Flake Orientation in Injection Molding of Pigmented Thermoplastics

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In the present work, experimental studies are carried out to understand orientation kinematics of pigment flakes during the injection molding process. The injection molding experiments are carried out using ABS resin compounded with aluminum flakes. Thin specimens are sliced off from the injection molded sample, and then the orientation distribution is observed using transmitted microscopy. Generally, the microscopic result shows a sandwich structure where the orientation state near the mid-plane differs significantly from that around the surface. Particularly at the weldline region, locally different orientation is observed near the part surface, which is the result of fountain flow at the melt front. Also the effect of mold temperature on the flake orientation is presented. [DOI: 10.1115/1.4005309]

1 Introduction

As the interest of customers on product appearance is increasing in the recent years, the manufacturers of plastic products have been developing new materials and new processing technologies for aesthetic products. A composite material, in which pigment flakes, e.g., aluminum and mica flakes, are compounded with a thermoplastic resin, is now widely used in injection molding process to manufacture metal-, pearl-, or china-like plastic products. In terms of the processing, the most advantageous feature for using such composite materials would be that coloring process, e.g., spray coating, is not required after the molding process.

Generally, the flow field during the injection molding results in inhomogeneous and anisotropic orientation of the suspending nonspherical fillers. For the short-fiber reinforced thermoplastic composites, the thermo-mechanical property of the injection molded part depends on the fiber orientation state [1]. Thus, extensive theoretical, numerical and experimental investigations have been carried out to predict and characterize the fiber orientation in the injection molded part [2–9]. For the composites with flake or mica fillers, however, only limited numbers of reports could be found in the literature [10–12].

For the flake pigmented thermoplastic composites, the surface appearance of the injection molded part is significantly affected by the orientation state of the pigment flakes [12]. Thus, it would be an important issue to understand the basic orientation behavior of the flakes for the injection molding of aesthetic plastic parts. Particularly, the orientation behavior at the weldline is of technical importance since the color defect at the weldline becomes more pronounced due to the pigment flake orientation. In this regard, the present study aims at understanding the basic orientation behavior of the flakes in injection molding. Particular interests of the present study are (i) the basic kinematics of the flake orientation, (ii) the orientation state in the weldline region, and (iii) the effect of mold temperature on the orientation at the weldline region. First, the major feature of flake orientation is discussed in comparison with the fiber orientation using Jeffery model. Then the experimental results are presented along with schematic diagrams describing the flake orientation kinematics.

2 Particle Orientation Kinematics

Before beginning the discussion of the experimental results, Jeffery model would be useful to understand the basic kinematics of the particle orientation. Since short fiber and flake fillers have been widely used in the composite materials for various applications, the major difference between their orientation kinematics is briefly studied. The Jeffery model, which describes the kinematics of single rigid ellipsoidal particle suspended in a viscous liquid, reads as follows [13]:

$$\dot{p}_i = -\frac{1}{2}\omega_{ij}p_j + \frac{1}{2}\lambda\left(\dot{\gamma}_{ij}p_j - \dot{\gamma}_{kl}p_k p_l p_i\right) \quad (1)$$

where p_i is the orientation vector of the particle, $\dot{p}_i$ is the angular velocity vector of the orientation, ω_{ij} is the vorticity tensor, and $\dot{\gamma}_{ij}$ is the rate-of-strain tensor with the subscript representing the index notation. The geometry effect of the ellipsoid appears in the model as a single parameter of λ which is defined as

$$\lambda = \frac{(L/D)^2 - 1}{(L/D)^2 + 1} \quad (2)$$

where L and D are length and diameter of ellipsoidal particle, respectively. For a fiber-like geometry where $L/D \gg 1$, the geometry parameter approaches to 1. On the other hand, λ is close to -1 for a disk-like geometry where $0 < L/D \ll 1$. Here, we compare two cases of: (i) a fiber-like geometry with negligible diameter ($L/D = \infty$ thus $\lambda = 1$) and (ii) disk-like geometry with negligible length ($L/D = 0$ thus $\lambda = -1$). The coordinate system and the velocity field are shown in Fig. 1. Both the fiber and the disk have initial orientation state of $\mathbf{p} = (1/\sqrt{2}, 1/\sqrt{2}, 0)$. Figure 2 shows the evolution of the fiber and disk orientation vectors for applied shear strain ($\gamma = \dot{\gamma}t$). Since the angular velocity vector ($\dot{p}_i$) depends linearly on the velocity gradient, the result is the same for any positive shear rate. The orientation evolution has its steady state because the diameter of the fiber and the length of the disk are neglected. The fiber aligns in the direction of x-axis as strain grows, thus p_x and p_y approach monotonically to their steady state value of 1 and 0, respectively. The disk, on the other hand, approaches to a different steady state of $\mathbf{p} = (0, -1, 0)$, and one can observe the overshoot of p_x and significant decrease of p_y around $\gamma = 1$ where the disk aligns in the direction of x-axis. This simple comparison demonstrates the most significant difference between the fiber and the disk orientation kinematics: the disk orientation vector tends to align in perpendicular to the shear direction, while the fiber orientation vector tends to align in the direction of shear.

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Contributed by the Manufacturing Engineering Division of ASME for publication in the Journal of Manufacturing Science and Engineering. Manuscript received April 3, 2011; final manuscript received September 30, 2011; published online January 11, 2012. Assoc. Editor: Allen Y. Yi.

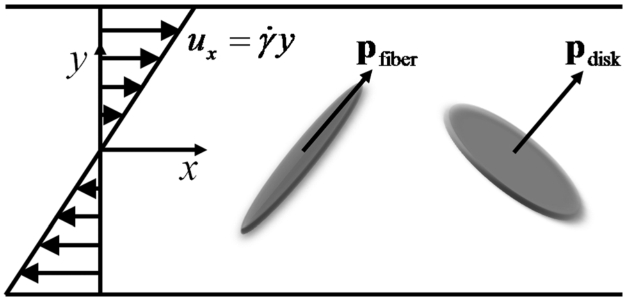


Fig. 1 Fiber and disk in simple shear flow

3 Experiment

ABS thermoplastic resin (XG569C, LG Chem.) is compounded with aluminum flakes (3% by volume) by extruder. The aluminum flake has a thickness of 1 μm and a characteristic radius of 95 μm. Figure 3 shows injection molding test geometry which has width of 320 mm and height of 100 mm. Several holes and ribs have been introduced to induce weldlines and flow marks intentionally for this study. Injection molding is carried out using LGH-450 N (LS Mtron). The processing condition is: filling time is 1.4 s; nozzle temperature is 220 °C; mold temperature for bottom surface is room temperature (RT); mold temperature for top surface varies with RT, 120 °C and 220 °C.

For a microscopic observation of the orientation state in the injection molded part, thin specimens are sliced off from the injection molded part by using low speed saw (IsoMet, Buehler). The specimen having a thickness of 200 μm is sliced along the thickness direction of the test geometry at the particular locations of interests. Then the orientation state in the specimen is observed using transmitted microscopy (Eclipse 80i, Nikon). Since the specimen has a finite thickness, total 30 layers of the microscopic images are captured with varying the focal position along the thickness of the specimen. After an assembly procedure of the layers using image processing software (iSolution DT, IMT i-Solution Inc.), the final microscopic image could be obtained.

4 Results and Discussion

Shown in Fig. 4 is a real image of the injection molded test geometry when the mold temperature is RT for both top and bottom surfaces. There are several color defects such as weldlines and flow marks, which is due to the presence of holes and ribs. Though not presented here, it is observed that such color defects tend to decrease as mold temperature increases. Particular interests of the present study are (i) the basic kinematics of the flake orientation, (ii) the orientation state in the weldline region and (iii) the effect of mold temperature on the orientation at the weldline region. Thus, three types of specimens are sliced from the test geometry. Figure 5 shows the location and the direction along which the specimens are sliced. The specimens of A and B are for observing the basic structure of the orientation state while the specimen of C is to investigate the weldline orientation as well as the mold temperature effect on the weldline orientation.

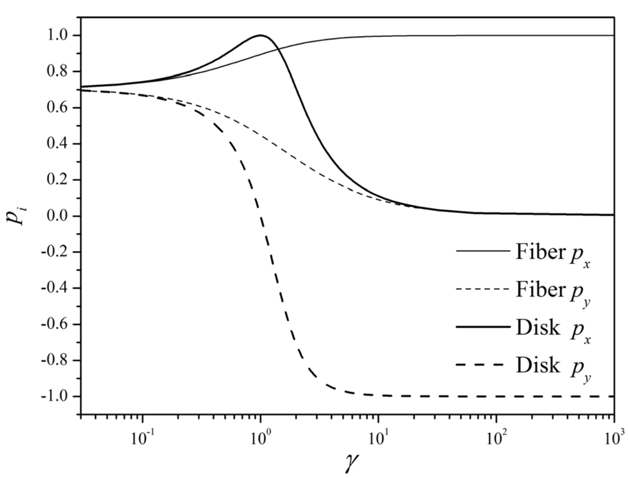


Fig. 2 Particle orientation vector evolution for fiber and disk

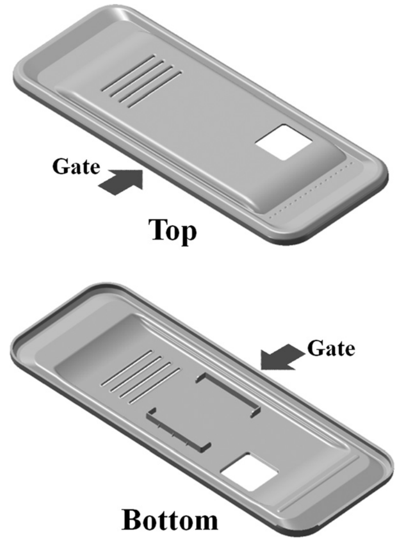


Fig. 3 Test geometry having holes and ribs

Fig. 4 Real image of injection molded test geometry

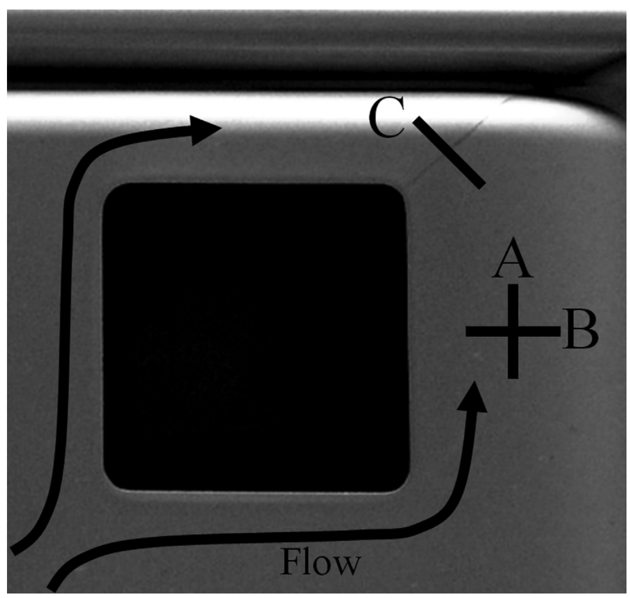


Fig. 5 Three locations where specimens are sliced off for microscopic observations

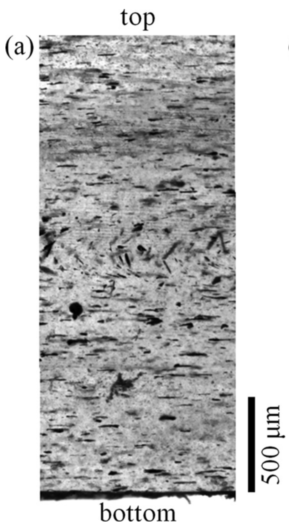


Fig. 6 Transmitted microscopic images for specimens from (*a*) location A and (*b*) location B

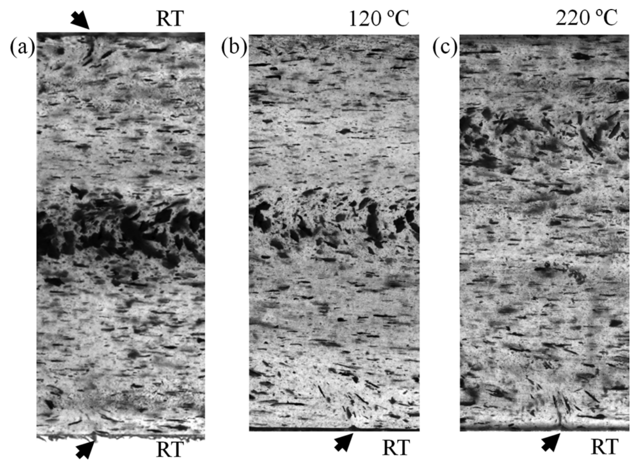
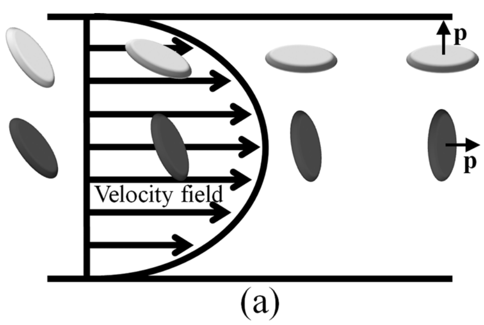


Fig. 8 Transmitted microscopic image of location C for three different mold temperature conditions of top surface: (*a*) room temperature, (*b*) 120 °C, and (*c*) 220 °C

Figure 6 shows the microscopic images for specimens of A and B when the mold temperature is RT for both top and bottom surfaces. These two images from different view directions will help understanding the three-dimensional orientation state in that particular location. The sandwich structure is clearly observable where the flake orientation near the mid-plane (namely the core layer) is significantly different from that around the surface (namely the shell layer). The flake orientation vector is defined as a surface normal vector on the flake plane as shown in Fig. 1. In the shell layer, the flakes tend to align in perpendicular to the surface plane. In contrast, the flakes align in parallel to the flow direction in the core layer thus the flake face can be observed in the specimen of B. The basic orientation kinematics of the pigment flakes would be better understood with the help of Fig. 7(*a*).



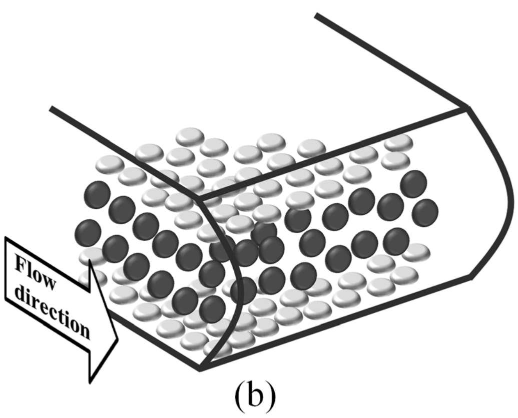


Fig. 7 Schematic representations of (*a*) disk orientation kinematics and (*b*) sandwich structure in injection molding

In this figure, a disk model represents the flake geometry. In the shell layer, the shearing dominates the material deformation, which drives the flakes to orient in perpendicular to the surface plane as observed from the result of Fig. 2. In the core layer, on the other hand, the shear is relatively small and velocity profile is symmetric with respect to the mid-plane, thus the flakes tend to have in-plane directional orientation. The three-dimensional sandwich structure is schematically represented in Fig. 7(*b*).

Figure 8 shows the microscopic images for specimens of C for three cases with different mold temperatures at the top surface (RT, 120 °C and 220 °C). At this location, two melt fronts merge with each other, which results in a weldline formation along the flow direction (see Fig. 5). When the mold temperature is RT at both surfaces (Fig. 8(*a*)), one can clearly observe that there are locally different orientation states close to the surface as pointed by arrows. At those locations, the flakes are not aligned in perpendicular to the surface plane. Such inhomogeneous orientation at the weldline will appear as a color defect since the reflection angle of the illumination light on the part surface depends on the flake orientation [12]. As the top mold temperature is increased to 120 °C and 220 °C (see Figs. 8(*b*) and 8(*c*), respectively), the locally different orientation at the top surface tend to disappear, while that at the bottom surface still remains as the temperature is not varied there. Another notable feature as the mold temperature of top surface increases is that the position of the core layer shifts close to the top surface (see Fig. 8(*c*)). Those orientation behavior and core layer shift can be explained as follows.

Figure 9(*a*) would be helpful to understand the flake orientation at the weldline region. The weldline is formed where two melt front meet with each other with a meeting angle (θ in Fig. 9(*a*)) between 0 deg and 135 deg. In the melt front, the flow field has three-dimensional characteristics, namely the fountain-flow, which has a velocity component of the thickness direction as shown in Fig. 9(*a*), and the fountain flow drives the flakes at the core layer to move to the shell layer. When two melt fronts merge, two fountain flows will meet with each other, which results in a local region near the surface where the flake orientation is not in perpendicular to the surface plane (see Fig. 9(*a*)). If the mold temperature is sufficiently low so that the solidification of the polymer takes place quickly, the orientation near the surface becomes frozen-in without any further reorientation. Therefore, the locally different orientation at the weldline is the result of the fountain flow at the melt front region and a rapid solidification of the polymer melt near the mold wall. As the mold temperature increases (only at the top surface), the polymer solidification near the top surface takes place more slowly, thus the flakes can reorient in perpendicular to the surface plane before they become frozen-in.

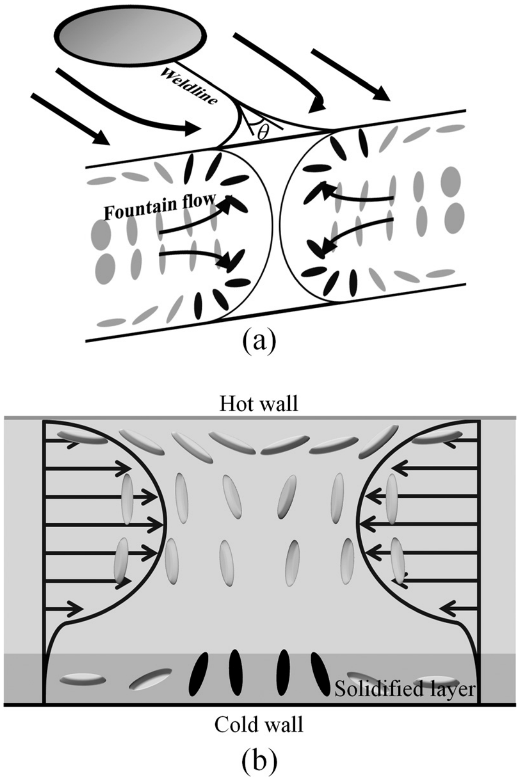


Fig. 9 Schematic representations of (*a*) flow and orientation kinematics at the weldline and (*b*) core layer shift

Also as the solidified layer thickness decreases at the top surface due to the temperature increase, the gap-wise velocity field becomes asymmetric with respect to the mid-plane, which results in a core layer shift, as represented schematically in Fig. 9(*b*). One would be able to obtain similar effects passively by introducing thermal insulation coating on the mold surface as discussed in Ref. [14].

5 Conclusion

The present study attempts to understand the basic kinematics of the flake orientation during injection molding. Especially, the orientation at the weldline and the effect of mold temperature on the weldline orientation are of particular interests in this study, which are also technically relevant issues for manufacturing the aesthetic plastic parts. A simple analysis is carried out by using the Jeffery model, which indicates that the fiber and the disk have totally different kinematics for the same shear flow. The experimental results show important features of the flake orientation in injection molding, which can be summarized as follows:

(i) Generally the flake orientation has a sandwich structure due to inhomogeneous shear rate along the thickness direction.

(ii) The flake orientation vector tends to align in in-plane direction near the core layer while they tend to align in perpendicular to the wall surface near the shell layer.

(iii) At the weldline, locally different orientation is observed close to the wall, which is the result of fountain flow and rapid cooling near the wall.

(iv) High mold temperature prevents the particle orientation being rapidly frozen-in near the wall, which can reduce the color defects at the weldline.

(v) Asymmetric temperature condition in top and bottom wall results in a core layer shift.

These results give a brief understanding on the flake orientation in injection molding of flake-pigmented composite. Further studies would be worth investigating for the modeling and simulation as well as quantitative characterization of the flake orientation in injection molded composite. In particular, predicting the flake orientation and consequently the surface color of the injection molded composite could be a useful tool to design the mold system for injection molding of the aesthetic plastic parts in the future.

Acknowledgment

Authors would like to thank financial and technical supports from LG Electronics. Also this research was supported by WCU (World Class University) program through the National Research Foundation of Korea funded by the Ministry of Education, Science and Technology (R31-30005).

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