INVESTIGATION OF FIBER ORIENTATION IN FILLING AND PACKING PHASES

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Abstract

Fiber-reinforced engineering materials are widely used for their superior mechanical properties in lots of plastic parts. And it is truly believed that in the injection molding process the fiber orientation and anisotropy shrinkage are very complex 3D phenomena which may influence the product properties deeply. In this research, the fiber orientation is considered both in filling and packing process numerically. The result of fiber orientation shows a good agreement with experimental data. Moreover, the investigation illustrates the strength of fiber orientation in filling and packing phases with detail.

Introduction

In recent years, the injection molding of fiber-reinforced thermoplastics has been widely used because of their superior mechanical properties in applications. The injection molding of fiber-reinforced composites is a complicated process, where the fiber-induced anisotropic mechanical properties strongly depend on the fiber orientation. The reinforced composites are stronger in the fiber orientation direction and weaker in the transverse direction; the thermal shrinkages are larger in the transverse direction and lower in the fiber orientation direction. In a result, the molded products may have high internal stress and warpage at unexpected locations. Therefore, the design of a new product must take account of processing details.

The flow-induced fiber orientation and anisotropic shrinkages in injection molding are complex 3D behaviors, which makes the properties of injected parts are difficult to be predicted. The direction of fiber orientation is full 3D components, which makes it difficult to study by the traditional 2.5D model. Thus, a true 3D injection molding simulation technique is therefore employed for obtaining the 3D distribution of fiber orientation in this study. For validation purpose, a ribbed flat plate with side gate positions is conducted by experiment to examine the effect of fibers in filling and packing process. Moreover, the anisotropic warpage behavior is also being discussed.

Governing equations

The polymer melt is assumed to behave as Generalized Newtonian Fluid (GNF). Hence the governing equations to simulate transient, non-isothermal 3D flow motion are shown as following:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u}\mathbf{u} - \boldsymbol{\sigma}) = \rho \mathbf{g} \tag{2}$$

$$\boldsymbol{\sigma} = -p\mathbf{I} + \eta\left(\nabla \mathbf{u} + \nabla \mathbf{u}^T\right) \tag{3}$$

$$\rho C_P\left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T\right) = \nabla(\mathbf{k}\nabla T) + \eta\dot{\gamma}^2 \tag{4}$$

where $\mathbf{u}$ is the velocity vector, T the temperature, t the time, p the pressure, $\boldsymbol{\sigma}$ the total stress tensor, ρ the density, η the viscosity, k the thermal conductivity, C_p the specific heat and $\dot{\gamma}$ the shear rate. The FVM due to its robustness and efficiency is employed in this study to solve the transient flow field in complex three-dimensional geometry.

Fiber orientation

The fiber orientation state at each point in the part is represented by a 2^{nd}-order orientation vector A, where

$$A_{ij} = \int (p_i p_j)\varphi(p)dp \tag{5}$$

The equation of orientation change for the orientation tensor proposed by Advani and Tucker is employed for the analysis:

$$\begin{aligned}\frac{\partial A_{ij}}{\partial t} + u_k \frac{\partial A_{ij}}{\partial x_k} &= A_{ik}\Omega_{kj} - \Omega_{ik}A_{kj} + \\ &\lambda\left(A_{ik}E_{kj} + E_{ik}A_{kj} - 2A_{ijkl}E_{kl}\right) + 2C_I\dot{\gamma}\left(\delta_{ij} - 3A_{ij}\right)\end{aligned} \tag{6}$$

Where C_I is the interaction coefficient with the value ranged from 10^{-2} to 10^{-3}. In this study, we take C_I as 10^{-2} for default value. For the fourth-order tensor A_{ijkl}, a closure approximation is needed in order to calculate the distribution of 2^{nd} order A on the basis of a velocity field. Here, the hybrid closure approximation will be primarily adopted.

Implementation details

The fiber-reinforced plastic material adopted in this study is DURANEX®3300(Grade name, written as PBT-GF in the following description). The molding condition is tabulated in Table 1. The geometry model is a ribbed flat plate with side gate positions, which is shown as Fig.1. The geometry model used to conduct the experiments is the same mold with side gate respectively. The node positions for measuring warpage behavior are illustrated in Fig. 2. The measurement results of deformation on these nodes are used to compare to simulation results. Furthermore, in order to observe the fiber orientation, the mold is divided into 20 layers in the experiment in the thickness direction, while the corresponding displayed layer number by simulation is 10. The schematic diagrams of fiber orientation for each layer using in the simulation are shown as Fig. 3 and 4.

Results and Discussions

In convenience to show the comparison of fiber orientation between experiment and simulation results, the orientation of the lines indicates the most favorable orientation direction, and the displayed color represents the degree of orientation. To clarify the fiber orientation inside the cavity, position 1~3 is investigated by three cutting plane: front, middle and back, and position 4 is done by left, center and right planes. Fig. 5~8 shows the comparison of fiber orientation between experiment and simulation results. Moreover, the simulation results in filling and packing process are also illustrated.

For observed positions 1 and 2 in Fig. 5 and 6, the evolution of fiber orientation is predicted well qualitatively as experimental result both in filling and packing process. We can see that due to the cooling effect in packing process, the polymer has solidified that there is little changes in fiber orientation. As for the front and back plane near the mold wall, the shearing flow tends to align the fibers along the flow direction. While the situation is different in the middle plane, the flow is shear free or lower and the fiber orientation no longer aligns the flow direction. Some even aligns perpendicular to the flow direction in the vicinity of the melt entrance region. However, as the melt starts developing flow pattern, the fiber continues to align to the specific directions under the effect of shear rate. This is obviously predicted as Fig. 5-(b) for distinct behavior in filling and packing process.

For observed position 3, Fig. 7 shows the fiber orientation in the end of flow line. There is some strength and direction difference in filling and packing phase. However, packing phase predicts better than filling in the phenomena that fibers tend to flip over and stand in the observed slicing plane. Observed position 4 as showing in Fig. 8 is taken to investigate the fiber orientation in the thickness direction. A simple sketch map of fiber orientation can be formed as Fig. 9. We can divide the fiber orientation distribution into three laminates, where zone A is the outermost skin with no distinct pattern of orientation. Zone B exposed the high shear rate that the fiber oriented in direction of flow. In the inner laminate zone C, medium shear rate or low shear rate may result in little orientation and even transverse to flow direction. Fig. 9 is typical in injection-molded part and can be predicted by the present analysis.

In Fig. 10, we show the numerical and experimental warpage measurement. The figure show that the trend of deformation on the nodes is in a good agreement with both experiment and simulation. Since the displacement strongly depends on the strength of fiber, an uneven distribution of fiber orientation due to flow pattern may lead the mechanical properties to be anisotropic.

Conclusions

In this research, the numerical algorithm to simulate fiber orientation is validated with corresponding experimental measurements. A ribbed flat plate with side gate is used as test models, and the comparison of the slicing fiber orientation between simulation and experiment results is in a good agreement. It is found that due to the growing layer of solidified polymer during the packing process, the fiber orientation behaves a little differently in the strength of magnitude and still keeps generally the same distribution as filling process. With the consideration of fiber orientation in packing process, the product property during the whole injection molding process is assured more. Moreover, the predicted warpage deformation values are being obtained with reasonable comparison with the experimental data under the considering of fiber orientation both in filling and packing process.

Reference

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2. W.H.Yang, David C. Hsu, Venny Yang and R. Y. Chang, “Computer Simulation of 3D Short Fiber Orientation in Injection Molding”, 470, ANTEC 2003, Nashville, (2003)
3. R. Y. Chang, W. S. Yang, “Numerical Simulation of Mold Filling in Injection Molding Using a Three-Dimensional Finite Volume Approach.”, 125, Int. J. Num. Meth. Fluids, Vol. **37**, (2001).

Table 1 Molding conditions

Melt temperature ($^{\circ}C$)	250
Mold temperature ($^{\circ}C$)	60
Injection velocity (m/min)	1.0
Holding pressure (MPa)	68.6
Injection time + Holding time (sec)	10
Cooling time (sec)	20
Cycle time (sec)	40

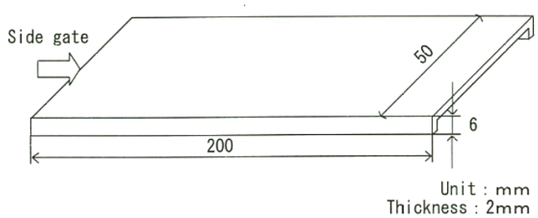


Fig.1 Geometry of mold cavity

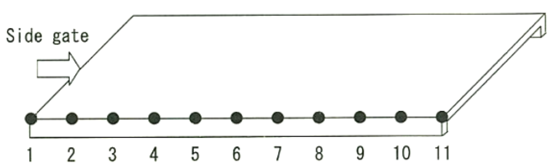


Fig.2 Measuring nodes for warpage behavior

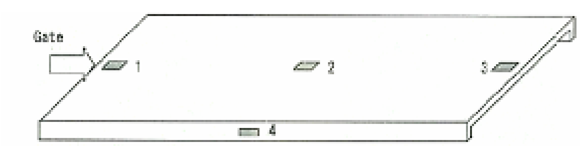


Fig. 3 Observation Position

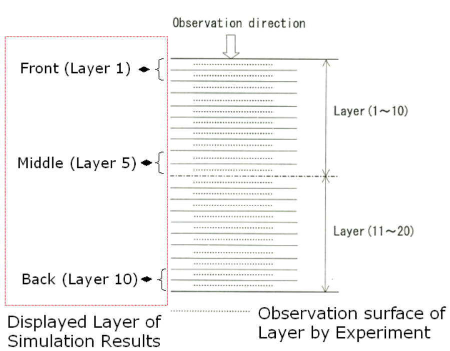
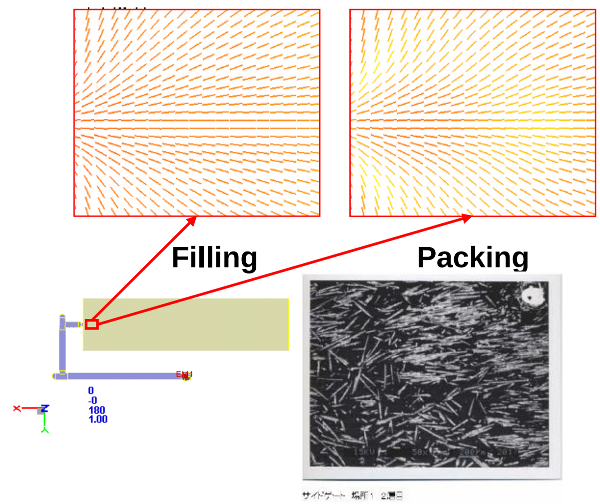
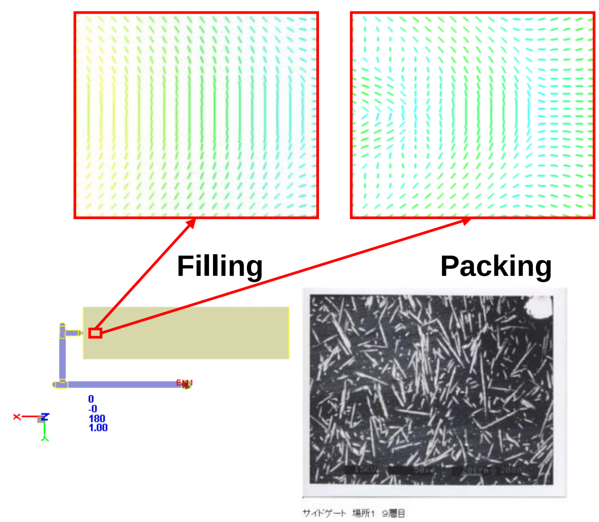


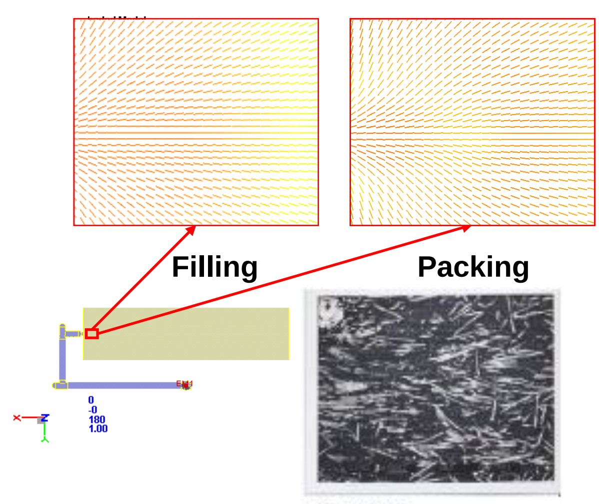
Fig. 4 Observation layers by experiment and corresponding layers by simulation.



(a) Position 1: Front

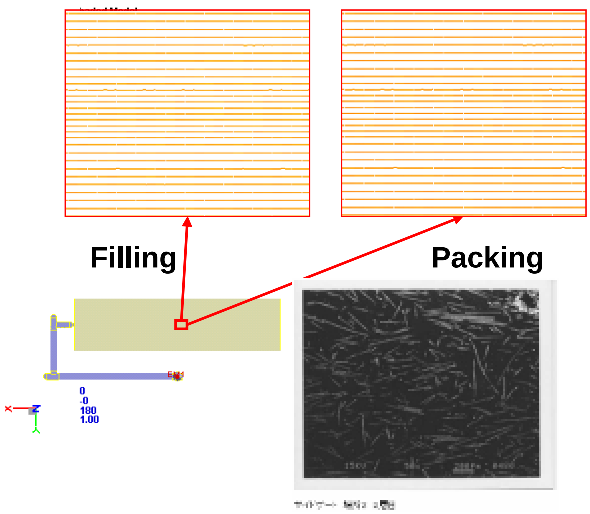


(b) Position 1: Middle

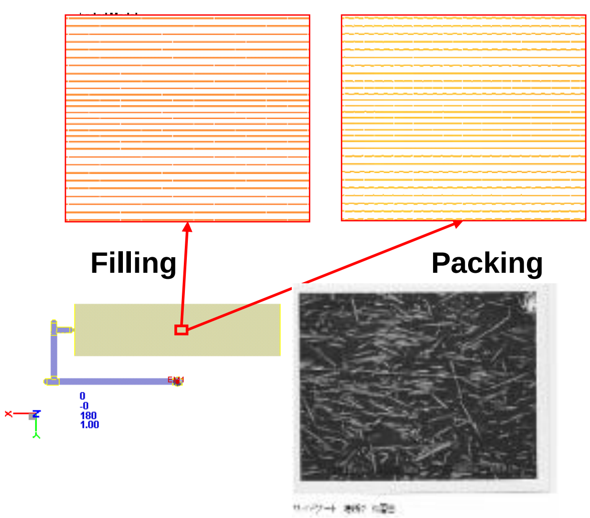


(c) Position 1: Back

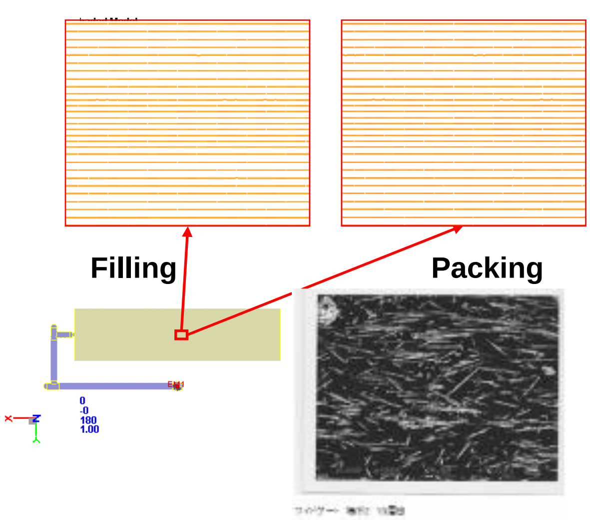
Fig. 5 Fiber orientation comparison for Position 1



(a) Position 2: Front

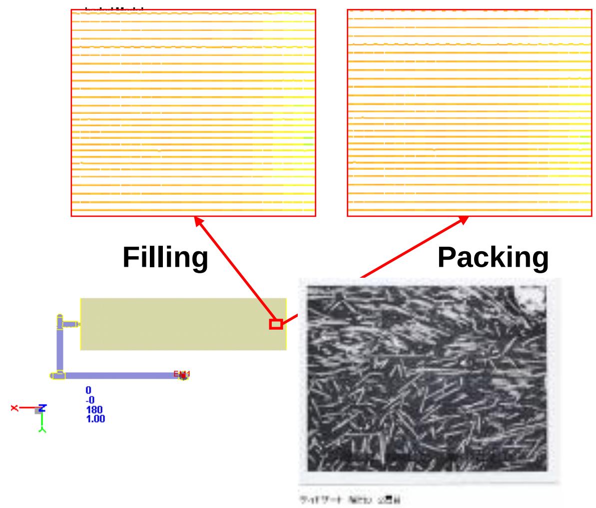


(b) Position 2: Middle

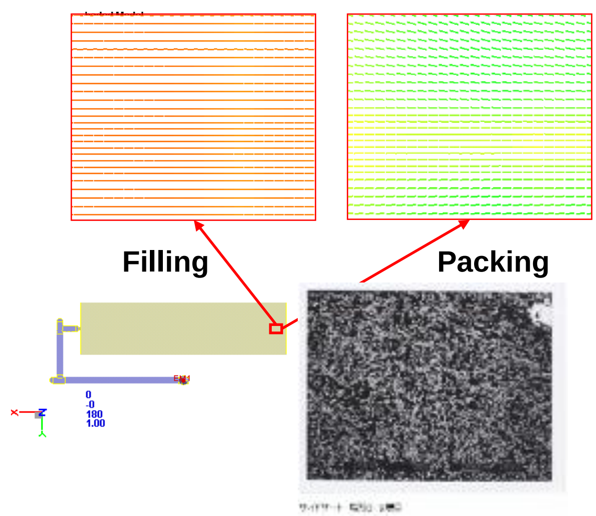


(c) Position 2: Back

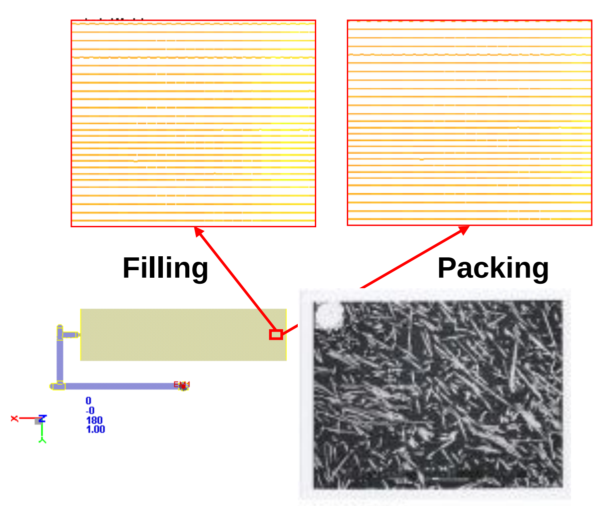
Fig. 6 Fiber orientation comparison for Position 2



(a) Position 3: Front

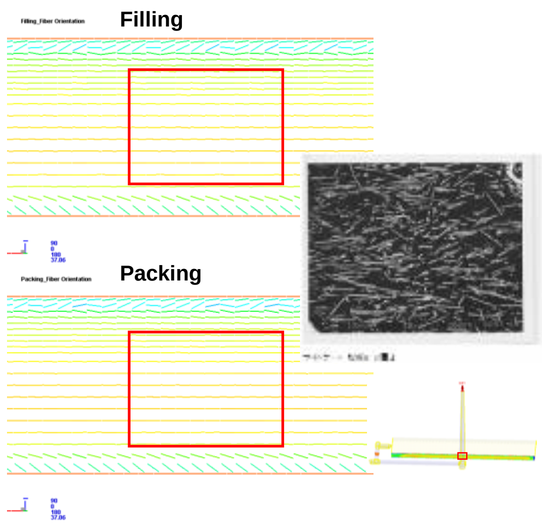


(b) Position 3: Middle

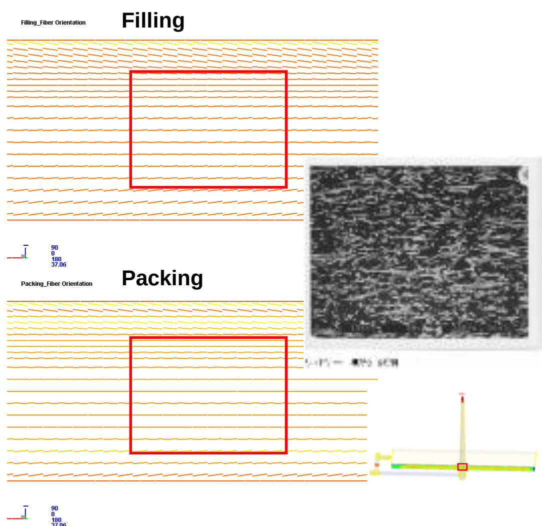


(c) Position 3: Back

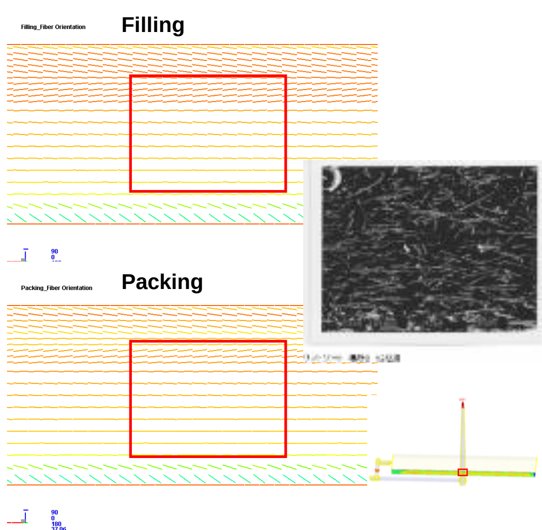
Fig. 7 Fiber orientation comparison for Position 3



(a) Position 4: Left



(b) Position 4: Center



(c) Position 4: Right

Fig. 8 Fiber orientation comparison for Position 4

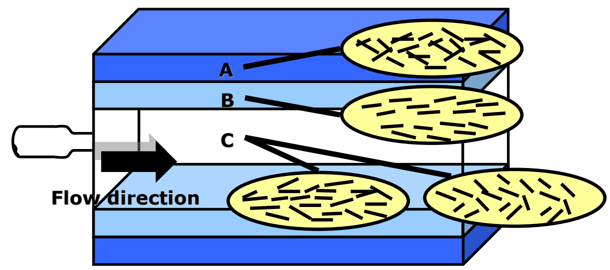


Fig. 9 Simple sketch map of fiber orientation

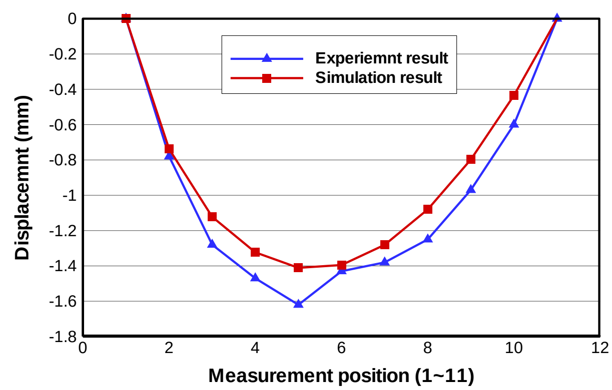


Fig. 10 The comparison of deformation between experiment and simulation results