SLIP AND WRINKLE BEHAVIOR OF MULI-LAYERED FIBER PREFORM IN RESIN TRANSFER MOLDING PROCESS

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Abstract
Fiber preforms with multi-layered laminate structure are widely used for composite parts which are required to have specific mechanical properties. The structure of perform is an important factor in determining the processing conditions as well as mechanical properties of final product. In resin transfer molding process, fiber preform deforms undesirably by the flow pressure of resin, which causes defectives in properties and appearance of the final products. In this study, structural factors of fiber preform and process conditions affecting the flow induced fiber deformation in resin transfer molding are investigated. Mechanism of the deformation is investigated by measuring two important factors which are hydrodynamic friction between fiber and mold surface and bulk stiffness of fiber preform in the mold. The former is related to slip and the latter is related wrinkle and compaction of fiber preform. Unidirectional and woven fabrics are tested with varying orientation angle and resin flow rate. The resulting flow induced deformations are predicted and compared with the experimentally observed deformations in resin transfer molding. It is expected that the unexpected fiber deformation can be prevented by optimum design of process conditions and laminate structure considering fiber deformation as well as mechanical properties of composite.

1. Introduction

Improving fuel efficiency of car by applying lightweight parts has been one of the most important issues because the international environment regulations for transportation equipment are strengthened. Carbon fiber reinforced composite is one of the most promising lightweight material with superior mechanical properties for the applications to various transport industries such as aerospace, automotive, train and ship. Transport industry often requires the mass production system of composite parts, for which cost reduction and fast speed of manufacturing process are inevitable. Besides many efforts for cost reduction of carbon fiber and matrix resin, development of optimum process for manufacturing composites has been promoted. High pressure resin transfer molding process has been applied to mass production of carbon fiber reinforced composite automotive parts in some of the companies [1].

Fiber preform can be deformed by flow induced force in the course of resin impregnation into the preform, which causes defects in appearance as well as mechanical properties. The deformation of fiber preform is probably influenced by structural factors such as fiber volume fraction, stacking structure, and friction coefficient, and process related factors such as injection pressure. Various types of deformation, slip, wrinkle, and shrinkage can be appeared [2,3].

In this study, various types of deformation in fiber preform were observed by changing laminate structure of fiber preform and the related forces were investigated to identify the mechanism of each

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deformation mode. It is expected that conditions for causing the deformation can be clarified, and optimum structural and process conditions without the undesired deformations can be designed.

Friction force is main force to resist flow induced preform deformation. To define friction forces during resin impregnation into the fiber preform, Coulomb friction coefficient was used in the unfilled region and hydrodynamic friction coefficient was used in the filled region as shown in Fig. 1. Hydrodynamic friction coefficient (μ) is defined by introducing Hersey number (H) as shown in equation 1, where η_R is viscosity of resin, U is moving velocity, and N is normal force onto the mold [4].

$$\mu=\mu(H), \quad H=\eta_R U/N \tag{1}$$

The resultant friction force at the specific time is estimated by applying rule of mixture on friction coefficients and the corresponding areas in the unfilled and filled regions. The friction force is mainly related with rigid body deformation of fiber preform by flow force of resin.

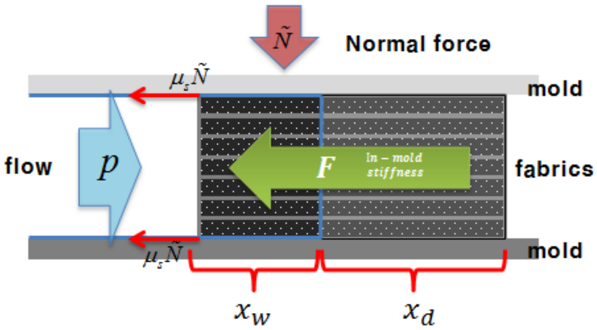

Figure 1. Schematic diagram of relating forces during resin impregnation in liquid composite molding

Fiber preform is generally not a rigid body but an easily deformable material which depends on orientation pattern. For example, whereas unidirectional fabric aligned to parallel direction of force shows a rigid body like behaviour, that aligned to vertical direction of force deforms easily by only a small force. In this study, stiffness of fiber preform placed in the mold is defined as in-mold stiffness, which is closely related to local deformation of fiber preform. Three main kinds of forces acting on the resin impregnation process in liquid composite molding are schematically described in Fig. 1.

2. Experiments

2.1. Measurement of hydrodynamic friction coefficient

Equipment for measuring Coulomb and hydrodynamic friction coefficients was prepared as shown in Fig. 2, which was composed by measuring frame for friction force, pneumatic cylinder for generating normal force, step motor controlling horizontal motion of fiber preform, etc [2]. Unidirectional (UD) carbon fabric from Zoltek (PANEX 35 50K UD150) and plain woven (PW) fabric from Mitsubishi (TR-30) were used for reinforcement and silicon oil from Shinetsu (KF-96H-10000CS) was used for matrix fluid. Friction coefficients at several Hersey numbers were investigated by combining several measurement conditions (normal force, viscosity, and moving speed).

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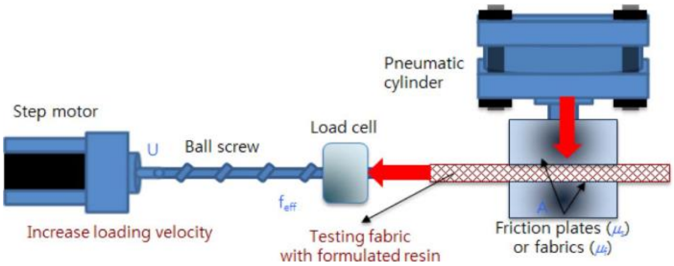

Figure 2. Schematic diagram of equipment for measuring coulomb and hydrodynamic friction coefficients

2.2. Measurement of in-mold stiffness of fiber mat

Experimental setup for measuring in-mold stiffness of fiber preform was shown in Fig. 3, which was composed of mold system of same geometrical structure with liquid molding experiment and universal test machine (UTM) to apply strain and measure stress in the fiber preform. Test conditions are summarized in table 1.

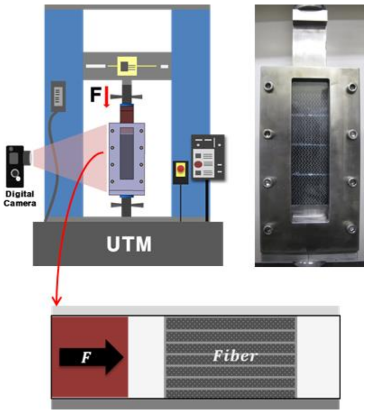

Figure 3. Measurement system for in-mold stiffness of fiber preform

Table 1. Test condition for measuring in-mold stiffness and flow induced deformation of fiber preform

Factor		Condition
Fiber	Fabric structure	Unidirectional (UD) fabric (orientation angle: 0/45/90°) / Plain woven (PW) fabric
	Volume fraction (%)	40 / 50 / 55
Fluid	Viscosity (Pa·s)	0.341
	Flow rate (cm³/s)	0.838 / 2.513

2.3. Observation of flow induced slip and wrinkle of fiber mat in resin transfer molding

Measurement system for observing the flow induced deformation of fiber preform in liquid composite molding was equipped as shown in Fig. 4. It is based on unidirectional resin transfer molding equipment with constant flow rate condition, and has transparent mold side from top and lateral sides, which makes it possible to observe flow front advancement. Several test conditions on orientation angle, volume fraction of fiber preform and flow rate of fluid were applied, which is equivalent to

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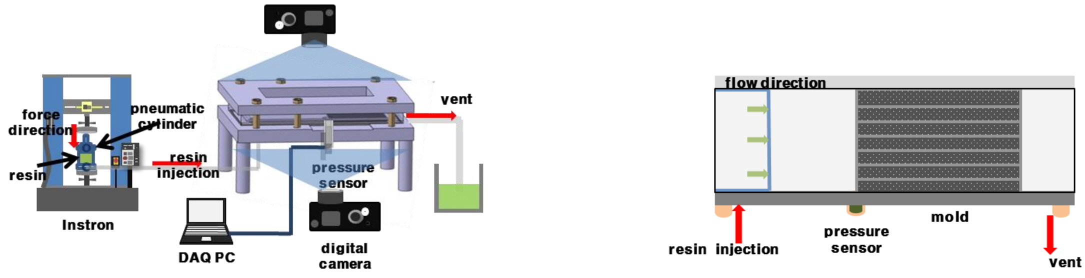
measurement of in-mold stiffness as shown in table 2.

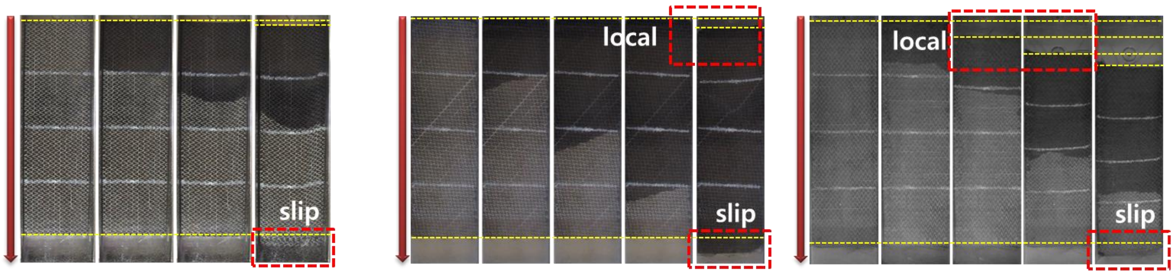


(a) (b)

Figure 4. Schematic diagram of equipment for measuring flow induced deformation of fiber preform in liquid composite molding. (a) overall equipment, (b) inside of mold

3. Results and discussion

Images of flow induced deformation in orientation angles of 0, 45, 90° are shown in Fig. 5. Different types of deformation are observed with respect to orientation angle of fiber preform. In the direction of 0°, only a rigid body deformation which is shown as slip was observed. However, local deformations were clearly observed in the direction of 45° and 90°. This kind of different deformation behavior may be caused by different force balance between the related forces during resin impregnation process is liquid composite molding.



(a) (b) (c)

Figure 5: Deformation image of fiber preform in various orientation angles. (a) 0°, (b) 45°, (c) 90°

Three kinds of the related forces which are friction, in-mold stiffness and flow induced forces were compared to investigate factors that caused various deformations of fiber preform at specific conditions (orientation angle of 0°, 90°, 45° in UD fabric at flow rate of 0.838 cm^3/s) in the Fig. 6. It is clearly verified that rigid body deformation such as slip of fabric is occurred when flow force is bigger than friction force regardless strength of in-mold stiffness induced force. On the other hand, local deformation such as wrinkle or compaction is occurred when flow force is bigger than in-mold stiffness even though it is smaller than friction force. Total slip was observed after local deformation at the edge part of fiber preform in the orientation angle of 45° and 90°. It means that in-mold stiffness induced force is increasing with flow front advances, which causes the change of the related force balance on the fiber preform.

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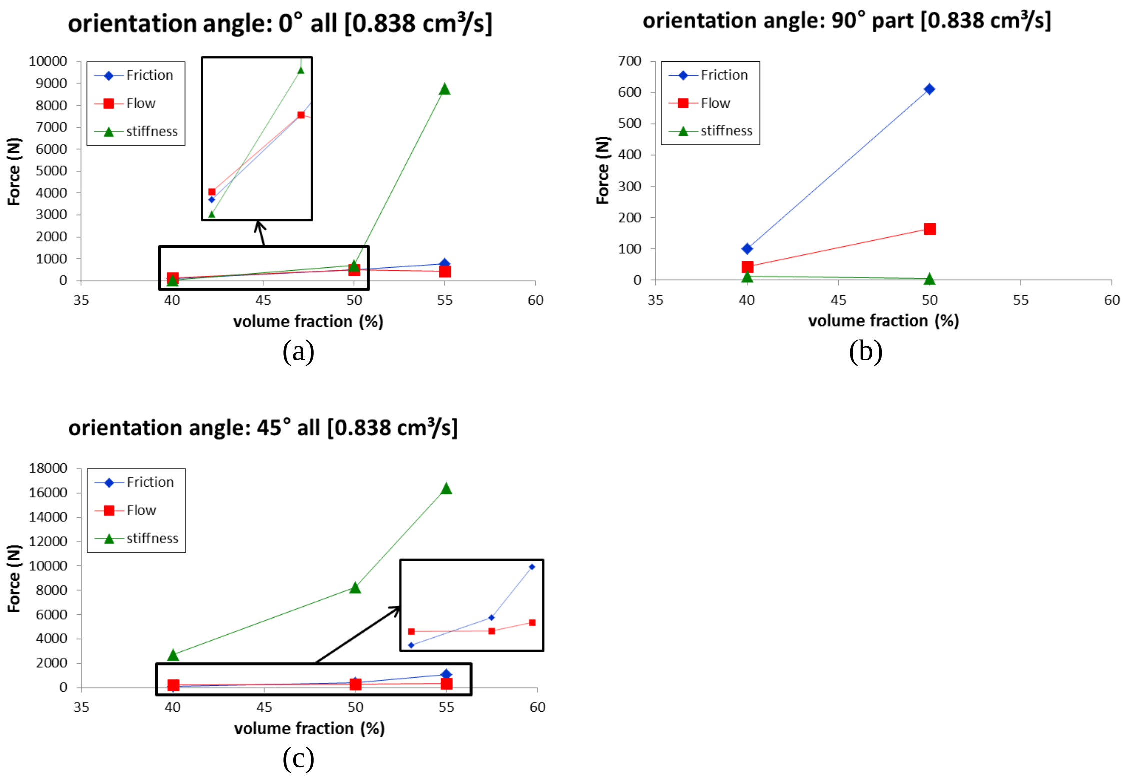

Figure 6: Comparison of the related forces for the various fiber deformations: friction, flow and in-mold stiffness induced force. (a) slip (UD 0°, 0.838 cm³/s) , (b) wrinkle (UD 90°, 0.083 cm³/s), (c) wrinkle (UD 45°, 0.083 cm³/s)

4. Conclusions

Several types of fiber preform deformation in liquid molding of carbon fiber reinforced composites were observed and the related forces are measured in order to investigate the mechanism of the deformations. Force balance between friction between fabric and mold surfaces, in-mold stiffness of fiber preform, and flow induced pressure was a key factor in determining types of the fiber preform deformation in liquid composite molding process. Strength of in-mold stiffness induced force in comparison with flow induced force and friction determined whether local deformation was occurred or only rigid body deformation was occurred at a specified process condition. It is expected that understanding of the mechanism for causing deformation of fiber preform will make it possible to optimize the structural and process condition prohibiting the undesired deformation in liquid composite molding.

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