impregnated. On the contrary, in the case of commingled yarn, the impregnation issue becomes an important matter as well as the consolidation between tow layers. The following assumptions are made for the modeling: (1) The glass fiber bundle is circular and uniform in size; (2) the fiber volume fraction is maintained constant throughout the impregnation; (3) the thermoplastic resin is in the first Newtonian region during the impregnation. The impregnation is driven by the pressure difference between air and resin. The degree of impregnation is defined by the ratio of impregnated glass fibers and total glass fibers. Furthermore, the distance that resin proceeds into fiber bundle is the impregnation distance. Applying the Darcy's law for one-dimensional cylindrical coordinate system and mass conservation with some integration, we obtain the following impregnation time.

$$t_f = \frac{(1-v_f)\mu r_o^2}{4K(p_o - p_a)} \times \left[(1-D_{imp})\ln(1-D_{imp}) + D_{imp}\right] \quad (4)$$

where D_{imp} is the degree of impregnation, which is defined as

$$D_{imp} = 1 - \frac{r_f^2}{r_o^2} \quad (5)$$

Besides, μ is the viscosity of resin, v_f is the fiber volume fraction, r_f is the impregnation distance, and r_o is the radius of single fiber bundle as illustrated in Fig.3. K is the permiability, p_o and p_a denote the induced and atmospheric pressures, respectively. As is evident from equation (4), in order to decrease the imprenation time required for achieving a certain degree of impregnation, the viscosity and the presure can be controlled because other parameters are generic properties of commigled yarn. The viscosity of resin is function of temperature. Hence, the temperature can be a process parameter. The temperature is to be controlled below the degradation temperature. The pressure is determined by the roller compaction force. The impregnation time is considered as the pressurized time, which is related to the feeding speed of commingled yarn. The feeding speed is controlled by the angular speed of madrel. As a consequence, the roller compaction force, the heating energy that is determined by the flow rate and the temperature of nitrogen, and the rotating speed of madrel are the process parameters affecting the impregnation.

Viscosity

For a thermoplastic resin, which is a Non-Newtonian fluid, show following three different viscosity behaviors with varying shear rate: (1) for low shear rate, the viscosity is constant (the first Newtonian region); (2) for increased shear rate, the viscosity is proportional to the

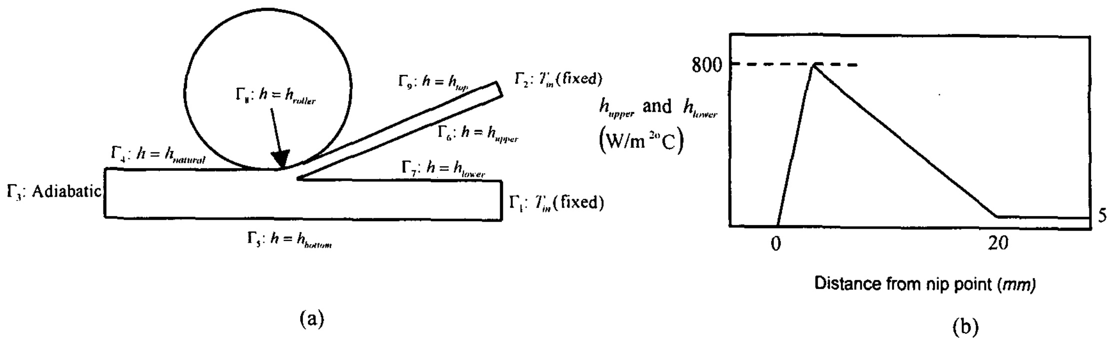

Figure 4 (a)Schematic view of the thermal model, and (b)heat transfer coefficient at the branch

exponential of the shear rate (the power-law region); (3) for further increased shear rate, the viscosity becomes constant again (the second Newtonian region). During the impregnation, the flow can be regarded as a creeping flow of which Reynolds number is smaller than 10^{-3}. Thus, The viscosity is considered to be existent in the first Newtonian region [8]. The temperature dependent viscosity is given as follows.

$$\mu(T) = \eta_o \exp\frac{\Delta E}{RT} \tag{6}$$

where $\eta_o = 0.6075$ and $\frac{\Delta E}{R} = 3315$. The specific values are evaluated empirically by Um [10].

Permiability

The permeability is to be known for the impregnation analysis. The Kozeny-Carman correlation can be used safely. The form is given by [14]

$$K = \frac{r_b}{4k_t}\frac{(1-v_f)^3}{v_f^{\,2}} \tag{7}$$

where r_b is the radius of single fiber string and k_t is the transverse Koneny constant. The specific value of k_t is provided from the previous study by Um [10].

Dimensional analysis

Various process parameters can be summarized to two dimensionless numbers [11]. The one (F_p) represents the external processing conditions such as the compaction force and the heating rate. The other number (F_r) is determined by the property of commingle yarn. They are of the following forms

$$F_p = \frac{(p_o - p_a)t_f}{\mu} \tag{8}$$

$$F_r = \frac{r_b^2}{r_o^2} \tag{9}$$

The degree of impregnation is related with $F_p \cdot F_r$. Thus, the degree impregnation is expressed as

$$D_{imp} = D_{imp}(F_p F_r, v_f) \tag{10}$$

Temperature field

Taking a control volume near the compaction roller, with the assumption that the energy transfer rate from the gas torch and the force applied by the compaction roller are constant over the process, we obtain a stationary thermal state. Besides, commingled yarn can be regarded macroscopically as a thermally orthotropic and homogeneous material. This study considers hoop winding only. Thus, the orthtropic steady conduction can be presumed. Because the width is sufficiently larger than the thickness, the conduction along the mandrel axis is ignorable. Consequently, a two-dimensional steady conduction problem with solid convection inside orthotropic medium is postulated. The schematic view of the thermal model is shown in Fig.4(a).

The specific thermal properties are shown in Fig.5. The governing equation is given by

$$\rho C V \frac{\partial T}{\partial x} = \nabla(\mathbf{K} \cdot \nabla T) \tag{11}$$

The overview of the control volume is displayed in Fig. 6. Constant temperature is prescribed on the right end o7f the incoming commingled yarn and the substrate. The left end is assumed adiabatic because the temperature gradient along the moving direction is expected to be negligible. Furthermore, natural convection with appropriate heat transfer coefficient is imposed on the upper surface. On the other hand, in the region where the incoming tow contacts with the roller and the substrate contacts with the mandrel, the heat transfer coefficient of the previous study are used ($h_{bottom} = 1000$ W/m^{2}K and $h_{roller} = 22800$ W/m^{2}K).

In the branch region, the heat transfer coefficient is available by the previous studies. Especially, Kim et al. estimated the heat transfer coefficient by the conjugate heat transfer analysis including flow analysis [15]. The result by Kim et al. is utilized in the simplified form as illustrated in Fig.4(b).

For the numerical discretization, the finite element method is utilized. In addition, in order to suppress the instability caused by the convective heat transfer, the streamline upwind scheme is incorporated to the formulation [16].

Experimental Aspects

In the present study, a laboratory scale filament winding machine is built to examine the applicability of the described models and the productivity. The overall system comprises the heating system, the compaction roller and eye assembly, and the winding system. The outline is displayed in Fig. 1.

In order to heat the composite tow and substrate locally, a sophisticatedly designed gas torch is utilized. Nitrogen is heated flowing through electrically heated hot coil. Hot nitrogen gas is effused from a rectangular nozzle of 6.2mm by 2.7mm. The gas flow rate is fixed as 30lpm to consider exit temperature change only.

The compaction force is crucial for the process in addition to sufficient heating. Thus, the device for controlling the compaction force is required. A reciprocating air cylinder is adopted for the compaction. The compaction force is controlled by adjusting the pressure inside the pneumatic cylinder. The compaction force is transmitted to the compaction roller of 20mm in diameter and 25mm in width. In this system, the eye, which is used for guiding the incoming tow, is made of stainless steel to be heat-resistant. Furthermore, in order to decrease friction and flaw of the incoming tow, the inner part of the eye is circular-shaped and polished.

A motor-driven winding system is designed and built to implement the hoop winding. A control unit controls the direction and speed of the motor. The mandrel is 0.015m in diameter and made of commercial steel. In this investigation, the winding has been performed for three different linear speeds of 15.71mm/s, 11.78mm/s, and 7.85mm/s on the mandrel surface. Additionally, a well-conditioned data acquisition system is utilized to record the temperature readings inside the composite during the process. In order to maintain the desired effusion temperature of gas torch, a reliable temperature controller is adopted.

As is described previously, the composite tow used for the winding is a commingled yarn composed of polypropylene fiber and glass fiber (Twintex® RPP75 yarn by Vetrotex International) The experiment is conducted for the following condition: (1) nozzle effusion temperature of gas torch is 200 ~ 500 °C; (2) the compaction force is 91.6N ~ 274.8N; (3) the angular speed of the mandrel is 30rpm ~ 60rpm.

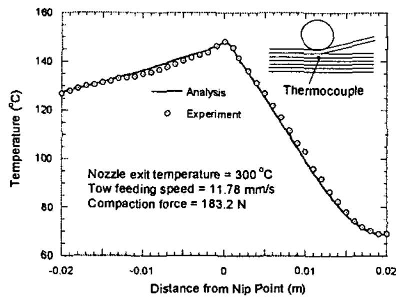

Figure 5 Comparison between the measured and computed temperature.

Results

The measured and estimated temperature distribution is compared. The temperature between the second and the third layer is considered. Figure 5 demonstrates the consistency between the measurement and the computation. Thus, the temperature distribution can be safely used for the impregnation analysis. Further demonstration is abbreviated because this kind of conduction analysis is performed in the previous studies for similar geometries [2][15].

In order to evaluate quantitatively the degree of impregnation from the experimental result, a simple image processing method is utilized. Generally, a well-impregnated composite holds only small portion of voids. On the contrary, a composite poorly impregnated has a lot of voids. The method utilizes the relation between void fraction and degree of impregnation. It is possible to find the correlation between the degree of impregnation and the void fraction with the use of the fiber volume fraction. In the current study, the fiber volume fraction is 0.5. The following expression provides the way of estimating the degree of impregnation.

$$D_{imp} = \frac{Y}{X+Y} = \frac{1-3.348A_v}{1-1.1174A_v} \tag{12}$$

where X and Y are the void and impregnated area inside the tow, respectively, and A_v is the area enclosed by the void excluding the fiber area, as shown in Fig.6. The comparison between degree of impregnation estimated by equation (12) and counting the impregrated fibers agrees quite well with the

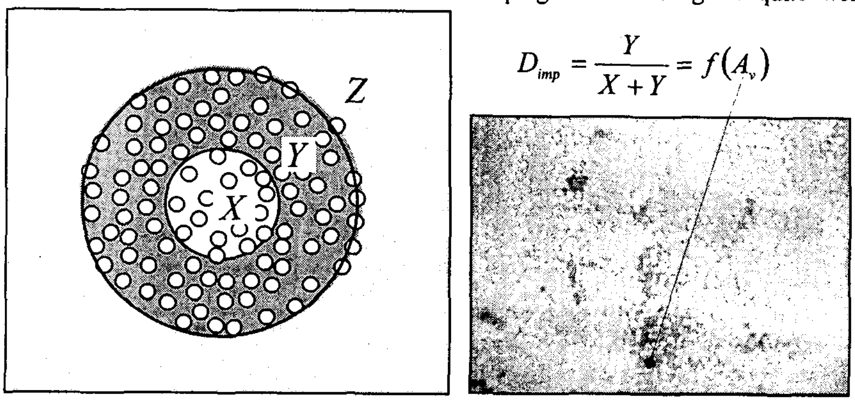

Figure 6 Schematic view of degree of impregnation calculation using cross-sectional image.

maximum deviation of 3.5%.

Figure 7 shows the effect of feeding speed on the degree of impregnation. The increased feeding speed results in apparent decrease in the degree of impregnation. This is caused by the decrease in the heating time and pressurized time. Furthermore, the increase in the compaction force renders enhanced impregnation as is observed. Figure 8 shows the influence of nozzle effusion temperature. As the nozzle effusion temperature increases, the thermal energy transfer is augmented. Thus, the viscosity is lowered and the impregnation is improved.

Figure 9 shows the comparison between the analysis and the image processing. The effect of dimensionless numbers on the degree of impregnation is investigated. F_p varies along with the change of the temperature and the pressure inside the composite during the process. Thus, F_p estimated by averaging over the time domain with the numerical integration. The result shows good agreement between the analysis and the experiment.

Conclusion

The filament winding process using commingled yarn is investigated. The required equipment is built. The study focuses on producing well-impregnated composites. In order to predict the degree of impregnation, appropriate models are proposed. The analytic model is examined by comparing with the result by image processing. The proposed thermal model and impregnation model are verified to be reliable.

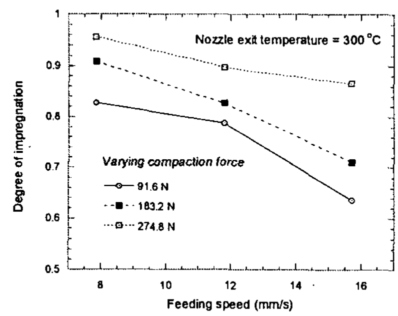

Figure 7 Effect of feeding speed on the degree of impregnation.

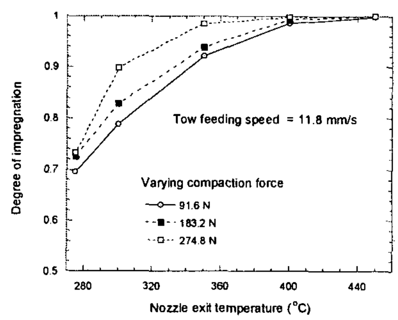

Figure 8 Effect of effusion temperature of gas torch on the degree of impregnation.

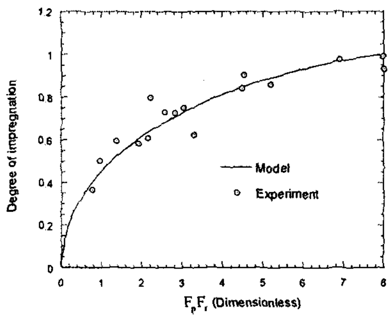

Figure 9 Comparison between the model and the *experiment in the degree of impregnation* estimation.

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