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A Review of Effects of Molding Methods, Mold Thickness and Other Processing Parameters on Fiber Orientation in Polymer Composites

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ABSTRACT

In injection molded fiber reinforced composites, the mechanical and physical properties of the final product are highly dependent on the patterns of fibers alignment. The orientation of the fibers can be influenced by many factors such as molding methods, materials used, geometry of the part and other processing parameters. Thus, there is considerable interest in studying the factors that affect the fiber orientation, hence the properties of the final product. This study presented a general review on the effects of these factors on fiber orientation in injection molded fiber-reinforced polymer composites. The fiber orientation of a part made by conventional injection molding is compared with those produced by injection-compression and push-pull injection techniques. Effects of injection speed, type of flow and mold thickness on fiber orientation are also discussed. Hence, this review could assist in decisions regarding the design of composite products.

Key words: Polymer composites, fiber orientation, injection molding, mechanical properties, fiber-reinforced

INTRODUCTION

In the last half century, polymer composite products have found applications in diverse areas such as high-end sport equipments, military applications, construction and automotive industries, biotechnology and electronic apparatuses. Polymer composite may be described as a combination of two materials, where one material acts as a suspending liquid and the other as reinforcement embedded within. Such type of composites may be classified as short (discontinuous) or long (continuous) fiber composites. The main difference between short and long fiber reinforcements is their initial fiber length. The former contains fibers having length 0.5 mm or less, whereas the later have fiber length which ranges from 10 to 50 mm (Parthasarathy, 2008; Kulkarni, 2010). Short fiber reinforced polymer composites show high strength and stiffness compared to the particle reinforced polymer composites (Mani *et al.*, 2012).

Short fiber reinforced polymer composites are widely used in manufacturing industries because of their lightweight, their attractive strength-to-weight ratios and their resistance to chemical attacks and high temperature (Azaiez *et al.*, 2002). Moreover, they reduce the shrinkage and warpage of the final product. Such composite products are commonly manufactured by injection molding, compression molding and extrusion processes. At least 50% by weight of short fiber reinforced plastics are produced using injection molding machines (Jones, 1998). In injection molded fiber reinforced composites, the mechanical and physical properties of the final product are

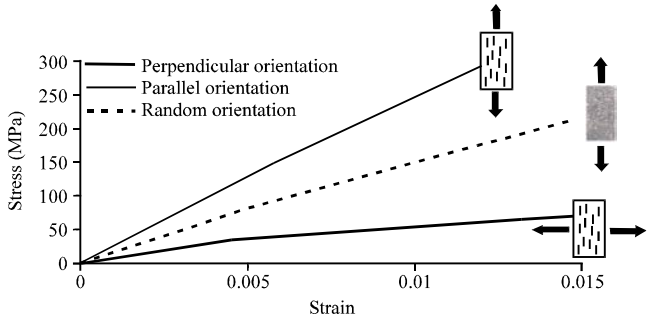

Fig. 1: Stress-strain graph of a fiber-reinforced sample with fibers oriented in the direction of strain, random oriented fibers and fibers oriented transverse to strain (Osswald *et al.*, 2001)

highly dependent on the type of the reinforcements used (Esfandiari, 2007), the adhesion between the fibers and the polymer matrix (Suradi *et al.*, 2010) and the patterns of the fibers alignment (Kardos, 1985). For instance, the strength and toughness of the final product is higher in the direction along which the most fibers align and weaker in the transverse direction (Kardos, 1985). The stress-strain graph shown in Fig. 1 illustrates this fact. The top curve in Fig. 1 indicates that when some amount of stress is applied in the direction of fiber orientation, the strength of the final product becomes high. However, if the stress is applied transverse to the fiber orientation, the strength of the product will be much smaller compared to the previous case as indicated by the bottom curve in Fig. 1. The middle curve in Fig. 1 shows the case when the stress is applied to the part having random fiber orientation. In this case, the strength of the final product will be in between the above two cases. Therefore, during processing, it is essential to make sure that the large proportion of the fibers orient in the desired direction during the filling stage of injection molding. However, due to the nature of the injection molding process it is very difficult to control the fiber orientation within the specimen during injection process.

The orientation of fibers in injection molded composites can be influenced by many factors. Some of the factors include molding methods (convectional injection molding, injection-compression molding and push-pull injection molding), materials used, geometry of the part and the processing parameters (Advani and Tucker, 1987; Advani and Sozer, 2003). Thus, there is considerable interest in studying the factors that affect the fiber orientation, hence the properties of the final product. This study presents a review on the effects of molding methods, mold thickness and other injection molding parameters on the fiber orientation of injection molded fiber-reinforced polymer composites.

EFFECT OF MOLDING METHODS

One of the most common injection molding methods for production of fiber reinforced plastic composites is Conventional Injection Molding (CIM). However, CIM has some limitations. To overcome the limitations of CIM other injection molding methods such as co-injection (sandwich) molding, gas and water-assisted injection molding, push-pull injection molding and injection-compression molding (ICM) have been in use (Somjate, 2006). For instance, ICM has advantages over CIM in decreasing molding pressure, reducing residual stress and uneven shrinkage, increasing dimensional accuracy and reducing molecular orientation (Avery, 1998; Yang *et al.*, 2010a, b). Here, the influences of ICM and push-pull injection molding processes on the

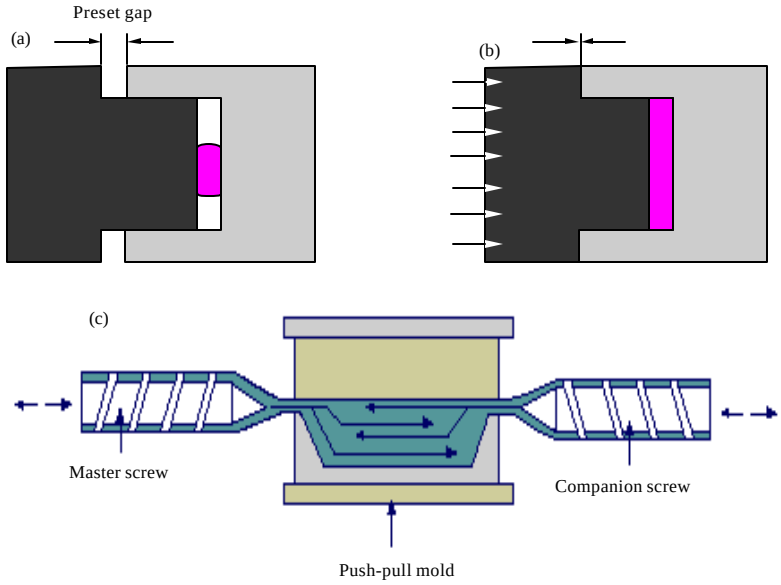

Fig. 2(a-c): Schematic representation of (a) Injection and (b) Compression molding (Avery, 1998) and (c) Push-pull injection molding

fiber orientation are discussed in comparison with the CIM technique. The ICM technique works first by injecting the fiber-polymer matrix into slightly opened mold cavity. Then after the injection is completed, the clamp closes compressing the material into the cavity. Push-pull molding works in a melt oscillation technique. In this molding process at least two gates which are connected to two separate injection units are needed. Moreover, it uses software modifications to control the injection units. The mold cavity is filled by the fiber-polymer matrix by flowing back and forth between the two injection units. This process is used to eliminate weld lines, voids and cracks and controls the fiber orientation. Both the ICM and push-pull injection molding processes are shown in Fig. 2.

To date, numerous studies have been done on the fiber alignment patterns in fiber-reinforced polymer composites (Bay and Tucker, 1992; McGrath and Wille, 1995; Chung and Kwon, 2002; Vincent *et al*., 2005). Most of them have used CIM technique to produce the parts. In a cross section of thin rectangular strip specimen produced using ICM, cut lengthwise in the flow direction and observed under a microscope, a five layer structure of fiber orientation is observed. The layers consist of a core layer in the middle and two skin and two shell layers on both sides of the specimen (Yang *et al*., 2010a,b). In this case, at near and far mold positions from inlet, more fibers in the core and skin regions orient randomly whereas more fibers orient to the main flow direction in the shell region. For the same specimen produced using CIM, however, most fibers orient parallel to the flow direction near the mold surfaces but perpendicular fiber orientation is observed in the core region (Vincent *et al*., 2005).

Figure 3 shows comparison of fiber orientation for thin tensile test bar produced using conventional and push-pull injection molding techniques. As can be seen from Fig. 3, the thickness directional orientation component (α_{33}) for both methods is almost the same having values below

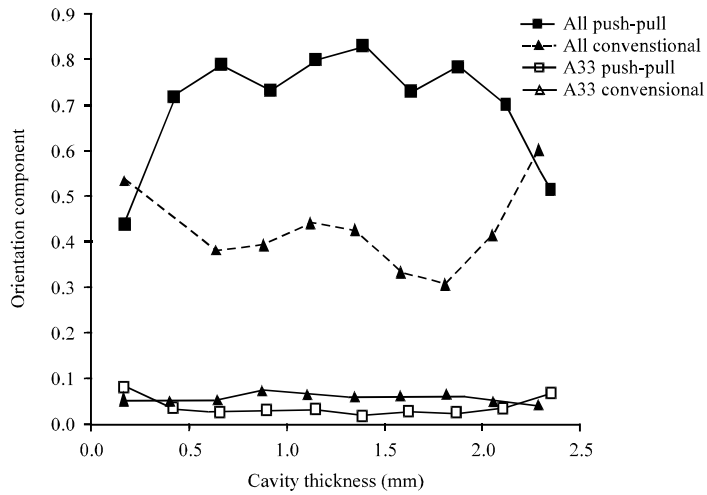

Fig. 3: Comparison of fiber orientation for thin tensile test bar in push-pull and conventional injection molding processes (Ludwig *et al.*, 1995)

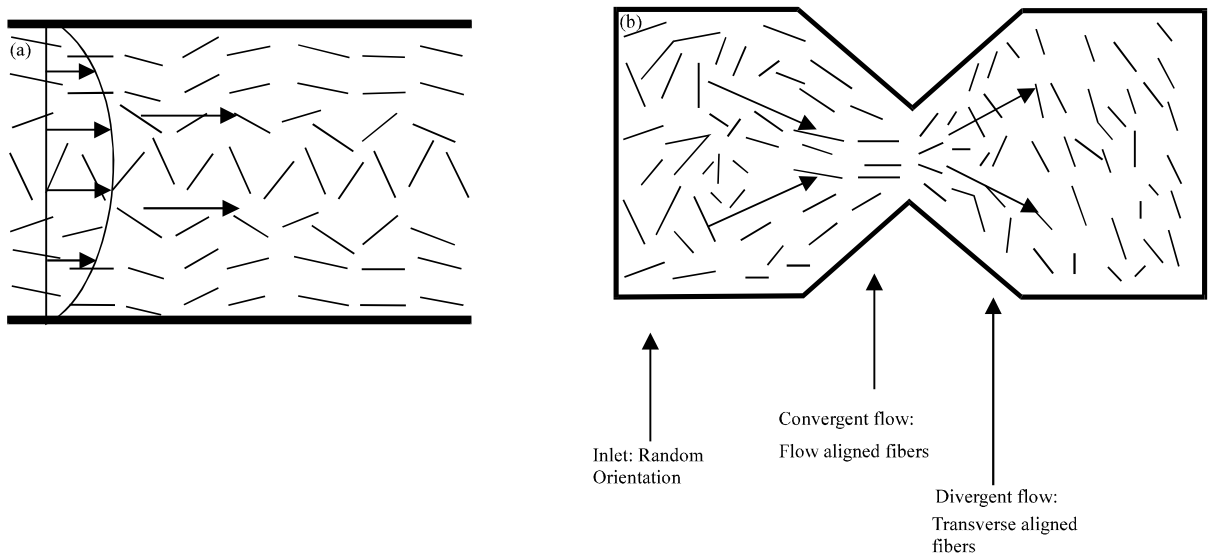

Fig. 4(a-b): Schematic representation of (a) Simple shear and (b) Convergent and divergent flows and their influence on fiber orientation

0.1. On the other hand, big difference is observed for the flow directional orientation component (α_{11}). In contrary to the fiber orientation by the conventional method, α_{11} values are large in the core region by the push-pull method.

EFFECT OF FLOW KINEMATICS

In injection molding, the fiber orientation is determined by the way the fiber-polymer matrix flows in the mold, i.e., the flow kinematics affects the fibers orientation (Bay, 1991; Sadabadi and Ghasemi, 2007). For instance, in a simple shear flow as shown in Fig. 4a, the fibers tend to align in the direction of flow. This is due to the fact that:

- The hydrodynamic force tends the fibers located out of the middle plane to rotate until they reach an equilibrium state and become fully aligned with the velocity field and
- For the fibers located around the flow symmetry plane, the velocity gradient will vanish resulting zero hydrodynamic force

The other type of flow is stretching or elongational flow. This type of flow forces the fibers to orient in the direction of stretch. Consider the one shown in Fig. 4b which is a combination of converging and diverging flows. In the converging flow region, the force due to the velocity gradient aligns the fibers in the flow direction. On the other hand in the diverging flow region the force aligns the fibers in the direction transverse to the flow. In general, due to the fact that shear flow is dominant near the mold walls, the fibers tend to align in the flow direction. In the core region, however, the shear stress decreases and the flow is extensional flow dominated, thus the orientation values will not change significantly from their initial value.

EFFECT OF MOLD GEOMETRY

In addition to the molding methods and the type of flow inside the mold cavity, mold thickness variations greatly affect the fiber orientation. So, in this section the fiber orientation variation is numerically investigated for different mold thicknesses. Five different rectangular molds with dimensions 200 mm long and 40 mm wide are considered. They have different thicknesses: 1, 1.5, 1.7, 3 and 5 mm. The material used is nylon 6/6 reinforced with 50% by weight of short glass fibers.

NUMERICAL MODEL DESCRIPTION

For the simulation, the well known Tucker-Folgar's fiber orientation prediction model for concentrated fiber suspensions is used. The model can be expressed as shown in Eq. 1 (Advani and Tucker, 1987):

$$\frac{\partial a_{ij}}{\partial t} + \frac{\partial a_{ij}}{\partial x_k} = -(\omega_{ik}\alpha_{kj} - \alpha_{ik}\omega_{kj}) + \lambda(\gamma_{ik}\alpha_{kj} + \alpha_{ik}\gamma_{kj} - 2\gamma_{kl}A_{ijkl}) + 2C_{I\gamma}[\delta_{ij} - 3\alpha_{ij}] \quad (1)$$

where, u_k is the velocity component, δ_{ij} is a unit tensor and ω_{ij} and γ_{ij} are the rotation rate and rate of deformation tensors respectively. λ is a constant that depends on the geometry of the fibers, defined as:

$$\lambda = (r_e^2 - 1)/(r_e^2 + 1)$$

with r_e being equivalent fiber aspect ratio. C_t is a dimensionless interaction coefficient introduced by Folgar and Tucker (1984) and it represents the degree of interaction between short fibers. The fourth order orientation tensor evolved in Eq. 1 needs to be approximated in terms of the second order tensor. In this paper, the hybrid closure approximation method proposed by Advani and Tucker (1990) is used. Hybrid closure approximation is a combination of quadratic model, which gives a correct answer for perfectly aligned fibers and linear model, which is exact for random alignments. The hybrid closure approximation for the fourth order tensor can be written as (Advani and Tucker, 1987, 1990).

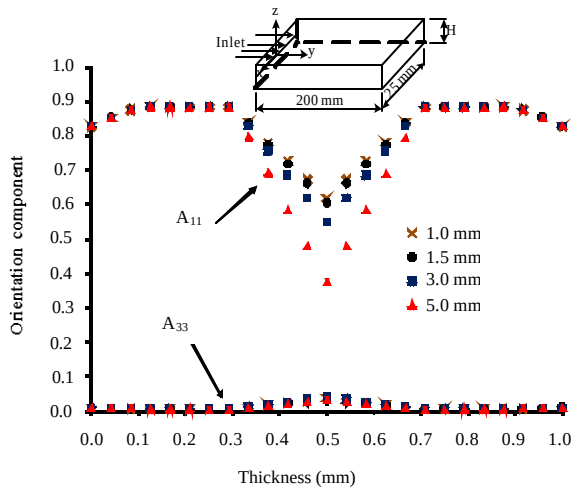

Fig. 5: Distribution of fiber orientation components A_{11} and A_{33} at position 160 mm from inlet for four different rectangular mold cavity thicknesses

$$A_{ijkl} = fa_{ij}a_{ij} + (1-f)\begin{bmatrix} -\frac{1}{35}(\delta_{lj}\delta_{ki} + \delta_{li}\delta_{jk}) \\ +\frac{1}{7}(\alpha_{ij}\delta_{kl} + \alpha_{ik}\delta_{jl} + \alpha_{il}\delta_{jk} \\ +\alpha_{kl}\delta_{ij} + \alpha_{jl}\delta_{ik} + \alpha_{jk}\delta_{il}) \end{bmatrix} \quad (2)$$

Where, f represents the scalar measure of orientation. It is equal to zero for randomly oriented fibers and one for perfectly aligned fibers. It is related to the orientation tensor by the following:

$$f = 1\text{-}27 \det [\alpha_{ij}] \quad (3)$$

Figure 5 shows flow and thickness directional fiber orientation components profiles for the five geometries at position 160 mm from the mold gate. For thicker geometry (5 mm), a thin core layer at the midplane of the cavity thickness is observed. As can be seen from the Fig. 5, the flow directional orientation component (A_{11}) has values larger than 0.8 near the mold walls (skin layer) and around 0.3 at the mid plane (core layer). On the other hand, for very thin geometry (1 mm), the flow directional orientation component has values greater than 0.6 throughout the thickness. These results indicate that in very thin cavities fibers perfectly orient in the flow direction and for thick cavities they orient in the flow direction near the mold walls and perpendicular to the flow direction at the mid plane of the thickness. For all thicknesses, the thickness directional orientation component (A_{33}) are very small (nearly zero near the mold walls). This indicates that the fibers are aligned in the plane of the mold.

Figure 6 Shows comparison between the numerical prediction and available experimental results (Vincent *et al.*, 2005) of flow directional orientation component at a distance of 160 mm from the mold gate for the 1.7 and 5 mm mold thicknesses. Generally, the numerical results are in fairly good agreement with the experiment for both thicknesses. The small difference near the mold walls for the 5 mm thick mold cavity might be reduced by including the gate in to the simulation and by varying the interaction coefficient.

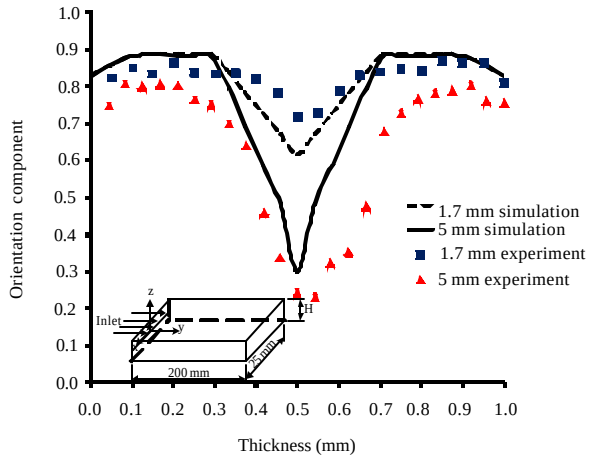

Fig. 6: Comparison of simulation and experimental (Vincent *et al.*, 2005) results of A_{11} in location 160 mm from inlet for the 1.7 and 5 mm mold thicknesses

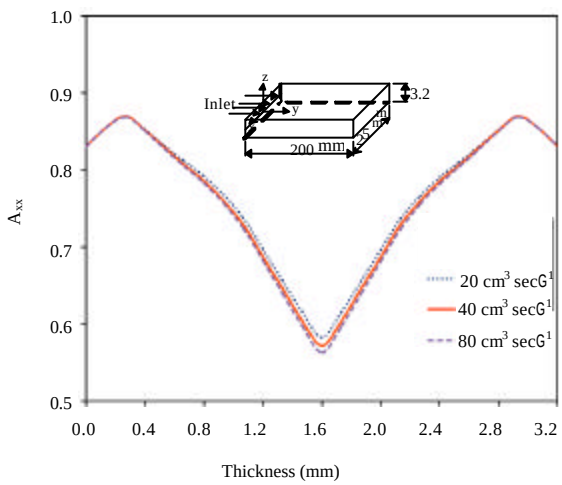

Fig. 7: Effect of injection flow rate on A_{11} in film-gated rectangular strip at the end of filling at position near to the mold inlet (Oumer and Mamat, 2012)

EFFECT OF INLET FLOW RATE

It is interesting to compare the effect of injection flow rate (injection speed) on the orientation of fibers. Sadabadi and Ghasemi (2007) has numerically studied the effect of inlet flow rate on the first component of the second-order orientation tensor (A_{11}) of a tensile test bar. From their simulation, they observed that A_{11} decreases in the higher flow rate region and increases in the lower flow rate region. Bright *et al.* (1978) has studied the effect of injection speed on fibre orientation in simple mouldings of short glass fibre-filled polypropylene (Bright *et al.*, 1978). They found out that injection speed highly affects the fiber orientation of fiber reinforced composites.

So, Fig. 7 and 8 show comparisons of flow directional orientation components for a thin rectangular cavity at two different locations from the inlet for three different injection flow rates: 20, 40 and 80 cm^3 sec^{-1}. Near to the mold inlet, the effect of flow rate on fiber alignment is not significant as shown in Fig. 7. However, at position far from the inlet, the effect of flow rate on fiber

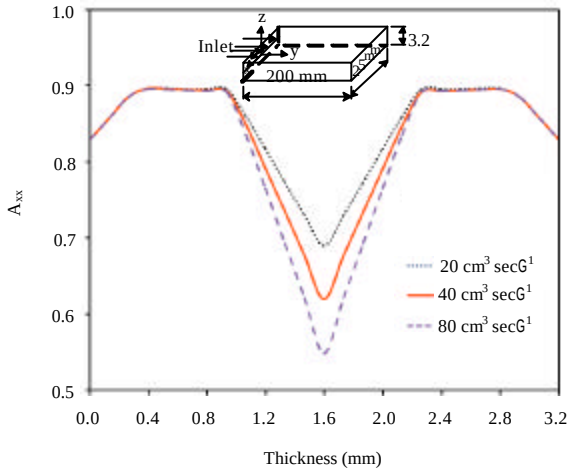

Fig. 8: Effect of injection flow rate on A_{11} in film-gated rectangular strip at the end of filling at half way from the mold inlet (Oumer and Mamat, 2012)

alignment is more significant. Figure 8 shows that lower flow rate causes good orientation of fibers in the flow direction whereas higher flow rate produces the opposite resulting too thin middle layer. In other words, for the same mold thickness, the core region (middle layer) is wider for strips with higher inlet flow rate. This is due to the fact that high filling flow rate widens the region of flat velocity profile near the midplane. However, it can be clearly seen from both figures that all the three flow rates give same prediction of fiber orientation near the mold walls.

CONCLUSION

In injection molded fiber reinforced composites, the mechanical and physical properties of the final product are highly dependent on the patterns of their fibers alignment. For instance, the strength and toughness of the final product is higher in the directions along which the most fibers align and weaker in the transverse direction. Therefore, during processing, it is essential to make sure that the large proportion of the fibers orient in the desired direction during the filling stage of injection molding. In this paper, a general review on the effects of molding methods, mold cavity thickness and other molding parameters on fiber orientation in injection molded polymer composites is presented.

For the same mold geometry and material composition, fiber orientation varies depending on the type of injection methods. In a cross section of a molded part produced by injection-compression molding, a five layer structure of fiber orientation (a core layer in the middle and two skin and shell layers on both sides of the part) is observed. Fiber orientation is also affected by the way the fiber-polymer matrix flows in the mold. In a simple shear flow the fibers tend to align in the direction of flow. In a converging flow, the force due to the velocity gradient aligns the fibers in the flow direction whereas in the diverging flow the force aligns the fibers in the direction transverse to the flow.

Regarding the effect of cavity thickness, the results indicate that in very thin cavities fibers perfectly orient in the flow direction. On the other hand, for thick cavities they orient in the flow direction near the mold walls and perpendicular to the flow direction at the mid plane of the thickness. Close to the mold inlet, the effect of flow rate (injection speed) on fiber orientation is not

significant. However, at position far from the inlet, the effect of flow rate on fiber orientation is more significant. At this position, lower flow rate causes good orientation of fibers in the flow direction whereas higher flow rate produces the opposite resulting too thin middle layer.

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